DIFFERENCES IN RAINFALL INTERCEPTION LOSSES FOR
THREE TREE SPECIES COMMON TO COLORADO: *Populus
tremuloides, Picea engelmannii, AND Pinus ponderosa*

by

SHANNON THOMAS

B.A., Colorado College, 2013

A thesis submitted to the Graduate Faculty of the
University of Colorado at Colorado Springs
in partial fulfillment of the
requirements for the degree of

Master of Arts

in

Applied Geography

Department of Geography and Environmental Studies

2016
This thesis for Master of Arts degree by

Shannon Thomas

has been approved for the

Department of Geography and Environmental Studies

by

________________________________________

Curt Holder, Chair

________________________________________

John Harner

________________________________________

Somayeh Dodge

________________________________________

Date
Rainfall interception is the amount of rainfall retained in a canopy after a storm event has occurred. This term is also referred to as rainfall interception loss since the water retained in the canopy is evaporated or “loss” back to the atmosphere and does not touch the forest floor. Although dependent on the total amount of rainfall, interception loss is also greatly affected by the type of species, tree structure, and specific characteristics such as leaf area. This study serves to answer the following research questions: are there differences in rainfall interception losses between *Populus tremuloides* (aspen), *Picea engelmannii* (Engelmann spruce), and *Pinus ponderosa* (ponderosa pine), and if so, what canopy characteristics influenced the interception? The results showed that the conifers, Engelmann spruce and ponderosa pine, contained higher interception losses compared to aspen in a majority of the samples. Many of the samples showed that a larger stand density and basal area corresponded with smaller interception losses. This could be due to a variety of reasons including perimeter drip, inclined rainfall, and wind. If urban planners were to choose the tree species that could decrease runoff, then ponderosa pine would be the best choice out of the three species.
DEDICATION

This thesis is dedicated to my family and J.T. Brlansky.
ACKNOWLEDGEMENTS

I’d like to thank my thesis committee, John Harner and Somayeh Dodge, and especially my advisor, Curt Holder, for his help and guidance throughout the process. I’d also like to thank the Catamount Center for providing me access to their land and resources. Additionally, I want to thank J.T. Brlansky for his continuous encouragement and support.
# TABLE OF CONTENTS

## CHAPTER

| I.       | INTRODUCTION .......................................... 1 |
| Purpose of the Study ..................................... 2 |
| II.      | REVIEW OF THE LITERATURE ............................. 3 |
| Definitions ............................................... 3 |
| Previous Literature ........................................ 4 |
| III.     | METHODOLOGY ........................................... 13 |
| Study Area .................................................. 13 |
| Data Measurements .......................................... 14 |
| Data Collection ............................................ 15 |
| Data Calculations .......................................... 17 |
| IV.      | RESULTS .................................................. 21 |
| Comparison of Rainfall Interception Losses between Species ............ 21 |
| Characteristics of Tree Species ................................ 26 |
| Effects of Wind on Rainfall Interception Losses .......................... 31 |
| Neighboring Effect on Rainfall Interception Losses ......................... 37 |
| V.       | DISCUSSION ............................................. 45 |
| VI.      | CONCLUSION ............................................. 52 |
| Future Research ............................................. 53 |
TABLES

Table

1. Total Precipitation, Throughfall, and Interception Losses
   for Aspen Trees ......................................................... 23

2. Total Precipitation, Throughfall, and Interception Losses
   for Engelmann Spruce Trees ......................................... 24

3. Total Precipitation, Throughfall, and Interception Losses
   for Ponderosa Pine Trees ............................................ 25

4. Comparison of DBH, Height, Stand Density and Basal Area
   between Species. ....................................................... 27

5. Comparison of DBH, Aboveground Foliage Biomass,
   Total Surface Area to Dry Weight, and Leaf Area .............. 28-29

6. Average Throughfall in the Cardinal Directions ................. 32

7. Date of Storm Event and Dominant Wind Direction ............. 37
FIGURES

Figure

1. Study Area of Sample Trees at the Catamount Center ......................14
2. Example of Throughfall Gauges in the Cardinal Directions ...............16
3. Polar Grid with Corresponding Angles ........................................20
4. Conversion from Polar to Cartesian Coordinates ...............................20
5. Comparison of Interception Losses between Aspen Trees ..................23
6. Comparison of Interception Losses between Engelmann Spruce Trees .....24
7. Comparison of Interception Losses between Ponderosa Pine Trees ..........25
8. Comparison of Interception Losses between Species ..........................26
9. Comparison of Leaf Area between Species .......................................29
10. Interception Losses Compared to Leaf Area for Aspen Trees ..............29
11. Interception Losses Compared to Leaf Area for Engelmann Spruce Trees ..30
12. Interception Losses Compared to Leaf Area for Ponderosa Pine Trees ....30
13. Average Throughfall Collection in the Cardinal Directions for Aspen Trees ..............................................................................32
14. Average Throughfall Collection in the Cardinal Directions for Engelmann Spruce Trees ................................................................33
15. Average Throughfall Collection in the Cardinal Directions for Ponderosa Pine Trees ................................................................33
16. Aspen Throughfall Collection in the Cardinal Directions ....................34
17. Engelmann Spruce Throughfall Collection in the Cardinal Directions ........35
18. Ponderosa Pine Throughfall Collection in the Cardinal Directions ............... 36
19. Location of Neighboring Trees for Aspen 1 ........................................ 38
20. Location of Neighboring Trees for Aspen 2 ........................................ 39
21. Location of Neighboring Trees for Aspen 3 ........................................ 39
22. Location of Neighboring Trees for Aspen 4 ........................................ 40
23. Location of Neighboring Trees for Engelmann Spruce 1 ....................... 40
24. Location of Neighboring Trees for Engelmann Spruce 2 ....................... 41
25. Location of Neighboring Trees for Engelmann Spruce 3 ....................... 41
26. Location of Neighboring Trees for Engelmann Spruce 4 ....................... 42
27. Location of Neighboring Trees for Ponderosa Pine 1 ......................... 42
28. Location of Neighboring Trees for Ponderosa Pine 2 ......................... 43
29. Location of Neighboring Trees for Ponderosa Pine 3 ......................... 43
30. Location of Neighboring Trees for Ponderosa Pine 4 ......................... 44
CHAPTER 1

INTRODUCTION

Rainfall interception is the amount of rainfall retained in a canopy after a storm event has occurred. This term is also referred to as rainfall interception loss since the water retained in the canopy is evaporated or “loss” back to the atmosphere and does not touch the forest floor. Although dependent on the total amount of rainfall, interception loss is also greatly affected by the type of species, tree structure, and specific characteristics (Aston 1979; Xiao et al., 1998; Van Stan et al., 2011; Holder 2013). The overall size of a tree can increase interception losses within a species, but unapparent characteristics such as leaf structure and positioning also have an impact (Aston 1979; Van Stan et al., 2011). Rainfall interception has been studied for almost a century with varying applications including categorizing interception losses for varying species, modeling interception losses, and studying the impacts of interception losses on urban environments.

Studies first centered on gaining scientific knowledge in the field, but have become more applicable with solving “real-world” problems. One central focus that has evolved in the latter half of the 20th century is using rainfall interception losses to decrease runoff as a stormwater management technique in urban areas (Sanders 1986; Xiao et al., 1998; Inkilaninen et al., 2013; Van Stan et al., 2015). With high intensity storms and the increasing amount of forest fires near urban areas, new solutions to decrease runoff and
prevent flooding are needed. In 2015, there were 68,151 wildland fires with 10,125,149 acres burned, causing an increased risk to flooding in areas close to these fires (National Interagency Fire Center 2016). Colorado for example, saw an increased flooding risk after the Waldo Canyon fire that began in June 2012. Therefore, studies related to rainfall interception and their impact on decreasing runoff can become an approach for urban planners to mitigate the consequences of forest fires on urban communities.

Because different species of trees contain different canopy characteristics, structure, and size, planting a specific species can result in varying interception losses. Therefore, if tree species are to be selected to decrease runoff, then their characteristics should be studied to determine if the species is best suited for decreasing runoff.

Purpose of Study

The following study serves to provide the rainfall interception losses for three species common to the Colorado region as well as a detailed description of their canopy characteristics in order to determine possible tree species that could aid in decreasing runoff in urban corridors. This study serves to answer the following research questions: are there differences in rainfall interception losses between *Populus tremuloides* (aspen), *Picea engelmannii* (Engelmann spruce), and *Pinus ponderosa* (ponderosa pine), and if so, what canopy characteristics influenced the interception?
CHAPTER 2

REVIEW OF THE LITERATURE

The study of rainfall interception loss dates back to the early 1900s and still remains a growing area of research. Rainfall interception loss is affected by a variety of factors from small-scale leaf hydrophobicity to macro-scale environmental factors and vegetation type. The following literature review of studies on rainfall interception provides comprehensive insight on these factors and processes that influence rainfall interception.

Definitions

Because the following studies examine rainfall interception, the terms gross precipitation, throughfall, and stemflow are commonly used. As mentioned previously, rainfall interception is the amount of rainfall retained in the canopy after a storm event. Gross precipitation is the total amount of rainfall during a storm event while throughfall is the amount of rain that falls through a tree canopy. Stemflow is the amount of rainfall that is intercepted by the branches and the trunk of the tree that flow down to the ground. Previous research has shown that stemflow shows little effect on rainfall interception when compared to total precipitation (Ubarana 1996; Marin et al., 2000).
Previous Literature

Macro-level processes, such as wind in particular, have significant impacts on rainfall interception. Herwitz and Slye (1995) found that in 80% of the rain events examined in Australia, rain droplets fell at an inclination as far as 19 degrees away from the vertical angle path. The authors suggest that future rainfall interception studies should consider the effects of wind when analyzing results, especially since neighboring trees of the same species could have different interception losses solely due to inclined rainfall. Van Stan et al. (2011) also discuss the impacts of inclined rainfall due to wind speed. Their findings showed that high wind speeds greatly affected rainfall collection. In the 30 storm events monitored, nearly all the storms were affected by wind speed and 25 of the 30 storms displayed a canopy rain shadow effect due to the differences in heights and structures of neighboring canopies. For example, the study showed that the taller species, *Liriodendron tulipifera*, was greater at intercepting vertical rainfall due to its large horizontal canopy area. The opposite result was seen in the canopy of *Fagus grandifolia* in which greater rainfall interception occurred with inclined rainfall due to the large vertical surface area of the canopy (Van Stan et al., 2011). Therefore, when these species are placed next to each other, the neighboring effect can greatly influence rainfall interception rates.

Leaf area also plays a significant role in rainfall interception rates. Leaf area index is a variable that is defined as the ratio of one-sided leaf area per ground surface area. Because coniferous species do not contain flat leaves that are equal in area, leaf area is commonly determined by using all sides (Jonckheere et al., 2004). A greater leaf area index
corresponds to a greater rainfall interception rate since the larger leaf area per ground area provides more opportunities to intercept rainfall.

Once rainfall interception or interception loss has occurred, the water retained in the canopy can then either drip down to the surface, flow down the branches and stem as stemflow, or evaporate back into the atmosphere. Throughfall is the precipitation that falls through the canopy or drips off vegetative surfaces. Two methods are commonly used to calculate rainfall interception. The two methodologies to calculate rainfall interception, also measure stemflow, evaporation, and throughfall. The first methodology involves collecting observed measurements conducted in the field or in a laboratory. For field studies, interception is measured by the equation:

\[ I = P_g - (T + S), \]

where \( I \) is the interception, \( P_g \) is the total amount of precipitation, \( T \) is the total amount of throughfall and \( S \) is the stemflow (Zinke 1967). \( P_g \) gauges are the control rainfall gauges that are placed in open areas to collect total precipitation while throughfall gauges are placed under the canopy to measure the precipitation that is not intercepted. Interception is then calculated by subtracting the throughfall and stemflow from the total precipitation. The second methodology for gathering these data involves calculating interception loss through the solution of models bounded by parameters which are determined through meteorological data or previous literature (Calder 1977; Bryant et al., 2005).

The first known study of rainfall interception started with Horton’s (1919a) research on rainfall interception loss for 11 tree species using rain gauges. In addition to showing that wooded areas intercepted larger amounts of precipitation than field crops,
results also showed that the average interception loss from the 11 species was 40 percent of the total precipitation; however, it should be noted that this research was more conceptually based rather than empirically proven. Zinke (1967) provided the first comprehensive review of rainfall interception studies, including specific rainfall interception amounts for 39 different species that were gathered from 29 studies, all of which used field observations from control and throughfall rainfall gauges. Zinke (1967) also concluded that rainfall interception ranged from 0.02 to 0.36 inches for varying species, and interception from conifers was greater compared to deciduous plants. Another example includes Aston’s (1979) research on rainfall interception rates for eight small trees. This study took small trees of each species to study under a rainfall simulator to determine if leaf area correlated to greater interception. Results inferred that the species with the largest leaf area, *Pinus radiata*, also had the highest interception.

After Zinke’s (1967) comprehensive review of rainfall interception studies, a new methodology came about in which models, bounded by parameters from meteorological weather stations or literature, provided a relatively close approximation of rainfall interception. Rutter et al. (1971) developed the Rutter model based on advanced mathematical formulas to calculate rainfall interception, throughfall, and evaporation rates over time. This model was then compared to field observations to determine its accuracy. The comparison showed that the Rutter model provided a fairly accurate representation of field observations, with a correlation coefficient of 0.65 when removing months that were considered outliers (July and August). However, when these months were included the correlation coefficient decreased to just 0.40, representing a weaker relationship with field observations (Rutter et al., 1971). Similar to the previous model, Gash (1979) also
developed a model to determine the amount of interception loss and corresponding evaporation rates. This model differs from the Rutter model in that Gash’s model analyzes rainfall interception for separate storm events and divides the storms into three phases: the wetting-up phase, followed by saturation, and then drying (Muzylo et al., 2009). Gash’s model was compared to data from the Thetford Forest, resulting in an adequate representation of the observed data. Gash et al. (1995) later updated the model to improve boundary conditions in order to provide more accurate results for sparse forests. Rather than determining evaporation from the canopy based on the ground area, the updated model uses the area of the canopy instead. The Rutter and Gash models are two of the most commonly used models in rainfall interception. Although many studies propose new models, these models are often variations of either the Rutter or Gash models (Muzylo et al., 2009).

Additional studies confirm the accuracy of the aforementioned models (Calder 1977; Bryant et al., 2005). Calder (1977) calculated evaporation from interception loss using the Rutter model for a spruce forest located in central Wales. Results concluded that observations from field measurements and the Rutter model were in good agreement for interception loss as long as the vapor pressure deficit was accurately calculated. Bryant et al. (2005) measured rainfall interception, throughfall, and evaporation rates in five forested areas in Georgia through field measurements that were then validated by the model developed by Gash et al. (1995). The results showed that the pine forest contained the highest interception loss, 22.6 percent, compared to differing forested areas. The Gash model produced results that were in good agreement with these values, with the exception of riparian wetland forests that required alterations to the model.
Even though the Rutter and Gash models were validated in the previous studies, there are many critiques of these models. Crockford and Richardson (2000) discussed the difficulty with accurately measuring rainfall interception based on vegetation type. Although canopy structure such as height, positioning of branches and leaves, leaf shape, and thickness all affect canopy interception, the environment also contributes significantly to this measurement. Factors like wind, duration and frequency of rainstorms, humidity, temperature, and even slope also greatly affect rainfall interception (Crockford and Richardson 2000). Therefore, interception rates will likely be varied for the same species at different locations. Modeling the complexity of these factors and their changing characteristics will likely lead to inaccuracies.

Micro-level processes, such as leaf hydrophobicity, also have significance on rainfall interception since they directly relate to leaf area and the tree structure. Leaf hydrophobicity is a measure of leaf water repellency, or more specifically, the measurement of the contact angle between the surface of the leaf and the line tangent to the edge of the water droplet. If the contact angle is greater, then the leaf hydrophobicity is also greater whereas a smaller angle corresponds to a more hydrophilic leaf. An angle greater than 130 degrees suggests water repellent leaves while angles of less than 110 degrees indicate non-repellent leaves (Holder 2007). In a more intuitive sense, the measurement is looking at the “beadiness” of the water droplet on the leaf surface, where a more spherical drop corresponds with greater hydrophobicity.

Adaptations of leaves to become more water repellent, such as waxy substances or hairs, could be to increase photosynthesis rates since carbon dioxide actually diffuses 10,000 times slower in water compared to air (Holder 2007). In a study conducted on leaf
hydrophobicity, three study areas with varying amounts of precipitation, including a lower-montane cloud forest, a tropical dry forest, and a foothills-grassland, were used to determine which location had the highest leaf hydrophobicity. Because the lower-montane cloud forest had a significantly higher amount of precipitation, it was hypothesized that this location would contain plants with the highest leaf hydrophobicity. The results, however, showed the opposite of the hypothesis. The cloud forest had the lowest leaf hydrophobicity while the driest area, the foothills-grassland, contained the highest leaf hydrophobicity (Holder 2007). This could be explained by the semi-arid climate of the foothills-grassland area. The leaves could be more hydrophobic in order to maximize the amount of water that reaches the soil to become available for root uptake. Additionally, persistent precipitation can also have an erosive impact on waxy surfaces of leaves, which could then decrease the leaf hydrophobicity.

Leaf hydrophobicity is studied on a micro-level, but the results of these studies can give insight into macro-level processes, such as canopy storage capacity and rainfall interception. Canopy storage capacity is the quantity of water held within the canopy after a rainfall occurrence, after drip has ceased and in the absence of wind. The plant’s leaves, branches, and even the trunk can intercept rainfall. The canopy storage capacity is dependent on leaf surface properties, leaf area, architecture of the tree type, proximity to neighboring trees, and wind. In a study testing the canopy storage capacity for seven different species, it was hypothesized that trees with the highest leaf hydrophobicity and lowest water droplet retention would have the lowest canopy storage capacity (Holder 2013). Leaf water droplet retention measures how easily a droplet drains off of a leaf when incrementally tilted from 0 (horizontal) to 90 degrees (vertical). For the results, leaf storage
capacity measured from branch samples was greatest for leaves with both the lowest leaf hydrophobicity and the lowest water droplet retention (Holder 2013).

Early studies on rainfall interception were usually conducted for insight on factors such as evaporation rates, leaching problems, and groundwater recharge, but more recent studies focus on the importance interception plays in urban planning and stormwater management. The following studies utilize the two methodologies aforementioned.

Sanders (1986) conducted a study in Dayton, Ohio, which examined the effect of human influence on urban runoff. By creating a hydrologic model for runoff, the study found that runoff was lowered by seven percent from canopy storage, but this number could increase to 12 percent with increasing the canopy coverage. In the scenario, exposed areas in the study zone were removed and canopy storage capacity was raised to 50 percent, representing human efforts to increase urban vegetation (Sanders 1986). These results showed that by implementing programs to increase vegetation cover, an impact could be made on decreasing runoff.

Similar research also focuses on urban studies to demonstrate the impacts of rainfall interception on runoff (Xiao et al., 1998; Inkilaninen et al., 2013; Van Stan et al., 2015). A study on rainfall interception in Sacramento County, California utilized remote sensing and field sampling. The results showed that annual rainfall interception for urban forest canopies was 11.1 percent for the study area and only 1.1 percent when looking at the whole county (Xiao et al., 1998). Additionally, rainfall interception was higher for smaller storms and lower for high intensity storms. Results also showed that evergreen trees (trees that do not lose their leaves throughout the year) were one of the most influential factors since most of the precipitation in Sacramento happens in the winter. The larger size of
evergreens also contributed to a greater rainfall interception when compared to the smaller deciduous plants (Xiao et al., 1998). The benefits from knowledge on the effects of canopy storage capacity for urban forests could help with stormwater management, water quality, and flooding in cities. In Raleigh, North Carolina, researchers studied the throughfall in residential urban vegetation from July to November 2010. From the 16 residential plots that were analyzed, rainfall interception ranged from 9.1 percent to 21.4 percent (Inkilaninen et al., 2013). The most influential factors in the study that affected throughfall were canopy cover and coniferous trees. The most recent study by Van Stan et al. (2015) focused on forest canopy interception between two common species in Maryland and its effects on stormwater management and urban sustainability plans. Interception loss, stemflow, and throughfall were measured for two deciduous tree species, *Fagus grandifolia* and *Liriodendron tulipifera*, for 52 storm occurrences from November 2007 to March 2011. Results showed that *L. tulipifera* had a significantly higher interception percentage compared to *F. grandifolia*. These results were expected due to the canopy structure of *L. tulipifera*. From these findings urban planners can utilize this knowledge to help determine types of trees to plant to decrease runoff, or in some cases increase runoff to recharge groundwater sources.

Another form of modeling that is receiving recognition in the field involves the use of geographic information systems (GIS). Mapping rainfall interception is a relatively unexplored field in GIS that is not covered in the above publications. However, a study by Peng et al. (2009) modeled the canopy interception of *Picea crassifolia* by using a hybrid of an empirical and theoretical model that estimated interception based primarily on precipitation and leaf area index. Remote sensing technologies were also used to collect
several vegetation indexes. Results showed that the estimations from the model were in good agreement with observed data, with a correlation coefficient of 0.715. Another study by Jain et al. (2004) modeled runoff by using a digital elevation model (DEM) that incorporated variables of vegetation, slope, soil properties, and rainfall intensity. Calculations for runoff were determined by running algorithms across the DEM with set parameters for the variables mentioned previously (Jain et al., 2004). Although this model inferred rainfall interception through several different factors, like vegetation drag, the model could be improved by including a separate variable for rainfall interception.

It is evident that there is an extensive amount of research in the field of rainfall interception due to the complexity in measuring variables related to canopy structure and environmental factors. Both methodologies of field observations and modeling are still in practice today and are often used in conjunction for data validation. GIS is another growing field that may improve already existing models to increase accuracy of estimating rainfall interception.

While research is quite extensive for rainfall interception, there is limited research on species present in the state of Colorado. Aspen, ponderosa pine, and Engelmann spruce are not included in present studies nor have these species been validated for the Gash and Rutter models. The proposed research will fill in this gap to provide information that can be utilized by city planners for urban greening initiatives like decreasing runoff.
CHAPTER 3

METHODOLOGY

Rainfall interception was determined for three common species in Colorado: aspen, Engelmann spruce, and ponderosa pine. Canopy characteristics, such as tree structure and the proximity to the neighboring trees, were investigated to determine their effect on interception losses. The effects of wind was also analyzed by measuring rainfall interception in the four cardinal directions. It was hypothesized that the coniferous species would have significantly higher interception losses compared to aspen based on previous research that showed higher interception losses for conifers based on their size, leaf area, and year-round foliage (Xiao et al., 1998; Inkilaninen et al., 2013).

Study Area

The research was conducted at the Catamount Center located 10.6 kilometers southwest of Woodland Park on the north slope of Pikes Peak (Figure 1). The Catamount Center is a non-profit organization that offers outdoor education programs and retreats to promote environmental stewardship. Founded in 1997 by Dr. Howard Drossman and Julie Francis, the site contains 177 acres of land at an elevation ranging from 2,850 to 3,000 meters with all three species common in various areas (Catamount Center 2016). Because
of the length of the study, it was important to find a location that was isolated to prevent disruption and tampering of the field equipment. The Catamount Center is located on private land and prohibits public access and thus provided an ideal site for this research.

![Image of the study area](image)

**Figure 1:** The study area for all sample trees (shaded in green) located at the Catamount Center.

**Data Measurements**

Data were collected during the months of August through early-September and stopped when the aspen leaves began falling from the canopy. Gross precipitation and throughfall data were collected for nine storm events that ranged in intensity and duration. Because limited equipment was available for this research, measurements from the rainfall
gauges were taken after a storm event ended rather than measuring the data at shorter time intervals throughout the storm which is typical in previous research since it shows the different phases of interception rates (Marin et al., 2000; Van Stan et al., 2015). For example, the canopy first experiences a “wetting up” phase until it is saturated at which point interception losses drastically decrease. Although the proposed research was not able to determine the point of saturation, total rainfall interception losses during each rainfall event were able to be recorded.

**Data Collection**

For this study, four trees from each species were measured, totaling 12 trees in all. After finding three different areas where the three species of interest were dominant, four trees were selected based upon their health (no disease or dying limbs) and the openness under the canopy so the throughfall gauges could be placed without any interference or additional interception from surrounding plants. For each individual tree, four throughfall gauges were randomly positioned under its canopy along the four cardinal directions (North, South, East, and West) (Figure 2). After each storm event, the throughfall gauges in each of the cardinal directions were moved randomly, ranging from the base of the tree to the outer perimeter that was measured in meters, through a random number generator to provide a more accurate estimation of the rainfall interception losses of the entire canopy. By placing throughfall gauges in the four cardinal directions, wind was also accounted for by comparing the measurements of throughfall in the cardinal directions. Three control
gauges were placed in open areas to measure gross precipitation that were at least 15 meters away from the nearest tree.

Gross precipitation and throughfall gauges were constructed from gallon milk jugs. Funnels were taped to the top of the milk jugs and weighted at the bottom to prevent being knocked over from wind. The orifice of the funnel was also leveled to avoid tilting. After each storm event, the water collected in the rainfall gauges were poured into a graduated cylinder to record precipitation volume. The depth equivalent of throughfall and gross precipitation in centimeters were calculated by dividing the precipitation volume in cubic centimeters by the area of the orifice of the funnel in square centimeters.

Figure 2: Example showing the four throughfall gauges randomly positioned under a tree canopy in the four cardinal directions.
Data Calculations

Interception ($I$) was calculated for each tree after every storm event for all gauges with the equation

$$I = P_g - T,$$

where $P_g$ is the gross precipitation measured by the control gauges and $T$ is the throughfall measured by the throughfall gauges (Zink 1967). The standard deviation for throughfall for the nine storm events was also calculated for each tree sample.

Average rainfall interception losses were determined for each individual tree. After determining these averages, canopy structure, the neighboring effect, and wind were examined to determine the extent of their effects on rainfall interception losses. For each tree, the structure and size were described in detail as well as their distance to neighboring trees.

To account for structure and size, the diameter at breast height (DBH) and height of each tree was recorded using diameter measuring tape and a clinometer. Stand density was also calculated by counting all neighboring trees within a 10 meter radius of each sample tree. The stand density was then converted to show the number of trees per hectare. The direction and distance to the neighboring trees from the sample were also recorded. The basal area, which provides the area of land that is taken up by tree stems, is calculated by the equation:

$$BA = \pi \cdot \left(\frac{DBH}{2}\right)^2,$$
where BA is the basal area and DBH is the diameter at breast height (Larsen 1999). However, this equation is used for DBH measured in inches. Because the DBH was measured in centimeters, the equation:

\[
BA = 0.00007854 \times DBH^2,
\]

was used instead (Larsen 1999). The basal area of a plot is then calculated by summing the basal areas of all trees (by the equation above) and dividing by the plot area, which was a 10-meter radius circle in this study. Leaf area was also calculated for each species. For Engelmann spruce and ponderosa pine, the diameter, length, and dry weight of 30 needles were recorded to determine the total surface area and dry weight. These values for aspen were provided from previous fieldwork by Dr. Curt Holder. Leaf area was calculated by the equation:

\[
LA = M \times \frac{\sum \text{Surface Area}}{\sum \text{Dry Weight}},
\]

where LA is the leaf area and M is the aboveground foliage biomass. The foliage biomass was determined through Ter-Mikaelian and Korzukhin’s tree biomass equations in which the only measured parameter needed is the DBH (1997). The leaf area is then calculated by multiplying the biomass by the surface area, dry weight ratio. To calculate surface area of the Engelmann Spruce needles, the equation for the surface area of a cylinder was assumed. For Ponderosa Pine, Johnson’s equation:

\[
A = \left(2r + \frac{2\pi r}{n}\right) \times l,
\]

where r is the radius of the needle, n is the number of needles in a fascicle, and l is the length of the needle, was used (Johnson 1984).
For wind, the prevailing wind patterns of storms in Woodland Park within the same 24-hour period as the storm event at the Catamount Center were recorded from the nearest weather station and then compared with the throughfall measurements of the rain gauges in each of the cardinal directions to determine if there was a correlation between the amount of throughfall and wind direction. Similarly, the neighboring effect of trees was determined by comparing the measurements of throughfall in the cardinal directions with the locations of neighboring trees. Additionally, a scatterplot of tree location and the corresponding DBH was constructed to further analyze the effects of neighboring trees and wind. The scatterplot was constructed by converting the distance and azimuth (or the Polar coordinates) from the sample tree to all neighboring trees within a 10 meter radius to Cartesian coordinates. Figure 3 displays the polar grid with the corresponding angles. It should be noted that the angles move counterclockwise rather than clockwise. The Polar coordinates were then converted to Cartesian coordinates by the following equations:

\[ X = r \cos \phi \] and \[ Y = r \sin \phi, \]

where \( r \) is the distance and \( \phi \) is the azimuth converted to radians (Figure 4). Although it is intuitive to think of the cardinal directions as moving clockwise, by using polar coordinates and Cartesian coordinates, the positive x-axis represents North and moves counterclockwise with the positive y-axis as West and so on. The size of the points on the scatterplot were also symbolized to be proportional to the DBH of each tree. The scatterplots were then compared with the data on interception in the cardinal directions to determine if the neighboring effect and wind had a significant impact on rainfall interception.
The analyses described above provided a greater insight into rainfall interception losses. For each tree sample, tree structure, wind, and neighboring trees were analyzed to determine and compare their effect on rainfall interception losses.

Figure 3: Polar grid with corresponding angles (Florida Center for Instructional Technology 2007).

Figure 4: Conversion from Polar to Cartesian coordinates (MathHands.com 2007).
CHAPTER 4

RESULTS

Comparison of Rainfall Interception Losses between Species

Interception losses for aspens varied from -0.279 (in which negative rainfall interception occurred) to 0.233 cm. For the first sample tree, interception losses ranged from -0.165 to 0.049 cm. The second tree ranged from -0.131 to 0.114 cm, the third tree ranged from -0.005 to 0.233 cm, and the fourth sample tree ranged from -0.279 to 0.027 (Table 1). For at least one storm event, all four aspens showed that negative interception occurred. The third aspen tree only showed negative interception for one storm event, the second tree showed negative interception for four storm events, sample one showed negative interception for seven storm events, and sample four showed negative interception losses for eight out of nine storm events. Sample three showed the highest average rainfall interception loss over the nine-storm events and was the only sample to have a positive value for the interception loss (Figure 5). Sample four showed the least amount of rainfall interception.

Interception losses for Engelmann spruce were larger compared to aspen and varied from -0.230 to 1.970 cm. For the first sample tree, interception losses ranged from 0.032
to 0.602 cm while the second tree ranged from -0.003 to 0.215 cm. The third sample tree ranged from -0.230 to 0.182 cm and the fourth tree ranged from 0.048 to 1.970 cm (Table 2). For only one storm event, Engelmann spruce samples two and three showed negative rainfall interception loss. Sample four showed the highest average rainfall interception loss over the nine-storm events while sample three showed the lowest rainfall interception loss (Figure 6).

Interception losses for ponderosa pine were also larger compared to aspen and contained the highest interception loss overall. The interception losses varied from -0.157 to 1.970 cm. For the first tree, interception losses ranged from 0.032 to 0.602 cm while the second tree ranged from -0.003 to 0.215 cm. The third tree ranged from -0.230 to 0.182 cm and the fourth tree ranged from 0.048 to 1.970 cm (Table 3). For only one storm event, sample three showed negative rainfall interception loss. Sample one showed the highest average rainfall interception loss over the nine-storm events while the third sample showed the lowest rainfall interception loss (Figure 7). Sample one also had the highest rainfall interception loss compared across species (Figure 7).
| Date   | Pg   | T    | T SD | I    | T    | T SD | I    | T    | T SD | I    | T    | T SD | I    |
|--------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 08/10  | 0.069| 0.234| 0.077| -0.165| 0.034| 0.022| 0.035| 0.032| 0.036| 0.037| 0.093| 0.025| -0.023|
| 08/13  | 1.970| 2.095| 0.405| -0.125| 2.111| 0.445| -0.141| 1.738| 0.142| 0.233| 2.249| 0.494| -0.279|
| 08/15  | 0.269| 0.219| 0.072| 0.049| 0.154| 0.019| 0.114| 0.242| 0.061| 0.027| 0.242| 0.058| 0.027|
| 08/17  | 0.069| 0.096| 0.076| -0.027| 0.049| 0.011| 0.021| 0.034| 0.003| 0.035| 0.075| 0.027| -0.005|
| 08/20  | 0.132| 0.172| 0.034| -0.040| 0.162| 0.025| -0.030| 0.096| 0.035| 0.036| 0.187| 0.074| -0.055|
| 08/27  | 0.050| 0.068| 0.031| -0.018| 0.047| 0.027| 0.003| 0.029| 0.037| 0.021| 0.093| 0.038| -0.043|
| 08/29  | 0.091| 0.091| 0.028| 0.000| 0.068| 0.011| 0.023| 0.096| 0.013| -0.005| 0.114| 0.033| -0.023|
| 09/02  | 0.048| 0.070| 0.011| -0.022| 0.055| 0.012| -0.008| 0.042| 0.016| 0.005| 0.076| 0.024| -0.029|
| 09/06  | 0.416| 0.479| 0.087| -0.063| 0.464| 0.047| -0.049| 0.361| 0.116| 0.055| 0.492| 0.049| -0.076|

Table 1: Total precipitation (Pg), average throughfall in the cardinal directions (T), throughfall standard deviation (S.D.), and the interception losses (I) in centimeters for the for the aspen samples from 10 August 2015 to 6 September 2015.

![Comparison of Interception Losses between Aspen](image)

**Figure 5:** Comparison of the average interception losses for the samples of aspen.
Table 2: Total precipitation (Pg), average throughfall in the cardinal directions (T), throughfall standard deviation (S.D.), and the interception losses (I) in centimeters for the Engelmann spruce samples from 10 August 2015 to 6 September 2015.

<table>
<thead>
<tr>
<th>Date</th>
<th>Pg</th>
<th>T</th>
<th>T SD</th>
<th>I</th>
<th>T</th>
<th>T SD</th>
<th>I</th>
<th>T</th>
<th>T SD</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/10</td>
<td>0.069</td>
<td>0.001</td>
<td>0.002</td>
<td>0.068</td>
<td>0.003</td>
<td>0.004</td>
<td>0.066</td>
<td>0.034</td>
<td>0.013</td>
<td>0.035</td>
</tr>
<tr>
<td>08/13</td>
<td>1.970</td>
<td>1.315</td>
<td>0.602</td>
<td>0.655</td>
<td>1.973</td>
<td>0.248</td>
<td>-0.003</td>
<td>2.201</td>
<td>1.068</td>
<td>-0.230</td>
</tr>
<tr>
<td>08/15</td>
<td>0.269</td>
<td>0.034</td>
<td>0.013</td>
<td>0.234</td>
<td>0.054</td>
<td>0.047</td>
<td>0.215</td>
<td>0.086</td>
<td>0.103</td>
<td>0.182</td>
</tr>
<tr>
<td>08/17</td>
<td>0.069</td>
<td>0.016</td>
<td>0.012</td>
<td>0.053</td>
<td>0.023</td>
<td>0.004</td>
<td>0.047</td>
<td>0.031</td>
<td>0.018</td>
<td>0.038</td>
</tr>
<tr>
<td>08/20</td>
<td>0.132</td>
<td>0.067</td>
<td>0.062</td>
<td>0.066</td>
<td>0.052</td>
<td>0.053</td>
<td>0.080</td>
<td>0.054</td>
<td>0.026</td>
<td>0.078</td>
</tr>
<tr>
<td>08/27</td>
<td>0.050</td>
<td>0.018</td>
<td>0.028</td>
<td>0.032</td>
<td>0.005</td>
<td>0.006</td>
<td>0.045</td>
<td>0.036</td>
<td>0.041</td>
<td>0.014</td>
</tr>
<tr>
<td>08/29</td>
<td>0.091</td>
<td>0.012</td>
<td>0.013</td>
<td>0.079</td>
<td>0.001</td>
<td>0.002</td>
<td>0.090</td>
<td>0.011</td>
<td>0.019</td>
<td>0.080</td>
</tr>
<tr>
<td>09/02</td>
<td>0.048</td>
<td>0.002</td>
<td>0.003</td>
<td>0.046</td>
<td>0.002</td>
<td>0.003</td>
<td>0.046</td>
<td>0.024</td>
<td>0.041</td>
<td>0.023</td>
</tr>
<tr>
<td>09/06</td>
<td>0.416</td>
<td>0.164</td>
<td>0.209</td>
<td>0.252</td>
<td>0.206</td>
<td>0.193</td>
<td>0.209</td>
<td>0.237</td>
<td>0.277</td>
<td>0.179</td>
</tr>
</tbody>
</table>

Figure 6: Comparison of the average interception losses for the samples of Engelmann spruce.
<table>
<thead>
<tr>
<th>Date</th>
<th>Pg</th>
<th>T</th>
<th>T SD</th>
<th>I</th>
<th>T</th>
<th>T SD</th>
<th>I</th>
<th>T</th>
<th>T SD</th>
<th>I</th>
<th>T</th>
<th>T SD</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/10</td>
<td>0.069</td>
<td>0.001</td>
<td>0.002</td>
<td>0.068</td>
<td>0.006</td>
<td>0.009</td>
<td>0.063</td>
<td>0.002</td>
<td>0.003</td>
<td>0.067</td>
<td>0.021</td>
<td>0.026</td>
<td>0.048</td>
</tr>
<tr>
<td>08/13</td>
<td>1.970</td>
<td>1.250</td>
<td>0.893</td>
<td>0.720</td>
<td>1.778</td>
<td>0.656</td>
<td>0.192</td>
<td>2.127</td>
<td>0.764</td>
<td>-0.157</td>
<td>1.180</td>
<td>1.017</td>
<td>0.791</td>
</tr>
<tr>
<td>08/15</td>
<td>0.269</td>
<td>0.104</td>
<td>0.021</td>
<td>0.165</td>
<td>0.015</td>
<td>0.006</td>
<td>0.254</td>
<td>0.154</td>
<td>0.052</td>
<td>0.114</td>
<td>0.138</td>
<td>0.119</td>
<td>0.130</td>
</tr>
<tr>
<td>08/17</td>
<td>0.069</td>
<td>0.024</td>
<td>0.006</td>
<td>0.045</td>
<td>0.008</td>
<td>0.010</td>
<td>0.061</td>
<td>0.049</td>
<td>0.024</td>
<td>0.021</td>
<td>0.029</td>
<td>0.020</td>
<td>0.040</td>
</tr>
<tr>
<td>08/20</td>
<td>0.132</td>
<td>0.028</td>
<td>0.031</td>
<td>0.104</td>
<td>0.049</td>
<td>0.051</td>
<td>0.083</td>
<td>0.063</td>
<td>0.025</td>
<td>0.069</td>
<td>0.054</td>
<td>0.062</td>
<td>0.078</td>
</tr>
<tr>
<td>08/27</td>
<td>0.050</td>
<td>0.006</td>
<td>0.013</td>
<td>0.043</td>
<td>0.001</td>
<td>0.002</td>
<td>0.049</td>
<td>0.011</td>
<td>0.023</td>
<td>0.038</td>
<td>0.021</td>
<td>0.042</td>
<td>0.029</td>
</tr>
<tr>
<td>08/29</td>
<td>0.091</td>
<td>0.000</td>
<td>0.000</td>
<td>0.091</td>
<td>0.000</td>
<td>0.000</td>
<td>0.091</td>
<td>0.036</td>
<td>0.027</td>
<td>0.055</td>
<td>0.020</td>
<td>0.035</td>
<td>0.071</td>
</tr>
<tr>
<td>09/02</td>
<td>0.048</td>
<td>0.000</td>
<td>0.000</td>
<td>0.048</td>
<td>0.001</td>
<td>0.002</td>
<td>0.047</td>
<td>0.005</td>
<td>0.006</td>
<td>0.043</td>
<td>0.001</td>
<td>0.002</td>
<td>0.047</td>
</tr>
<tr>
<td>09/06</td>
<td>0.416</td>
<td>0.026</td>
<td>0.052</td>
<td>0.390</td>
<td>0.146</td>
<td>0.210</td>
<td>0.270</td>
<td>0.279</td>
<td>0.166</td>
<td>0.136</td>
<td>0.109</td>
<td>0.105</td>
<td>0.307</td>
</tr>
</tbody>
</table>

Table 3: Total precipitation (Pg), average throughfall in the cardinal directions (T), throughfall standard deviation (S.D.), and the interception losses (I) in centimeters for the ponderosa pine samples from 10 August 2015 to 6 September 2015.

Figure 7: Comparison of the average interception losses for the samples of ponderosa pine.
Experimental tree one of the ponderosa pine had the highest rainfall interception loss compared across species (Figure 8). Three out of the four aspen species showed average rainfall interception losses that were negative, meaning that precipitation was greater than throughfall.

![Comparison of Interception Losses between Species](image)

**Figure 8:** Comparison of the average interception losses between the three species from 10 August 2015 to 6 September 2015.

**Characteristics of Tree Species**

The DBH and the height of the four aspen trees did not vary greatly in their size. The stand density for each tree in a 10 meter radius plot was very high for the plot surrounding the first aspen, which corresponded in a larger basal area as well. Although the stand density of the fourth tree was much lower, its basal area was higher due to the surrounding Engelmann Spruce in its 10 meter radius (Table 4). The least amount of
throughfall corresponded to the third tree, which did not contain the largest DBH or height, but it did contain the smallest stand density and basal area.

The Engelmann spruce samples contained the tallest trees with heights ranging from 12.75 to 16 meters. Even though stand density was greatest for the plot surrounding the first sample tree, the fourth sample tree contained the largest basal area. This is again due to the larger Engelmann Spruce trees that surrounded the fourth tree. The fourth tree also had the least amount of throughfall compared to the three samples.

The first ponderosa pine contained the largest DBH overall and showed the least amount of throughfall. The stand densities surrounding the four ponderosa pines were the lowest compared to all the samples, which also corresponded to the smallest basal area.

<table>
<thead>
<tr>
<th>Species</th>
<th>DBH (cm)</th>
<th>Height (m)</th>
<th>Stand Density (number of trees/hectare)</th>
<th>Basal Area</th>
<th>Average Throughfall</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aspen</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>10.4</td>
<td>9.25</td>
<td>61/ 0.0314</td>
<td>0.0000208</td>
<td>0.392</td>
</tr>
<tr>
<td>2</td>
<td>12.4</td>
<td>9.25</td>
<td>29/ 0.0314</td>
<td>0.0000189</td>
<td>0.350</td>
</tr>
<tr>
<td>3</td>
<td>10.4</td>
<td>9.00</td>
<td>25/ 0.0314</td>
<td>0.0000172</td>
<td>0.297</td>
</tr>
<tr>
<td>4</td>
<td>9.8</td>
<td>8.25</td>
<td>35/ 0.0314</td>
<td>0.0000254</td>
<td>0.402</td>
</tr>
<tr>
<td><strong>Engelmann Spruce</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>25.2</td>
<td>13.25</td>
<td>29/ 0.0314</td>
<td>0.0000177</td>
<td>0.181</td>
</tr>
<tr>
<td>2</td>
<td>19.6</td>
<td>12.75</td>
<td>27/ 0.0314</td>
<td>0.0000227</td>
<td>0.258</td>
</tr>
<tr>
<td>3</td>
<td>35.1</td>
<td>15.25</td>
<td>40/ 0.0314</td>
<td>0.0000213</td>
<td>0.301</td>
</tr>
<tr>
<td>4</td>
<td>34.2</td>
<td>16.00</td>
<td>14/ 0.0314</td>
<td>0.0000239</td>
<td>0.085</td>
</tr>
<tr>
<td><strong>Ponderosa Pine</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>49.1</td>
<td>13.00</td>
<td>9/ 0.0314</td>
<td>0.0000024</td>
<td>0.160</td>
</tr>
<tr>
<td>2</td>
<td>32.3</td>
<td>8.25</td>
<td>1/ 0.0314</td>
<td>0.0000112</td>
<td>0.233</td>
</tr>
<tr>
<td>3</td>
<td>22.4</td>
<td>5.75</td>
<td>3/ 0.0314</td>
<td>0.0000002</td>
<td>0.303</td>
</tr>
<tr>
<td>4</td>
<td>17.8</td>
<td>6.50</td>
<td>3/ 0.0314</td>
<td>0.0000106</td>
<td>0.175</td>
</tr>
</tbody>
</table>

**Table 4**: Comparison of characteristics including DBH (cm), height (m), stand density (number of trees per hectare), and basal area to the average throughfall for each sample from the three species.
For leaf area, ponderosa pine contained the tree with the largest leaf area overall which corresponded to the least amount of throughfall (Table 5). The two larger samples of ponderosa pine had larger leaf areas than all of the Engelmann spruce and three out of the four samples of aspen (Figure 9). If averaged, Engelmann spruce contained the lowest leaf area compared to ponderosa pine and aspen. The ponderosa pines had the highest average (Figure 9).

When comparing the leaf areas to rainfall interception losses, there did not appear to be a strong correlation as expected. A greater leaf area would infer larger rates of interception, but the trends did not follow for the three species. The aspen with the largest leaf area only had the second highest average interception losses (Figure 10). For the Engelmann spruce, the tree with the highest leaf area actually had the lowest interception losses over the nine storm events (Figure 11). Only the ponderosa pine showed that the tree with the highest leaf area had the greatest interception losses, however, the sample with the second largest leaf area only had the third greatest rainfall interception losses (Figure 12).

<table>
<thead>
<tr>
<th>Species</th>
<th>DBH (cm)</th>
<th>M (kg)</th>
<th>SA/DW cm²/kg</th>
<th>LA</th>
<th>Average Throughfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>10.4</td>
<td>3.861</td>
<td>245077</td>
<td>946279</td>
<td>0.392</td>
</tr>
<tr>
<td>2</td>
<td>12.4</td>
<td>5.988</td>
<td>245077</td>
<td>1467602</td>
<td>0.350</td>
</tr>
<tr>
<td>3</td>
<td>10.4</td>
<td>3.861</td>
<td>245077</td>
<td>946279</td>
<td>0.297</td>
</tr>
<tr>
<td>4</td>
<td>9.8</td>
<td>3.329</td>
<td>245077</td>
<td>815887</td>
<td>0.402</td>
</tr>
<tr>
<td>Engelmann Spruce</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>25.2</td>
<td>20.579</td>
<td>29309</td>
<td>603131</td>
<td>0.181</td>
</tr>
<tr>
<td>2</td>
<td>19.6</td>
<td>14.931</td>
<td>29309</td>
<td>437612</td>
<td>0.258</td>
</tr>
<tr>
<td>3</td>
<td>35.1</td>
<td>31.413</td>
<td>29309</td>
<td>920680</td>
<td>0.301</td>
</tr>
<tr>
<td>4</td>
<td>34.2</td>
<td>30.389</td>
<td>29309</td>
<td>890653</td>
<td>0.085</td>
</tr>
<tr>
<td>Ponderosa Pine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>49.1</td>
<td>41.806</td>
<td>57908</td>
<td>2420916</td>
<td>0.160</td>
</tr>
<tr>
<td>2</td>
<td>32.3</td>
<td>17.374</td>
<td>57908</td>
<td>1006084</td>
<td>0.233</td>
</tr>
</tbody>
</table>
Table 5: Comparison of characteristics including diameter at breast height (DBH), aboveground foliage biomass (M) from the Ter-Mikaelian and Korzukhin’s equation (1997), total surface area/dry weight, and leaf area (LA).

<table>
<thead>
<tr>
<th>3</th>
<th>22.4</th>
<th>8.065</th>
<th>57908</th>
<th>467040</th>
<th>0.303</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>17.8</td>
<td>4.981</td>
<td>57908</td>
<td>288433</td>
<td>0.175</td>
</tr>
</tbody>
</table>

Figure 9: Comparison of the leaf areas between the three species.

Figure 10: Rainfall interception losses compared to leaf area for the aspen samples.
Figure 11: Rainfall interception losses compared to leaf area for the Engelmann spruce samples.

Figure 12: Rainfall interception losses compared to leaf area for the ponderosa pine samples.
Effects of Wind on Rainfall Interception Losses

Table 6 shows the average rainfall for each of the cardinal directions collected in the throughfall gauges for the nine storm events. Generally, the North and West directions captured more rainfall than the East and South throughfall gauges.

Figure 13 shows that either the North or West rainfall gauges for the four samples of aspen collected the most rainfall during the nine storm events. For Engelmann spruce, the West throughfall gauge collected the most rainfall for three out of the four samples. The other sample showed that the North throughfall gauge collected the most rainfall (Figure 14). Similarly, the West throughfall gauges again collected the most rainfall for three out of the four samples with one sample showing that the North throughfall gauge collected the most rainfall (Figure 15).

Figures 16 through 18 also show the throughfall amounts in the cardinal directions for each storm event rather than the average. For the aspen samples, the second and last storms produced the most throughfall and also showed more throughfall in the North and West gauges. The remaining seven storm events do not show as clear of a difference in throughfall amounts. For Engelmann spruce, again the second and last storm showed significantly higher amounts in the North and West throughfall gauges. For the sixth and eighth storm, the throughfall amounts for the North and South gauges were zero. The ponderosa pine throughfall gauges also displayed similar trends in which the second and last storm show the most throughfall in the West gauges and there was no throughfall collected in the South and East gauges for the sixth and eighth storm. Table 7 shows the dominant wind direction from the dates of the storms, not the dates of data collection.
(Woodland Park Weather 2016). Four out of the nine storms showed the dominant wind direction from the West or Southwest which corresponds to the results that the West throughfall gauges contained the most precipitation.

<table>
<thead>
<tr>
<th>Species</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Sample 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aspen</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>0.458</td>
<td>0.300</td>
<td>0.287</td>
<td>0.490</td>
</tr>
<tr>
<td>East</td>
<td>0.414</td>
<td>0.313</td>
<td>0.264</td>
<td>0.337</td>
</tr>
<tr>
<td>South</td>
<td>0.303</td>
<td>0.361</td>
<td>0.303</td>
<td>0.380</td>
</tr>
<tr>
<td>West</td>
<td>0.390</td>
<td>0.425</td>
<td>0.333</td>
<td>0.402</td>
</tr>
<tr>
<td><strong>Ponderosa Pine</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>0.098</td>
<td>0.228</td>
<td>0.315</td>
<td>0.379</td>
</tr>
<tr>
<td>East</td>
<td>0.057</td>
<td>0.139</td>
<td>0.211</td>
<td>0.001</td>
</tr>
<tr>
<td>South</td>
<td>0.228</td>
<td>0.168</td>
<td>0.252</td>
<td>0.134</td>
</tr>
<tr>
<td>West</td>
<td>0.258</td>
<td>0.355</td>
<td>0.435</td>
<td>0.184</td>
</tr>
<tr>
<td><strong>Engelmann Spruce</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>0.209</td>
<td>0.306</td>
<td>0.402</td>
<td>0.133</td>
</tr>
<tr>
<td>East</td>
<td>0.114</td>
<td>0.238</td>
<td>0.130</td>
<td>0.074</td>
</tr>
<tr>
<td>South</td>
<td>0.117</td>
<td>0.195</td>
<td>0.186</td>
<td>0.223</td>
</tr>
<tr>
<td>West</td>
<td>0.284</td>
<td>0.291</td>
<td>0.487</td>
<td>0.229</td>
</tr>
</tbody>
</table>

Table 6: Average throughfall in the cardinal directions for all of the samples for the nine storm events from 10 August 2015 to 6 September 2015.

Figure 13: Average throughfall in the cardinal directions for the aspen samples for the nine storm events from 10 August 2015 to 6 September 2015.
Figure 14: Average throughfall in the cardinal directions for the Engelmann spruce samples for the nine storm events from 10 August 2015 to 6 September 2015.

Figure 15: Average throughfall in the cardinal directions for the ponderosa pine samples for the nine storm events from 10 August 2015 to 6 September 2015.
Figure 16: Average throughfall for the aspen samples in the cardinal directions for the separate nine storm events from 10 August 2015 to 6 September 2015
Figure 17: Average throughfall for the Engelmann spruce samples in the cardinal directions for the separate nine storm events from 10 August 2015 to 6 September 2015.
Figure 18: Average throughfall for the ponderosa pine samples in the cardinal directions for the separate nine storm events from 10 August 2015 to 6 September 2015.
<table>
<thead>
<tr>
<th>Date</th>
<th>Dominant Wind Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-Aug</td>
<td>East</td>
</tr>
<tr>
<td>12-Aug</td>
<td>West</td>
</tr>
<tr>
<td>14-Aug</td>
<td>East</td>
</tr>
<tr>
<td>16-Aug</td>
<td>Northeast</td>
</tr>
<tr>
<td>19-Aug</td>
<td>Southeast</td>
</tr>
<tr>
<td>26-Aug</td>
<td>Southwest</td>
</tr>
<tr>
<td>28-Aug</td>
<td>North</td>
</tr>
<tr>
<td>1-Sep</td>
<td>West</td>
</tr>
<tr>
<td>5-Sep</td>
<td>West</td>
</tr>
</tbody>
</table>

Table 7: Date of storm and dominant wind direction.

Neighboring Effect on Rainfall Interception Losses

Figure 19 shows the location of neighboring trees within a 10 meter radius area surrounding the first aspen experimental tree. The experimental tree is surrounded in all directions, but the stand density is greatest in the Northeast and Southwest directions. For the second aspen tree, the stand density is greatest in the Southeast and Southwest directions, with significantly larger trees in the Southwest direction (Figure 20). There are no trees in the in the Northwest quadrant and only one neighboring tree in the Northeast quadrant. The third sample is similar to the second aspen with neighboring trees in that the Southeast and Southwest directions contain the majority of neighboring trees (Figure 21). There are two other trees located in the Northwest quadrant. The last aspen shows a similar
stand density with the location of the majority of trees in the Southeast and Southwest quadrants (Figure 22).

For Engelmann spruce, the first and second tree contained similar patterns in the location of neighboring trees (Figures 23-24). A majority of the trees are located in the Northeast and Northwest quadrants, but both trees also have neighboring trees in the Southwest section. Similarly, most of the trees for sample three are located in the Northeast and Northwest directions, but there are trees in the other directions as well (Figure 25). The fourth tree sits near a very large tree in the Southwest direction, but there are also smaller trees in the Northwest quadrant (Figure 26).

![Location of Neighboring Trees for Aspen 1](image)

**Figure 19:** Scatterplot showing the location of neighboring trees to the aspen sample 1 tree. The sample tree is located at (0, 0) with the x,y axis in meters. The positive x-axis represents North and the width of the symbol sizes are proportional to the DBH of each tree.
Figure 20: Scatterplot showing the location of neighboring trees to the aspen sample 2 tree. The sample tree is located at (0, 0) with the x,y axis in meters. The positive x-axis represents North and the width of the symbol sizes are proportional to the DBH of each tree.

Figure 21: Scatterplot showing the location of neighboring trees to the aspen sample 3 tree. The sample tree is located at (0, 0) with the x,y axis in meters. The positive x-axis represents North and the width of the symbol sizes are proportional to the DBH of each tree.
Figure 22: Scatterplot showing the location of neighboring trees to the aspen sample 4 tree. The sample tree is located at (0, 0) with the x,y axis in meters. The positive x-axis represents North and the width of the symbol sizes are proportional to the DBH of each tree.

Figure 23: Scatterplot showing the location of neighboring trees to the Engelmann spruce sample 1 tree. The sample tree is located at (0, 0) with the x,y axis in meters. The positive x-axis represents North and the width of the symbol sizes are proportional to the DBH of each tree.
Figure 24: Scatterplot showing the location of neighboring trees to the Engelmann spruce sample 2 tree. The sample tree is located at (0, 0) with the x,y axis in meters. The positive x-axis represents North and the width of the symbol sizes are proportional to the DBH of each tree.

Figure 25: Scatterplot showing the location of neighboring trees to the Engelmann spruce sample 3 tree. The sample tree is located at (0, 0) with the x,y axis in meters. The positive x-axis represents North and the width of the symbol sizes are proportional to the DBH of each tree.
Figure 26: Scatterplot showing the location of neighboring trees to the Engelmann spruce sample 4 tree. The sample tree is located at (0, 0) with the x,y axis in meters. The positive x-axis represents North and the width of the symbol sizes are proportional to the DBH of each tree.

Figure 27: Scatterplot showing the location of neighboring trees to the ponderosa pine sample 1 tree. The sample tree is located at (0, 0) with the x,y axis in meters. The positive x-axis represents North and the width of the symbol sizes are proportional to the DBH of each tree.
Figure 28: Scatterplot showing the location of neighboring trees to the ponderosa pine sample 2 tree. The sample tree is located at (0, 0) with the x,y axis in meters. The positive x-axis represents North and the width of the symbol sizes are proportional to the DBH of each tree.

Figure 29: Scatterplot showing the location of neighboring trees to the ponderosa pine sample 3 tree. The sample tree is located at (0, 0) with the x,y axis in meters. The positive x-axis represents North and the width of the symbol sizes are proportional to the DBH of each tree.
Figure 30: Scatterplot showing the location of neighboring trees to the ponderosa pine sample 4 tree. The sample tree is located at (0, 0) with the x,y axis in meters. The positive x-axis represents North and the width of the symbol sizes are proportional to the DBH of each tree.

All four ponderosa pines do not contain as many neighboring trees as the other species. The first ponderosa pine contains the most neighboring trees in the Northeast and Northwest quadrants (Figure 27). The second ponderosa pine only has one larger neighbor located in the Northeast direction (Figure 28). Sample three contains three smaller neighbors in the Northeast, Northwest, and Southwest directions (Figure 29). The last tree also has three neighboring trees in the Northwest and Southeast quadrants (Figure 30).
CHAPTER 5

DISCUSSION

Both the Engelmann spruce and ponderosa pine samples intercepted more rainfall than three out of the four aspen samples (Figure 8). This matches the results of the studies conducted by Xiao et al. (1998) and Inkilaninen et al. (2013) in which coniferous species showed a significantly higher interception loss due to their size, leaf area, and year-round foliage. However, sample three of the aspens intercepted more rainfall than one of the Engelmann spruce and ponderosa pine samples. This was quite surprising since sample three of the aspens did not contain the highest height nor the largest DBH. However, it had the lowest stand density and thus lowest basal area, meaning that the fewer trees around the aspen actually led to greater interception losses (Table 4). The location of the neighboring trees did not seem to have as significant of an impact as the basal areas since the second and fourth sample of aspens had neighboring trees in a similar distributed manner and in close proximity (Figure 19–22). It was also surprising that three of the four aspens showed negative rainfall interception, which is not common in interception studies involving storm events. Studies that do result in negative interception typically focus on fog precipitation. Prada et al. (2009) found negative rainfall interception losses, but stated that when this occurs, the supplementary precipitation is assumed to come from fog that is intercepted by the canopy. Therefore, it is unusual to find additional throughfall, causing
negative interception, in an arid environment during the summer months when fog it typically unusual in the area.

Because all four of the aspens were close in proximity and were in the same aspen grove, results could be completely different for aspens that were not located in a grove and had few trees in the surrounding area. There are several explanations for why the greater density of aspens leads to decreased rainfall interception losses. First, the shape of the aspens is different than the conifers studied. The canopy is larger at the very top and narrows down to the stem. This creates a funnel shape that could cause increased throughfall. Additionally, the gauges could collect more rainfall from perimeter drip and the surrounding trees with perimeter drip since the aspens were located in an aspen grove with stand densities that ranged from 25 to 61 trees per 0.0314 hectare for the four samples (Table 4). Another reason could be the wind. The tips of the aspen branches are not as sturdy as many of the conifer branches and can therefore be affected by wind. If the branches start shaking, then this could lead to increased throughfall. Similarly, the leaves of the aspens are very thin and also shake whenever wind is present. Again, with many neighboring trees surrounding the sample tree, perhaps the additional throughfall was caused by throughfall from the surrounding trees’ leaves. It is also important to note that rainfall typically falls at an angle rather than just straight vertically (Horton 1919b). Because the aspen canopies contain their branches and leaves towards the top of their crowns and do not have branches near the base of the tree, inclined rainfall could cause the negative interception rates. If the rainfall is inclined to a great extent, then the throughfall gauges could receive the same or nearly the same amount of rainfall as the control gauges since the canopy wouldn’t be intercepting vertical rainfall. The canopies would still get
saturated, however, and could still drip down additional rainfall into the throughfall gauges which could cause the greater amount of throughfall and thus, negative interception. Although the negative interception was unexpected, there could be a variety of reasons for the results as explained previously.

When investigating the characteristics of the Engelmann spruce, the tallest sample with the smallest basal area contained the greatest interception loss (Figure 6 and Table 4). The sample with the largest DBH, however, intercepted the least amount of rainfall. This same sample also had the highest stand density and basal area (Table 4). This was surprising since this sample was located within 10 meters of six other Engelmann spruce, which would be associated with additional coverage and greater rainfall interception. However, it could be that the surrounding aspens and even the other Engelmann spruce near the tree led to greater throughfall.

The largest ponderosa pine in both height and DBH collected the greatest amount of rainfall overall (Figure 7 and Table 4). Sample one contained a height of 13 meters and a DBH of 49.1 centimeters. Although not the tallest out of all the samples, sample one did have the greatest DBH overall. It also had the largest stand density, but not the greatest basal area. Sample two had the largest basal area, but with only one tree in its stand density. This tree, however, was a much larger lodgepole pine that was only 4.5 meters away. Its branches actually shaded the tree and thus provided another layer of canopy that could have intercepted rainfall. Sample three intercepted the least amount of rainfall. It contained a very low basal area and was only 5.25 meters tall.

For leaf area, there did not appear to be a strong relationship between rainfall interception losses and the leaf area for each sample. It would be expected that the third
aspen that intercepted the most rainfall out of the four samples would contain the largest leaf area. However, it tied for the second largest leaf area. The Engelmann spruce with the largest leaf area actually intercepted the least amount of rainfall (Table 5). The ponderosa pines that intercepted the most rainfall also had the largest leaf area; however, the ponderosa pine that had the second largest interception losses actually had the lowest leaf area (Table 5). This leads to the conclusion that leaf area does not have as significant of a role as the stand density, height, and DBH. The results of the lack of relationship between leaf area and interception losses could be explained by the small number of samples studied. Typically, there is a positive relationship associated with leaf area and interception losses (Aston 1979). However, the relationship is usually based on numerous samples rather than just four trees. It could be that the one of the trees is an outlier, but this cannot be determined unless there is a larger sample of trees. Additionally, leaf area was determined by assuming foliage biomass through the Ter-Mikaelian and Korzukhin’s equations (1997). The parameters for these equations were determined through field studies in numerous areas. For aspen, the equation was based on parameters collected from Utah and Wyoming. Engelmann spruce was determined by studies in Idaho and Montana and ponderosa pine was determined through field studies in Arizona. Because the climates, elevation, and even the characteristics of the species vary from location to location, using these equations could create an error in calculating the leaf area of the three species in Colorado. This could then lead to a misrepresentation in the relationship between leaf area and interception losses.

When comparing the average throughfall amounts in the cardinal directions for the nine storm events, it becomes evident that wind does have an influence over rainfall
interception (Herwitz and Slye 1995; Crockford and Richardson 2000; Van Stan et al., 2011). In all of the samples, either the North or West throughfall gauges contained the greatest average amount of rainfall. This means that the greatest interception occurred on the South and East sides. Additionally, the analysis of the throughfall gauges in the cardinal directions for separate storm events also showed a similar trend to the overall average. For Aspen, only three out of the nine storm events showed results where the North or West gauges did not contain the most throughfall and instead the East throughfall gauges had the most rainfall. These storms occurred on August 9th, August 14th, and August 26th (Figure 16). When viewing the wind data from these storms, the prominent directions were East, Northeast, and Southwest respectively. It makes sense for the first two storms that the dominant wind direction was from the East and would lead to increased throughfall in the East throughfall gauges, but the third storm could be influenced from other factors such as the neighboring effect. For Engelmann spruce, six out the nine storm events showed that the West gauges contained the most throughfall while the other three showed the North throughfall gauges with the most rainfall. Similarly, for ponderosa pine, the North and West gauges contained the most throughfall, with the North gauges containing the most throughfall for five storm events while the West contained the most for four storm events. When viewing this data, it would be assumed that the wind direction would be primarily West or North, meaning that it originates either from the West or the North and blows East or South. Four out of the nine storms showed the dominant wind direction from the West or Southwest and two showed the direction from the North or Northeast, which is to be expected from the results. The average throughfall was lowest for all samples for the East throughfall gauges. It is surprising, however, to see that three of the nine storms showed
the dominant wind direction as East or Southeast. However, because wind direction and speed can change constantly throughout a 24-hour period, the dominant wind direction shown in the table may have not been the wind direction during the storms.

When comparing the wind results to the distribution of neighboring trees, it becomes evident that the neighboring effect could be contributing to the differences in rainfall in the throughfall gauges. Since the Aspens contained the most storms where throughfall was greatest for the East gauges, it could be caused by surrounding trees. Figures 19-22 show that there are a significant amount of trees located in the Northwest quadrant for the first aspen sample, and a significant amount of trees located in the Southwest quadrant for other three aspen samples. Therefore, rainfall could be intercepted by these neighboring trees, leading to increased throughfall in the East gauges. For the Engelmann spruce samples, since all the storms showed the most throughfall in the North and West gauges, there could be surrounding trees in the South and East quadrants intercepting additional rainfall that could lead to these results. The first sample contains many large trees in the Southeast quadrant and sample two and four also show a larger tree in the Southeast and Northeast quadrants that could be intercepting rainfall and preventing greater throughfall. Sample three actually contains larger trees in the Northwest and Southwest quadrants, but the tree is so large that its interception was much higher than almost all of the other samples so neighboring trees may not be as significant. The ponderosa pine samples had few neighboring trees, but the second sample had a larger tree in the Northwest quadrant and the fourth sample has larger trees in the Southwest and Northeast quadrants. Winds blowing from the West to the East could be intercepted from
the neighboring tree for the second sample while winds from the East to the West could be intercepted by the trees in the Northeast quadrant for the fourth sample.
CHAPTER 6

CONCLUSION

The hypothesis that the conifers, Engelmann spruce and ponderosa pine, would contain higher interception losses compared to aspen was accepted in a majority of the samples. Only one sample of the aspens showed a larger interception loss than two of the other samples, one each from Engelmann spruce and ponderosa pine. The largest ponderosa pine contained the largest interception loss overall. This was most likely due to its size with the largest DBH of all the samples and its small basal area. Many of the samples showed that a larger stand density and basal area corresponded with smaller interception losses. This could be due to a variety of reasons including perimeter drip and wind. Leaf area did not appear to play as significant of a role with influencing interception losses for the three species. There was not a clear trend in the data, but this could be caused by the small sample size. It is difficult to determine whether wind or the neighboring effect has a greater influence on rainfall interception. Additional studies would need to look at these two factors more closely to determine if one has a greater influence than the other.

From the results, if urban planners were to choose the tree species that could decrease runoff, then ponderosa pine would be the best choice out of the three species for several reasons. First, ponderosa pine contained the greatest interception loss as well as the greatest overall average of interception losses. Although Engelmann spruce also contained
positive interception losses for all samples, ponderosa pine can thrive at a variety of elevations whereas Engelmann spruce is more common at higher elevations. More specifically, in the Front Range area, ponderosa pines can survive at elevations as high as 3070 meters, but it is most commonly found at elevations ranging from to 1830 to 2770 meters (Huckaby et al., 2003). Engelmann spruce, however, thrives at higher elevations ranging from 2440 to 3350 meters (Colorado State Forest Service 2016). Since many urban areas are not as common at such high elevations, ponderosa pine would have the best chance of thriving near urban areas in Colorado.

**Future Research**

Future research could further examine the cause for the negative interception losses for the aspen trees. By setting up a weather station at the site location, more accurate interpretations could be made about the impact of wind speed, wind direction, storm intensity, and storm duration. Additional aspen samples could be included in the study that are not located in the same aspen grove to determine if interception losses are affected by this.

More species in Colorado could also be studied in future research to better understand interception losses in the region. The species’ characteristics and structure could be further analyzed to determine what characteristics have the greatest impact on interception losses.

GIS could also be utilized in future research to further analyze the effects of wind and additional factors such as slope at the study site. Remote sensing imagery could be
used to collect data on vegetation type and indexes, slope, soil, and rainfall intensity in order to determine their impact on rainfall interception and throughfall.
CHAPTER 7

REFERENCES


