Portland State University

PDXScholar

1-1-2011

Interception in Open-grown Douglas-fir (*Pseudotsuga menziesii*) Urban Canopy

Mitchell Bixby
Portland State University

Recommended Citation

Interception in Open-grown Douglas-fir

(*Pseudotsuga menziesii*) Urban Canopy

by

Mitchell Bixby

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Environmental Sciences and Resources

Thesis Committee
J. Alan Yeakley, Chair
Andrew Fountain
Joseph Maser

Portland State University
2011

ABSTRACT

I hypothesized that Douglas-fir trees (*Pseudotsuga menziesii*) standing apart from other trees ('open-grown') will intercept more rainfall than Douglas-fir trees standing near other trees ('closed-canopy').   Open-grown trees differ structurally and are more common in urban settings, yet have been infrequently studied. Existing literature, based primarily on closed-canopy trees, suggests Douglas-fir trees in Pacific Northwest forests intercept approximately 25% of rainfall annually. Because open-grown trees have more vertical leaf area than individual trees in closed-canopy forests, I expected to find higher interception by open-grown trees.

I collected throughfall under four open-grown Douglas-firs using six static collectors ('buckets') per tree, and two closed-canopy Douglas-firs using six buckets per tree. I compared their throughfall to the incident rainfall in two adjacent open-field buckets. Gross interception was measured in 53 collections during rainy weather from 16Nov07 to 31Mar08. Over the same period, rainfall per hour, wind speed, gust speed, wind direction, temperature and relative humidity were collected at a weather station located within 1 km of the site. For comparison, average hourly rainfall at Portland International Airport from 1950 to 2005, for the same months of the collection period, showed a comparable number of medium- to high-intensity storms, but more low-intensity storms.

I found that incident rainfall for the adjacent open-field buckets totaled 65.6cm and 71.6cm over the study period. Interception values for closed-canopy trees averaged 26%, corresponding to the literature, with results of 22 and 30%.

Interception values for open-grown trees averaged 31%, with results ranging from 15 to 45%. Three of the 24 buckets returned overall negative interception rates over five months.

Given the lower storm intensity of 2007-08, interception rates may be somewhat high, compared to the historical average. The negative interception rates at three buckets were likely due to their locations under high drip points, as has been observed in other studies. Considering the wide range of canopy architecture among open-grown trees, the high variability in interception was not surprising. My hypothesis was supported by the data, but requires more testing to better generalize these results. Future studies that link open grown tree canopy morphological characteristics to interception are warranted.

Dedication

For Becky—you were right.

Acknowledgements

The designing, doing, reviewing and writing of this project was a collaboration, if not of a cast of thousands, of several dozen. Chief among them was Alan Yeakley. Many thanks, Alan, for believing in this project and in me. Here's to Cubs and Cards going out for beers together. Go C[ ]s!!

Also, my thanks to Andrew Fountain and Joe Maser, for their interest and contributions. This was perhaps an unusual ride, this thesis journey. Thanks for sticking with me.

Of course, a gigantic shout out goes to everyone from the lab: Kate, Ben, Robin, Adelaide, Noah, Sarah and particularly Josh. I couldn't have figured it all out without the peanut gallery. I think we laughed a little along the way, too.

At the same time, I am deeply indebted to Dan Moeller and all the great people at Hoyt Arboretum. Meaning all the people at Hoyt Arboretum. This project simply wasn't do-able without your support. Thank you for looking after all my baby blue buckets.

The support of Jennifer Goodridge, Paul Ketcham and James Allison at the Bureau of Environmental Services also played no small role in my completing this thesis. They recognized that the schedule juggling involved was, mm, non-trivial and I am grateful for their understanding.

It's easy to see how acknowledgements could go on for pages, but the aid of Brett and Leah Schaerer really does require recognition. Brett was the ideal methods partner, with a legion of tricks and tools at his disposal. Leah, though, asked The Question: why not use a water bottle as bucket AND funnel? At which point Brett and I, buried in the wreckage of multiple futilities, both slapped our respective foreheads. Leah is the real genius behind it all.

Which leads inevitably to James and the folks at Culligan Water. Their willingness to help out in a really reasonable exchange allowed my rainfall collection to happen. It was new and it was weird but they heard me out and then played along. Thank you so much.

And, finally, a word of appreciation to everyone who kindly inquired how my thesis was (hi, Mom). It was fine. Really.

Now, it's better. Thanks for asking.

TABLE OF CONTENTS

List of Tables

List of Figures

Introduction

Studies of interception by tree canopy have been carried out for decades. Beginning at least as far back as the eminent hydrologist R.E. Horton (1919), scientists have explored how tree canopy acts as a platform for rain, allowing it to evaporate and preventing it from reaching the ground ("interception"). Helvey and Patric (1965) began using regression models to describe interception data relationships, before Zinke (1965), Rutter et al. (1971), and Mulder (1985) shifted to more complex, process-based models.

Interception studies since the 1970s have focused almost exclusively on existing forests or plantations (Rutter et al. 1971, Gash 1979, Liu 2001, Pypker et al. 2005), which are structurally distinctive. Trees growing in these conditions ("closed-canopy") develop vertically shallower canopies, and lower interception capacity (Xiao et al. 2000a). Conversely, trees in cities are frequently found standing on their own, either along streets, or in yards, or in parks. These trees have grown sufficiently apart from other trees or other structures ("open-grown"). The result is often that they have full canopies and maximum branching, leading to high-light availability, and high-evaporation capacity (Teklehaimanot et al. 1991).

Interception capacity of urban trees represents an important, and under-studied, component of urban hydrology. In the absence of natural forests, the larger canopies of open-grown urban trees may play a disproportionate role in managing the quantity and rate of rain entering an urban ecosystem. Also, from a practical standpoint, urban

stormwater managers believe that tree canopy helps mitigate the growing runoff

caused by the increasing hardscape of cities (McPherson et al. 1999, Xiao et al. 2000a,

McPherson et al. 2005). The role of trees in urban hydrology and the quantification of

their impact remains an important research question.

Interception Background

The combination of a large number of variables affecting interception with our

inability to directly measure interception makes the description of rain/tree

interactions complicated and difficult. Some key variables are brought out in the

literature, of which several important studies are listed below in Table 1.

Author	Year	Species	Location	Interception	Canopy
Rothacher	1963	*Pseudotsuga menziesii*	W. Oregon, USA	24% summer/ 14% winter*	Closed
Rutter, et al.	1970	*Pinus nigra*	SE England, UK	~34%	Closed
Gash	1979	*Pinus sylvestris*	East Anglia, UK	unknown	Closed
Teklehaimanot, et al.	1990	*Picea sitchensis*	SE England, UK	unknown	Open
Xiao, et al.	1999	*Pyrus calleryana* & *Quercus suber*	Davis, California, USA	15 and 21%	Open
Price & Carlyle-Moses	2003	Deciduous hardwoods	Ontario, Canada	18.8%	Closed
Link, et al.	2004	*Pseudotsuga menziesii*	S. Washington, USA	22.8 and 25.0%	Closed
Pypker, et al.	2005	*Pseudotsuga menziesii*	S. Washington, USA	25%	Closed

Table 1. Leading Studies on Interception. These studies focused on either
Douglas-fir forests, open-grown trees, or interception in general. *Rothacher found
throughfall of 76% summer and 86% winter; I have converted to interception without
factoring stemflow.

Closed-canopy v. open-grown

Canopies of forests or plantations are more or less continuous from tree to tree. Indeed, branches of neighboring Sitka spruce (*Picea sitchensis*) frequently overlap (Ford and Deans 1978), although increasing age of the forest can lead to gaps where limbs or whole trees have fallen down (Gash et al. 1995, Link et al. 2004). Due to the close proximity of trees in forests, light intensity decreases from the top of the canopy, which can result in lower branches dying off and reducing a tree's total leaf area. These conditions lead to high, shallow canopies, and lower Leaf Area Indices (LAI) (Makela 1997). Furthermore, the tight-knit canopy of forests may prevent moist air from leaving shaded areas, thus reducing evaporation (Teklehaimanot et al. 1991). Anecdotally, a walk in the forests of the Pacific Northwest can show that the conditions underneath closed canopy are often more humid, with less airflow, than conditions outside the forest. In these conditions, the closed-canopy of mature Douglas-fir forests catches between 22 and 25% of spring, summer and winter rainfall (Link et al. 2004, Pypker et al. 2005).

For open-grown trees, the interceptions rates on a single 9-year-old, 8.5 m-tall Bradford pear and a single 8-year-old, 5.6 m-tall cork oak were 15 and 27%, respectively (Xiao, 2000b). However, these trees were not coniferous, and may not be analogous to the conifers native to the Pacific Northwest. Furthermore, the sample size was small, with only one tree for each species. Therefore, comparison of open-grown and closed-canopy interception for Douglas-fir is warranted.

Storm gaps

Storm gaps are the times between the end of one storm and the beginning of the next. During the course of a rain event, rain stoppage may allow the canopy to partially dry. However, in interception studies, it is useful to know when the canopy is completely dry and evaporation from wet leaves is complete (Gash 1979). The quantification of 'storm gap' depends on the study goals and is a key issue addressed in interception studies. For example, Rutter et al. (1971) sought a fine time-scale understanding of how and when interception occurred in canopy, and used five-minute intervals during rainy periods. In contrast, Gash (1979) tested a model which assumed a single storm per day, applying his model only to trees completely dry at storm's onset. In between, Mulder (1985) chose two-hour gaps while Link (2004) selected gaps of six hours. Ultimately, distinguishing the individual non-convective storms that dominate from November to March in the Pacific Northwest may not be possible without highly sophisticated methods (George Taylor, pers. comm.).

I used Link's six-hour gap because it allowed me to distinguish between rain events without having to bundle storms, for example, an early-morning storm and a late-afternoon storm, into a single rain event. On the other hand, a six-hour gap allowed a description of the Pacific Northwest's chronic, multi-day rainy periods, during which long periods of drizzle might not immediately register in a tipping-bucket rain gauge, but would prevent measurable evaporation.

Tree morphology

Scientists have studied interception on a myriad of tree species, from pines (Rutter et al. 1971, Gash 1979) to cork oak (Xiao et al. 2000b) to a suite of eastern North American hardwoods (Price and Carlyle-Moses 2003). The species of tree studied affects interception in three major respects: leaf fall dynamics, bark roughness, and tree architecture. Whether a species is deciduous or not affects its interception capacity. Trees that have lost their leaves have reduced surface area and support less water, reducing interception capacity. In the Pacific Northwest, most of a year's rain occurs in the months when deciduous trees are without foliage. In particular, Portland, Oregon's airport receives 67% (i.e. 61.5cm of 92.2cm) of its average annual rainfall during the five months from November through March, during a period that deciduous trees typically have no leaves (National Weather Service 2011).

Bark roughness is another important factor in interception differences among tree species. Trees with smooth bark tend to have high rates of stemflow, or flow down branches or trunks. Horton (1919) found that, in the heaviest storms, 10% of the rain falling on beech (*Fagus* spp.) was stemflow, as compared to pine (*Pinus* spp.), for which stemflow leveled off at 2% for the same storms. High rates of stemflow mean rain is less likely to be held in cracks along stem and branch surfaces, giving the water less time to evaporate back into the atmosphere. Smooth bark allows water to quickly

run off its surface, leading to larger collection volumes than expected for rough bark (Voigt 1961, Rothacher 1963).

Trees with rougher, craggier bark, on the other hand, can hold more water, creating another reservoir that intercepts rainfall. Several studies of Douglas-fir forest (Rothacher 1963, Link et al. 2004, Pypker et al. 2005), and of maritime pine (*Pinus pinaster*) (Lankreijer et al. 1993) indicated that stemflow constituted a minor, even negligible, destination of rainfall on rough-barked species.

Tree architecture describes how the parts of a tree are arranged. Within the field of interception studies, canopy is affected in at least three ways: abrasion, leaf layering and variability. Increased density increases abrasion, the process by which branches on neighboring trees break the others' branch tips. Higher density, or stocking rates, leads to greater degrees of self-pruning, and smaller, less filled-in canopies as a result (Takahashi 1996).

The way in which a species tends to layer its leaves, either predominantly monolayer or predominantly multilayer, also helps explain how canopies change from closed to open growth scenarios (Horn 1971). A tendency towards multiple layers may represent a species response to reduced moisture through smaller, widely-spaced leaves, or greater light availability. Both smaller leaves and greater light availability would be increasingly appropriate in open-grown trees.

Variability of canopy structures can occur in a number of ways, including branch angle (Horton 1919), petiole sturdiness (Liu 1997), maximum foliage height

(Godfree 2000), live crown ratio (Godfree 2000), gap fraction (Gash et al. 1995),

biomass and branch diameter (Ishii et al. 2000), needle age (Jensen and Long 1983)

and specific leaf area (St. Clair 1994). These structures can vary among species

(Horton 1919), and can vary within a species (Godfree 2000). The work done on

specific leaf area, for example, describes leaf areas ranging from 60.9cm^2/g (St. Clair

1994) to 85.7cm^2/g (Del Rio and Berg 1979) per tree. The variability in specific leaf

area would have obvious consequences for interception: the larger a tree's leaf area,

the more rain it is likely to intercept. Variability has been observed as the source of

important channeling effects and gaps, making large error estimates unavoidable (Ford

and Deans 1978).

Evaporation

Interception is the evaporative process that occurs when water is resting on a

plant. It is a purely physical process, unrelated to the physiology of the supporting

organism. Evapotranspiration is the process by which the water at the top of a plant's

water column is either used in photosynthesis or exits the leaves' pores as water vapor.

The process of interception inhibits that of evapotranspiration. Once leaves are dry,

stomata can begin releasing water vapor from within the plant. Until all the leaves are

dry, the water remaining on the canopy surface is said to be stored. The length of time

needed to completely dry, thus restoring a tree's full storage capacity, varies according

to many of the environmental factors mentioned below.

The physical basis of canopy evapotranspiration from vegetation canopies is frequently modeled by the Penman-Monteith equation (Dingman 2002):

$$E = \frac{\Delta \cdot (K + L) + \rho_a \cdot c_a \cdot C_{at} \cdot e_a^* \cdot (1 - W_a)}{\rho_w \cdot \lambda_v \cdot [\Delta + \gamma \cdot (1 + C_{at} / C_{can})]}. \qquad (1)$$

which incorporates a wide range of environmental factors to estimate evapotranspiration for vegetation. The equation calculates evapotranspiration [E] by combining the short- and long-wave radiation multiplied by the slope of the curve of saturation-vapor vs. temperature [$\Delta \cdot (K+L)$] with an atmospheric term composed of current air density [ρ_a], the specific heat of air [c_a], and saturation vapor pressure [e_a^*]. The combination of energy and air capacity are then divided by a water term, composed of the current density of water [ρ_w], the latent heat of vaporization of water [λ_v], and, once again, the slope of the curve of saturation-vapor vs. temperature [Δ], the psychometric constant [γ] and the fraction of atmospheric conductance for water vapor [C_{at}] out of a canopy's conductance [C_{can}]. Rutter (1971) adjusted this equation to better account for evaporation from the uneven surface of tree canopy.

Gash's (1979) work incorporated models by Rutter et al. (1971) and Penman-Monteith (Dingman 2002), but proposed a model simplifying the data needs of earlier approaches. He described interception on the basis of daily rainfall, with the assumptions that rainfall and evaporation were consistent throughout the day's storms, and that water dripping from the canopy is nearly non-existent at the start of storms ("wetting up") and short-lived afterwards (Gash 1979). Gash's model is a

simplification of Rutter et al. (1971), in that it describes interception only on the basis of daily rainfall, not as an up-to-the-minute total (Lloyd et al. 1988, Hormann et al. 1996). However, the assumptions used by Gash limit the usefulness of this model as a practical way to describe interception at a given site. Despite their shortcomings, physically-based models have proven adequate in various applications, and, more importantly, have framed the interception discussion by describing the key concepts of interception. Several of those concepts are central to the idea of an interception water balance.

Water Balance

Dating back to Horton (1919), but more explicitly starting with Helvey and Patric (1965), interception models use some variant of a water balance calculation:

$$I = R - T - Tr, \qquad\qquad (2)$$

where (I) is interception), (R) is incident rainfall, (T) is canopy throughfall, and (Tr) is stemflow. However, after a certain amount of rainfall, a tree's canopy reaches its storage capacity (S), and no longer intercepts rain. All rainfall after this time is assumed to be throughfall.

Some studies have tried to measure these fluxes directly. For example, Helvey and Patric (1965) compiled a number of interception datasets from throughout eastern North America and used linear regression models to estimate interception rates among them. That approach, though, was thought only applicable to eastern North American

hardwood forests (Aston 1979). Rutter et al. (1971) found evaporation from pine forests to be many times that predicted by the Penman-Monteith equation (Dingman 2002). Thus, Rutter et al. (1971) combined Penman-Monteith with a rigorous, computerized approach to atmospheric measurements that formed the basis for many interception studies that have followed (e.g. Gash 1979, Lankreijer et al. 1993, Liu 1997). Teklehaimanot et al. (1991) suspended cut trees by cranes during wetting and measured the time at which their storage capacity leveled off. The effort required for such a technique is substantial, not to mention destructive.

Liu's model was instructive in that, unlike Rutter et al. (1971), it used no empirical parameters, relying on a canopy dryness index, rain intensity, and a time interval (Liu 1997). The data requirements for the Liu model include maximum canopy storage, the range of meteorological data required to assess evaporation rate, and both pre- and post-storm precipitation. While many studies have attempted to measure the inputs and outputs of a forest system necessary for modeling, this kind of rigor was beyond the scope of my study.

Spacing

Despite attempts to fine-tune models for the lattice of spaces in natural forest canopies referred to as "gap fraction" (Aston 1979, Gash et al. 1995), most studies have neglected the effects of wide spacing on interception; it remains a factor for which no model explicitly accounts. A study of specifically-spaced plantation trees

correlated increased drying with increased spacing of trunks, as one might expect, although the mechanics of how this happens were not described (Teklehaimanot et al. 1991). Furthermore, their subject trees were grown in rows 2m apart, so it is not clear to what extent these trees were truly open-grown. It seems likely that trees in the same row grew up with trees close by on two sides, although this was not specified.

Wind

While increased spacing improves airflow, and thus interception, wind can also decrease the amount of rain being held in storage. High winds can cause trees to sway, shaking water off their leaves, and converting potential interception to mere throughfall (Hormann et al. 1996). Wind also changes the angle of leaves, causing them to drain their stored water (Xiao et al. 2000a).

Urban Hydrology

The effect of trees on urban hydrology is just starting to be understood. Trees are not part of the standard city stormwater system of gutters, pipes and treatment plants. However, as ecologists expand their studies to include the built environment of cities and towns, the linkage between urban forest and urban hydrology becomes more important.

Urban forests

The spacing of urban trees is markedly different from that of forest trees. Urban areas, almost by definition, tend to have very little remaining forest land, though some cities such as Portland, Oregon, have preserved sizable stands of mature forest within parks. In such environments, interception may reflect that of native forests.

City parks composed of mature stands, however, are relatively infrequent. Urban trees are more likely found in less arboreal parks, in private yards, and along streets; these trees can be described as open-grown, growing with wide gaps between individuals. A hike in any forested environment readily shows that open-grown trees are comparatively rare, suggesting different, and perhaps higher, rates of interception per tree in the overall urban forest, as compared to native forests.

Urban Stormwater

The hydrology of urban systems is also quite different from the hydrology of forested systems. Urban environments tend to have much more impervious surface, in the form of streets, parking lots, sidewalks and roofs: in Portland they cover at least 30% of 350 square kilometers. Impervious surfaces prevent infiltration of rainwater as well as directing it into stormdrains. These larger flows suspend more pollutants and

transport them into waterways; their higher energy can also damage infrastructure, as well as natural channels (Walsh et al. 2005).

In some cities, stormwater and sewage are conveyed to treatment facilities in shared pipes. When large storms create volumes of water larger than can be treated, the excess water is shunted to nearby waterways, creating Combined Sewer Overflows (CSOs). Spills of untreated water can create additional costs in the form of fines or, in the case of Portland, significant lawsuits. The lawsuits filed by Northwest Environmental Advocates as a response to excessive CSOs have forced the City to increase stormwater storage and management capacity through pipe upgrades, construction of ecoroofs and bioswales, and increased tree-planting. Interception is seen as an integral part of mitigating stormwater (Environmental Services 2011), and many studies support the idea that vegetation, in general (Sanders 1986), and interception, in particular (McPherson et al. 1999, Xiao and McPherson 2003, McPherson et al. 2005), are critical in this role. At the same time, the general lack of intact, contiguous tree canopy in cities means fewer trees are available to mitigate stormwater. Filling gaps in the canopy by planting more trees, especially around impervious areas, would decrease stormwater runoff by increasing interception. A better understanding of interception would allow a better calculation of how many trees to add and at what spacing.

Reasons to Research Open-Grown Trees

The definition of open-grown trees is potentially broad, encompassing any tree able to grow a full canopy with maximum branching. In cities, branches are often pruned up a trunk for safety or access reasons, though the tree might still be considered open-grown. Another definition might include trees whose stems are far enough apart to allow full sun on the whole canopy. For my study, I considered trees with a gap around their perimeters at least as wide as the tree crown's perimeter to be open-grown.

My hypothesis that distance between trees increases interception is based on two observations. First, given a crown-width gap, an open-grown tree has much higher light availability. Increased light over the tree's lifetime typically leads a tree to retain branches much further down the trunk than trees with less light. My first observation, then, is that the fuller canopies of open-grown trees tend to have a larger leaf area and, thus, larger storage capacities. Larger storage means a greater volume of water can be held in place to evaporate, although this could also mean longer drying times with no net benefit. My second observation is that having sufficient space around the tree leads to an increased ability to dry the canopy. Open-grown trees have better airflows, drying more quickly and allowing a shorter "recharge" time (Teklehaimanot et al. 1991).

Research Questions and Hypotheses

In this thesis, I hypothesized that Douglas-fir trees (*Pseudotsuga menziesii*) standing apart from other trees ('open-grown') intercept a larger volume of water than Douglas-fir trees standing near other trees ('closed-canopy'). To test my hypothesis, I have measured throughfall and incident rainfall to determine interception, and compared:

a) open-grown interception to published interception rates in forests;

b) open-grown interception to *in situ* closed-canopy interception.

15

Methods

<u>Overview</u>

My overall approach was to capture rain dripping through the canopy of four open-grown and two closed-canopy Douglas-fir trees at Hoyt Arboretum, Portland, Oregon, from early November 2007 through March 2008. I measured throughfall in six fixed buckets per tree, at a frequency of every 1-3 days, depending on rain conditions. During the same time, I collected unobstructed rainfall at two "open-field" buckets, identical to those under the trees. Over the same period, I also took weekly readings from a nearby tipping-bucket raingauge in the Hoyt Arboretum Visitor's Center maintenance yard. This raingauge, along with the open-field buckets and a tipping-bucket raingauge near the Children's Museum that was operated by the City of Portland's HYDRA network (site #192), provided an estimate of the local incident rainfall. The difference between the throughfall and incident rainfall provided an interception value of the subject trees.

<u>Site</u>

I chose Hoyt Arboretum, in the West Hills of Portland, Oregon, as my study site. The Arboretum features a wide range of trees, but was created in 1929 as a preserve for genetic specimens of soft-wood species, and particularly Douglas-fir. As a result, a large number of mature Douglas-fir trees occur mostly in small patches of forest, and occasionally as individuals. The Arboretum is 2.5 km west of the center of

Portland [45.52˚N, 122.73˚W], making it a convenient study location. The West Hills

(elevation: 244 m) tend to get more rain than the official weather station at Portland

International Airport [elevation: 61m; 45.53˚N, 122.67˚W] (Johnson 1987). The study

sites all occupied the south-facing slopes of the Arboretum (Figure 1), along regularly-

maintained trails and close to two tipping-bucket raingauges.
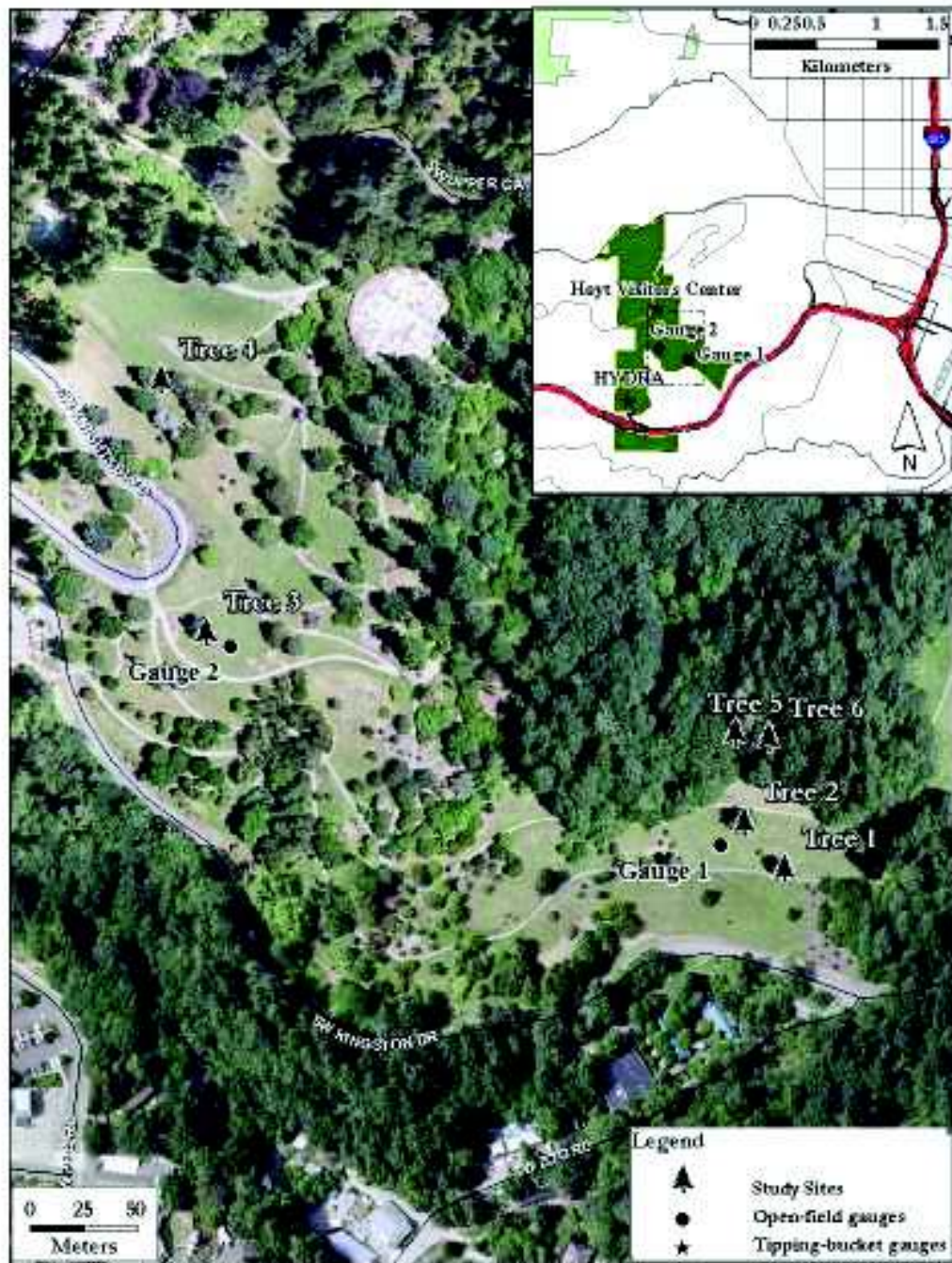
Figure 1. Map of Study Sites and Raingauges at Hoyt Arboretum in Portland, Oregon. Trees 1-4 are open-grown while trees 5-6 are closed canopy. Hoyt Arboretum is 2.5km west of downtown Portland. All four gauges (2 tipping-bucket and 2 open-field) are shown in the inset map.

<u>Trees</u>

I selected Douglas-fir trees as the single species of study primarily because it is the dominant local conifer. Furthermore, in situations where increased urban interception is desired (for stormwater mitigation, for example), the ability of Douglas-fir trees to catch water during winter's high-rain season make this species an obvious candidate. The height and aspect were determined by clinometer, diameter at breast height (DBH) was measured by logging tape, and elevation was noted from a GIS contour layer. Projected crown area was estimated at the time of bucket placement; the method for finding estimated leaf area is described later in this section. The findings of these measurements are presented in Table 2.

Open-grown

I selected four Douglas-fir trees as my open-grown study subjects #1-4 (Figure 2). All trees had a DBH of at least 40 cm, and an estimated height of at least 11m (Table 2). All would have been considered mature (Figure 2), and were probably at least 30 years old, although I did not core them. Tree 4 was part of the Arboretum collection; records indicate it was planted in 1980, though the age at planting is not known. All trees were on south to southwest aspects, at elevations between 221m and 242m. All trees also had branches to within 3m of the ground, with branches present along more than three-quarters of their height. Three trees had no other trees or structures within at least a full-canopy-width around their perimeter. Tree 4 was

neighbored by one full-grown tree to the southeast, with touching canopy edges, and another to the northeast, with canopy edges about 7m apart. Tree 4 had full canopy on all sides, indicating little or no growth interference by either neighbor. Despite the relative abundance of open-grown Douglas-fir trees at the Arboretum, most had had enough lower limbs missing to disqualify them from the study. Tree 4 was included, then, despite neighboring trees, because of its full vertical canopy.

Trees 1 and 2 were located within 50m of each other, between the Maple and Hawthorne Trails at Hoyt Arboretum, at elevations of 236m and 241m and on the same, due-south-facing aspect (Figure 1). Open-field collection bucket #1 stood in their vicinity, at least 10m distant from any obstruction. Tree 3 stood about 500m to the west of trees 1 and 2, near a hairpin bend in Knights Road, at an elevation of 255m and on a slope with an aspect of 253 degrees. Open-field collection bucket #2 was about 15m east of tree 3. Tree 4 stood about 120m north-northwest of tree 3, along the Holly Trail, at an elevation of 258m, and on a slope with an aspect of 219 degrees (Figure 1).

Figure 2: Photos of Open-grown Douglas-firs. Study trees 1 [upper left], 2 [upper right], 3 [lower left] and 4 [lower right].

Closed-canopy

I selected two trees, #5 and 6, from within a forested stand just uphill from the Hawthorne Trail and tree 2 (Figure 3). The edge of the stand was 20m from trees 1 and 2, although trees 5 and 6 were another 35m into the patch, and 5m higher in elevation. Trees 5 and 6 had a similar girth (at least 40cm) to the open-grown trees, although they were at least twice as tall. These trees were surrounded (>90%) by other trees of similar height, and their branches began at least 15m up the trunk.

	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5	Tree 6
Height (m)	11.3	15.0	15.3	13.4	44.6	41.0
Diameter Breast Height (cm)	43	48	51	45	81	70
Aspect	181	181	253	219	175	175
Projected Crown Area (m^2)	63.9	111.5	66.2	55.2	42.4	34.4
Leaf Area (m^2)	66.1	93.0	70.9	69.5	n/a	n/a
Elevation at base (m)	236	241	255	258	246	246
Canopy Type	open	open	open	open	closed	closed

Table 2. Characteristics of Study Trees. The table summarizes some of the key physical characteristics of all six trees studied.

Figure 3. Photo of Closed-canopy Douglas-fir Stand. Trees 5 and 6 stood in the center of the stand in the distance, about 35m uphill from the clearing edge.

<u>Collecting throughfall</u>

Buckets v. troughs

Most interception studies have used either buckets or troughs to collect throughfall. The buckets are cylinders of various sizes topped with funnels (Gash 1979), while troughs are shaped like, and often made of, ordinary rain gutters (Rutter et al. 1971). It has been argued that troughs, because they capture both high-drip and low-drip areas under canopy, better reflect the variability of a tree's throughfall

(Kostelnik et al. 1989). The steep sides of the funneled tops of buckets, however, are thought to reduce splash; the relatively shallow angle at which troughs are placed encourages loss of throughfall via splashing (Puckett 1991). Direct comparison of the two methods found no statistical difference between bucket catch and trough catch, for either Sitka spruce (*Picea sitchensis*) or Japanese larch (*Larix kaempferi*) (Reynolds and Neal 1991).

A study of throughfall variability under a Western redcedar (*Thuja plicata*) and Western hemlock (*Tsuga heterophylla*) forest demonstrated the relationship between variability and the number of bucket collectors (Kimmins 1973). The study, which used 94 collectors, found that rainfall totals of less than 6.0cm per week had increasing variance, requiring more buckets to reduce variation (i.e. within 10% standard deviation). Given the increasingly large number of buckets required to maintain small standard deviations, the author recommended stopping at 30 collectors and accepting larger (20%) standard deviations (Kimmins 1973).

From a practical standpoint, buckets were much simpler and much less costly to use than troughs. Troughs required many pieces to prevent evaporation loss and to accurately convey rainfall to storage. They also required careful calibration to determine their catchment area. Finally, they were relatively delicate and unstable; it took little interference to render a trough unusable. In contrast, buckets were cheap, easily installed, presented minimal evaporation and had no additional parts. Damaged buckets were quickly replaced. Given that recent studies have used arrays of up to 24

tipping-bucket raingauges and up to 48 manual raingauges to assess throughfall (Link et al. 2004, Pypker et al. 2005), the use of buckets for my study seemed appropriate.

Number of buckets

 To determine how many buckets should be placed per tree, I ran a pilot test in the spring of 2007, placing 14 buckets under a Douglas-fir for several rain events. Most storms were too small for the canopy saturation that leads to throughfall, but two storms provided at least 2.5cm of throughfall. I randomly sampled from the throughfall totals of a given number of the 14 buckets. Using a Monte Carlo analysis written in R, a statistical software, I randomly sampled and averaged each of the given number 50 times for a progression of sample sizes, starting with 1-bucket samples and ending with a 14-bucket sample (and the actual sample mean).   A variogram suggested that the range of covariance dropped into a more consistent range at about six buckets (Figure 4).
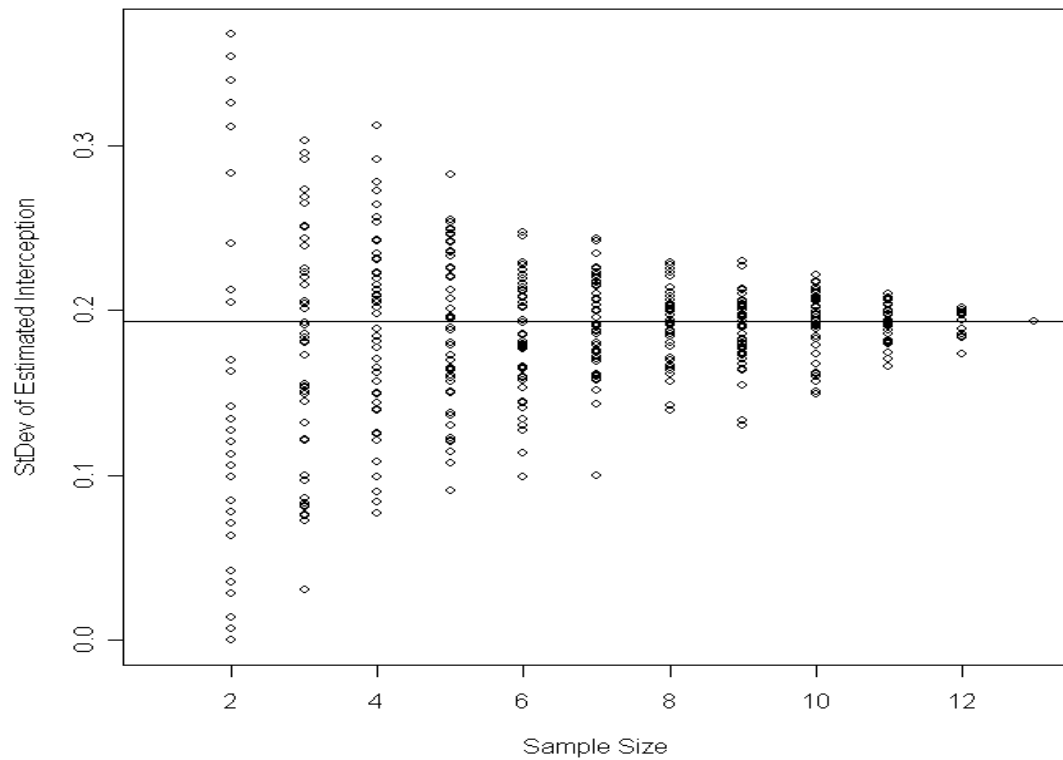
Figure 4. Variogram of May 2007 Storms. The variogram shows decreasing variability of measured throughfall with an increasing number of collectors. The x-axis is the sample size of the collectors, while the y-axis shows the standard deviation of the estimated interception.

The throughfall data from those two storms supported two conclusions. First, six was an adequate number of buckets for capturing the variability of throughfall for this particular tree. Second, the data showed that the south side of the tree had more throughfall. For my target tree in May, the south side allowed more rain to come through, suggesting the importance of storm direction. Given that the angle of incidence might differ from storm to storm, as well as from tree to tree, a truly random

placement of buckets might put my buckets largely out of the key sector for that storm at that tree. For this reason, I used a stratified approach, dividing the crown area into three equal wedges. Within each 120-degree-wedge, two buckets were placed randomly.

Construction

Given limitations in funding and concerns about vandalism, I attempted an approach that did not use large numbers of tipping-bucket rain gauges, instead modifying 5-gallon polycarbonate water cooler bottles ("buckets"). I cut the top off each bottle about 17cm below the end of the spout, and flipped it, creating a tight-fitting funnel (Figure 5). I recorded the width of the newly formed opening and numbered each bucket. I tried several methods for keeping the buckets in place under the trees. The cheapest, most reliable method was duct-taping a 5cm section of 1.1cm (0.5in)-diameter PVC pipe to the side of each bucket, using the PVC pipe as a sleeve around a 0.7m section of rebar staked in the ground (Figure 6). I gave most of the buckets a slug of cement ballast. As the undersides of the bottles resemble the bottoms of wine-bottles, I poured Portland cement into the dimple and then epoxied the slug into place once it had dried. This ballast proved unnecessary, since the PVC sleeve/rebar combination was sufficient support, and the epoxy holding the cement failed on many buckets after 8-10 weeks.

27
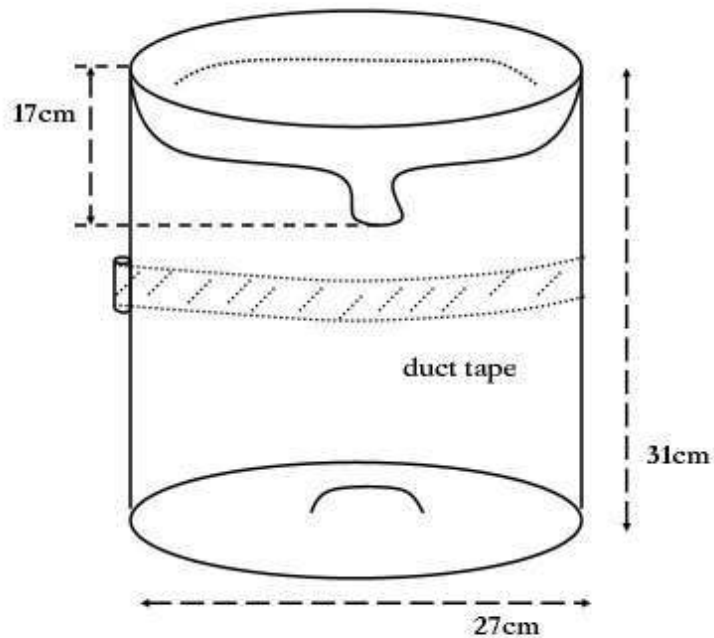
Figure 5. Schematic of a Sample Collection Bucket. The spout of a 5-gallon water cooler bottle is cut off and flipped over to act as a funnel, while a short section of duct-taped PVC pipe holds the bucket onto a rebar stake.

Figure 6. Photo of Buckets at Study Tree 4. The photo shows bucket placement and attachment to rebar stakes.

Placement

The location of each of the six buckets per tree was partly randomized. For each 120˚ wedge, starting at 0-degrees north, I randomly picked a bearing between 0 and 120 degrees. At that bearing, I measured the radius from the trunk surface to a point where the number of branches breaking a vertical line extending up from the tape went from three to two. This measurement was intended to make a somewhat conservative estimate of the canopy area, so as not to have buckets near the canopy edge. I then calculated the square root of a randomly-generated decimal to determine the bucket's placement in centimeters along the randomly-generated bearing (Figures 7-12). This procedure effectively randomized location over a circular area, although it was somewhat biased towards the interior.
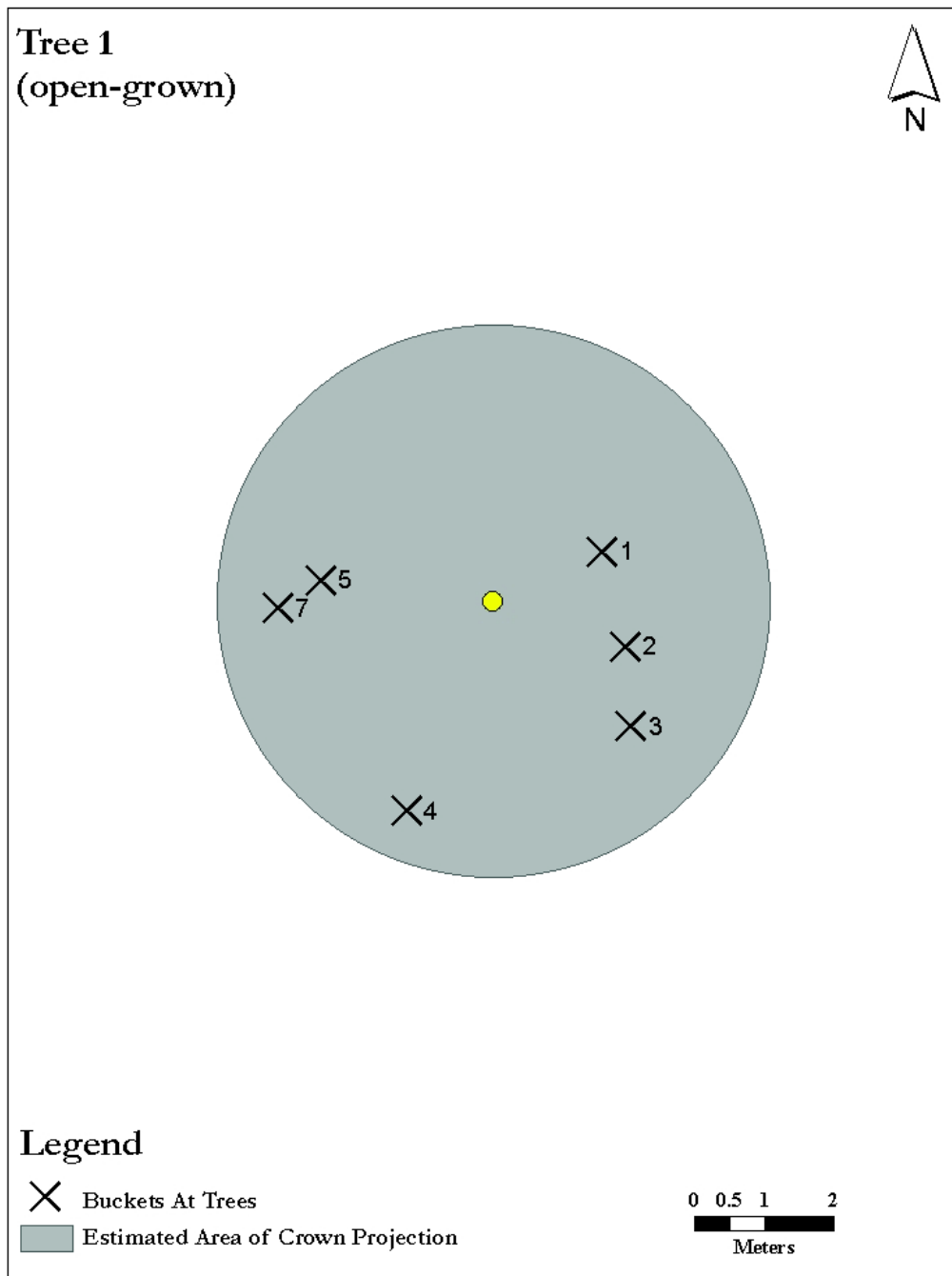
Figure 7. Bucket Placement at Study Tree 1. Tree 1 was open-grown, 20m south of tree 2, and near open-field raingauge #2. It grew just south of the forested area where trees 5 & 6 grew. The approximate radius of the projected crown area is 4.0m.
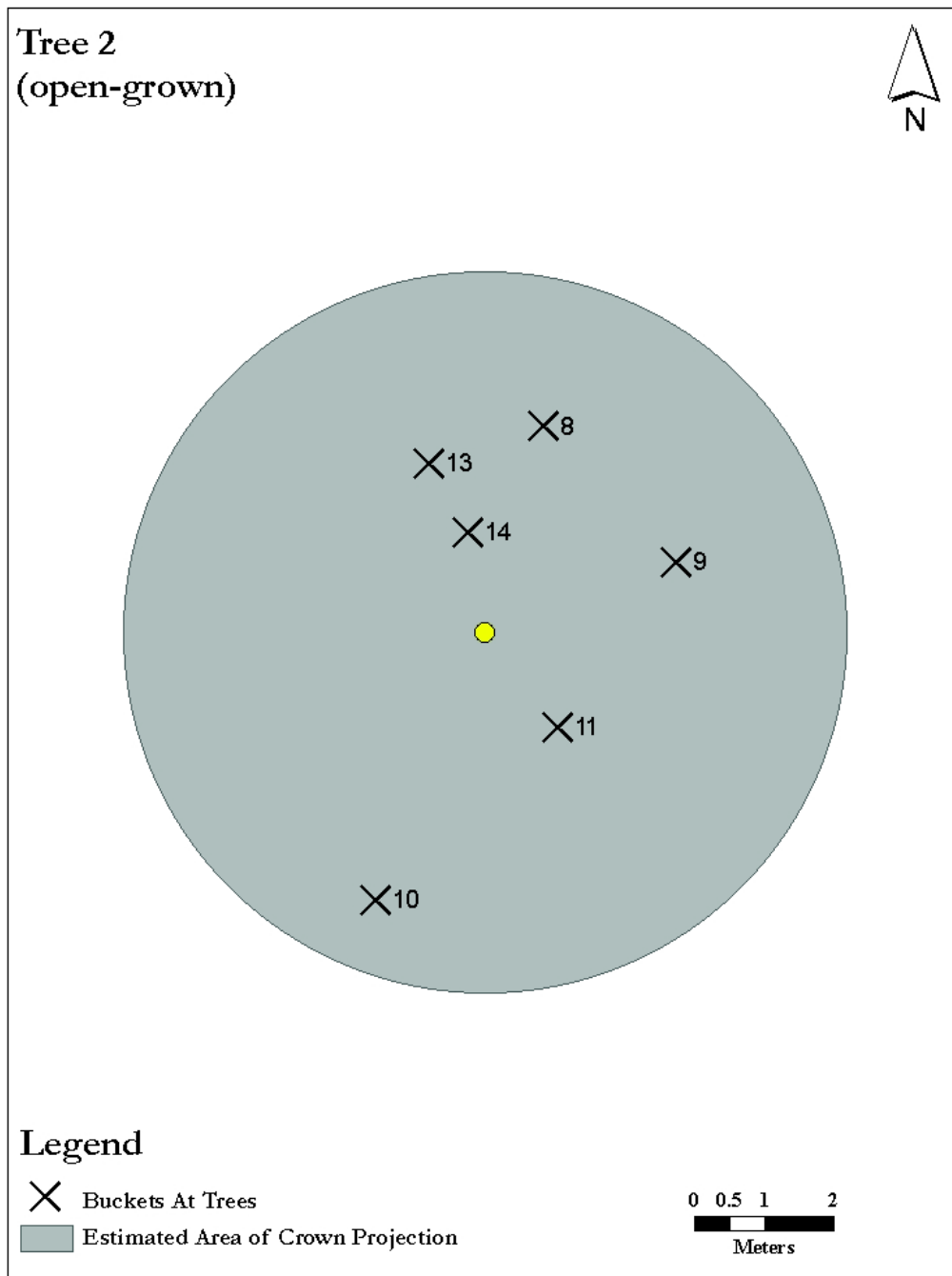
Figure 8. Bucket Placement at Study Tree 2. Tree 2 was open-grown, 20m north of tree 1, and near open-field raingauge #2. It grew just south of the forested area where trees 5 & 6 grew. The approximate radius of the projected crown area is 5.3m.
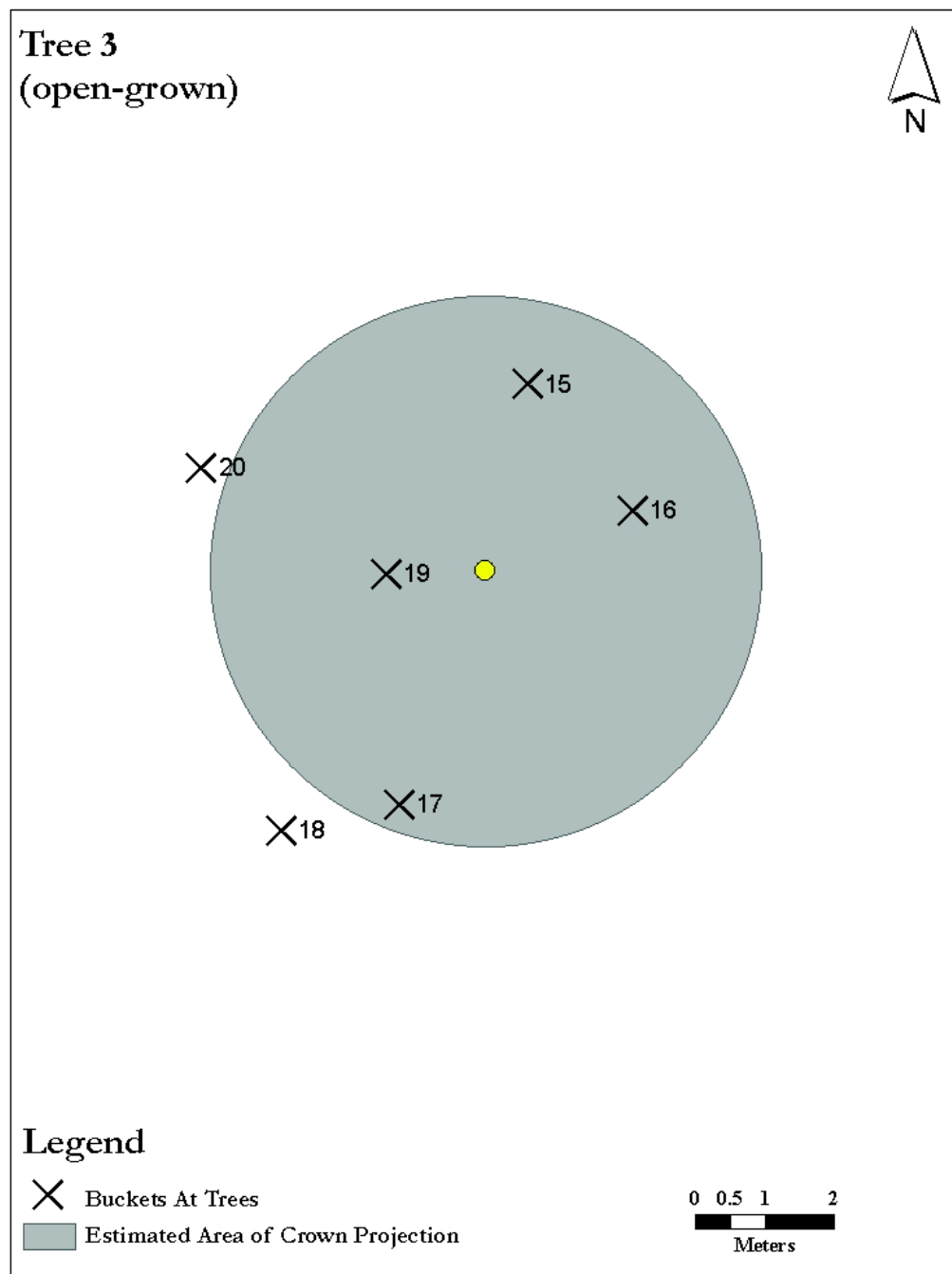
Figure 9. Bucket Placement at Study Tree 3. Tree 3 was open-grown, at the bend in Knights Road, and near open-field raingauge #1. The approximate radius of the projected crown area is 4.1m.
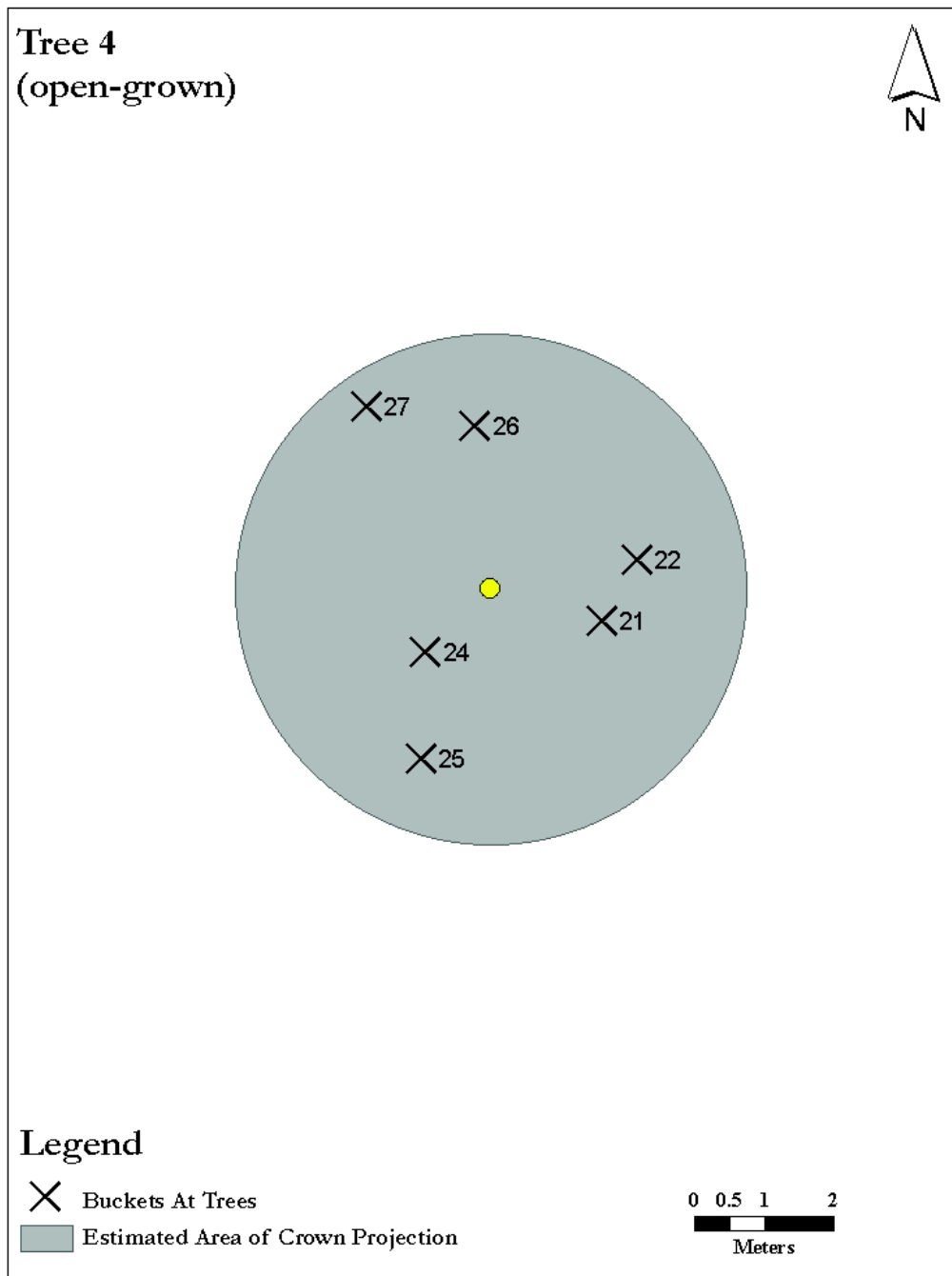
Figure 10. Bucket Placement at Study Tree 4. Tree 4 was open-grown, north of Knights Road, and about 200m from open-field raingauge #1. The approximate radius of the projected crown area is 3.7m.
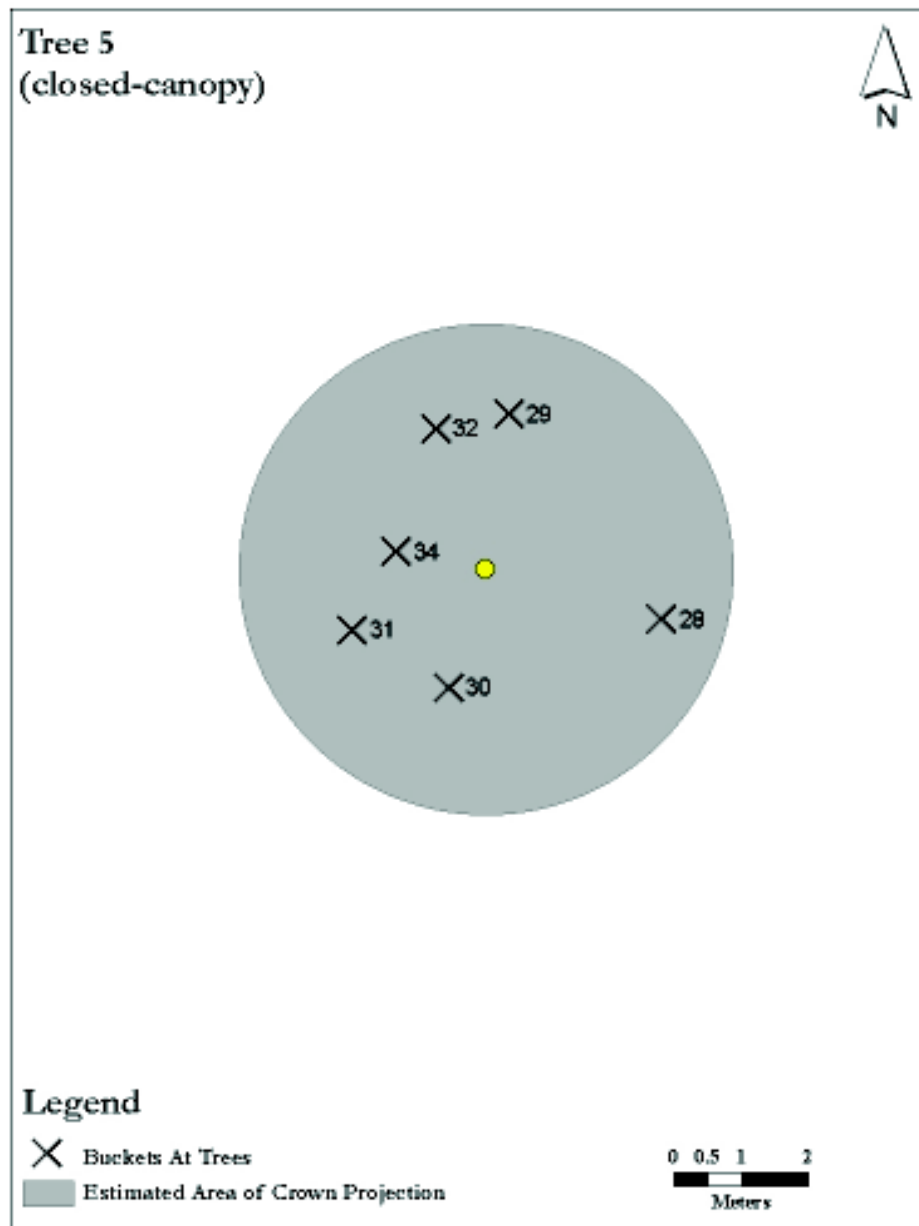
Figure 11. Bucket Placement at Study Tree 5. Tree 5 was a closed-canopy tree, growing in a stand of primarily Douglas-firs north of the clearing where trees 1 & 2 grew. Tree 6 was 5m west. The approximate radius of the projected crown area is 3.7m.
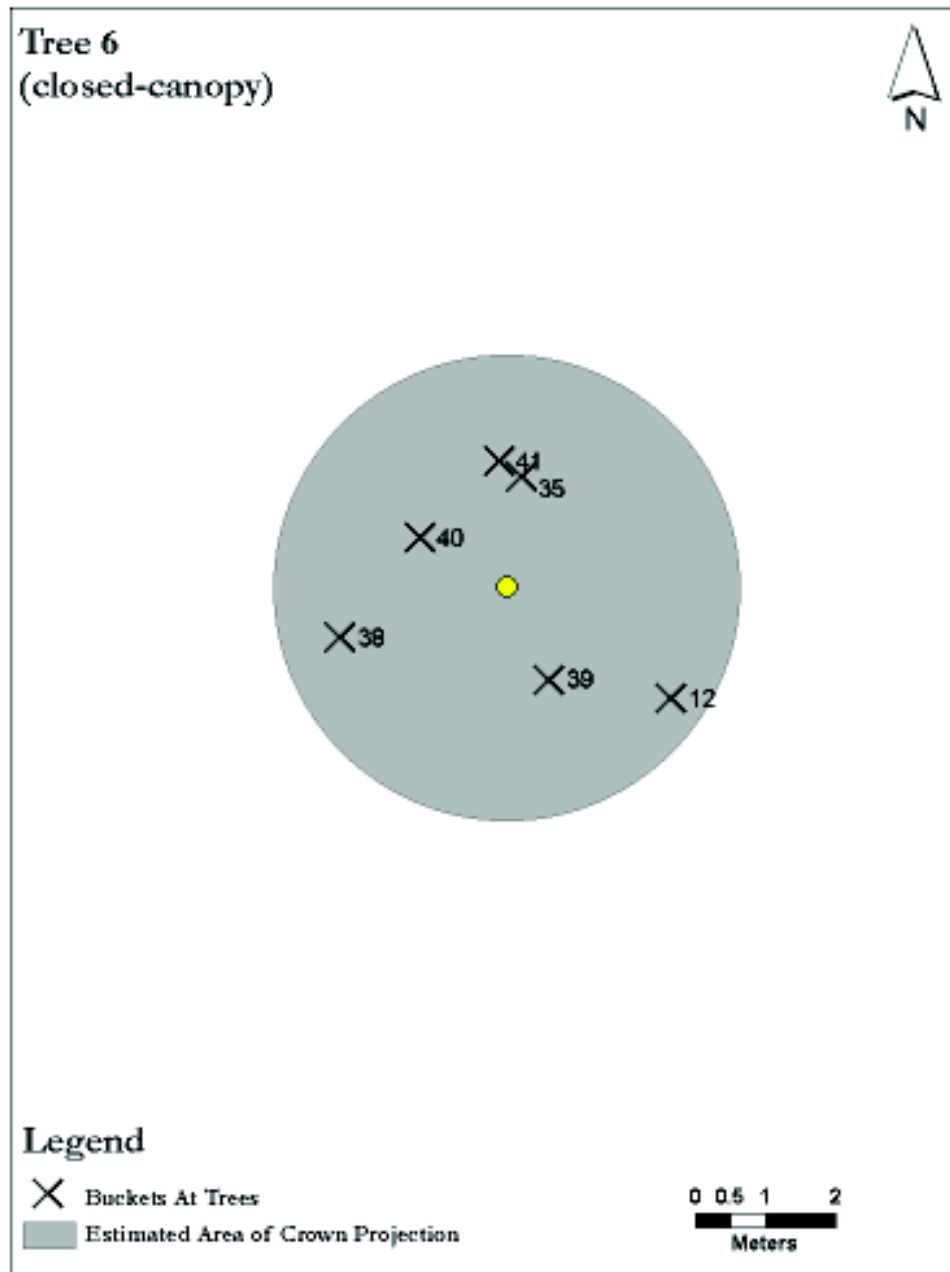
Figure 12. Bucket Placement at Study Tree 6. Tree 6 was a closed-canopy tree, growing in a stand of primarily Douglas-firs north of the clearing where trees 1 & 2 grew. Tree 5 was 5m east. The approximate radius of the projected crown area is 3.3m.

Trunkflow

A study of the Wind River Canopy Crane Research Facility (2005) found that trunkflow for Douglas-fir does not typically contribute significant volumes to total throughfall. Previous work also indicated that trunkflow for Douglas-fir (Rothacher 1963), as well as other coniferous species (Mulder 1985, Lankreijer et al. 1993), is minimal. The roughness of Douglas-fir bark, and that of many mature conifers, prevents channeling and provides additional water storage in all but the heaviest storm events. Based on these studies, I did not collect trunkflow in this study.

Leaf area

I used a method for determining leaf area based on Peper and McPherson (2003). I took color digital photos of each tree from two angles approximately perpendicular to each other and at a distance of 18m from estimated trunk centers. A white board of known dimensions was also photographed at a distance of 18m. Two pictures of each tree, as well as one of the white board, were reduced to monochromes in PhotoShop, and the pixels of each were counted. For each tree, the number of pixels from the two profiles that were perpendicular were averaged, and the average count divided by the number of pixels on the white board to get a canopy area estimate. Leaf area estimates using this method approximate leaf area as measured by comprehensive, fully-destructive means (Peper and McPherson 2003). Leaf area

estimates of the open-grown study trees are included among the trees' characteristics (Table 1). Directly photographing the closed-canopy trees was not practical.

Collection

Sample collections were made daily during rainy periods, with each collection period as short as possible. Usually a collection took about 45 minutes to complete for all trees, though for the sake of differentiating events, each sample collection is considered a moment in time. Attempts were made to collect during periods of no rainfall, in hope of bracketing a storm between collections, although this was not always successful. I collected water from buckets by pouring into either a 100 mL or a 1000 mL graduated cylinder, as conditions warranted. Ultimately, this led to a precision of 10mL, since I used the 1000mL cylinder for most collections. Time of 'first bucket emptied' was recorded for every tree, and the time of the first bucket emptied at the first tree was used for all trees during that collection. This convention allowed for clearer comparison with the Hoyt weather station data. The water volume in each bucket was divided by its measured aperture area (in cm) to give a linear rainfall depth for that bucket during that collection period. Linear depths were compared to incident rainfall depths and the difference was calculated as the interception for that bucket for that collection. I averaged all bucket interception values to arrive at a mean interception value for that tree over the given storm event. Study period interception averages are discussed in the next section.

Interception calculation

Calculations were based on the water balance equation already described (equation 2) as: $I = R - T - Tr$. Rainfall totals (R) were taken from open-field collectors set up near the study trees; tipping-bucket gauges at each tree were not cost-effective when compared to the potential risk of vandalism. Trunkflow (Tr) was assumed to be zero, as described above. Throughfall (T) was calculated from the bucket collectors by dividing the collected water volume by the area of each bucket's opening, giving a depth. For each collection, these depths were averaged at each tree. The mean of those averages gave a tree's interception over the study period. The difference between the nearest open-field bucket (R) and the throughfall recorded under the study trees (T) was restated as a percentage of R, thus providing interception (I). To calculate study period interception, I summed the average depths of all collections for a given tree, then compared to the sum of all incident depths for the same period. This approach minimized rounding error. A representative sample of data follows (Figure 13); results will be shown later, and the complete dataset is available in Appendix A.

		60	61	62	63	64
Tree 1	bucket 1	0.009	0.983	0.073	0.107	0.902
	bucket 2	0.035	1.329	0.114	0.158	0.951
	bucket 3	0.170	0.947	0.109		
	bucket 4	0.115	2.182	0.245	0.293	1.490
	bucket 5	0.043	1.422	0.127	0.165	0.711
	bucket 7	0.041	1.671	0.130	0.179	0.911
	mean (cm)	0.069	1.422	0.133	0.180	0.993
Tree 2	bucket 8	0.021	1.340	0.120	0.179	0.902
	bucket 9	0.007	1.030	0.079	0.114	0.968
	bucket 10	0.194	1.819	0.289	0.475	1.864
	bucket 11	0.059	1.787	0.143	0.214	1.170
	bucket 13	0.032	1.446	0.082	0.133	0.656
	bucket 14	0.067	1.444	0.144	0.202	0.810
	mean (cm)	0.063	1.477	0.143	0.220	1.062
OF Gauge 1		0.477	1.755	0.870	1.062	3.043

Figure 13. A Sample of Throughfall Data. The figure shows five collections (#60-64) for trees 1 and 2 as an example of collected data; values are given as depths in centimeters, and averaged at the bottom of each collection for each tree. The nearest open-field gauge recorded incident rainfall for the same period.

Full-season interception analysis

The beginning of the study had several candidate 'start dates.' I was first able to collect from the open-grown buckets on 9Oct2007, which is referred to as collection #1. All subsequent collections proceed in order; the collection number is useful when referring to the data. Calibration and testing of the Hoyt Arboretum weather station (see 'Local weather data' for details) were completed on 18Oct2007 [collection 5]. The open-field gauges were finally ready on 25Oct2007, and the next rain occurred on

10Nov2007 [collection 10]. I put the closed-canopy sites out on 12Nov2007, getting

first results on 16Nov2007 [collection 12]. Collection 12 is the first one that provided

data from both open-grown and closed-canopy sites, while having local incident

rainfall from the open-field gauges. Collections that contained more than two

irregularities (buckets with no water) in either the open-grown or the closed-canopy

group were removed from analysis. Of the 64 collections, 43 had sufficient data by

these standards and comprised the final datasheet.

Storms

I further analyzed individual rain events, or 'storms,' which I defined as a

period of continuous or discontinuous hourly rainfall in which no rain-free gaps of

more than 5 hours occurred. Gaps of 6 hours or more were assumed to indicate two

different 'storms' (Link et al. 2004). The Hoyt Arboretum raingauge provided the

hourly rainfall totals for determining gaps within/between storms. By this definition, I

selected collections or combinations of collections in which the only rain in the bucket

would be rain from a single, continuous period of rain. The first active day for all six

buckets was 12Nov2007, while 30Mar2008 was the last active day. I captured data on

76 total storms between those dates, isolating sixteen for analysis.

<u>Weather</u>

Low Temperatures

On 20Jan2008, I discovered fractures in several buckets. All cracks occurred in the plastic forming the bottom dimples of buckets. The fractures were likely a result of interaction between frozen water on the inner surface of the dimple and very cold concrete bonded to the outer surface of the plastic. The cracks resulted in lower collection volumes, which would in turn led to artificially high interception rates. It was important to know how far back the cracking occurred to correctly interpret the data already collected. Examining average hourly temperature data (Hoyt gauge) starting in October, there were a few nights of freezing and slightly-below-freezing (0° to -1.5°C) temperatures between 23Nov2007 and 26Nov2007. No sub-freezing period lasted for more than 11 hours. An 11-hour period of below-freezing temperatures also occurred the night of 9Dec2007. That stretch also included a three hour period of somewhat-colder-than-freezing temperatures (-1.5° to -3.0°C). Several periods of slightly below-freezing temperatures followed into the New Year.

The first night of not only extended sub-freezing temperatures but also colder temperatures was 15Jan2008. Average temperatures were freezing and below-freezing for 18 hours, including 9 hours of somewhat-colder-than-freezing (-1.5° to -3.0°C) temperatures. Because of the additional duration and the deeper cold, this night was a likely period to create and widen cracks to the point of leaking.

After discovering fractures on 20Jan2008, I recorded colder temperatures from the night of 21Jan2008 to the night of 24Jan2008 with periods of sub-freezing temperatures for up to 20 hours per day, with well below-freezing (<-3.0˚C) temperatures for 7-11 hours each night. It seemed more likely that many of the cracks occurred during this time, though the water in buckets at that time was limited. All buckets were removed from the field on 28Jan2008 and leaks were tested on all buckets with fractures from 3pm on 28Jan2008 to 4pm on 30Jan2008. I added 1000mL of water to each bucket, and set them in an outdoor, covered area in the Arboretum maintenance yard. The weather station recorded a 17-hour period of slightly below-freezing temperature during that time. Of the 38 buckets deployed, 12 leaked, and were replaced. Also, I have removed data from all buckets for the period 7pm on 15Jan2008 to 3pm 28Jan2008 [collections 41, 42 & 43], prior to replacing visibly fractured buckets because too few intact buckets remained to give a consistent picture of the data.

Local weather data

The Hoyt Arboretum weather station was about 250 meters from the study sites. The raingauge [Onset's S-RGA-M0002], wind direction sensor, wind speed sensor, and temperature/relative humidity sensor were all linked to the data logger [Onset's HOBO Micro Station H21-002]. Incident rainfall, wind speed, wind gusts, temperature, and relative humidity were recorded in 1-minute increments; these data

were downloaded after every collection to a laptop using Boxcar software. I placed

two additional buckets in the open near Trees 2 and 3. To avoid rain shadow, both

stood apart from all trees by at least the height of the neighboring trees. Minute-by-

minute weather data from the Arboretum were aggregated into hourly totals of rainfall,

and hourly averages of wind speed, wind gusts, temperature and relative humidity.

Down the hill about 300m and near the Childrens' Museum, the City of Portland

operated a tipping bucket raingauge as part of its HYDRA network (Figure 1); the

gauge has been recording data since at least March, 2005.

Citywide weather data

I compared the storm data collected in the fall and winter of 2007-08 with

long-term data to obtain a better sense of what to expect for regional rainfall patterns.

Long-term data for Hoyt Arboretum were not available; however, the Portland

International Airport had rainfall records from 1Jan1950 to 31Dec2005. Assuming a

6-hour gap minimum between storms (discussed above) and that 'missing/trace' data

could all be interpreted as 'no rainfall,' I analyzed the hourly rainfall data available

from the National Weather Service. A script written for the statistical software, R,

was used to determine the average length and intensity of storms over the 55-year

period. I also analyzed these characteristics for the hourly data from both the airport

and the Hoyt Arboretum weather station over my study period. I divided storm

intensity into four categories based on rain intensity in the tipping bucket raingauge:

low (<0.25mm/hr), medium (0.25-0.75mm/hr), high (0.75-1.25mm/hr), and very high

(>1.25mm/hr). Both the historical data and the 2007-2008 field data were divided into

these categories and compiled as shown in Figure 14. The filled-in bars represent

historical data, while the striped bars represent airport data from 2007-2008.

Results

<u>Citywide weather data</u>

   Data from Portland International Airport showed that, on average, nearly 90
storms, as defined by the six-hour gap, occurred there per year. On the left hand side
of the Figure 14, the lowest-intensity storms at Portland International Airport were
nearly twice as numerous during the study year than during an average year, while
other categories were more within expected ranges.
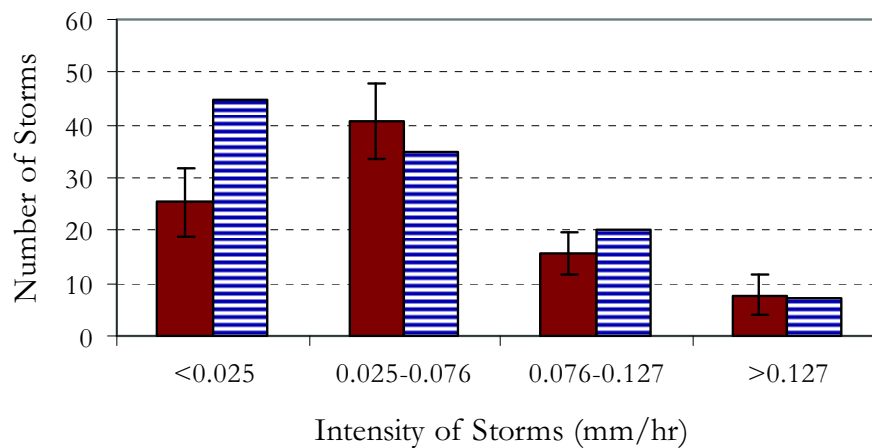
Figure 14. Comparison of Historic Storm Intensity. The 55-year average storm
intensity from Portland International Airport from 1950 to 2005 [solid], as compared
to that of the study period from 2007 to 2008 [lined]. Error bars show standard
deviations for 55-year means.

<u>Isolated storms</u>

   Intensity of the sixteen isolated storms ranged from 0.17 mm/hr to 2.02 mm/hr.
The most intense storm was also the longest storm at 64 hours, though duration and
intensity do not appear to correspond (Figure 15).   Many of the higher intensity

storms, with values above 1.0 mm/hr, were comparatively short, with durations of 14,

18, and 21 hours; conversely, one very long storm (58 hours) had a relatively low

intensity of 0.46 mm/hr. Duration did not appear to affect interception (Figure 15).
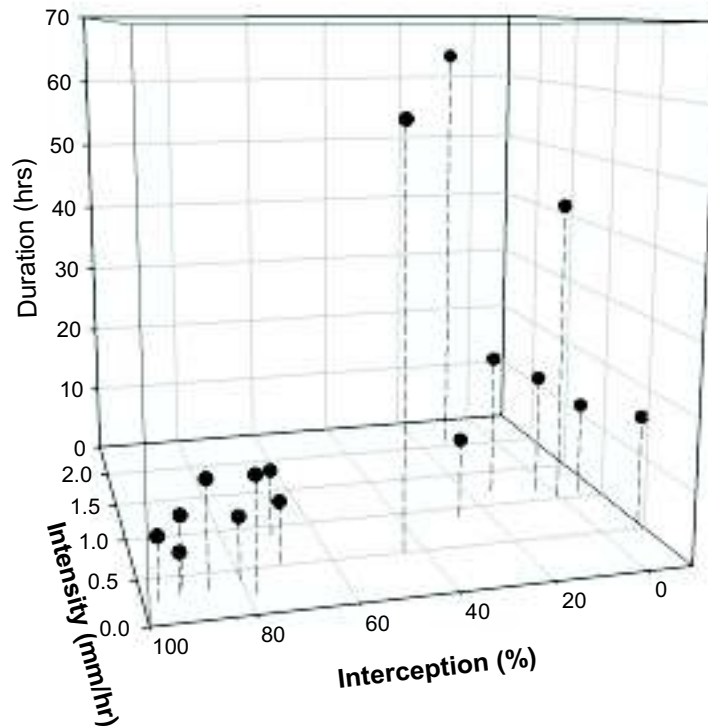
**Figure 15. Sixteen Isolated Storms Compared by Intensity, Duration and
Interception.**   Interception decreases from left to right while intensity (mm/hr)
increases from front to back.

      The prevailing wind direction for all sixteen storms, as tracked by the weather

station at Hoyt Arboretum, was southerly (Figure 16). Hourly averages were

compiled from minute-by-minute data taken for the duration of each storm; most

storm tracks clustered around 180 degrees. Interception was not related to wind

direction. Additional comparisons between interception and wind speed (Figure 17),

and between interception and relative humidity (Figure 18) did not show relationships.
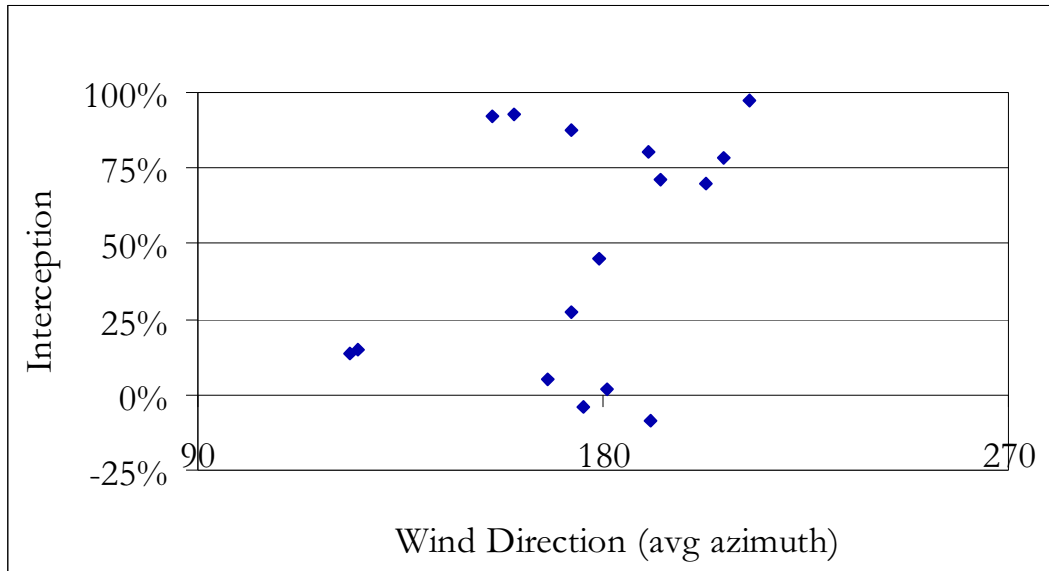
Figure 16. Average Wind Direction of Sixteen Isolated Storms. Average hourly wind directions compiled over the length of each isolated storm show southerly winds prevailing.
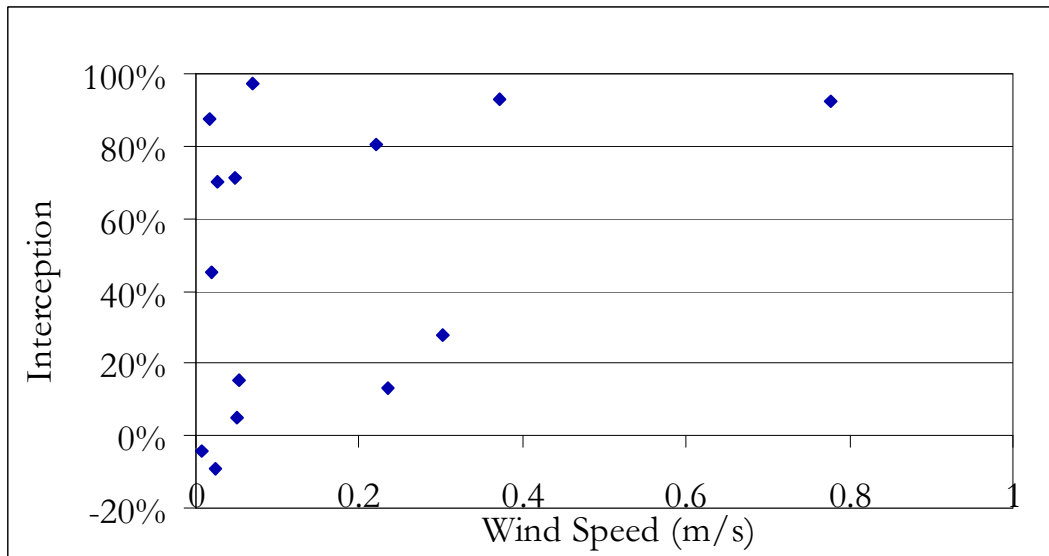
Figure 17. Average Wind Speed of Sixteen Isolated Storms. Average hourly wind speeds (m/s) compiled over the length of each isolated storm.

47
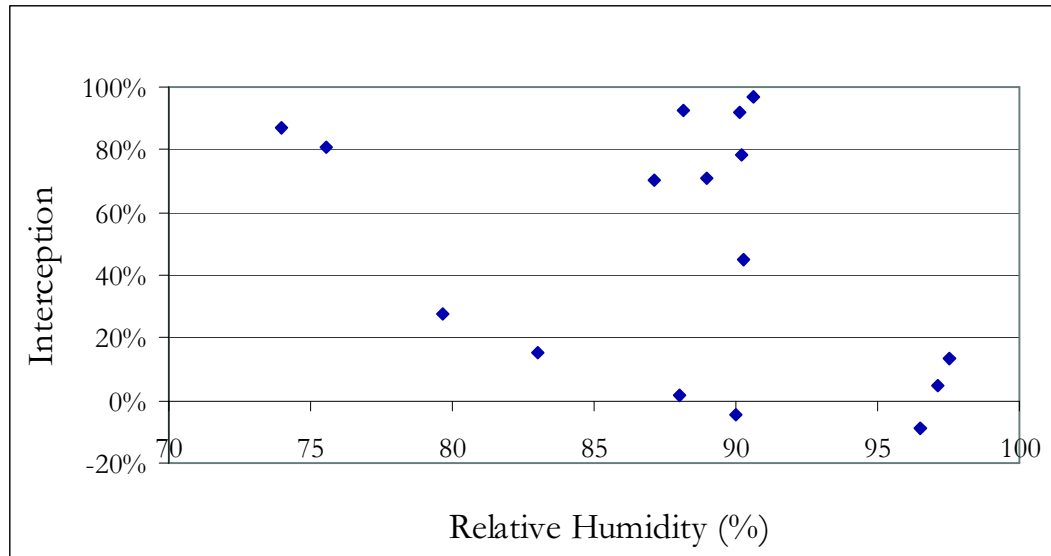
Figure 18. Average Relative Humidity of Sixteen Isolated Storms. Average relative humidity (%) compiled over the length of each isolated storm.

Interception results

As shown in Figure 19, the study period-long interception of the open-grown trees ranged widely, including one tree that averaged well below expected values, one tree at a level near closed-canopy values, and two trees performing well above closed-canopy. The average interception rate of the open-grown trees was 31%, whereas the closed-canopy trees averaged 26%, similar to other studies (Link 2004, Pypker 2005).
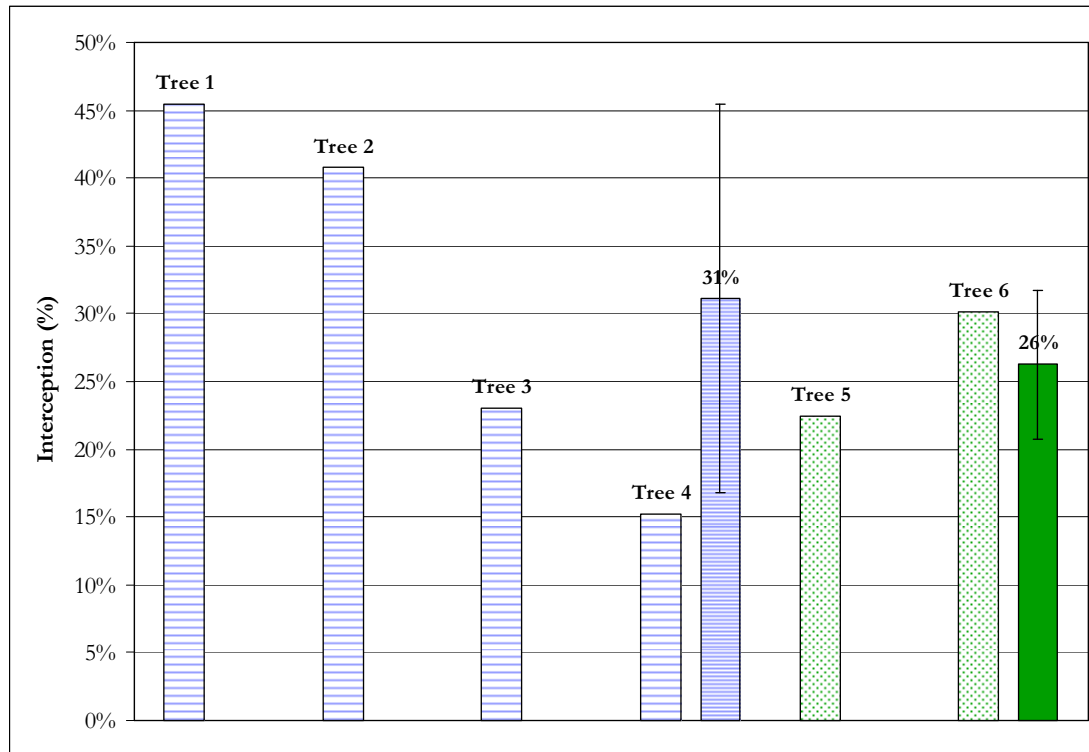
Figure 19. Study-long Interception for Each Study Tree. Trees 1-4 were open-grown trees, with interception ranging from 15-45%, with overall average of 31% (diagonal lines). Trees 5 & 6 were closed-canopy trees, with interception of 22% and 30%, with an overall average of 26% (horizontal lines). All interception values were determined using local (open-field) rainfall data. Error bars show standard deviation on open-grown and closed-canopy summary bars.

Interception values varied slightly with the raingauge used; see Appendix B for discussion of raingauges. For the purposes of local interception, the local, open-field gauges were used; they are the basis for the overall summary (Figure 19) as well as the summaries of individual trees (Figures 20 & 21). Interception values for all trees were generally low in November and March, and high in December, January and February. The study period-long pattern of interception by open-grown trees reflected that by closed-canopy trees.

Figure 20. Study-long Interception of Open-grown Trees. Each panel shows the interception one of the four open-grown trees for all collections, starting with #12 on 12Nov2007 and ending with #64 on 30Mar2008, but excluding collections with multiple missing data.

Figure 21. Study-long Interception of Closed-canopy Trees. Each panel shows the interception of both closed-canopy trees for all collections, starting with #12 on 12Nov2007 and ending with #64 on 30Mar2008, but excluding collections with multiple bucket failures.

51

Discussion

Error and precision

   The raw data are composed of 64 collections at each of 36 collecting buckets.

Collection periods ranged in length from 18 to 197 hours. Measurements were

ultimately made using either a 100-mL or a 1000-mL graduated cylinder. Given the

use of the 1000-mL graduated cylinder, data will have precision of 10mL. The larger

storms will have a correspondingly larger amount of error, due to the number of times

necessary to pour larger volumes. Other sources of error led to "irregularities," or

incidental missing data. Those sources include ice, snow, errors in technique and

human interference. I have tried to account for these by excluding data from

collections known to have irregularities. For example, six collections in January were

removed because of ice; four were removed because of vandalism. My study

benefitted from having several trees of a single species in one location; sources of

error such as topography and microclimate were minimized.

Variation in interception

   Larger leaf area did not correspond to higher interception (Table 2), as might

be expected. Tree 1 was the shortest tree of the four, with smallest diameter and

smallest leaf area [66.1m^2]. Yet, its interception totals were the highest of the group.

Tree 2, with the largest leaf area [93.0m^2], yielded similar, slightly lower rates of

interception. Interception at tree 3 seemed not to differ much from that of closed-

canopy trees, despite a leaf area of [69.5m^2], while tree 4, with slightly larger area than tree 1 [70.9m^2], allowed a noticeably larger amount of rain through its canopy.

Something is clearly different in the branch structure of tree 4. It may be that the pixel method was not giving an accurate representation of canopy, or that the tree's particular location received more rainfall or allowed more to fall into the buckets at an angle. A weather station at that site, while costly and prone to vandalism, would allow a more accurate picture of local weather to be drawn. Another strong possibility is that tree 4 is less densely branched, allowing more rain to fall through. A photographic comparison (Figure 2) of the four open-grown trees suggests a more open canopy in tree 4, perhaps leading to lower interception values. Future interception studies of open grown trees would benefit from a detailed analysis of canopy morphology.

Greater-than-incident rainfall

In larger rain events, three buckets (#18 [tree 3], #21 [tree 4], and #30 [tree 5]) recorded more water caught than fell in the open. In Link's (2004) buckets, 23% recorded such an event, so it is not uncommon. Several possible explanations exist. The first explanation is that the buckets were placed too far out from under the canopy. All buckets were some distance from the trunk, although the determination of the canopy's edge at the time of bucket placement was somewhat conservative. A more definite means of determining canopy edge would mitigate this issue.

A second explanation might be that the buckets sat at a drip point, and received throughfall falling outside the vertical cylinder it was intended to represent. This phenomenon is the reason why many buckets are necessary for good statistical analysis: some buckets may get a relatively large amount of water, while others get much less. During the largest storm, I observed that bucket 30 sat at a very pronounced drip point, explaining its substantial catches. Increasing the number of buckets under each tree would help smooth out the extreme results. Rotating the buckets to new locations was another common technique in closed-canopy studies, though it proved impractical in an open-grown study (Gash 1979, Pypker 2005).

A third possible explanation is aspect. All three of the buckets in question were positioned on the downhill portion of the tree, which in my study also gave them a more southerly position. The Hoyt weather station shows that our sample storms tended to be southerly, though this could be an artifact of the weather station station's placement; wind data at the trees would be necessary to be certain. If storms are tending southerly, then their leading edges would be falling on that side of the tree, which might, in turn, cause water to "pile up" in those buckets. In that case, one might expect all southerly buckets to show this pattern, but they do not. More than likely, a combination of these factors accounts for the greater-than-incident collections.

Historical vs. field data

The rain regime during my study appeared to shift towards the lower end of the intensity spectrum (Figure 14). The result suggests that in more average years, interception might be lower, because rain tended to be more intense. Intensity was correlated inversely with interception (R^2=0.84) so my interception rates may actually be on the high side, but further study would be necessary to confirm this.

Further Study

There is substantial interest in the topic of urban interception, mostly from a purely practical standpoint, though interception's role in an urban hydrologic scheme still requires further attention. This study demonstrated the possibility of increasing interception in cities, and at the same time highlights some of the challenges and unanswered questions about how to fully quantify this process. Still to be addressed are the abilities of deciduous trees, though lacking foliage for several months, as well as other conifers. The role of microclimate in a given tree's interception capacity has been hinted at, but still needs systematic treatment. And, perhaps most importantly, the idea that spacing improves interception needs to be tested at more length. A single year's investigation cannot capture the full range of interception, and so a multi-annual study that accounts for climate variability would be desirable.

Management Implications

The interception rates for open-grown Douglas-firs are encouraging, with an average open-grown rate of 31%, as compared to an average closed-canopy rate of 26%. The variability of interception rates for the open-grown trees is an intriguing finding for future study. The wide variation in canopy morphology of open grown trees likely plays an important role in an given tree's interception capacity.

If one continues from the premise of my study that open-grown Douglas-fir intercepts at least as well as closed-canopy Douglas-firs, and likely more, then their usefulness in mitigating urban stormwater runoff might be re-assessed. As a species, Douglas-fir already comprises an important part of the urban forest, particularly in parks and in off-street locations. The rainwater that these trees intercept and block entering a city's stormwater system in cities in the Pacific Northwest west of the Cascades is already substantial. If, on the other hand, Douglas-fir is not seen as a preferred species for further planting in some locations (e.g. in parking strips adjacent to city streets), then I have at least provided an approach for gauging which other species might be preferred.

Conclusion

My study findings support the hypothesis that open-grown Douglas-firs intercept more rain than closed-canopy Douglas-firs. The mean interception rate for 5 month winter study period was higher for open grown trees than for nearby closed canopy. On an individual tree basis, half of the open-grown trees I examined had interception rates substantially higher than nearby closed-canopy trees. The interception values for closed canopy trees in the study were representative of Douglas-fir canopies, as suggested by other researchers. The range of interception results in open grown Douglas-fir trees was likely tied to the inherent variability in tree architecture, such as leaf area or branch density. At the same time, I have shown that separation of trees in some cases does result in an increased interception capacity. These findings could have direct implications for stormwater management, leading to the planting of more Douglas-fir with wide spacing, or indirect implications, as other species are tested for their interception capacities.

References

Aston, A. R. 1979. Rainfall interception by eight small trees. Journal of Hydrology **42**:383-396.

Del Rio, E., and A. Berg. 1979. Specific leaf area of Douglas-fir reproduction as affected by light and needle age. Forest Science **25**:183-186.

Dingman, S. L. 2002. Physical Hydrology., 2nd edition. Prentice-Hall, Inc., Upper Saddle River, NJ.

Environmental Services, Portland [OR] Bureau of. 2011. Grey-to-Green Street Trees on 5/19/11 at http://www.portlandonline.com/bes/index.cfm?c=50795.

Ford, E. D., and J. D. Deans. 1978. The effects of canopy structure on stemflow, throughfall and interception loss in a young Sitka spruce plantation. Journal of Applied Ecology **15**:905-917.

Gash, J. H. C. 1979. An analytical model of rainfall interception by forests. Quarterly Journal of the Royal Meterological Society **105**:43-55.

Gash, J. H. C., C. R. Lloyd, and G. Lachaud. 1995. Estimating sparse forest rainfall interception with an analytical model. Journal of Hydrology **170**:79-86.

Godfree, R. C. 2000. Lodgepole pine dwarf mistletoe (*Arceuthobium americanum*) in central Oregon lodgepole pine (*Pinus contorta* var. *murrayana*) stands: effects on crown architecture, population dynamics, canopy structure and understory composition. Portland State University, Portland, Oregon.

Helvey, J. D., and J. H. Patric. 1965. Canopy and litter interception of rainfall by hardwoods of eastern United States. Water Resources Research **1**:193-206.

Hormann, G., A. Branding, T. Clemen, M. Herbst, A. Hinrichs, and F. Thamm. 1996. Calculation and simulation of wind controlled canopy interception of a beech forest in Northern Germany. Agricultural and Forest Meteorology. **79**:131-148.

Horn, H. 1971. The adaptive geometry of trees. Princeton University Press, Princeton, N.J.

Horton, R. E. 1919. Rainfall interception. Monthly Weather Review **47**:603-623.

Ishii, H., J. H. Reynolds, E. D. Ford, and D. C. Shaw. 2000. Height growth and vertical development of an old-growth *Pseudotsuga-Tsuga* forest in southwestern Washington State, U.S.A. Canadian Journal of Forest Research **30**:17-24.

Jensen, E. C., and J. N. Long. 1983. Crown structure of a codominant Douglas-fir. Canadian Journal of Forest Research **13**:264-269.

Johnson, D. M. 1987. Weather and Climate in Portland. Pages 20-37 *in* L. W. Price, editor. Portland's Changing Landscape. Department of Geography, Portland State University, Portland, OR.

Kimmins, J. P. 1973. Some statistical aspects of sampling throughfall precipitation in nutrient cycling studies in British Columbian coastal forests. Ecology **54**:1008-1019.

Kostelnik, K. M., J. A. Lynch, J. W. Grimm, and E. S. Corbett. 1989. Sample size requirements for estimation of throughfall chemistry beneath a mixed hardwood forest. Journal of Environmental Quality **18**:274-280.

Lankreijer, H. J. M., M. J. Hendriks, and W. Klaasen. 1993. A comparison of models simulating rainfall interception of forests. Agricultural and Forest Meteorology **64**:187-199.

Link, T. E., M. Unsworth, and D. Marks. 2004. The dynamics of rainfall interception by a seasonal temperate rainforest. Agricultural and Forest Meteorology. **124**:171-191.

Liu, S. 1997. A new model for the prediction of rainfall interception in forest canopies. Ecological Modelling **99**:151-159.

Liu, S. 2001. Evaluation of the Liu model for predicting rainfall interception in forests world-wide. Hydrological Processes **15**:2341-2360.

Lloyd, C. R., J. H. C. Gash, and W. J. Shuttleworth. 1988. The measurement and modeling of rainfall interception by Amazonian rain forest. Agricultural and Forest Meteorology **43**:277-294.

Makela, A. 1997. A carbon balance model of growth and self-pruning in trees based on structural relationships. Forest Science **43**:7-24.

McPherson, E. G., J. R. Simpson, P. J. Peper, S. E. Maco, and Q. Xiao. 2005. Municipal forest benefits and costs in five U.S. cities. Journal of Forestry:411-416.

McPherson, E. G., J. R. Simpson, P. J. Peper, and Q. Xiao. 1999. Benefit-cost analysis of Modesto's municipal urban forest. Journal of Arboriculture **25**:235-248.

Mulder, J. P. M. 1985. Simulating interception loss using standard meteorological data. Pages 177-196 *in* B. A. Hutchison and B. B. Hicks, editors. The Forest-Atmosphere Interaction. D. Reidel Publishing Company, Dordrecht, The Netherlands.

Peper, P. J., and E. G. McPherson. 2003. Evaluation of four methods for estimating leaf area of isolated trees. Urban Forestry & Urban Greening **2**:19-29.

Price, A. G., and D. E. Carlyle-Moses. 2003. Measurement and modeling of growing-season canopy water fluxes in a mature mixed deciduous forest stand, southern Ontario, Canada. Agricultural and Forest Meteorology **119**:69-85.

Puckett, L. J. 1991. Spatial variability and collector requirements for sampling throughfall volume and chemistry under a mixed-hardwood canopy. Canadian Journal of Forest Research **21**:1581-1588.

Pypker, T. G., B. J. Bond, T. E. Link, D. Marks, and M. H. Unsworth. 2005. The importance of canopy structure in controlling the interception loss of rainfall: Examples from a young and an old-growth Douglas-fir forest. Agricultural and Forest Meteorology. **130**:113-129.

Reynolds, B., and C. Neal. 1991. Trough versus funnel colllectors for measuring throughfall volumes. Journal of Environmental Quality **20**:518-521.

Rothacher, J. 1963. Net precipitation under a Douglas-fir forest. Forest Science **9**:423-429.

Rutter, A. J., K. A. Kershaw, P. C. Robins, and A. J. Morton. 1971. A predictive model of rainfall interception in forests; 1. Derivation of the model from observations in a plantation of Corsican pine. Agricultural Meteorology **9**:367-384.

Sanders, R. A. 1986. Urban vegetation impoacts of the hydrology of Dayton, Ohio. Urban Ecology **9**:361-376.

St. Clair, J. B. 1994. Genetic variation in tree structure and its relation to size in Douglas-fir. II. Crown form, branch characters, and foliage characters. Canadian Journal of Forest Research **24**:1236-1247.

Takahashi, K. 1996. Plastic response of crown architecture to crowding in understory trees of two co-dominating conifers. Annals of Botany **77**:159-164.

Taylor, G. Personal communication, March 2007. Oregon Climate Service (Oregon State University).

Teklehaimanot, Z., P. G. Jarvis, and D. C. Ledger. 1991. Rainfall interception and boundary layer conductance in relation to tree spacing. Journal of Hydrology **123**:261-278.

Voigt, G. K. 1961. Distribution of rainfall under forest stands. Forest Science **6**:2-10.

Walsh, C. J., T. D. Fletcher, and A. R. Ladson. 2005. Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. Journal of the North American Benthological Society **24**:690-705.

Xiao, Q., and E. G. McPherson. 2003. Rainfall interception by Santa Monica's municipal urban forest. Urban Ecosystems **6**:291-302.

Xiao, Q., E. G. McPherson, S. L. Ustin, and M. E. Grismer. 2000a. A new approach to modeling tree rainfall interception. Journal of Geophysical Research **105**:29,173-129,188.

Xiao, Q., E. G. McPherson, S. L. Ustin, M. E. Grismer, and J. R. Simpson. 2000b. Winter rainfall interception by two mature open-grown trees in Davis, California. Hydrological Processes **14**:763-784.

Zinke, P. 1965. Forest interception studies in the United States. Pages 137-161 *in* W. Sopper and H. Lull, editors. Forest hydrology: the proceedings of a National Science Foundation advanced seminar at the Pennsylvania State University.... Pergamon Press, Pennsylvania State University.

Appendix A: Rainfall Depths Per Bucket in cm (vol/area)								
	Nov 16	Nov 17	Nov 19	Nov 20	Nov 28	Nov 29	Dec 1	Dec 2
break	12	13	14	15	16	17	18	19
tree 1	0.603	3.547	1.756	0.689	0.405	0.913	0.189	0.448
	0.792	2.782	1.725	0.563	0.546	0.827	0.176	0.651
	0.745	2.164	1.552	0.532	0.532	0.763	0.098	0.834
		2.776	1.454	0.568	0.692	1.011	0.035	0.949
	0.947	1.707	1.063	0.340	0.429	0.572	0.045	0.500
		2.555	1.474	0.509	0.590	0.724	0.054	0.554
	0.772	**2.588**	**1.504**	**0.533**	**0.532**	**0.802**	**0.099**	**0.656**
tree 2		2.984	2.073	0.643	0.581	0.858	0.357	0.581
	0.411	3.342	2.752	0.625		0.983	0.322	0.554
	1.348	3.033	2.093	0.692	0.665	1.002	0.204	0.958
	0.920	1.653	0.849	0.295	0.384	0.482	0.045	0.643
	0.697	3.306	2.627	0.661	0.411	0.929	0.223	0.447
	0.958	2.980	2.199	0.568	0.443	0.709	0.231	0.594
	0.867	**2.883**	**2.099**	**0.581**	**0.497**	**0.827**	**0.230**	**0.629**
OF Gauge 1		**2.908**	**2.602**	**0.711**	**1.071**	**1.557**	**0.333**	**1.926**
tree 5	0.885	1.943	1.301	0.338	0.399	0.598	0.069	0.598
	1.561	3.296	2.515	0.746	0.876	1.388	0.269	0.885
	4.328	4.097	3.130	1.481	1.224	1.348	0.115	2.288
	1.471	3.400	2.806	0.713	0.749	1.426	0.155	0.850
	1.519	2.850	2.252	0.733	0.715	0.983	0.214	0.893
	1.653	2.931	2.287	0.715	0.876	1.260	0.143	0.893
	1.903	**3.086**	**2.382**	**0.788**	**0.806**	**1.167**	**0.161**	**1.068**
tree 6	1.386	3.151	2.422	0.684	0.738	1.242	0.180	1.008
	1.452	3.195	2.764	0.572	0.651	1.039	0.282	0.766
		3.048	2.338	0.711	0.739	1.141	0.224	1.085
	1.578	2.404	1.669	0.599	0.635	0.943	0.245	0.853
	1.544	2.446	2.342	0.668	0.737	1.180	0.252	0.919
	1.408	2.887	2.377	0.757	0.634	1.047	0.229	0.863
	1.474	**2.855**	**2.318**	**0.665**	**0.689**	**1.099**	**0.235**	**0.916**

	Nov 16	Nov 17	Nov 19	Nov 20	Nov 28	Nov 29	Dec 1	Dec 2
break	12	13	14	15	16	17	18	19
tree 3	0.568	3.654	2.926	0.674	0.355	0.922	0.488	0.621
	0.692	2.678	1.614	0.505	0.399	0.621	0.195	0.709
	1.430	2.948	1.867	0.661	0.625	0.804	0.170	1.269
	2.305	3.109	1.912	0.840	1.108	1.019	0.125	1.823
	1.769	3.020	2.296	0.679	0.616	0.742	0.197	1.019
	1.110	2.845	3.044	0.798	0.494	0.737	0.425	0.893
	1.312	**3.042**	**2.277**	**0.693**	**0.600**	**0.807**	**0.267**	**1.056**
OF Gauge 2	**1.908**	**2.975**	**2.654**	**0.963**	**1.006**	**1.492**	**0.347**	**1.674**
tree 4	0.861	4.477	2.238	0.999	1.050	1.636	0.207	1.791
	1.695	5.347	2.516	0.716	0.909	1.293	0.393	0.559
	1.643	2.726	1.870	1.110	0.961	1.503	0.044	1.031
	1.518	2.949	1.873	0.833	0.781	1.023	0.087	1.101
	0.745	4.301	3.352	0.763	0.390	0.816	0.532	0.639
	0.936	4.663	3.367	0.846	0.432	0.774	0.594	0.810
	1.233	**4.077**	**2.536**	**0.878**	**0.754**	**1.174**	**0.309**	**0.989**
Hoyt	**1.727**	**2.667**	**2.210**	**0.914**	**1.219**	**0.940**	**0.279**	**1.600**
Breaks 30, 31, 41, 42, 43 & 44 were removed for ice								
Breaks 36, 41, 54 & 59 were removed for vandalism								

	Dec 3	Dec 4	Dec 6	Dec 7	Dec 10	Dec 15	Dec 17	Dec 19
Appendix A:								
break	20	21	22	23	24	25	26	27
tree 1	7.266	1.007	0.878	0.069	0.017	0.005	0.069	0.930
	10.862	1.523	0.748	0.026	0.009	0.005	0.032	0.898
	8.043	1.082	0.505	0.027	0.002	0.009	0.067	0.505
	10.863	1.543	0.443	0.035	0.002	0.016	0.053	0.426
	6.308	0.920	0.348	0.027	0.005	0.002	0.005	0.205
	6.603	0.983	0.438	0.045	0.005	0.004	0.014	0.384
	8.324	**1.176**	**0.560**	**0.038**	**0.007**	**0.007**	**0.040**	**0.558**
tree 2	8.095	1.340	0.876	0.036	0.018	0.007	0.054	1.135
	8.550	1.197	1.197	0.054	0.009	0.014	0.080	1.045
	9.808	1.366	0.665	0.053	0.009	0.009	0.050	0.683
	7.952	1.278	0.348	0.027	0.005	0.005	0.014	0.590
	6.540	1.108	0.893	0.063	0.018	0.002	0.018	0.733
	6.562	1.117	0.931	0.044	0.018	0.011	0.035	0.851
	7.918	**1.234**	**0.819**	**0.046**	**0.013**	**0.008**	**0.042**	**0.839**
OF Gauge 1	**11.369**	**1.593**	**1.017**	**0.126**	**0.144**	**0.342**	**0.510**	**2.241**
tree 5	4.536	0.945	0.486	0.035	0.035	0.043	0.071	0.416
	7.094	1.362	0.963	0.035	0.035	0.083	0.139	0.859
	14.907	3.813	0.568	0.044	0.027	0.122	0.140	0.727
	10.692	1.261	0.877	0.055	0.027	0.099	0.128	0.621
	7.166	1.430	0.983	0.045	0.036	0.077	0.098	0.840
	6.263	1.233	0.625	0.036	0.018	0.073	0.089	0.733
	8.443	**1.674**	**0.750**	**0.041**	**0.030**	**0.083**	**0.111**	**0.699**
tree 6	8.066	1.458	0.954	0.036	0.045	0.043	0.140	0.549
	5.924	1.118	1.039	0.044	0.062	0.039	0.097	0.810
	8.144	1.552	0.842	0.047	0.037	0.086	0.116	0.655
	6.975	1.243	0.689	0.027	0.036	0.042	0.091	0.644
	7.407	1.353	0.763	0.035	0.035	0.061	0.075	0.763
	6.470	1.347	0.757	0.035	0.053	0.048	0.092	0.836
	7.164	**1.345**	**0.841**	**0.037**	**0.045**	**0.053**	**0.102**	**0.709**

	Dec 3	Dec 4	Dec 6	Dec 7	Dec 10	Dec 15	Dec 17	Dec 19
break	20	21	22	23	24	25	26	27
tree 3	6.146	1.499	1.383	0.080	0.106	0.021	0.009	0.816
	7.476	1.978	0.736	0.027	0.027	0.009	0.018	0.718
	12.374	3.395	0.697	0.036	0.009	0.029	0.071	0.733
	12.643	3.127	0.572	0.027	0.009	0.114	0.161	1.269
	9.667	2.779	0.876	0.027	0.018	0.020	0.014	0.536
	7.320	2.186	1.336	0.035	0.035	0.012	0.009	1.127
	9.271	**2.494**	**0.933**	**0.038**	**0.034**	**0.034**	**0.047**	**0.867**
OF Gauge 2	**9.497**	**1.891**	**1.041**	**0.113**	**0.151**	**0.330**	**0.468**	**2.151**
tree 4	16.280	4.606	1.145	0.069	0.034	0.031	0.009	0.895
	5.373	1.328	1.503	0.044	0.087	0.031	0.014	0.944
	8.711	2.245	0.428	0.035	0.017	0.037	0.009	0.524
	7.884	1.951	0.711	0.035	0.009	0.029	0.009	0.451
	7.724	2.519	1.862	0.080	0.098	0.005	0.000	1.171
	7.778	2.205	2.395	0.072	0.090	0.013	0.000	1.152
	8.958	**2.476**	**1.341**	**0.056**	**0.056**	**0.024**	**0.007**	**0.856**
Hoyt	**9.119**	**2.311**	**0.838**	**0.051**	**0.127**	**0.254**	**0.432**	**1.295**
Breaks 30, 31, 4								
Breaks 36, 41, 5								

Appendix A:								
	Dec 20	Dec 22	Dec 26	Dec 28	Dec 29	Dec 31	Jan 3	Jan 4
break	28	29	30	31	32	33	34	35
tree 1	1.093	0.689			0.456	0.189	2.419	0.241
	1.382	0.792			0.405	0.194	2.368	0.290
	1.188	0.736			0.408	0.302	1.295	0.390
	2.297	1.215			0.603	0.461	2.057	0.426
	1.072	0.768			0.357	0.304	0.965	0.331
	1.465	0.867			0.411	0.348	2.234	0.348
	1.416	**0.844**			**0.440**	**0.300**	**1.890**	**0.338**
tree 2	1.340	1.072			0.465	0.420	2.725	0.536
	0.786	0.742			0.384	0.223	3.216	0.572
	2.252	1.658			0.532	0.603	1.898	0.789
	1.474	0.795			0.447	0.393	1.233	0.286
	1.117	0.938			0.411	0.232	2.520	0.393
	1.339	0.958			0.381	0.479	2.306	0.461
	1.385	**1.027**			**0.437**	**0.392**	**2.316**	**0.506**
OF Gauge 1	**1.665**	**1.665**			**0.846**	**1.296**	**2.917**	**1.440**
tree 5	1.145	0.867			0.330	0.529	1.691	0.442
	1.648	1.370			0.503	0.919	2.654	0.694
	6.740	2.891			1.011	2.439	2.128	0.816
	1.407	1.270			0.503	0.658	1.919	0.548
	1.805	1.438			0.465	0.795	2.493	0.545
	1.394	1.081			0.447	0.661	1.653	0.518
	2.356	**1.486**			**0.543**	**1.000**	**2.090**	**0.594**
tree 6	1.854	1.422			0.414	0.702	2.377	0.522
	1.373	1.180			0.475	0.827	2.042	0.616
	1.814	1.431			0.542	0.842	1.964	0.655
	1.823	1.224			0.544	0.816	1.850	0.635
	1.804	1.266			0.555	0.850	2.324	0.633
	1.866	1.461			0.493	0.748	2.042	0.563
	1.756	**1.331**			**0.504**	**0.798**	**2.100**	**0.604**

	Dec 20	Dec 22	Dec 26	Dec 28	Dec 29	Dec 31	Jan 3	Jan 4
break	28	29	30	31	32	33	34	35
tree 3	0.905	0.772			0.470	0.399	2.785	0.709
	1.144	0.772			0.443	0.284	1.827	0.426
	2.216	1.340			0.822	0.804	1.376	0.608
	3.181	1.769			0.715	1.233	1.662	0.920
	2.037	1.170			0.536	0.643	0.849	0.438
		1.110			0.442	0.590	2.168	0.659
	1.896	**1.155**			**0.571**	**0.659**	**1.778**	**0.627**
OF Gauge 2	**1.535**	**1.535**			**0.850**	**1.162**	**2.801**	**1.405**
tree 4	3.323	2.152			1.722	1.102	3.513	0.895
	1.057	0.900			0.419	0.507	2.953	0.550
	2.272	1.415			0.725	0.786	1.983	0.751
	2.108	1.249			0.624	1.006	1.388	0.555
	1.774	1.100			0.754	0.310	2.306	0.302
	1.692	1.017			0.666	0.450	1.656	0.378
	2.038	**1.306**			**0.818**	**0.694**	**2.300**	**0.572**
Hoyt	**1.930**	**0.584**			**1.651**	**1.067**	**2.438**	**1.270**
Breaks 30, 31, 4								
Breaks 36, 41, 5								

	Jan 6	Jan 7	Jan 9	Jan 12	Jan 15	Jan 19	Jan 27	Jan 28
break	36	37	38	39	40	41	42	43
tree 1		0.103	2.772	1.257	0.327			
		0.114	2.605	1.197	0.563			
		0.168	1.295	0.905	0.443			
		1.383	1.383	0.975	0.993			
		0.134	0.759	0.697	0.840			
		0.134	1.045	0.813	0.858			
		0.340	**1.643**	**0.974**	**0.671**			
tree 2		0.143	2.305	1.644	0.849			
		0.071	1.662	1.519	0.474			
		0.248	1.153	1.242	0.869			
		0.304	2.609	0.840	0.733			
		0.071	1.894	1.367	0.911			
		0.151	2.394	1.383	0.851			
		0.165	**2.003**	**1.332**	**0.781**			
OF Gauge 1		**0.297**	**2.395**	**2.503**	**1.170**			
tree 5		0.278	1.336	1.240	0.980			
		0.356	1.856	1.769	1.336			
		1.720	2.634	2.341	1.623			
		0.256	1.435	1.179	1.042			
		0.429	1.912	1.796	1.296			
		0.268	1.555	1.215	1.126			
		0.551	**1.788**	**1.590**	**1.234**			
tree 6		0.522	1.800	1.800	1.026			
		0.317	1.602	1.699	1.356			
		0.430	1.590	1.683	1.159			
		0.544	1.651	1.614	1.234			
		0.408	1.630	1.500	1.153			
		0.440	1.866	1.928	1.232			
		0.444	**1.690**	**1.704**	**1.193**			

Appendix A:

	Jan 6	Jan 7	Jan 9	Jan 12	Jan 15	Jan 19	Jan 27	Jan 28
break	36	37	38	39	40	41	42	43
tree 3		0.115	1.516	1.570	0.639			
		0.177	1.579	1.233	0.603			
		0.357	1.644	1.340	1.090			
		0.608	1.832	1.698	1.572			
		0.447	1.394	0.983	1.447			
		0.260	1.110	1.327	0.954			
		0.327	**1.512**	**1.358**	**1.051**			
OF Gauge 2		**0.260**	**2.272**	**2.359**	**1.101**			
tree 4		0.852	3.814	2.548	1.016			
		0.245	1.844	1.503	0.437			
		0.367	2.289	1.512	1.057			
		0.425	1.908	1.249	1.127			
		0.355	2.208	1.898	0.905			
		0.360	2.214	1.404	1.224			
		0.434	**2.380**	**1.686**	**0.961**			
Hoyt		**0.279**	**1.981**	**2.108**	**0.991**			
Breaks 30, 31, 4								
Breaks 36, 41, 5								

68

Appendix A:								
	Feb 1	Feb 3	Feb 8	Feb 9	Feb 10	Feb 14	Feb 21	Feb 25
break	44	45	46	47	48	49	50	51
tree 1		2.505	1.294		0.005	0.000	0.000	
		3.081	1.376	0.264	0.004	0.000	0.000	
		1.412	1.862	0.366	0.002	0.000	0.000	
		1.472		0.603	0.002	0.000	0.000	
		0.989	1.224	0.434	0.005	0.000	0.000	
		1.072		0.447	0.007	0.000	0.000	
		1.755	**1.439**	**0.423**	**0.004**	**0.000**	**0.000**	
tree 2		2.368	1.304	0.304	0.007	0.000	0.000	
		1.752	1.470	0.229	0.004	0.004	0.000	
		1.499	1.928	0.585	0.007	0.031	0.000	
		1.501	1.358	0.447	0.005	0.000	0.000	
		2.075	1.082	0.302	0.007	0.000	0.000	
		2.253	1.127	0.405	0.004	0.007	0.000	
		1.908	**1.378**	**0.378**	**0.006**	**0.007**	**0.000**	
OF Gauge 1		**2.532**	**2.899**	**0.720**	**0.056**	**0.308**	**0.094**	
tree 5		4.851	1.490	0.523	0.018	0.050	0.009	
		1.840	1.127	0.423	0.007	0.051	0.012	
		1.912	2.878	1.197	0.025	0.090	0.011	
		2.038	1.407	0.457	0.011	0.090	0.005	
		1.858	1.501	0.563	0.016	0.075	0.007	
		2.113	1.251	0.447	0.009	0.080	0.005	
		2.435	**1.609**	**0.602**	**0.014**	**0.073**	**0.008**	
tree 6		2.109	1.068	0.534	0.007	0.028	0.002	
		1.760	1.118	0.449	0.005	0.039	0.002	
		2.151	1.833	0.673	0.021	0.099	0.011	
			1.379	0.535	0.009	0.036	0.000	
		2.003	1.665	0.650	0.012	0.078	0.003	
		2.174	1.532	0.704	0.007	0.049	0.004	
		2.040	**1.432**	**0.591**	**0.010**	**0.055**	**0.004**	

	Feb 1	Feb 3	Feb 8	Feb 9	Feb 10	Feb 14	Feb 21	Feb 25
break	44	45	46	47	48	49	50	51
tree 3		1.889	1.277	0.390	0.005	0.103	0.028	
		1.845	1.383	0.514	0.005	0.009	0.000	
		2.167		0.769	0.007	0.014		
		2.055		0.840	0.018	0.036	0.000	
		1.778	1.644	0.661	0.007	0.014	0.000	
		1.388	1.388	0.572	0.003	0.082	0.002	
		1.853	**1.423**	**0.624**	**0.008**	**0.043**	**0.006**	
OF Gauge 2		**2.449**		**0.633**	**0.043**	**0.338**	**0.082**	
tree 4		4.442	2.540	0.981	0.010	0.002	0.000	
		2.202	1.040	0.341	0.003	0.002	0.000	
		2.429	1.590	0.577	0.005	0.054	0.000	
		2.099	1.500	0.598	0.005	0.038	0.000	
		3.166	1.437	0.621	0.009	0.007	0.000	
		2.665	1.503	0.648	0.005	0.068	0.000	
		2.834	**1.602**	**0.628**	**0.006**	**0.029**	**0.000**	
Hoyt		**2.311**	**2.515**	**0.610**	**0.025**	**0.356**	**0.051**	
Breaks 30, 31, 4								
Breaks 36, 41, 5								

Appendix A:								
	Mar 1	Mar 2	Mar 4	Mar 8	Mar 11	Mar 13	Mar 15	Mar 16
break	52	53	54	55	56	57	58	59
tree 1	0.005	0.000		0.509	0.002	0.929	0.125	
	0.016	0.000		0.361	0.005	0.827	0.158	
		0.000		0.500	0.032	0.983	0.268	
	0.067	0.000		0.913	0.028	1.126	0.355	
	0.028	0.000		0.546	0.017	0.781	0.225	
	0.043	0.002		0.679	0.014	0.876	0.268	
	0.032	**0.000**		**0.585**	**0.017**	**0.920**	**0.233**	
tree 2	0.020	0.000		0.643	0.014	1.001	0.277	
	0.004	0.002		0.458	0.002	1.135	0.123	
	0.031	0.002		1.353	0.117	1.188	0.667	
	0.045	0.002		0.357	0.025	0.652	0.250	
	0.023	0.000		0.639	0.012	1.100	0.142	
	0.062	0.002		0.563	0.039	1.056	0.255	
	0.031	**0.001**		**0.669**	**0.035**	**1.022**	**0.286**	
OF Gauge 1	**0.385**	**0.272**		**1.116**	**0.457**	**1.622**	**1.431**	
tree 5	0.160	0.035		1.046	0.186	1.215	0.709	
	0.088	0.018		0.625	0.100	1.144	0.423	
	0.238	0.060		1.241	0.266	1.540	1.074	
	0.121	0.048		1.115	0.121	0.923	0.731	
	0.161	0.038		0.947	0.175	1.126	0.661	
	0.107	0.030		1.090	0.127	0.911	0.679	
	0.146	**0.038**		**1.011**	**0.163**	**1.143**	**0.713**	
tree 6	0.124	0.015		0.620	0.096	1.257	0.491	
	0.095	0.018		0.880	0.106	1.056	0.475	
	0.181	0.039		0.926	0.187	1.356	0.739	
	0.116	0.013		0.898	0.098	0.934	0.481	
	0.139	0.029		0.997	0.163	1.067	0.703	
	0.136	0.026		1.003	0.192	1.268	0.599	
	0.132	**0.023**		**0.887**	**0.140**	**1.156**	**0.581**	

	Mar 1	Mar 2	Mar 4	Mar 8	Mar 11	Mar 13	Mar 15	Mar 16
break	<u>52</u>	<u>53</u>	<u>54</u>	<u>55</u>	<u>56</u>	<u>57</u>	<u>58</u>	<u>59</u>
<u>tree 3</u>	0.021	0.041		0.816	0.021	1.188	0.204	
	0.021	0.002		0.452	0.005	1.029	0.222	
	0.132	0.004		0.786	0.104	1.108	0.554	
	0.379	0.020		1.054	0.343	1.179	1.054	
	0.079	0.004		0.965	0.066	0.786	0.465	
	0.097	0.014		0.616	0.078	1.188	0.312	
	0.122	**0.014**		**0.782**	**0.103**	**1.080**	**0.468**	
OF Gauge 2	**0.314**	**0.246**		**1.058**	**0.390**	**1.764**	**1.336**	
<u>tree 4</u>	0.048	0.003		0.895	0.043	2.109	0.654	
		0.003		0.856	0.026	1.083	0.349	
	0.128	0.002		1.083	0.105	1.311	0.769	
	0.123	0.002		1.041	0.109	1.058	0.633	
	0.016	0.005		0.390	0.011	1.339	0.133	
	0.031	0.013		0.738	0.023	0.738	0.252	
	0.069	**0.005**		**0.834**	**0.053**	**1.273**	**0.465**	
Hoyt	**0.305**	**0.178**		**0.991**	**0.406**	**1.499**	**1.194**	
Breaks 30, 31, 4								
Breaks 36, 41, 5								

Appendix A:						
	Mar 17	Mar 18	Mar 21	Mar 24	Mar 30	
break	60	61	62	63	64	
tree 1	0.009	0.983	0.073	0.107	0.902	
	0.035	1.329	0.114	0.158	0.951	
	0.170	0.947	0.109			
	0.115	2.182	0.245	0.293	1.490	
	0.043	1.422	0.127	0.165	0.711	
	0.041	1.671	0.130	0.179	0.911	
	0.069	**1.422**	**0.133**	**0.180**	**0.993**	**35.259**
tree 2	0.021	1.340	0.120	0.179	0.902	
	0.007	1.030	0.079	0.114	0.968	
	0.194	1.819	0.289	0.475	1.864	
	0.059	1.787	0.143	0.214	1.170	
	0.032	1.446	0.082	0.133	0.656	
	0.067	1.444	0.144	0.202	0.810	
	0.063	**1.477**	**0.143**	**0.220**	**1.062**	**38.562**
OF Gauge 1	**0.477**	**1.755**	**0.870**	**1.062**	**3.043**	**63.743**
tree 5	0.213	1.738	0.326	0.443	1.703	
	0.132	1.655	0.243	0.317	1.611	
	0.306	6.593	0.669	0.748	3.134	
	0.214	1.334	0.329	0.420	1.928	
	0.209	2.082	0.348	0.393	1.769	
	0.191	1.483	0.340	0.393	1.778	
	0.211	**2.481**	**0.376**	**0.453**	**1.987**	**49.886**
tree 6	0.124	2.109	0.329	0.362	1.894	
		1.514	0.204	0.299	1.250	
	0.226	2.020	0.398	0.468	2.113	
	0.151	2.050	0.239	0.317	1.705	
	0.222	1.839	0.324	0.416	1.908	
	0.199	2.245	0.299	0.370	1.928	
	0.184	**1.963**	**0.299**	**0.372**	**1.800**	**44.339**

	Mar 17	Mar 18	Mar 21	Mar 24	Mar 30	
break	60	61	62	63	64	
tree 3	0.060	0.816	0.103	0.142	1.117	
	0.053	1.188	0.117	0.186	1.188	
	0.248	2.144	0.331	0.465	1.054	
	0.708		0.591	0.786		
	0.200	2.144	0.214	0.348	1.912	
	0.156	1.457	0.165	0.286	0.980	
	0.238	**1.550**	**0.253**	**0.369**	**1.250**	**44.893**
OF Gauge 2	**0.439**	**1.457**	**0.805**	**0.971**	**2.663**	**58.929**
tree 4	0.086	3.358	0.157	0.362	2.187	
	0.108	1.145	0.114	0.175	1.363	
	0.203	0.245	0.255	0.437	1.555	
	0.215	1.925	0.262	0.390	1.500	
	0.039	1.809	0.057	0.089	0.736	
	0.112	1.989	0.095	0.126	1.071	
	0.127	**1.745**	**0.157**	**0.263**	**1.402**	**50.402**
Hoyt	**0.432**	**1.422**	**0.762**	**0.838**	**2.565**	**56.744**
Breaks 30, 31, 4						
Breaks 36, 41, 5						

My study period lasted from 16Nov2007 to 30Mar2008. Incident rainfall varied somewhat among my three sources of incident rainfall. The tipping-bucket gauges at Hoyt Arboretum and the City of Portland's HYDRA gauge operated more-or-less continuously over the length of the study. The raingauge at Hoyt recorded 66.2cm, while the HYDRA gauge recorded 69.7cm. The third source, the open-field buckets, were occasionally subjected to ice, snow, and vandalism. During that same period, 221 hours of rainfall were not available in the open-field gauge record. Open-field gauges recorded 65.6cm (by tree 3) and 71.6cm (by tree 2). For the purposes of comparison, I include the totals for the first two sources over the more limited time: the Hoyt raingauge recorded 62.2 cm of rainfall (about 24 inches), while the HYDRA gauge recorded 61.6cm of rainfall.

I used both rainfall recorded by the Hoyt raingauge and rainfall recorded at the open-field gauges. The Hoyt raingauge data were essential for tracking rainfall intensity through minute-by-minute data recording, and also for providing other useful meteorological data. The incident values were comparable to those recorded at the HYDRA site, and somewhat smaller than those from my own open-field collectors. Of the two numbers I have given here for the Hoyt rainfall (66.2cm and 62.2cm), I have used the smaller value, since it mirrored the data gaps present in the field data.

I have also used the incident values collected at the open-field gauges. Because they were much closer to and more representative of the study sites, they

likely much better reflected conditions at the study sites. Their larger incident rainfall

totals translated into higher interception rates.

Interception calculated using Hoyt rainfall totals was somewhat lower for all

trees (Figure 22). When using Hoyt rainfall, interception rates for open-grown trees

(#1-4) went from 45, 40, 24 and 15% to 38, 32, 21, and 12%. At closed-canopy trees,

interception went from 22 and 30% to 12 and 22%. Despite this difference, the Hoyt

totals were still valuable for establishing context and I used them to compute rainfall

intensity, to determine meteorological characteristics during the study period, and to

make comparisons with historical airport data. Because these analyses were largely

relative to each other, they should not be seen as affecting overall conclusions drawn

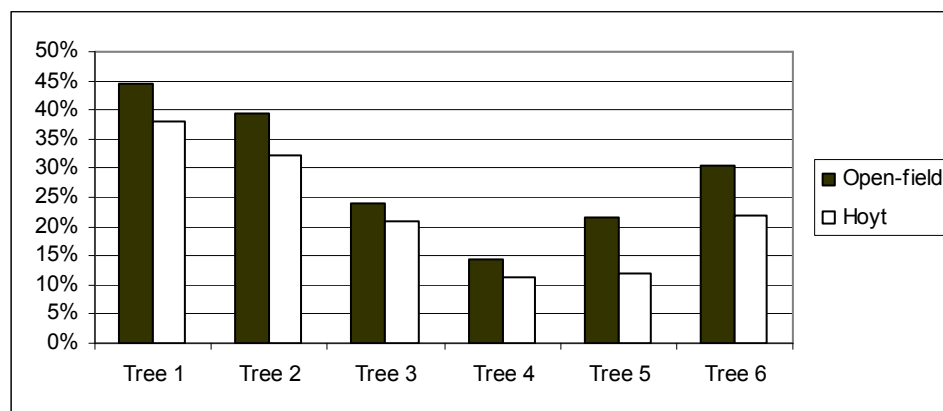regarding open-grown interception.

Figure 1. Determining Interception of Study Trees. A comparison of interception
at each study tree: solid bars based computations on local, open-field incident totals;
hollow bars based computations on the Hoyt Arboretum raingauge incident totals.
Trees 1-4 were open-grown, while trees 5&6 were in a closed-canopy forest patch.