INTERCEPTION AND SOIL EVAPORATION WITHIN LOBLOLLY PINE AND AMERICAN SWEETGUM STANDS

by

JUSTIN ARTHUR VINING

(Under the Direction of C. Rhett Jackson)

ABSTRACT

Short-rotation woody crops are a staple in the economics of forestry in the Southeastern United States. With increasing demand for water supplies, accurate measurements of water use in forested areas are vital for proper planning. We measured precipitation, throughfall, soil moisture storage, and lysimeter drainage to estimate interception and soil evaporation among typical forest-crop plots using a variety of methods. Results indicate a small difference in seasonal soil evaporation between the deciduous (American sweetgum) and evergreen (loblolly pine) species used here. Results also showed substantial differences in soil evaporation when compared to unvegetated plots of the same size. Interception among plots was significantly different (α=0.05) in the growing months, and loblolly intercepted 2.2% more precipitation than sweetgum over winter. Conclusions point to 1) the importance of soil cover to an area's hydrologic water budget, and 2) that little difference in annual evaporation rate is evident between loblolly and sweetgum.

INDEX WORDS: loblolly pine, *Pinus taeda*, American sweetgum, *Liquidambar styraciflua*, evaporation, throughfall, interception, box lysimeter, water budget, short rotation woody crop

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JUSTIN ARTHUR VINING

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JUSTIN ARTHUR VINING

Major Professor: C. Rhett Jackson
Committee: Todd C. Rasmussen
Doug P. Aubrey

Electronic Version Approved:

Suzanne Barbour
Dean of the Graduate School
The University of Georgia
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DEDICATION

This example of hard work and persistence is in many ways thanks to the patience and encouragement of my wife, Eva Kennedy. This accomplishment is also very much dedicated to my mother and father, Claudia and Peter Vining, who have given me every chance in the world to succeed. A special thanks to my grandmother from another mother, Joanne Allen, who led me through my early days with steady advice; “Choices equal consequences.” Lastly, this incredible adventure in Athens, GA would not have been nearly as smooth and successful without the assistance of Jeanne Dietsch and Bill Kennedy.

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CHAPTER 1

INTRODUCTION

Freshwater demands are increasing for the use in drinking supply, crop irrigation, industrial use, and environmental purposes. Tree production affects several components of the water budget, including interception, transpiration, and soil evaporation. While this does change some portion of local water levels, the relative impact is difficult to measure. Water budgeting is a fundamental aspect of evaluating the potential effect of land use changes on water resources.

For this study, we examined the water budget for three soil environments; 14-15 year old loblolly pine (*Pinus taeda*) plantation, 14-15 year old American sweetgum (*Liquidambar styraciflua*) plantation, and bare-soil. We measured the precipitation, throughfall, soil moisture content within a box lysimeter, outflow from a box lysimeter, and infiltration using data loggers and weekly sampling where appropriate. These were measured year round to incorporate frequency in both the growing (April-November) and non-growing (November-April) seasons. Through this comparison, we have established a range of evaporation parameters and provide values for often disregarded flux components of model parameters important in water balance equations. Of particular interest was how these flux components differ between species through the growing and dormant seasons.

A water budget is a useful tool in hydrologic measurements for the estimation of water available to a watershed of a particular size. The water budget is an equation with inputs to the watershed on one side balanced by all the outputs on the other, along with changes in storage. Inputs are precipitation and inflows from surface and or groundwater flow. Outputs are surface and subsurface outflow, evaporation, and transpiration. A primary unknown is storage, which is typically estimated to be negligible over a certain timespan. Energy Balance equations are also used, but typically for the quantification of evapotranspiration through estimations by way of meteorological data instead of actual physical measurements.

Evapotranspiration (ET) is the simultaneous action of evaporation and transpiration in a foliated watershed. It is typically a major component of a water budget for any drainage basin and can vary drastically according to plant consumptive use and time of year (Thompson, 1999). Evapotranspiration includes several components within itself: canopy interception and throughfall, stem flow, transpiration, soil evaporation, and evaporation from open water (streams, wetlands, etc). Total ET can be measured at the watershed scale in place by use of equipment or estimated from afar through one of many models or equations presently available.

Transpiration is the loss of soil water through leaf stomata as it is transported through the plants vascular system from the roots, escaping the plant as part of the process of photosynthesis. As stated, transpiration is a process unique to plants. Transpiration and soil evaporation are environmentally linked processes, and though each contributes a substantial but variable portion to a water budget, they are often discussed together as evapotranspiration (Wythers et al, 1999). Transpiration can be estimated by finding certain variables pertaining to the canopy, including the vapor pressure deficit, the canopy area coverage, the canopy or stomatal conductance, and available solar energy, or by more invasive techniques such as measuring sapflow using Granier probes.

Interception is difficult to measure as it is affected by climate, environment, time of day, wind speed, vapor pressure deficit, azimuth of rainfall, leaf area index (LAI), canopy area, and others. Methods for measuring interception include a variety of designed collectors placed either randomly or according to plant area index (PAI), LAI, canopy structure, and understory presence, and can involve stemflow.

Evaporation is the loss of liquid water to the atmosphere by the addition of energy to the latent point of vaporization. Evaporation can occur from any surface or biological interface with the addition of energy. Evaporation from a bare-soil is comprised of two components; liquid flow and vapor flow. Liquid flow remains the major component of evaporation under moderate climate conditions, whereas vapor flow is the major component of or becomes increasingly important in arid rangelands and deserts. Subsurface water can then flow laterally as interflow or percolate downward toward the groundwater table. Water remaining in the porous areas of the soil can then evaporate or return to the atmosphere by way of root water uptake, or transpiration. Typically this loss of water to evaporation and transpiration are combined into one measurement as evapotranspiration. This concept is based on the idea from Monteith (1981) that evaporation can occur from wet soil remaining below a progressively deepening dry layer. Soil evaporation, as a small component of ET, is typically ignored in forest studies as an understood error or is factored in afterward as a modeling calculation correction.

Evaporation from a forested area differs greatly from that of open pasture, grassland, crop land, or bare-soil. A forested area offers the ground shelter from intense and direct irradiance. In maintained woody crop plots such as those featured in this study, the ground cover is restricted to leaf litter. The leaf litter in this fashion acts as an impediment to water loss through a mulching effect, further protecting the soil water from evaporation due to changes in humidity and temperature. In addition to evaporative demand, the rainfall, the soil, and the vegetation also play important roles in determining the rate of evaporation.

Soil moisture content is fundamental in partitioning mass and energy flux between the hydrosphere, biosphere, and atmosphere through its interaction with processes relating to evaporation from bare-soil and transpiration from vegetated areas (Albergel et al 2012). Soil moisture content can also impact plant growth and watershed carbon fluxes (Dirmeyer et al, 1999; Entekhabi et al, 1999).

Loblolly pine and sweetgum are both common species native to the forests of the southeastern United States. Both species have been the subject of interest for short rotation woody biomass production in the region. From an interception and soil evaporation standpoint, they make for an interesting comparison as the interest in sweetgum is presently growing, though the production and plantation acreage numbers belong to loblolly pine.

Loblolly pine is one of the fastest growing pine species (9 Mg/ha/yr dry from Kline and Coleman, 2010), making it the most commercially important timber species in the southeastern United States. In fact, the southeastern US comprises 40% of the nation's timber land (Wear and Gries, 2012), where loblolly pine accounts for more than 84% of seedlings planted (McKeand et al, 2003) and represents nearly 50% of the standing pine (Oswalt et al, 2014). Sweetgum has great potential for commercial pulp or biomass feedstock production with growth rates deemed moderate to fast (6 Mg/ha/yr dry from Kline and Coleman, 2010) on good sites (Dirr 1983). Sweetgum has long been considered an undesired pest species by forest plantation managers due to its ability to rapidly invade and dominate an area. Among loblolly plots, the presence of sweetgum reduces survival rates by directly competing for limited resources. For example, young established sweetgum reduces soil moisture at critical depths for pine of 60-90cm (Mitchell et al 1993). This kind of aggressive behavior, however, is seen as a positive trait of sweetgum due to adaptability, ease of propagation, and fast growth rate (Adams et al, 2015).

Future production of this species is expected to create substantial contributions to the biomass energy industry as sweetgum continues to be a focus, with other native hardwoods (Merkle and Cunningham, 2011).

Purpose

This investigation was part of a larger study designed to quantify the distinct differences in water use, if any, between loblolly pine and American sweetgum stands. **The goal of this particular work is to investigate, quantify, and compare what are typically the neglected components of a water budget, specifically, throughfall, interception, and soil evaporation.** We hypothesize a significant difference in interception between species, particularly seasonally. We expect sweetgum to intercept a greater amount of precipitation during the growing season than loblolly based on leaf area index. We expect a greater amount of soil evaporation from the bare plot than either forested plot.

Knowing the variation between these two popular species of short rotation woody crop can allow researchers, planners, and foresters the ability to determine the best use of timberland in water sensitive areas. We examined how seasonal interception affects the volume of water reaching the soil surface by measuring precipitation and throughfall. We examined the variance in soil moisture between all plots. We examined the difference in soil evaporation using the VMC measured within unvegetated box lysimeters. Finally, by measuring throughfall, volumetric moisture content (VMC), and lysimeter outflow, we developed weekly water budgets to examine the differences in soil water content from unvegetated box lysimeters found in loblolly pine (*Pinus taeda*), American sweetgum (*Liquidambar styraciflua*), and bare (open) plots.

CHAPTER 2

LITERATURE REVIEW

Interception and soil evaporation are commonly spoken and referred to among forest hydrologists everywhere. The value of these processes has gone from being measured to being neglected as attention has turned from catchment to larger scale estimation of water use for large portions of the country. As a result, published information on physically measured soil evaporation is scarce. Measurements of interception are also not common. Both measurements are difficult, soil evaporation is often considered negligible, and literature values are often used in place of interception measurements. This body looks to investigate the need to readdress these hydrologic processes and their measurement.

Calder (1976) wrote that theoretical estimation of water loss from a forested area cannot be adequately accomplished, and field measurements for interception and transpiration are needed for calibration of model equations. In many ways, it seems, this still holds true today. Other than for micrometeorological methods, a water balance equation is necessary for most experimental measurements of actual evaporation. Water balance equations are used to analyze groundwater recharge and stream-flow from catchments; to model pasture, crop, or forest production; and to schedule agricultural irrigation. These important measurements need to be sufficiently accurate if the water budget estimate is to be meaningful.

Soil Evaporation and Transpiration

Evapotranspiration is the simultaneous action of both evaporation and transpiration. It is a major component of any water budget involving a vegetated watershed. Evapotranspiration in a given area or watershed can vary based on the seasonal consumptive use of the species present.

Evaporation is the change of water into vapor from wet leaves, moist soil, and open water sources. Two variables are necessary for evaporation; water and energy. Water is the supply for evaporation, while net radiation as an energy source actually drives the process. The rate of evaporation tends to be limited by one of these. For ease of comparison with rainfall rates, evaporation is commonly expressed as the depth of water lost from a unit of land area over a unit of time, typically mm/day. Direct evaporation is a commonly overlooked or underappreciated component in calculations of the soil water balance. Morton (1983) showed that evaporation from any small water-filled container reasonably reflected the potential evaporation value for an area. Stated sources of error with this simple, but popular method, are from differences in actual albedo, surface roughness, and the ratio of latent heat area to sensible heat area.

Transpiration is the action of root water uptake by plants to account for water lost through leaf stomata during the process of photosynthesis. Relative humidity in the canopy, along with vapor pressure and wind speed, directly affect transpiration, and there-by the soil moisture content within the forested area. Whelan et al (2013) found that evapotranspiration rates vary with wind speed, as does interception. Low overstory density and trees of smaller stature do not impede wind flows as the taller trees with denser canopies do. Scotter and Kelliher (2004) found the aerodynamic resistance in a forest is roughly an order of magnitude lower than open pasture, meaning the rates of loss observed depend more on wind speed (ET) and vapor pressure deficit (transpiration) than on net radiation (evaporation). This information can relate to higher

ET through the increase in transpiration from increases in wind speed on the site as it affects stomatal vapor pressure deficits, increasing sapflow, and reducing soil moisture in the dense root area of the upper soil regime. Similarly, in areas of restricted understory, increases in wind speed can increase the potential evaporation rate in the upper soil regime.

These effects of wind speed on evaporation and transpiration can differ substantially between wet and dry conditions, however. Kelliher and Jackson (2001) showed that when leaves are dry, effects of low aerodynamic resistance and evaporation rates can be less than those of a heavily watered pasture. With wet foliage, aerodynamic resistance is effectively zero and high rates of evaporation can occur. They found that such instances of interception in the forest have resulted in the evaporative loss of 12% to 50% of rainfall. In moist bare-soil, once 2 mm to 12 mm of water are lost, the soil surface became air dry and evaporation rates fell. It was reported this was the resistance of gravity to the upward movement of soil moisture and not a limited supply of energy from solar radiation. Kelliher and Jackson (2001) also stated another 6 mm to 30 mm can be lost from bare-soil during this phase of declining evaporation rate. It should be noted that this is from heavily watered pasture where the amount of precipitation or irrigation is not expressly given and it is assumed the rate of evaporation is maximized as a result of the water supply.

A mechanistic approach to bare-soil evaporation describes the near-surface soil as a multilayer system and physically represents the mass and heat exchange between these layers and the atmosphere (Chanzy and Bruckler, 1993; Yamanaka et al, 1998). A simplified approach describes the soil as a single-layer system while empirically representing actual evaporation using a resistance factor which accounts for potential evaporation, or the evaporative loss in relation to evaporative demand (Noilhan and Planton, 1989; Mihailovic et al, 1993). Monteith

(1981) describes bare-soil evaporation as the composition of liquid water and vapor flow. He states infiltration is dominant under moderate climate conditions but rising vapor flow is important in arid environments or during drought. The concept was based on the idea that evaporation does occur from wet soil beneath a progressively deepening dry layer.

Wythers et al (1999) gravimetrically measured bare-soil evaporation from various soil-textures and used lysimeters to develop an energy balance equation in semi-arid conditions. They found that bare-soil evaporation rates were controlled by atmospheric demand along with conductive propertie’s intrinsic to the soil. Once the voids within the soil profile are dry, water loss occurs in the form of vapor diffusion, which requires greater inputs of energy than does capillary conduction (van de Griend and Owe, 1994). Volumetric soil moisture content was measured at specific depths with time-domain reflectometry (TDR). Their findings for sandy loam showed a bulk density of 1.41 (±0.040) g/cm, field capacity of 0.264 (±0.005) cm^3/cm^3, and a decrease of soil moisture content by 44% within the first four days of the precipitation event.

Soil texture, bulk density, soil structure, and organic carbon content all contribute to affect the hydraulic properties of the soil in an environment (Lin et al, 2005). This includes the soil conductivity and water retention characteristics, which can affect the rate of soil water loss through the physical mechanics of water movement within a soil profile. These contributing factors are strongly influenced by land use and management regardless of any similarity in soil classification (Zhou et al, 2007). Soil compaction alters the pore structure resulting in reduced hydraulic conductivity and reduced downward movement of soil water. While tillage can help to create large soil pores, it also disrupts the macro and micropore connectivity to subsurface flow (Buczko et al, 2006). This allows for shallow infiltration but only to the depth of tillage.

Acs (2003) noted a lack of published comparisons between transpiration and bare-soil evaporation for such environmental conditions as global radiation, air temperature, air humidity, wind speed, and soil content. Acs (2003) paper analyzed model simulations in with these atmospheric conditions and soil moisture content were the same for both vegetated and bare-soil areas. According to the results, the differences between transpiration and bare-soil evaporation were pronounced, especially in dry conditions. The energy differences were much less notable. The results suggested that transpiration was much more non-linearly related to environmental conditions than bare-soil evaporation. These results did not involve advective effects or mesoscale circulation patterns and featured unstable soil stratification.

Torres and Calera (2010) investigated evaporation in a semi-arid region using data from eight micro-lysimeters and a Bowen station. They observed daily evaporation to be lower than potential evaporation under high atmospheric demand. The authors suggest that once evaporation dries out the first few centimeters of soil, the evaporative process changes as potential evaporation cannot be met by the gradual supply of water from deeper and wetter soil layers. Their conclusion states that after the first few days of steady evaporation, the physical discontinuity of water transport is evident at the soil surface, and as the interface of liquid and vapor water is now under a thin layer of dry soil, resistance to evaporative loss increases as the incoming solar radiation and latent heat flow is shielded by the dry top soil layers. This is consistent with the findings of Van Bavel and Hillel (1976) which refer to the change in evaporation rate as taking place once 100% relative humidity is not met. This same finding is opposite the conclusion of Kelliher and Jackson (2001), which states that soil evaporation ceases once the top 12 cm of soil is fully dried. Van Bavel and Hillel (1976) also note that semi-arid conditions work slightly faster and findings are comparable with temperate humid environments as these values are largely a function of time elapsed after precipitation events.

Albergel et al (2012) noted the meteorological variables of precipitation and air temperature were particularly affected by variation in soil moisture in the transitional zones between arid and humid areas. This error should be attributed to the differences in potential and actual evaporation based on wind, locally, as was reported in Whelan et al (2013). For their model comparisons, Albergel et al (2012) compared in situ soil moisture data measured by dielectric constant devices with those obtained from the International Soil Moisture Network, a data hosting center for globally available ground-based soil moisture measurements. Their findings were in agreement with Mahfouf and Noilhan (1991) and their formulation for bare ground resulted in more realistic values for dry land, also mentioned in Balsamo et al (2011). The report from Albergel et al (2012) continues, stating that evaporation from bare-soil responds to a different physical mechanism than an area with dense vegetation. Over bare-soil, water vaporization in soil pores takes place in a thin near-surface layer as a direct effect of incoming solar radiation, which provides the latent heat requirements. The effects are similar to those in Scotter and Kelliher (2004) but the focus differs in the two publications, with Scotter and Kelliher attributing the cause to wind speed. It is worth noting that they purposefully avoided seasonal effects by using monthly time series calculations with a five week sliding window, and scaled the difference to the standard deviation.

Van Bavel and Hillel (1976) published a numerical model to estimate the instantaneous evaporation rate from bare-soil, regardless of wetness, using standard weather data and the physical characteristics of the soil profile. Their model required global and shortwave irradiance, air temperature, air humidity, and wind speed, all at a standard height of 2 meters. The method was a combination method taking into account the surface energy balance and the transport of heat and water above and below the soil-atmosphere interface. The results showed the soil heat flux and the soil surface emittance may vary with soil water content so much as to make the concept of potential evaporation ambiguous. The results state a four day period of surface evaporation at the potential rate of 7-8 mm/day, making the relative humidity stable at 100%, followed immediately by water loss declining at an accelerating rate with a magnitude comparable to the drainage rate. There is a marked contrast between soil and air heating with surface soil resisting temperature increases due to evaporative cooling until actual evaporation drops below potential evaporation. At that point, the daytime surface temperature rose steeply. It is noted that results vary by soil properties and local climate. They conclude only two stages of evaporation occur, with the separation marked at the first day the air at the surface is not at saturation humidity, and the second stage of drying depicted by a rapid decline which gradually tapers off. The authors emphasize that all results obtained are theoretical and approximate, but give no level of error. They conclude their model is useful only to simulate evaporation from dry surfaces. They assume zero heat flux and unit hydraulic gradient at the bottom of the soil layers, no evaporation other than from the surface, and no water transfer in vapor form.

Lysimeters

Lysimeters are soil-filled tanks buried flush with the ground. Many lysimeter designs have been used in a variety of published experiments. Through measurement of inputs, output, and storage, they allow for considerable control during the course of an experiment while operating on a principle of continuity. Since they are sealed by design, they do not permit evaluation of transpiration as roots are not present, unless vegetation is permitted to grow within the confines of the unit itself. This allows for the measurement of evaporation solely as the difference of precipitation less the drainage volume along with soil moisture storage.

Lysimeters have been shown to be an accurate means of quantifying water loss. Boast (1986) and Boast and Robertson (1982) used micro-lysimeters and estimated evaporation by weighing the units before and after precipitation events. These methods are useful for a short period of time (1-2 days) and can have significant error of up to 0.5 mm within that time frame. It is likely the design of micro-lysimeters led to inherent error termed wall effects due to their small diameter and the cohesive behavior of liquid water.

Slatyer and McIlroy (1961) listed design requirements for a lysimeter in five steps. First, the dimensions should be large enough to allow for a fully representative sample of the plant community and to minimize boundary effects. This part of the design illustrates their interest in quantifying both evaporation and transpiration, while we are only interested in the former. Secondly, the container walls should be designed so that the gap between the internal and external crop is as small as possible. This step seems to demonstrate the importance of allowing precipitation to find the actual ground surface equally. Third, the difference in the level of the water table between the lysimeter and that of the external crop should be minimized. This requirement brings up the realization that the authors are relying on some natural impermeable layer from which they are measuring drainage. The error associated with this can be extremely high, for which a completely sealed boundary is recommended. The fourth requirement stated the soil structure inside the lysimeter must closely resemble the surrounding area. The final requirement was that the site should be representative of the area under investigation. In a study by Calder (1976) using these requirements, the annual loss at the lysimeter was found to be twice the calculated Penman evaporation. This is most likely due to error in design, as the bottom of their lysimeter was the natural clay layer, with the sides consisting of hammered steel, placed tightly together.

Canopy Interception

Interception is the term used to refer to precipitation that is caught up by plant foliage and in turn, evaporates without ever making it to the ground. Principle methods for measuring interception involve funnel gauges and trough collectors. Throughfall is the term describing precipitation that makes it through any canopy coverage and reaches the ground. Both are infrequently measured components of any water budget.

A canopy increases the spatial heterogeneity of throughfall depth relative to precipitation depth. Measurements of throughfall require a large collection area to account for this heterogeneity. This can be achieved either by placing a large number of rain gauges or funnel collectors underneath the canopy, or by using elongated collection surfaces like gutters to sample transects under the canopy. Calder (1976) stated interception contributed to major losses of gross precipitation, and that for areas of high rainfall, a need was clearly present for accurate methods of measuring loss to interception. Since interception is calculated as the difference between precipitation and throughfall totals, which are typically large numbers, a small fraction of uncertainty in either measurement can generate large error in the final value (Herbst et al, 2008).

Stogsdill et al (1989) performed a study looking at the increase in loblolly trunk diameter with increased throughfall by way of crop thinning. They used an 11-year-old loblolly plantation in southeastern Oklahoma as their study site. Throughfall was sampled using 10 funnel collectors of 150 mm diameter located on each plot. They found for every 4 m^2/ha reduction in basal area, throughfall increased by approximately 3% of total precipitation.

Herwitz and Slye (1994) investigated how the structural heterogeneity of tropical rainforest canopies change throughfall patterns for the understory. Throughfall was collected around each tree using funnel collectors of 50 mm diameter and/or two throughfall troughs of 530 mm^2 area. The results showed that intercepted precipitation exceeding leaf surface area capacity will runoff to the edges of the basal area, and fall to the next tallest tree canopy, where the same pattern will continue. This resulted in a highly variable throughfall pattern in the understory.

Herbst et al (2008) measured gross precipitation, net precipitation, and stem flow in a mixed deciduous woodland in southern England over a 14 month period in an attempt to fit measured results to a model. Throughfall was measured with funnel collectors of 146 mm diameter and with four large troughs made from plastic guttering attached to automatic tipping bucket gauges. These were placed at random throughout the site. The loss of precipitation to interception was found to be 29.3% for the leafed canopy, 19.8% for the leafless canopy, and 29.4% annually. They note attempts to derive structural parameters from measured interception in temperate forests to have been inconclusive (Hormann et al, 1996) or restricted to the growing season (Price and Carlyle-Moses, 2003). They concluded their model did explain seasonal variability and was suitable to analyze interception in deciduous forests, but a correction factor was necessary to compensate for splash or spillage of throughfall.

Absolute (mm/yr) and relative (% of precipitation) interception can vary among both climate and vegetation type (see Table 7.9 by Dingman (1994), Appendix B). Two studies from plantation settings in South Carolina, Hoover (1953) and Swank et al (1972), found canopy interception in young loblolly to be as high as 27% of gross annual precipitation, as reported in Stogsdill et al (1989). Kelliher and Jackson (2001) reported certain instances of wet conditions with low vapor pressure deficit resulting in forest interception reducing total precipitation by 12% to 50%. Herbst et al (2008) mention studies in their findings regarding interception in temperate monoculture plantations to be between 25% and 50% in coniferous forest (Rutter et al, 1975; Gash et al, 1980; Johnson, 1990) and between 10% and 35% in deciduous broadleaved forest (Rutter et al, 1975; Rowe, 1983; Nizinski and Saugier, 1989). From past studies, we can expect annual interception in loblolly and sweetgum forests of the southeastern US to be in the range of 15-45% and 10-35%, respectively. It is with the results of seasonal measurements we expect to see the actual split in the value of interception between the species.

CHAPTER 3

METHODS AND MATERIALS

The experimental plots are located near Aiken, South Carolina, within the U.S. Department of Energy's Savannah River Site (Figure 1). The Savannah River Site is a national environmental research park in the Carolina sandhills physiographic region (33°23'N.; 81°40'E). The site is operated by the Department of Energy, with lands managed by the U.S. Forest Service in coordination and cooperation with the Department of Energy.

Soils are Blanton sands with 0 to 6% slopes as mapped by the NRCS. Topsoil's are sandy clay loams followed by several cm of sandy loam and sand overlying a sandy clay loam argillic layer at a depth of 120-200 cm. The site is classified as Cfa under the Koppen-Geiger climate classification system. The Cfa label means the site is in a temperate to mesothermal climate with significant precipitation in all seasons and the warmest month has an average temperature above 22°C with at least four months averaging above 10°C.

According to the Annual Climatological Summary for Aiken, South Carolina provided by the National Oceanic and Atmospheric Administration for 2014, the average annual temperature was 17.0°C. The average minimum temperature was 10.67°C. The average maximum temperature was 23.3°C. The depth of annual precipitation was 1039.1 mm. The long-term annual average precipitation on site is 1225 mm and the long-term temperature averages as reported in Kilgo and Blake, 2005 are a minimum of 14.6°C, a maximum of 21.8°C, and an average of 18.2°C.

The 0.22 ha plantation plots were created for and used by a previous replicated factorial study (see Coleman et al, 2004; Allen et al, 2005; Coyle and Coleman, 2005; Coyle et al, 2005; Coyle et al, 2006; Coyle et al, 2006; Aubrey et al, 2007; Coleman 2007; Sanchez et al, 2007; Samuelson et al, 2008; Samuelson et al, 2009; Im et al, 2009; Coyle et al, 2010; Aubrey et al, 2012; Gong et al, 2012; Coyle et al, 2013; Kaczmarek et al, 2013; Coyle et al, 2015) investigating the effects of irrigation and fertilization on tree growth. The spacing of individual trees was 2.5 m by 3 m for a planting density of 1,333 trees per hectare so that each treatment plot consisted of 294 trees. Prior to the installation of these plots, the previous pine stand was harvested and the remaining slash and stumps were pulverized and incorporated into the top 30 cm of soil. Dolomite lime was applied at a rate of 3.4 Mg/ha to achieve a target soil pH of 6.5.

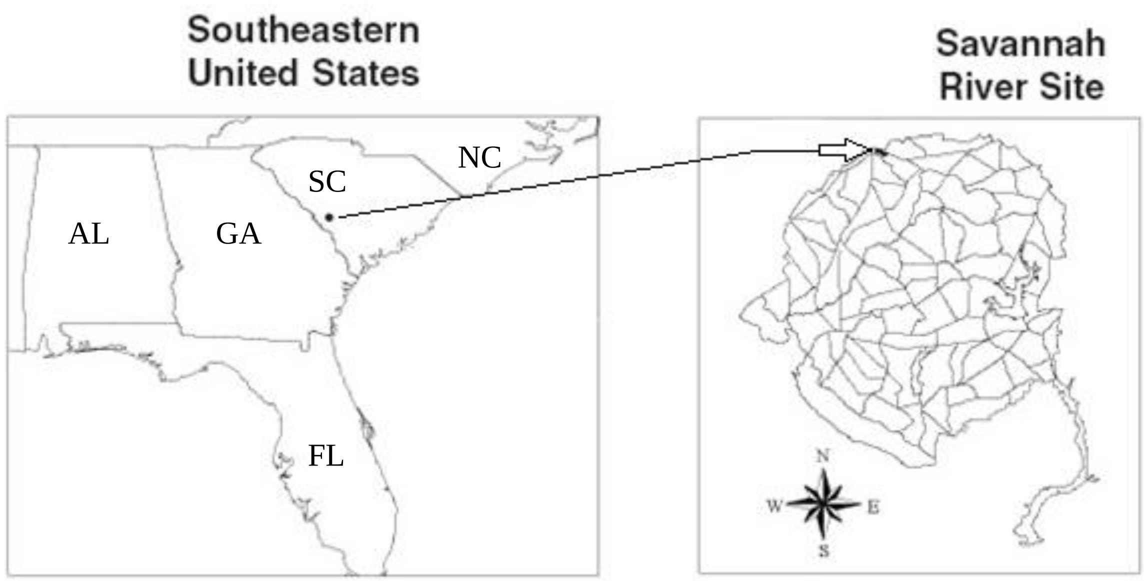

Figure 1. Location of study site within Savannah River Site, USDA, USFS. GPS coordinates (33°23’N.; 81°40’E). Figure taken from Coleman et al. 2004 (Figure 1).

Sweetgum were sourced from Westvaco, family WV340. Average diameter at breast height (DBH) in 2015 for sweetgum plots in blocks 1, 2, and 3 was found to be 21.14 cm, 20.20 cm, and 18.18 cm, respectively. Average canopy height in 2015 for the sweetgum plots in blocks

1, 2, and 3 was found to be 20.5 m, 20.4 m, and 19.2 m, respectively. Loblolly were sourced from International Paper, family 7-56. Average DBH in 2015 for loblolly plots in blocks 1, 2, and 3 was found to be 27.23 cm, 23.34 cm, and 19.43 cm, respectively. Average canopy height in 2015 for the loblolly plots in blocks 1, 2, and 3 was found to be 20.2 m, 17.3 m, and 18.0 m, respectively.

Table 1. Leaf Area Index data recorded in August of 2014 and 2015 for each species within each block. Loblolly pine is represented by LP and American sweetgum is represented by SG.

Year	2014						2015					
Block	1		2		3		1		2		3	
Species	LP	SG	LP	SG	LP	SG	LP	SG	LP	SG	LP	SG
LAI	2.25	5.74	2.75	5.39	3.15	5.49	3.01	5.66	3.45	5.39	3.61	5.65

Installation of equipment for this study began in 2013, 13 years after trees were planted for the Coleman et al. study. The loblolly and sweetgum stands were near 15 years old and approaching maximum leaf area, just prior to when biomass harvest is optimal (see Table 1). Enough time had elapsed for natural soil partitioning, supplemental vegetation growth, and local runoff behavior to return to near normal after the severe change in land use.

We randomly selected three loblolly pine plots, three sweetgum plots, and three additional bare-soil plots at the Savannah River Site (SRS) location (Figures 2 and 3).

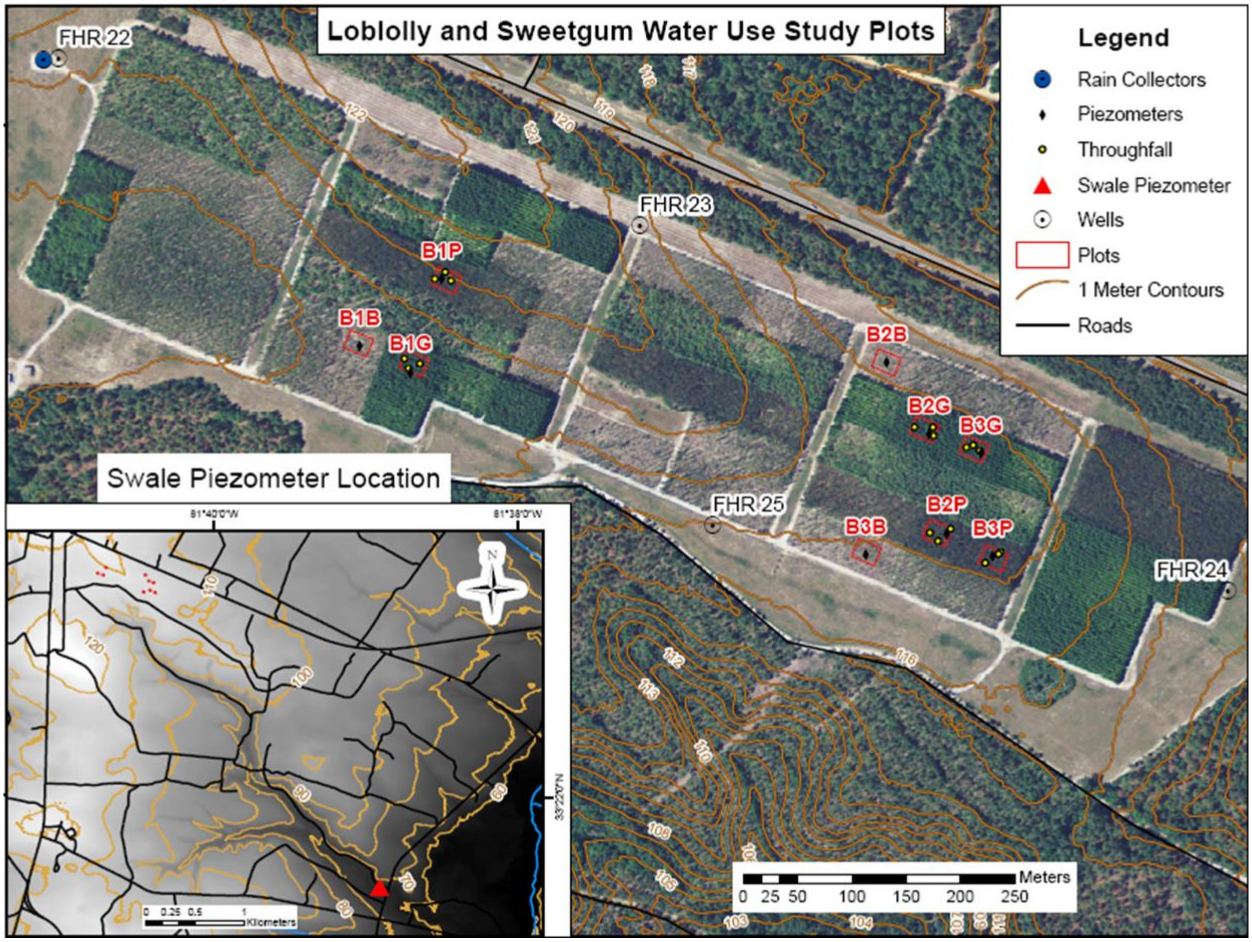

Figure 2. Study site area near Aiken, South Carolina. GPS coordinates: 33°23’N.; 81°40’E. Plots are pictured with red borders. The first letter, B, refers to block. The number refers to which block. The third letter, B, P, or G, refers to bare plots, pine (loblolly) plots, or gum (sweetgum) plots, respectively.

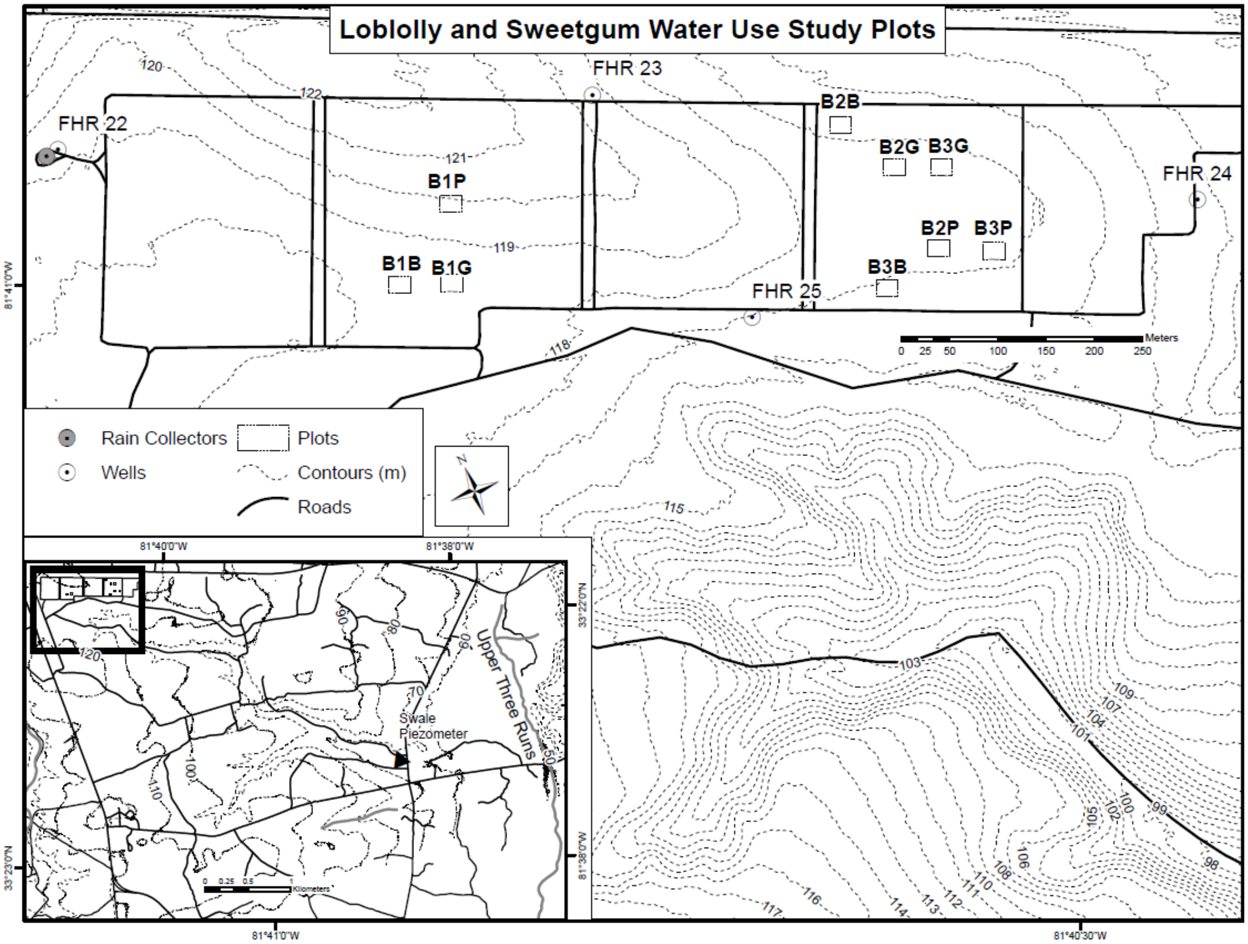

Figure 3. Study site near Aiken, SC. GPS coordinates: 33°23'N.; 81°40'E.

In blocks 1 and 2, both loblolly and sweetgum plots were treated with 120 kg N/ha/year and irrigated with water 3 cm/week from April to October of 2000. The bare plots received neither fertilizer nor irrigation. In block 3, the loblolly plot was treated with 120 kg N/ha/year and no irrigation was given. The sweetgum plot was treated the same. The bare plot was given no fertilizer, but was irrigated at a rate of 3 cm/week.

For our use, bare plots were created from what had been cottonwood plots, of which the majority had been killed by disease. The remaining material was cut, chipped, and applied to the land. Herbicides were used to suppress vegetation growth in the bare plots.

Precipitation

Tipping-bucket rain gauges were placed in each of the bare-soil plots used in the experiment. The locations met recommended standards for proper rain gauge sites; no obstruction (e.g. tree or building) was within a 30 degree angle from the top of the rain gauge. Data were recorded every 15 minutes and downloaded weekly from a Campbell® data-logger. Data were then transferred onto a lab computer and put into a master spreadsheet for further analysis.

The data-logger in block 3 bare plot was inactive or otherwise not recording from 5/14/2014 until 6/18/2014. The data-logger in block 2 was inactive or otherwise not recording from 2/28/2014 until 4/23/2014. A technique described in Thompson (1999) states that for missing precipitation data, it is acceptable to assign the arithmetic average of values at three surrounding stations provided the normal annual precipitation at those stations is within 10% of the normal annual precipitation at the station missing data. We used precipitation values recorded by the two other data-loggers, along with SRS meteorological data, to provide for the missing data.

Throughfall

Throughfall collectors were created by hand and randomly located in each of the forested plots. The design was based on a similar structure used in Keim and Skaugset (2003). There was no need to measure throughfall in the bare-soil plots, as no vegetation was present. Polyvinyl chloride tubing (PVC) with 1½ inch diameter was cut to 152.4 cm lengths. Each length then had a 148 cm section removed from only half the diameter of the pipe, as to make a trough. The remaining solid pipe was used to insert into 22.5 degree pipe fittings which were then subsequently inserted into a T fitting. With an angled trough on each side, the lower end of the T was arranged on a metal garden post so that it faced the ground. The PVC assembly was attached to the post with stainless steel hose clamps and zip ties. Clear vinyl tubing was used to then allow for drainage into 18.9 L water storage containers (Figure 4). Measurements of depth of rainfall in millimeters were found by dividing the volume collected by the surface area of the arms of the collectors, with respect to the angle of the arms.

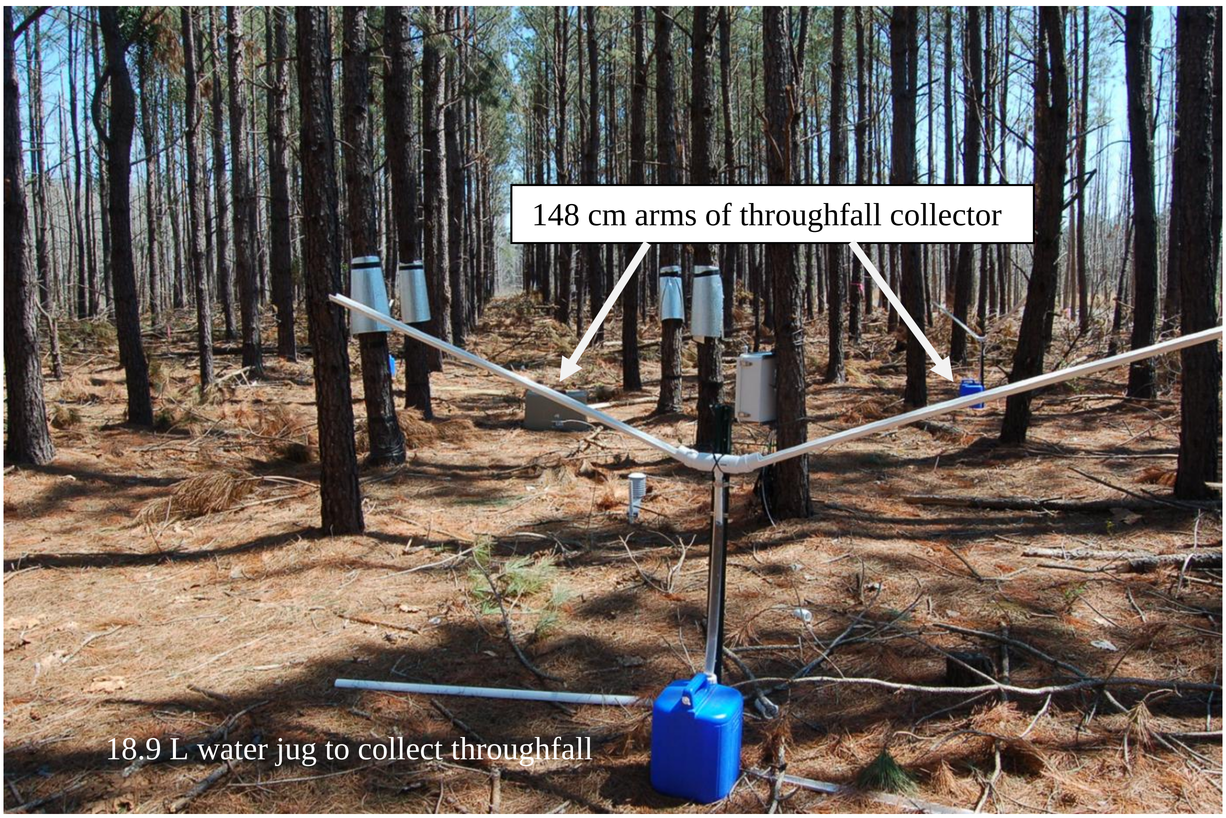

Figure 4. An installed throughfall collector.

Lysimeter Outflow

Unvegetated box lysimeters were placed in Block 3 plots only. Aluminum lysimeters were custom made at a metal fabrication shop in Athens, GA to specifications. Each lysimeter had an internal measurement of 60.33 cm wide, 80.65 cm long, and 49.61 cm deep (to the start of the V bottom). The tops of the lysimeters were placed just above ground level to ensure no overland flow could enter the lysimeter (Figure 5). A deeper hole was dug adjacent to the lysimeter to house a 55 gallon Brute® trashcan that would contain a 50 L Nalgene® carboy. A vinyl tube was attached to the pipe draining the box lysimeter and placed in the mouth of the 50 L Nalgene® carboy. Each Brute® trashcan was secured with rope and two metal garden stakes, and 45 lb weights were placed inside. This was done to prevent water filling the hole from entering the Nalgene® carboy, to prevent the Brute trashcan from floating when the hole filled with water causing the carboy to be displaced, and in limited cases where the outflow from the lysimeter exceeded 50L, allow for measurement of excess volume collected in the trashcan. Care was taken to remove soil in layers and fill box lysimeters in the reverse order so as to maintain soil layer orientation. The natural litter was replaced on top of the lysimeter soil. Volume in depth of infiltration in millimeters was measured by taking volume of outflow from the Nalgene® carboy and dividing by the surface area of the box lysimeter after conversions.

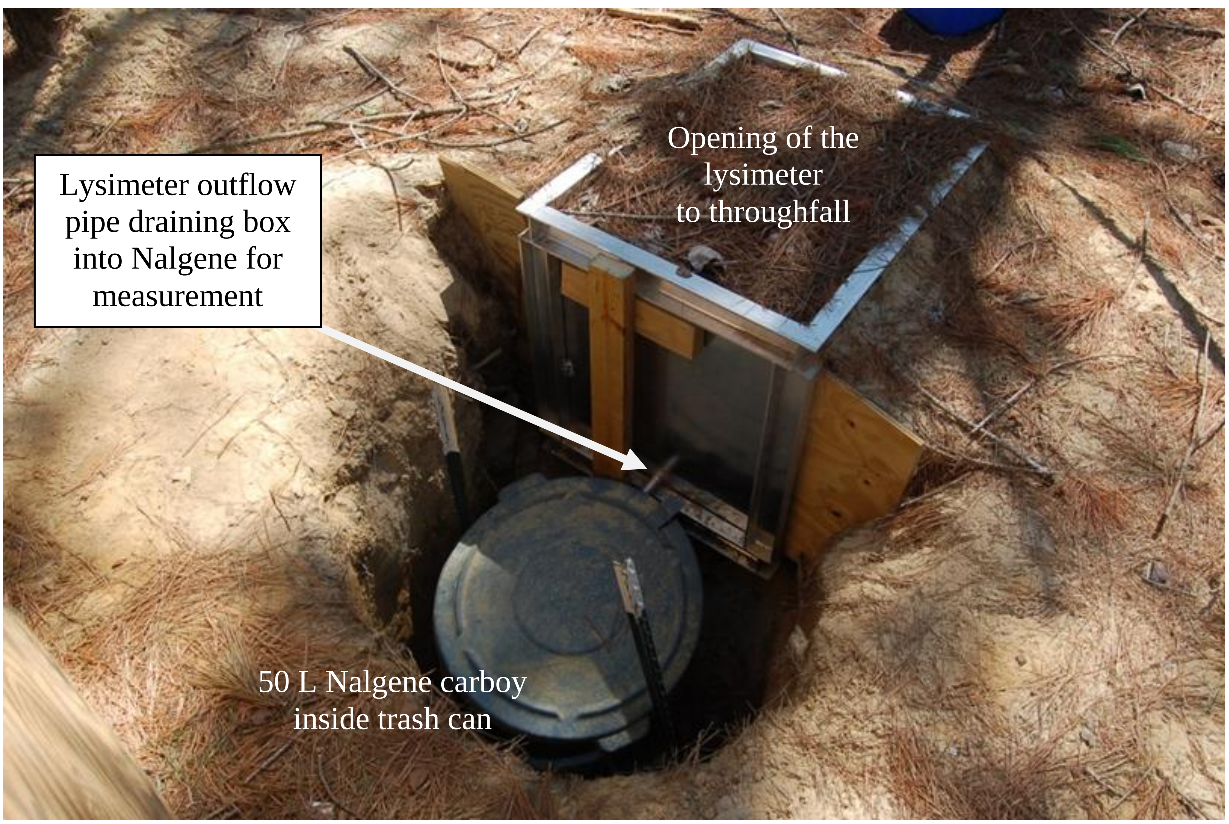

Figure 5. Image of fully installed box lysimeter in loblolly plot.

Soil Moisture

Volumetric moisture content (VMC) of the soils within the box lysimeters was measured in order to estimate the volume of precipitation stored in the soil pores. Volumetric soil moisture was measured using four soil-moisture sensors (ECH2O probes from Decagon Devices Inc.). The probes were placed the same in each box lysimeter, with two 30 cm and two 10 cm, in parallel 30 cm apart. Wires were run to the surface and then buried to the back of the box lysimeters. From the point of exit, they were protected using vinyl tubing up to the data-logger. Measurements were taken every hour during the course of the experiment. Data were averaged to give the depth of stored water in millimeters for each plot from each box lysimeter in block 3. The bulk density of soils in each plot on site was measured in 2011 and the values are listed in Table 2.

Table 2. Bulk density (BD) of soil by Block and Species

Block	1				2				3			
Species	LP		SG		LP		SG		LP		SG	
Depth (cm)	15	30	15	30	15	30	15	30	15	30	15	30
BD (g/cc)	1.37	1.52	1.56	1.6	1.68	1.78	1.62	1.74	1.6	1.71	1.55	1.58

Data Collection and Analysis

Measurements of volume were taken approximately weekly from each throughfall collector and box lysimeter outflow. Data were downloaded monthly from the Decagon® probes and the Campbell® recorder for soil moisture and precipitation measurements, respectively.

Using this information, we were able to measure evaporation for each species in each plot. We used precipitation (P) totals and then subtracted interception (I), box lysimeter outflow volume (O_L), and estimated change in soil moisture ($\Delta\theta$) for the total soil evaporation (E_S) in a simplified water balance equation: $P = I + \Delta\theta + E_S + O_L \; or \; E_S = P - I - \Delta\theta - O_L$.

We performed a linear regression on the throughfall data by block, species, and season to find any significant differences between them. We then performed an analysis of variance (ANOVA) on the same data to increase the strength of the test. Finally, we performed a linear regression using ordinary least squares with indicator variables to combine all the data into one statistical analysis. This provided the most powerful test of those listed here due to power associated with sample size, and gave significant results ($\alpha=0.05$) regarding seasonal interception.

CHAPTER 4

RESULTS AND DISCUSSION

Rainfall variation among all blocks was present even in such close proximity. While important week to week, these minor variations in values among plots may be expected to approach zero over the course of the annual timescale, as seen in the totals; Block 1=1,157 mm, Block 2=1,117 mm, Block 3=1,179 mm. The largest difference among the plots is of 62 mm, or 5.2% of the greatest depth of precipitation over one year of measurements.

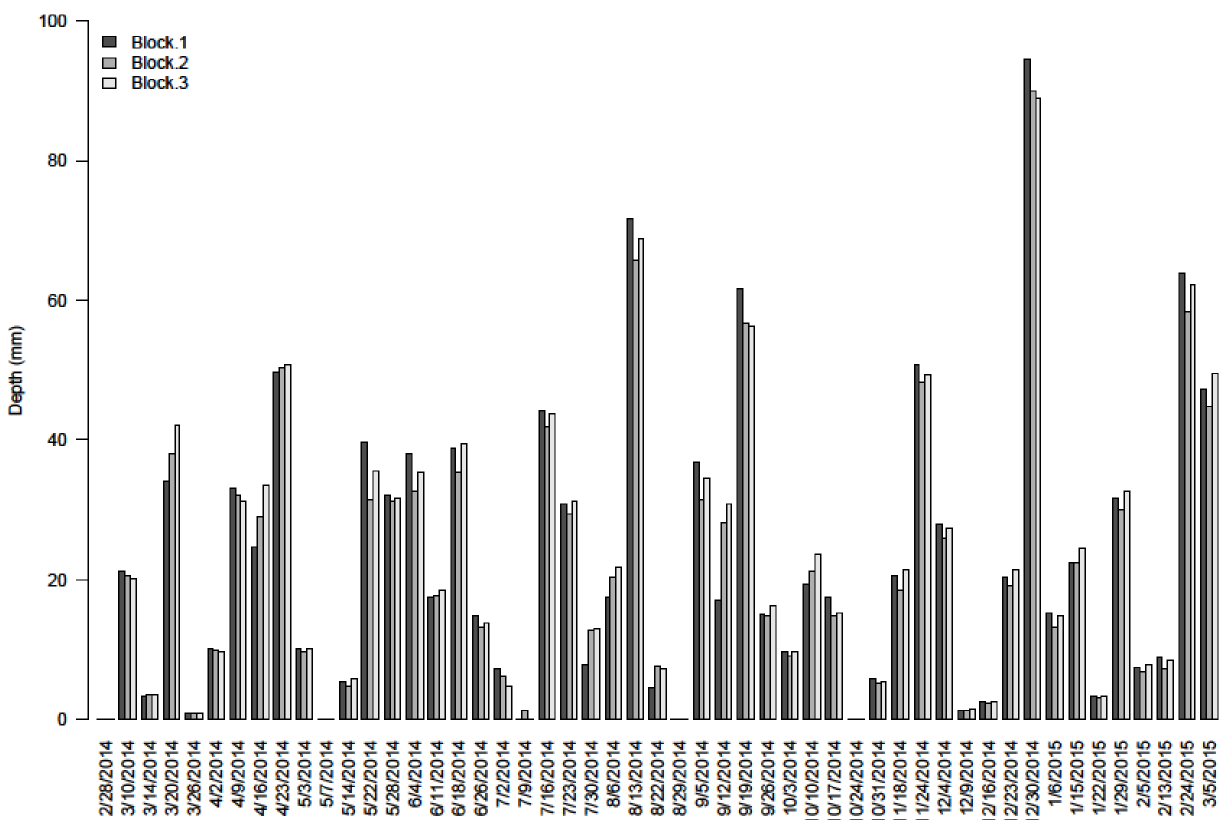

Figure 6. Precipitation among the three Blocks in the study site. Calculated from 15 minute measurements and totaled according to corresponding sampling dates.

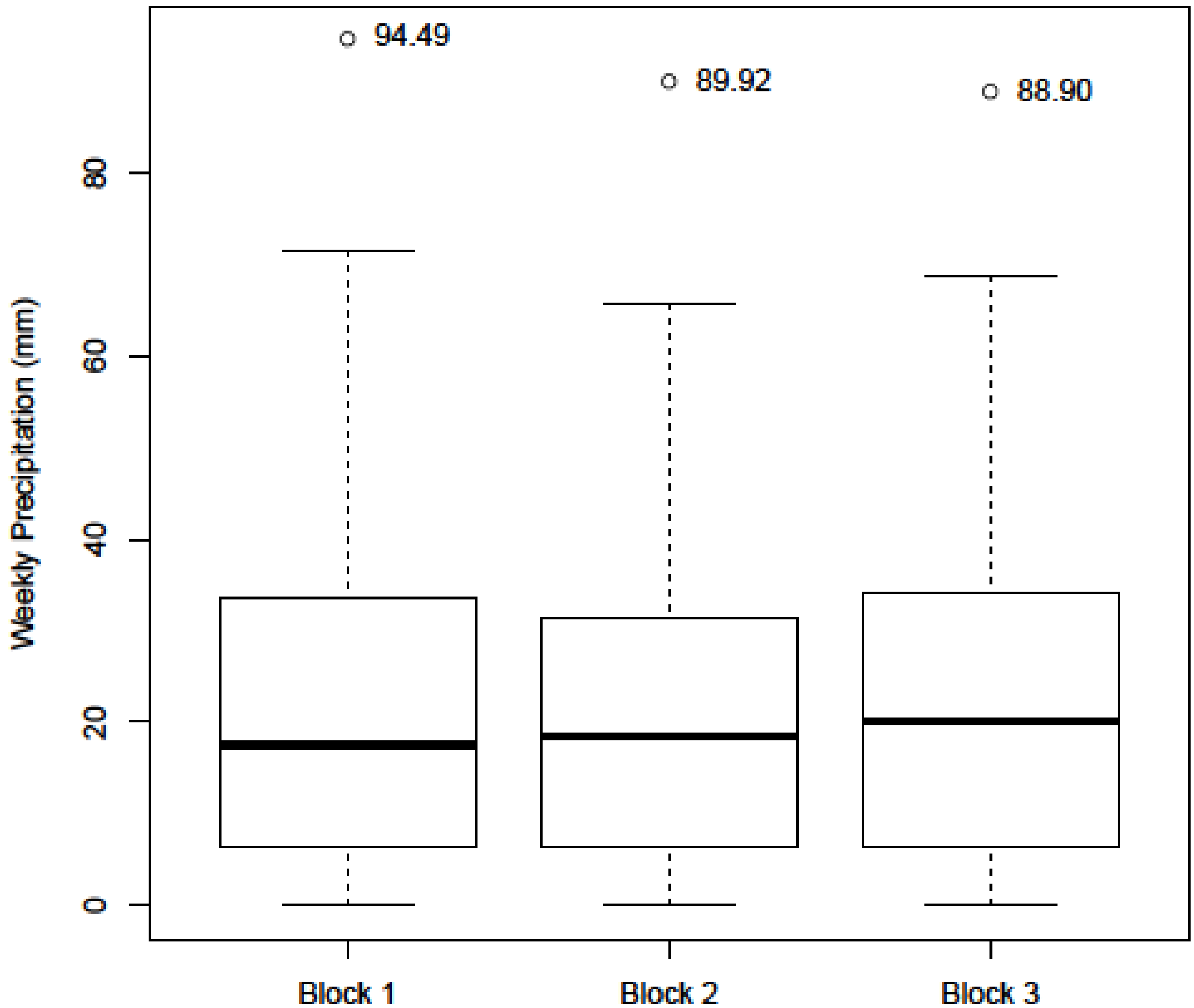

Figure 7. Boxplot of precipitation from weekly measurements.

Table 3. Data specific to the precipitation boxplot (Figure 7)

	Block 1	Block 2	Block 3
Minimum	**0**	**0**	**0**
Lower Quartile	**6.48**	**6.48**	**6.48**
Median	**17.53**	**18.54**	**20.07**
Upper Quartile	**33.53**	**31.5**	**34.04**
Maximum	**71.63**	**65.79**	**68.84**

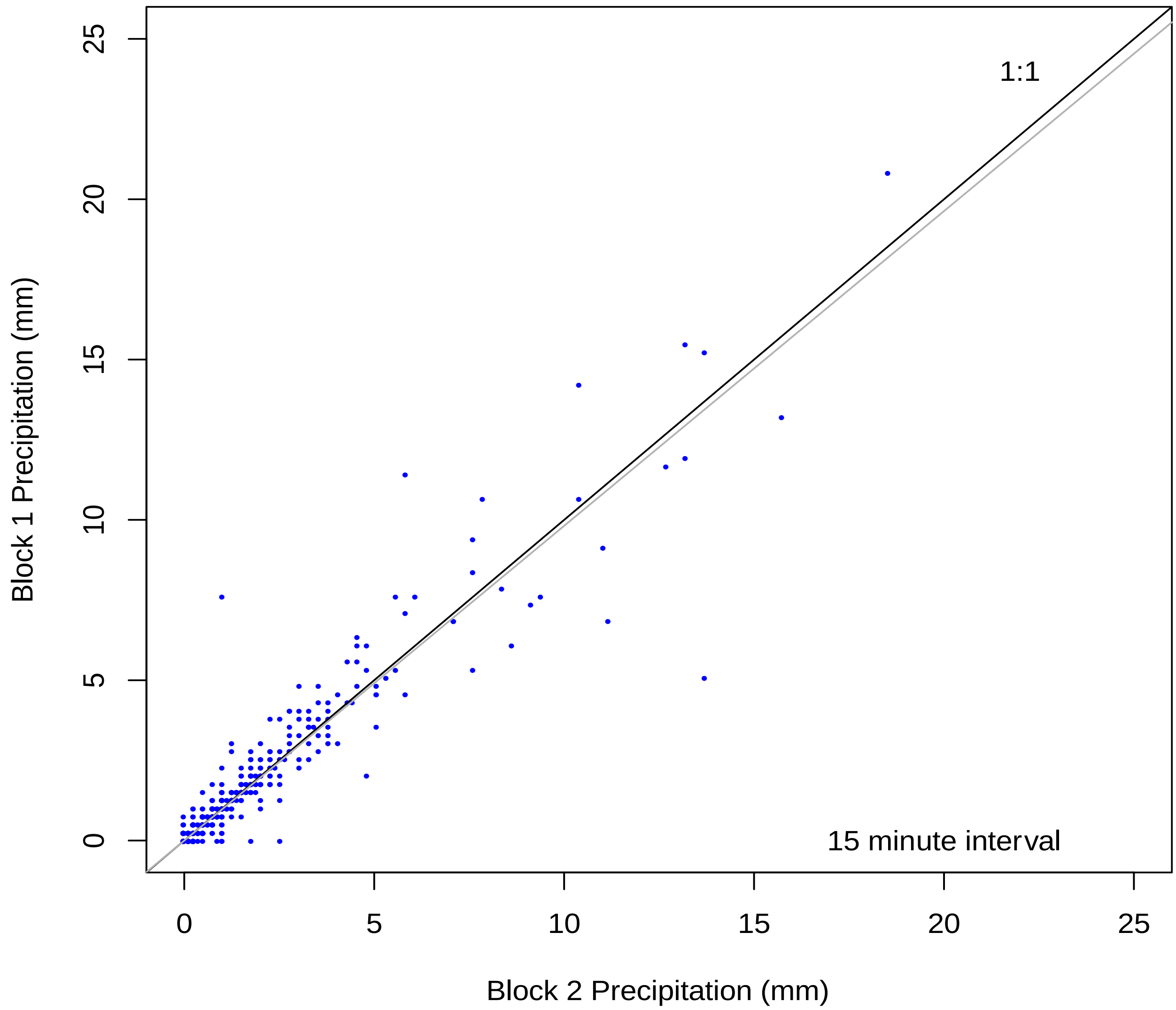

Figure 8. A comparison of Block 1 (1157 mm) and Block 2 (1117 mm) precipitation featuring 15 minute data taken over the course of the experiment. The Black line is the 1:1 line. The line of regression: y=0.9814(±0.0031)x+0.0017(±0.0011), R^2= 0.9167.

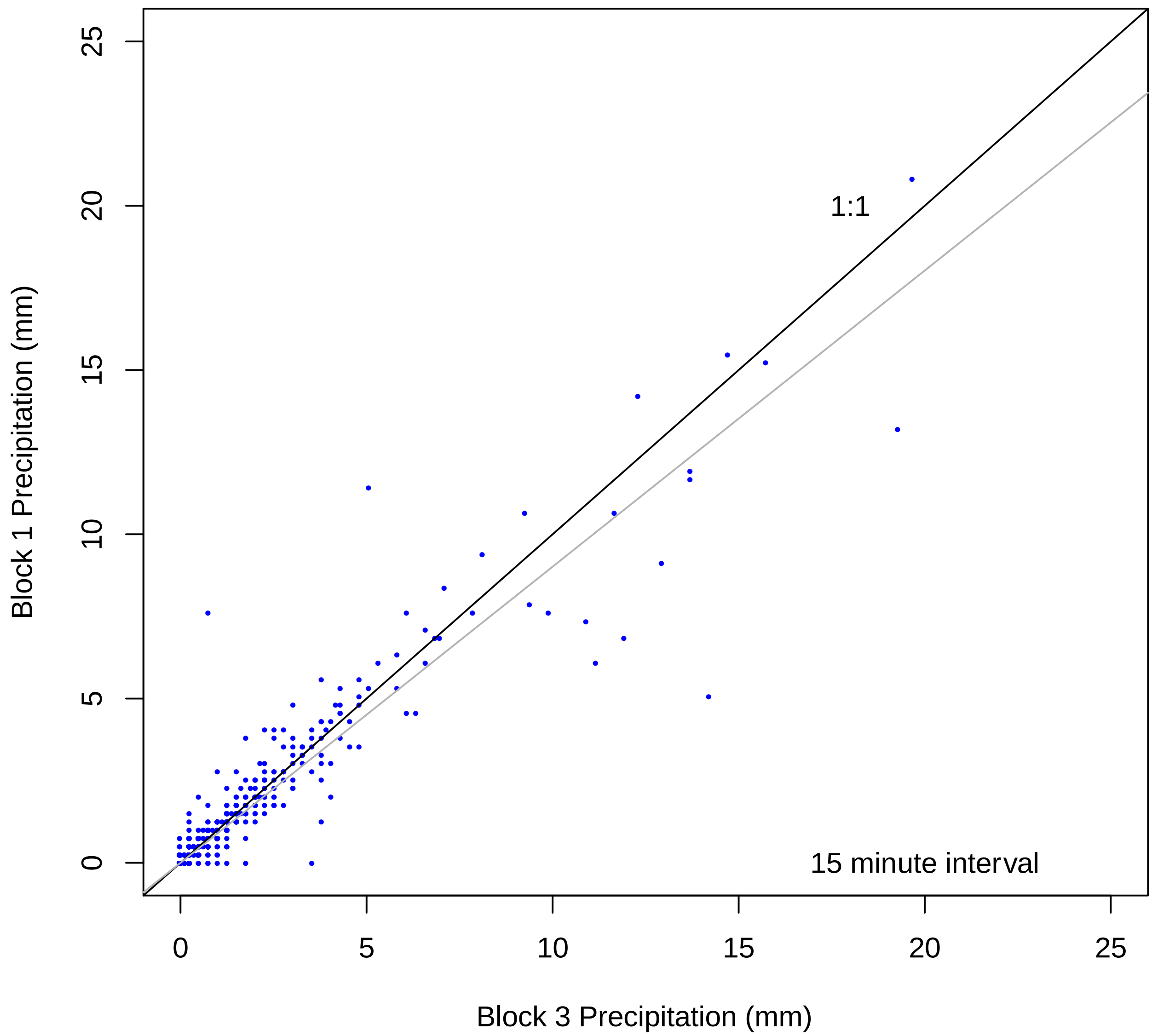

Figure 9. A comparison of Block 1 (1157 mm) and Block 3 (1179 mm) precipitation data from 15 minute data. The black line is the 1:1 line. The line of regression: y=0.9014(±0.0053)x+0.0015(±0.0012), R^2=0.9053

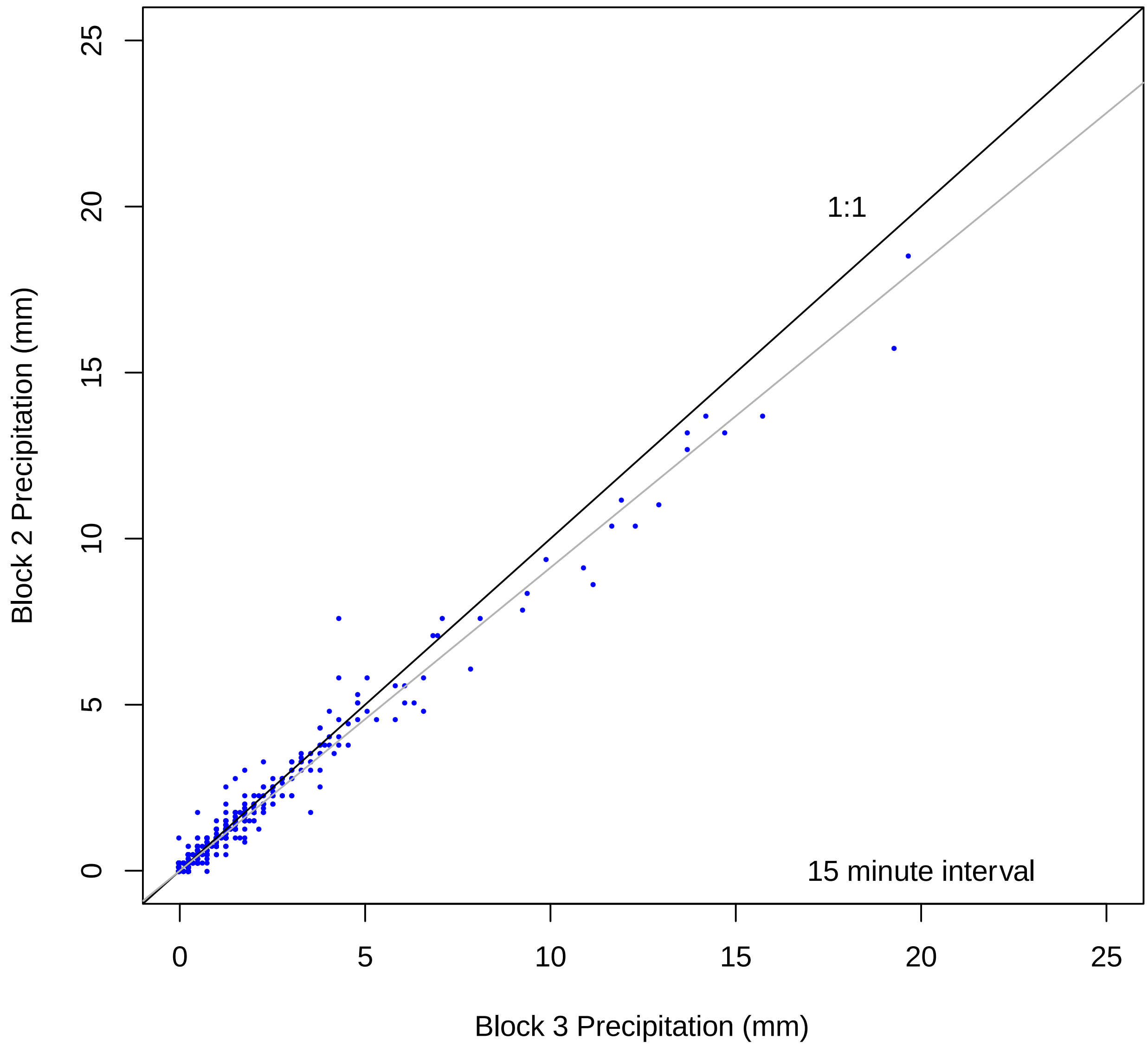

Figure 10. A comparison of Block 2 (1117mm) and Block 3 (1179mm) precipitation data from 15 minute data. The black line is the 1:1 line. The line of regression: $y=0.9126(\pm 0.0016)x+0.0012(\pm 0.0006)$, $R^2=0.9753$

Figure 8 shows what appeared to be nearly equal precipitation in both Block 1 and Block 2 plots. The differences in the data were in two weekly measurements, 8/1/14 and 9/12/14, where the depth in block 2 was over 5 mm greater than block 1. The number of events over 13 mm was also greater in block 2 than block 1. The slope of the line was found to be different from both 1 and 0 (α=0.05), meaning there was volume and the volume for the two plots was not equally dispersed.

Figure 9 shows the levels of precipitation in block 3 plots as having been slightly greater than the total precipitation in block 1. This was primarily due to 4 events above 10 mm in block 3. The slope of the line was found to be different from both 1 and 0 (α=0.05).

Figure 10 displays that for precipitation events greater than 5 mm, block 3 received a greater depth of rainfall than did block 2. The slope of the line was found to be different from both 1 and 0 (α=0.05).

An ANOVA was performed comparing measurements of rainfall for each block as were seen in Figures 8, 9, and 10. The results are seen in Table 4. Only the comparison of block 2 precipitation to block 3 precipitation was found to be significant (α=0.05).

Table 4. Statistical findings from the precipitation ANOVA. B1vB2 corresponds to block 1 precipitation versus block 2 precipitation. B1vB3 corresponds to block 1 precipitation versus block 3 precipitation. B2vB3 corresponds to block 2 precipitation versus block 3 precipitation. SD represents the standard deviation. SE represents the standard error.

	B1vB2	**B1vB3**	**B2vB3**
Mean	**0.800**	**-0.442**	**1.242**
SD	**3.121**	**3.286**	**1.577**
SE	**0.441**	**0.465**	**0.223**
T-stat	**1.812**	**-0.951**	**5.569**
Count	**50**	**50**	**50**

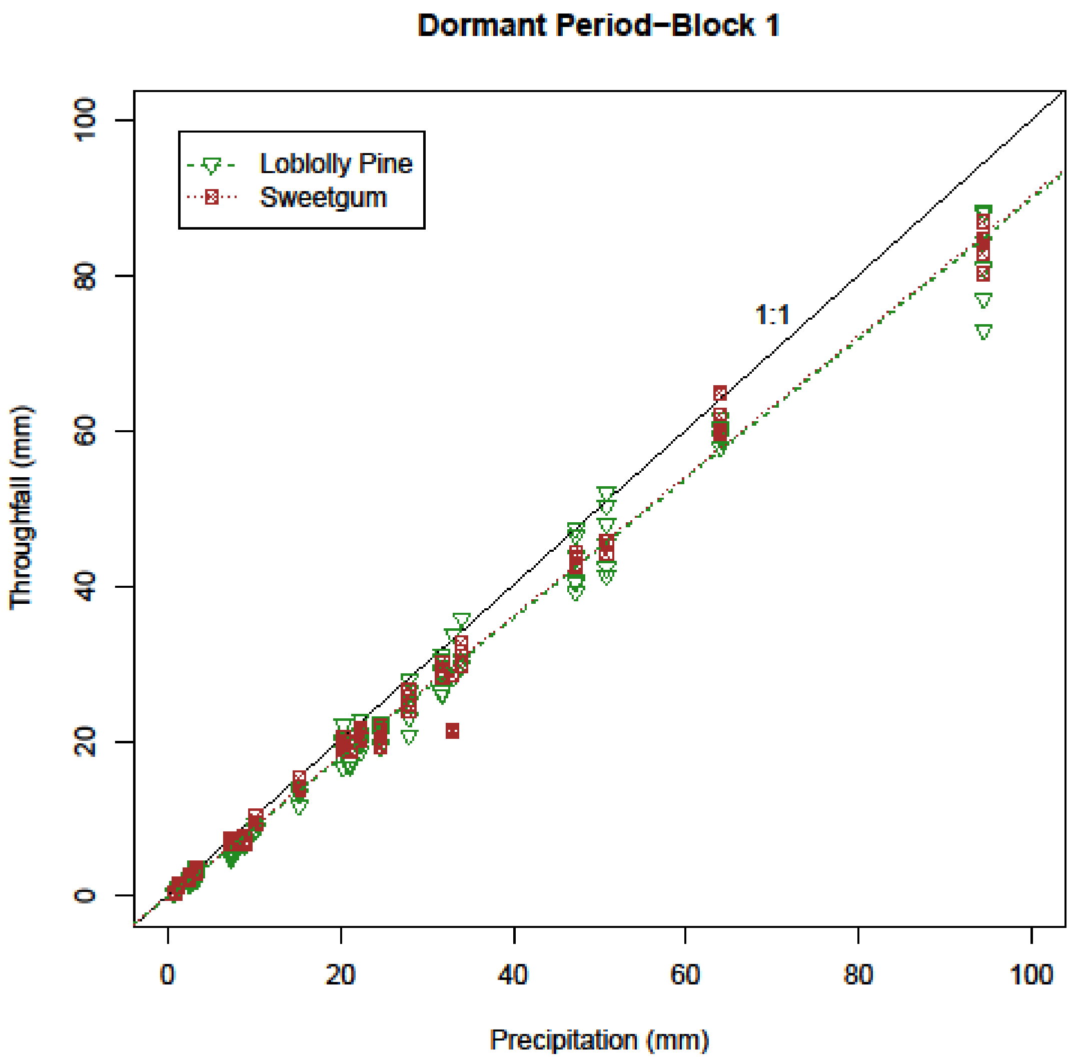

Figure 11. Captured throughfall versus precipitation for the time period of February 28, 2014 to April 16, 2014 and November 18, 2014 to March 5, 2015. Each mark represents one of the six throughfall collectors in each of the forested plots in block 1. The black line is the 1:1 line.

Loblolly: y=0.8985(±0.0303)x-0.3117(±1.037), t-val=59.281, R^2=0.9946

Sweetgum: y=0.9015(±0.0418)x-0.1675(±1.427), t-val=43.213, R^2=0.9899

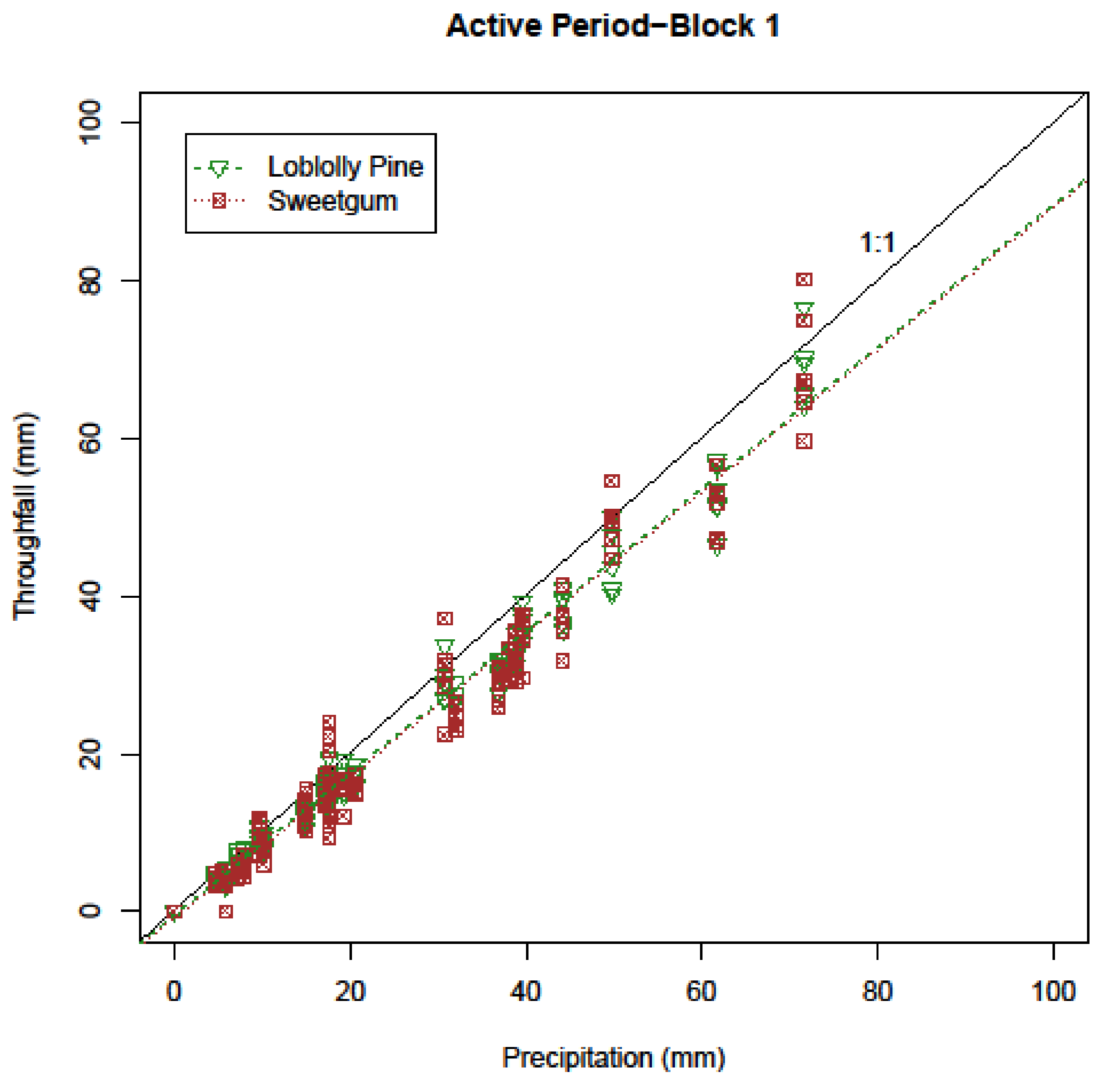

Figure 12. Captured throughfall versus precipitation for the time period of April 16, 2014 to November 18, 2014. Each mark represents one of the six throughfall collectors in each of the forested plots in block 1.The black line is the 1:1 line.

Loblolly: y=0.9014(±0.0282)x-0.4916(±0.8138), t-val=63.817, R^2=0.9934

Sweetgum: y=0.9022(±0.0486)x-0.8939(±1.398), t-val=37.196, R^2=0.9809

In Figure 11, the weekly throughfall measured versus the corresponding weekly totals from the precipitation gauges for the dormant period in block 1 showed a slope of 0.90 (R^2=0.9946) for the loblolly plot and a slope of 0.90 (R^2=0.9989) for the sweetgum plot. The Y intercepts were found to not be significantly different from 0. The slopes of the lines were found to not be significantly different from one another (α=0.05).

In Figure 12, the weekly throughfall measured versus the corresponding weekly totals from the precipitation gauges for the active period in Block 1 showed a slope of 0.90 (R^2=0.9934) for the loblolly plot and a slope of 0.90 (R^2=0.9809) for the sweetgum plot. The slopes of the lines were found to not be significantly different from one another (α=0.05).

This is interesting in that we expected there to be a difference in both species seasonally along with a difference between loblolly and sweetgum during the dormant period. In block 1, the linear regression shows no difference at all between the species or the seasons. As the slope of each line is the percentage of throughfall, we can multiply by the volume of rainfall over the measured time period to solve for the depth of interception. There was 499.9 mm of throughfall in block 1 during the dormant season, and 657.9 mm during the growing season. Loblolly intercepted 65 mm of precipitation in the dormant season to sweetgum's 50 mm. Loblolly intercepted 85.5 mm in the active season to sweetgum's 65.8 mm.

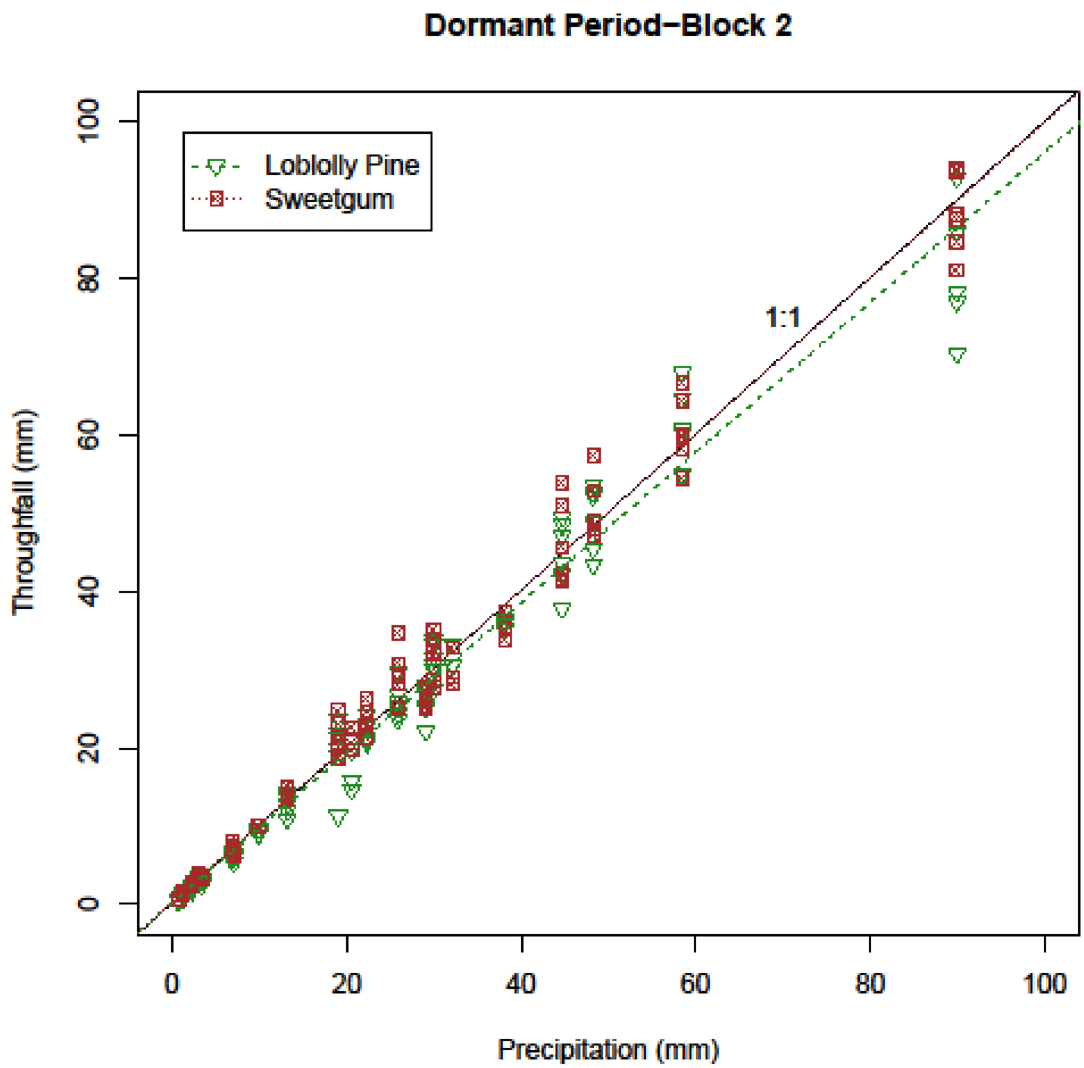

Figure 13. Captured throughfall versus precipitation for the time period of February 28, 2014 to April 16, 2014 and November 18, 2014 to March 5, 2015. Each mark represents one of the six throughfall collectors in each of the forested plots in block 2.The black line is the 1:1 line.

Loblolly: y=0.9591(±0.0400)x+0.2030(±1.306), tval=47.965, R^2=0.9918

Sweetgum: y=0.9937(±0.0316)x+0.4251(±1.029), tval=63.114, R^2=0.9953

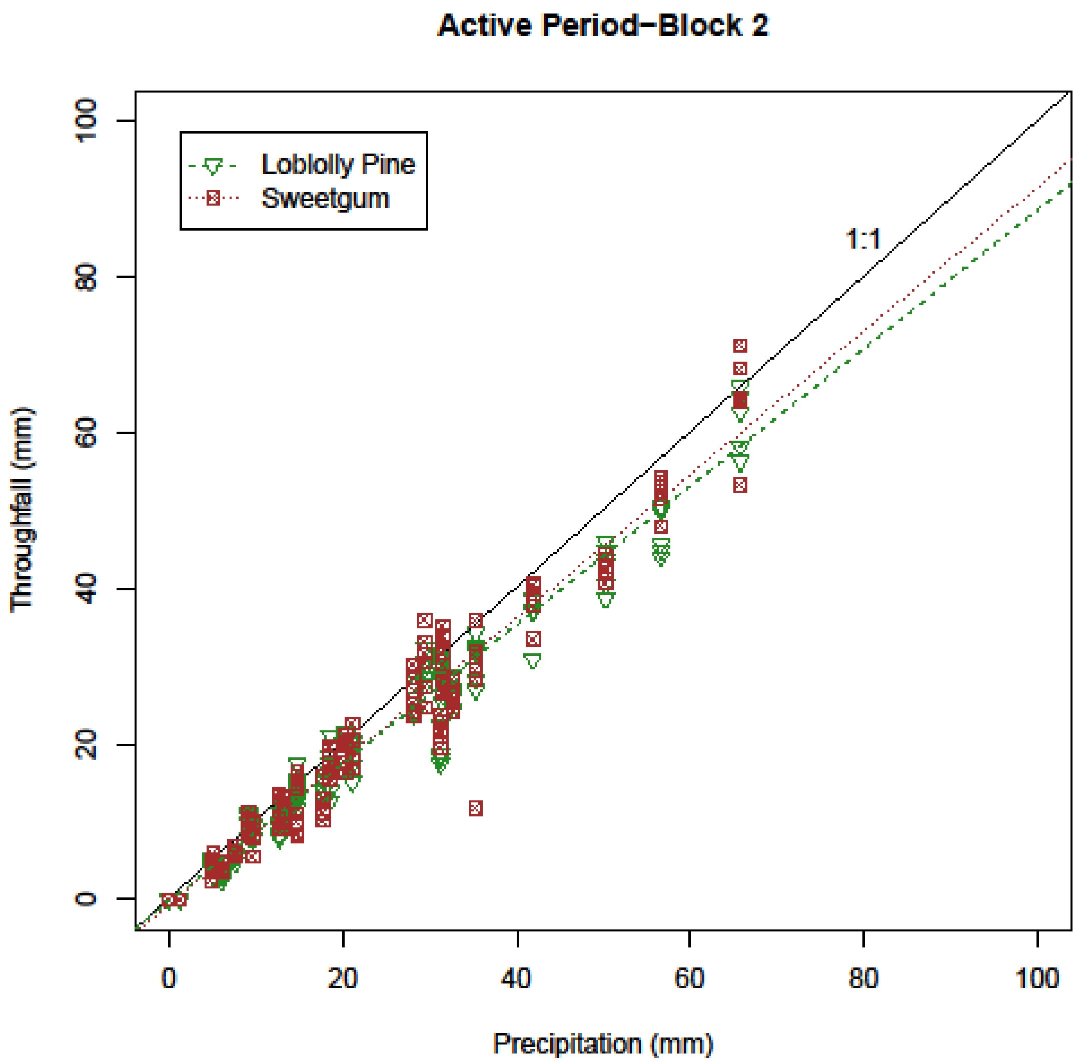

Figure 14. Captured throughfall versus precipitation for the time period of April 16, 2014 to November 18, 2014. Each mark represents one of the six throughfall collectors in each of the forested plots in block 2.The black line is the 1:1 line.

Loblolly: y=0.8881(±0.0520)x-0.2456(±1.412), tval=34.143, R^2=0.9774

Sweetgum: y=0.9221(±0.0552)x-0.6995(±1.498), tval=33.427, R^2=0.9764

In Figure 13, the weekly throughfall measured versus the corresponding weekly totals from the precipitation gauges for the dormant period in Block 2 showed a slope of 0.96 (R^2=0.9918) for the loblolly plot and a slope of 0.99 (R^2=0.9953) for the sweetgum plot. The Y intercepts were found to not be significantly different from 0. The slopes of the lines were found to not be significantly different from one another (α=0.05).

In Figure 14, the weekly throughfall measured versus the corresponding weekly totals from the precipitation gauges for the active period in Block 2 showed a slope of 0.89 (R^2=0.9774) for the loblolly plot and a slope of 0.92 (R^2=0.9764) for the sweetgum plot. The Y intercepts were found to not be significantly different from 0. The slopes of the lines were found to not be significantly different from one another (α=0.05).

This again showed no difference in both species seasonally or between loblolly and sweetgum during the dormant period. In block 2, the linear regression shows no difference at all between the species or the seasons. As the slope of each line is the percentage of throughfall, we can multiply by the volume of rainfall over the measured time period to solve for the depth of interception. There was 477.3 mm of throughfall in block 2 during the dormant season, and 640.5 mm during the growing season. Loblolly intercepted 19.1 mm of precipitation in the dormant season to sweetgum’s 0 mm. Loblolly intercepted 70.5 mm in the active season to sweetgum’s 51.2 mm.

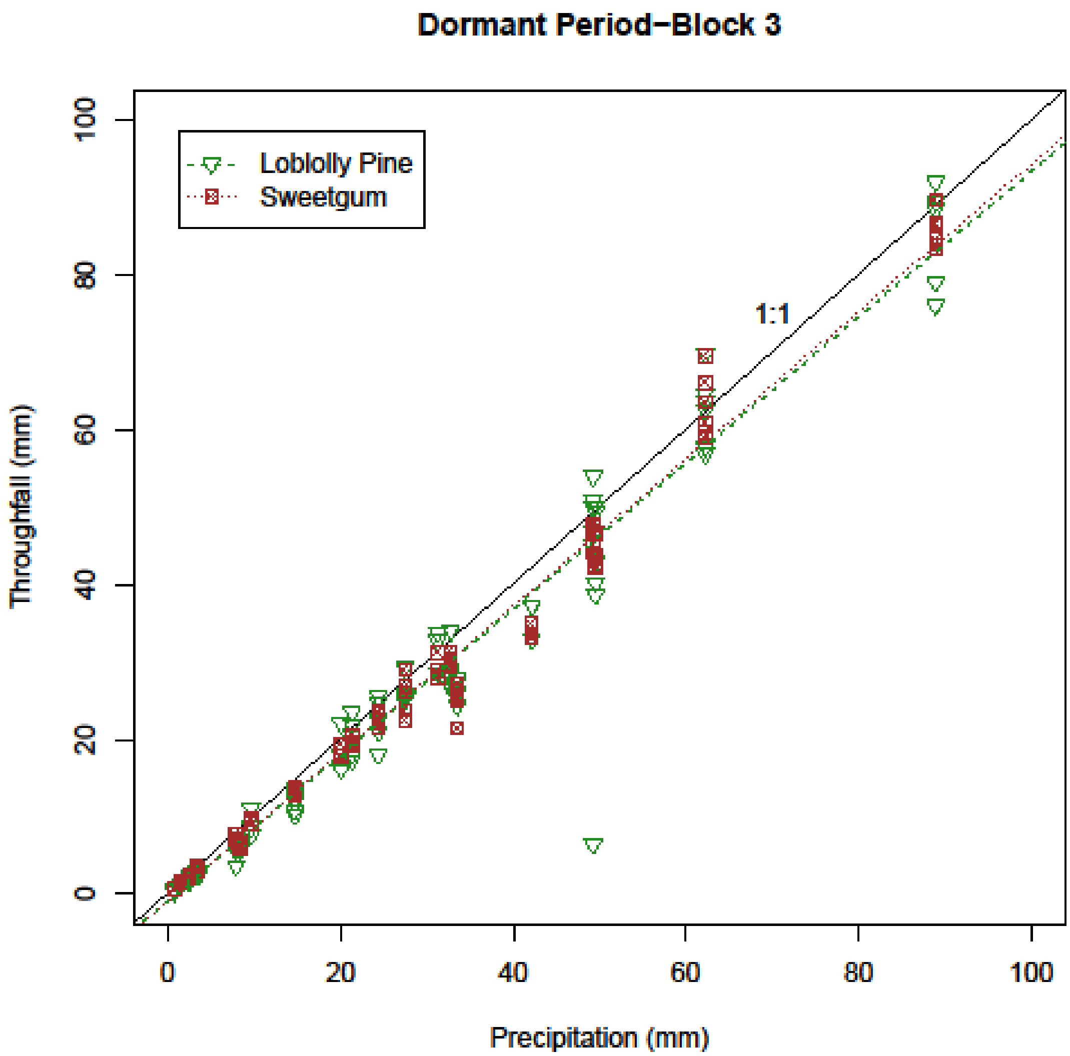

Figure 15. Captured throughfall versus precipitation for the time period of February 28, 2014 to April 16, 2014 and November 18, 2014 to March 5, 2015. Each mark represents one of the six throughfall collectors in each of the forested plots in block 3. The black line is the 1:1 line.

Loblolly: y=0.9432(±0.0402)x-0.8714(±1.366), tval=46.966, R^2=0.9915

Sweetgum: y=0.9532(±0.0454)x-0.9031(±1.540), tval=42.091, R^2=0.9894

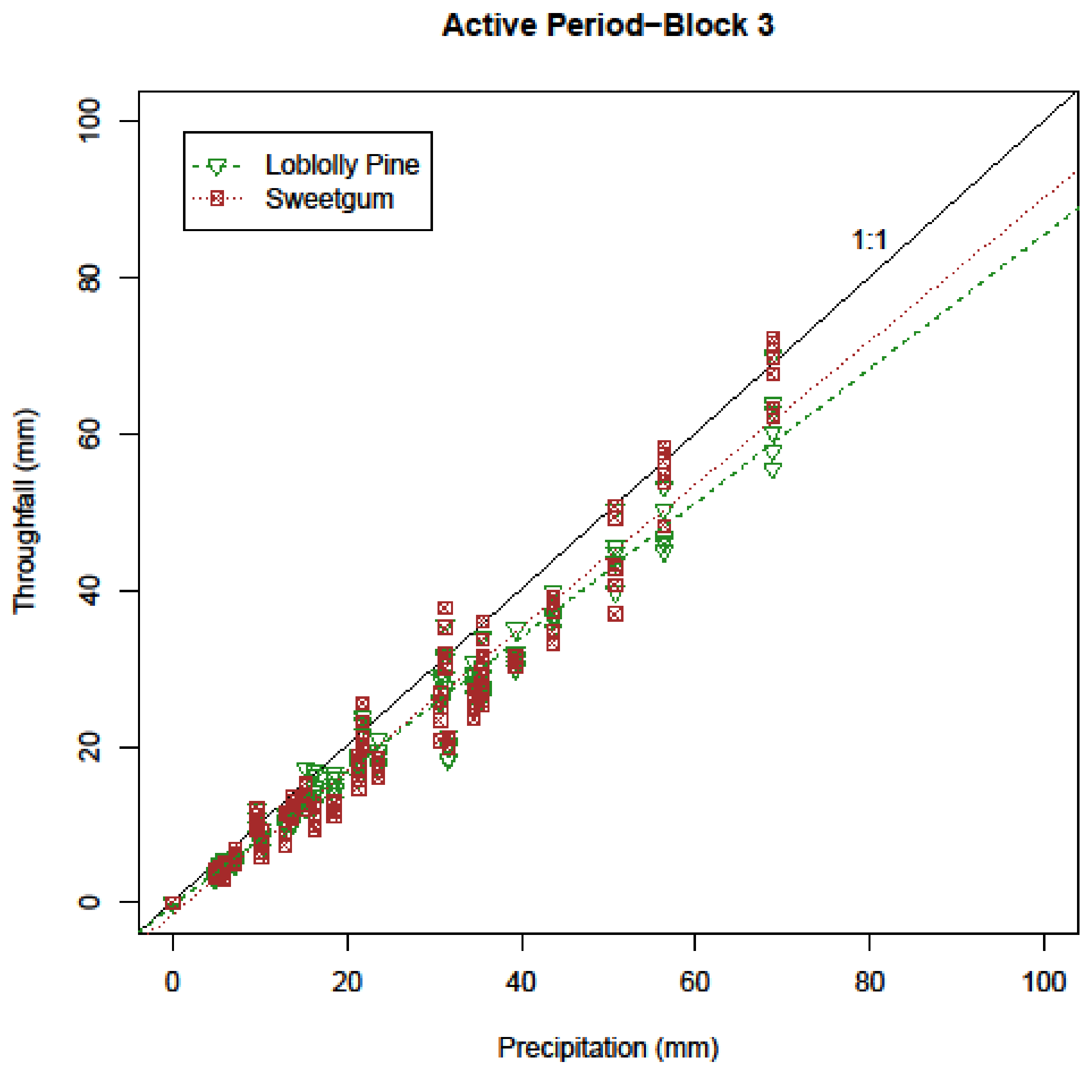

Figure 16. Captured throughfall versus precipitation for the time period of April 16, 2014 to November 18, 2014. Each mark represents one of the six throughfall collectors in each of the forested plots in block 3.The black line is the 1:1 line.

Loblolly: y=0.8593(±0.0427)x-0.3876(±1.217), tval=40.294, R^2=0.9836

Sweetgum: y=0.9176(±0.0634)x-1.5135(±1.810), tval=28.922, R^2=0.9687

In Figure 15 the weekly throughfall measured versus the corresponding weekly totals from the precipitation gauges for the dormant period in block 3 showed a slope of 0.94 (R^2=0.9915) for the loblolly plot and a slope of 0.95 (R^2=0.9894) for the sweetgum plot. The Y intercepts were not found to be significantly different from 0. The slopes of the lines were found to not be significantly different from one another (α=0.05).

In Figure 16, the weekly throughfall measured versus the corresponding weekly totals from the precipitation gauges for the active period in block 3 showed a slope of 0.86 (R^2=0.9836) for the loblolly plot and a slope of 0.92 (R^2=0.9687) for the sweetgum plot. The Y intercepts were found to not be significantly different from 0. The slopes of the lines were found to not be significantly different from one another. The confidence intervals of dormant pine (0.903) and growing pine (0.902) show a seasonal difference (α=0.05).

We observed no difference in species and one small instance of difference seasonally using linear regression. In block 3, the linear regression shows no difference at all between the species. As the slope of each line is the percentage of throughfall, we can multiply by the volume of rainfall over the measured time period to solve for the depth of interception. There was 501.6 mm of throughfall in block 3 during the dormant season, and 678.2 mm during the growing season. Loblolly intercepted 20.1 mm of precipitation in the dormant season to sweetgum’s 15 mm. Loblolly intercepted 81.4 mm in the active season to sweetgum’s 47.5 mm.

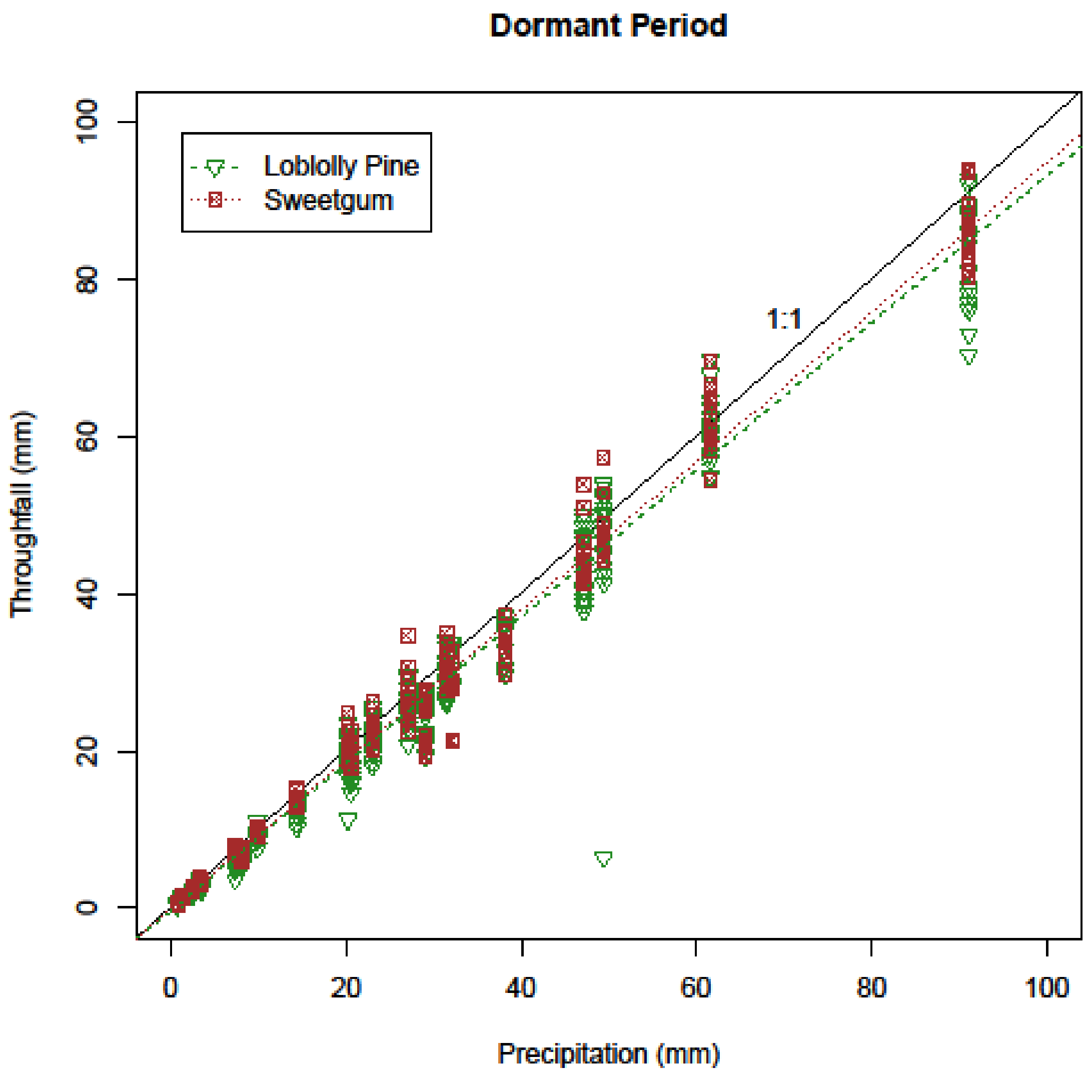

Figure 17. Captured throughfall versus precipitation for the time period of February 28, 2014 to April 16, 2014 and November 18, 2014 to March 5, 2015. This figure includes data from all blocks. Each mark represents one of the six throughfall collectors in each of the forested plots.The black line is the 1:1 line.

Loblolly: y=0.9357(±0.0262)x-0.3199(±0.8778), tval=71.521, R^2=0.9963

Sweetgum: y=0.9516(±0.0292)x-0.2162(±0.9770), tval=65.348, R^2=0.9956

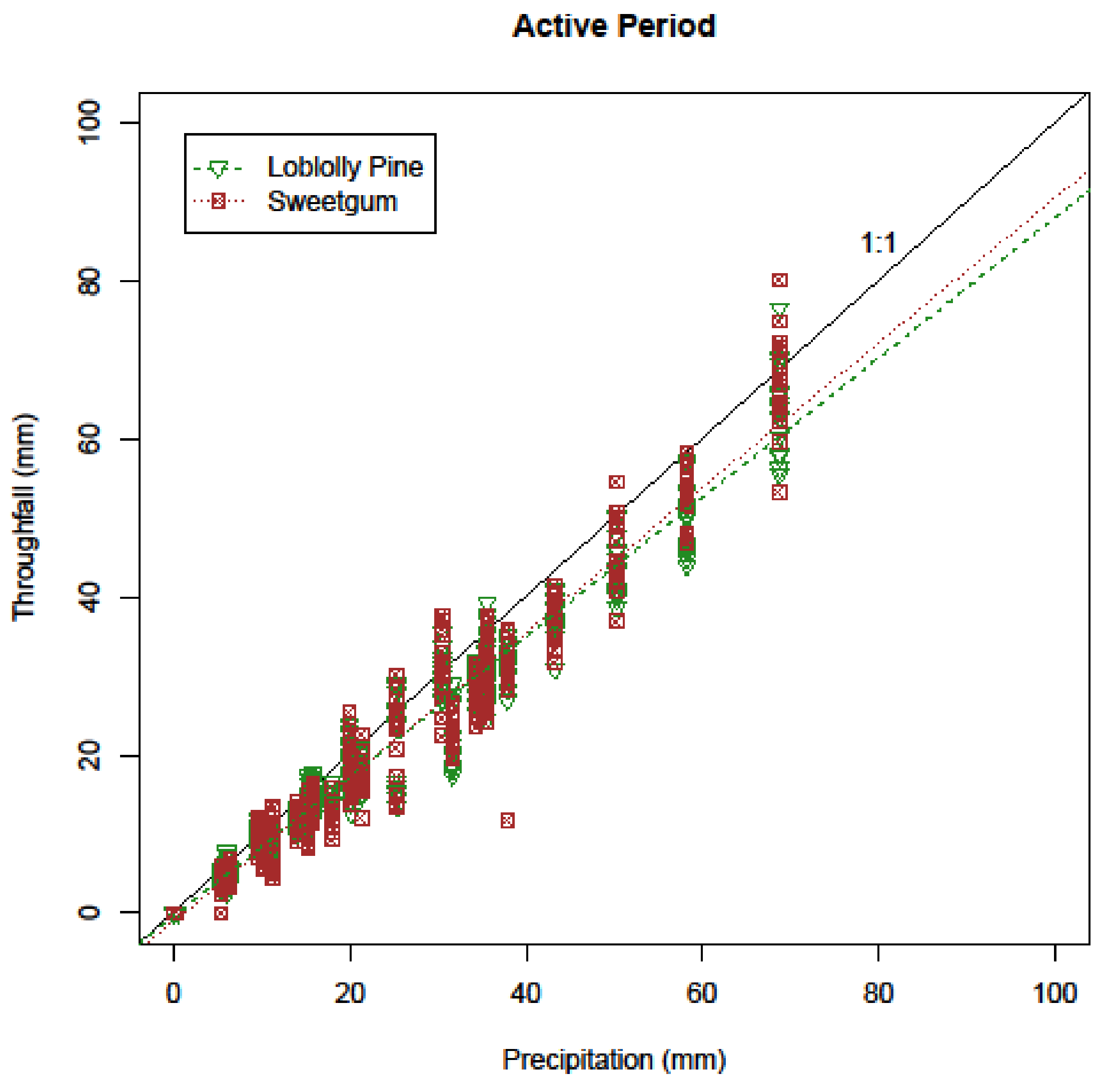

Figure 18. Captured throughfall versus precipitation for the time period of April 16, 2014 to November 18, 2014. Each mark represents one of the six throughfall collectors in each of the forested plots. This figure includes data from all blocks. The black line is the 1:1 line.

Loblolly: y=0.8838(±0.0356)x-0.3986(±1.001), tval=49.635, R^2=0.9892

Sweetgum: y=0.9162(±0.0484)x-1.0848(±1.361), tval=37.853, R^2=0.9815

In Figure 17, the weekly throughfall measured versus the corresponding weekly totals from the precipitation gauges for the dormant period in all Blocks showed a slope of 0.94 (R^2=0.9963) for the loblolly plots and a slope of 0.95 (R^2=0.9956) for the sweetgum plots. The Y intercepts were found to not be significantly different from 0. The slopes of the lines were found to not be significantly different from one another (α=0.05).

In Figure 18, the weekly throughfall measured versus the corresponding weekly totals from the precipitation gauges for the active period in all Blocks showed a slope of 0.88 (R^2=0.9892) for the loblolly plots and a slope of 0.92 (R^2=0.9815) for the sweetgum plots. The Y intercepts were found to not be significantly different from 0. The slopes of the lines were found to not be significantly different from one another (α=0.05).

Among the data from all blocks, the linear regression shows no difference at all between the species or the seasons. As the slope of each line is the percentage of throughfall, we can multiply by the volume of rainfall over the measured time period to solve for the depth of interception. There was an average of 492.9 mm of throughfall in all blocks during the dormant season, and 658.9 mm during the growing season. Loblolly intercepted 49.2 mm of precipitation in the dormant season to sweetgum's 34.5 mm. Loblolly intercepted 112 mm in the active season to sweetgum's 79.1 mm. While not statistically significant, the findings do show that loblolly intercepts a greater amount of rainfall than sweetgum no matter the season.

ANOVA of throughfall data

An ANOVA was performed on the block 1 data featured in Figures 11 and 12. The results are displayed in Table 5. We averaged the loblolly throughfall data and the sweetgum throughfall data to find the variance. No significance was observed ($\alpha=0.05$).

Table 5. ANOVA of the throughfall data at Block 1. SD represents the standard deviation. SE represents the standard error.

	Loblolly	**Sweetgum**	**Difference**
Mean	**0.86**	**0.87**	**-0.01**
SD	**0.09**	**0.12**	**0.12**
SE	**0.01**	**0.02**	**0.02**
T-stat	**65.95**	**48.14**	**-0.46**
Count	**45**	**45**	**45**

An ANOVA was performed on the block 2 data featured in Figures 13 and 14. The results are displayed in Table 6. We averaged the loblolly throughfall data and the sweetgum throughfall data to find the variance. The observed findings were significant ($\alpha=0.05$). They show that for block 2, loblolly intercepted 4% more rainfall than sweetgum during the timeframe of the experiment.

Table 6. ANOVA of the throughfall data at Block 2. SD represents the standard deviation. SE represents the standard error.

	Loblolly	**Sweetgum**	**Difference**
Mean	**0.90**	**0.94**	**-0.04**
SD	**0.11**	**0.13**	**0.10**
SE	**0.02**	**0.02**	**0.01**
T-stat	**53.43**	**49.68**	**-2.85**
Count	**46**	**46**	**46**

An ANOVA was performed on the block 3 data featured in Figures 15 and 16. The results are displayed in Table 7. We averaged the loblolly throughfall data and the sweetgum throughfall data to find the variance. No significance was observed (α=0.05).

Table 7. ANOVA of the throughfall data at Block 3. SD represents the standard deviation. SE represents the standard error.

	Loblolly	Sweetgum	Difference
Mean	**0.84**	**0.86**	**-0.02**
SD	**0.11**	**0.11**	**0.10**
SE	**0.02**	**0.02**	**0.02**
T-stat	**53.77**	**53.04**	**-1.36**
Count	**46**	**46**	**46**

An ANOVA was performed on the combined data from all blocks featured in Figures 17 and 18. The results are displayed in Table 8. We averaged the loblolly throughfall data and the sweetgum throughfall data to find the variance. We observed a significant finding showing loblolly intercepted 3% more precipitation than sweetgum during the timeframe of the experiment (α=0.05).

Table 8. ANOVA of the throughfall data among all Blocks. SD represents the standard deviation. SE represents the standard error.

	Loblolly	Sweetgum	Difference
Mean	**0.87**	**0.89**	**-0.03**
SD	**0.11**	**0.12**	**0.10**
SE	**0.01**	**0.01**	**0.01**
T-stat	**96.55**	**83.94**	**-3.73**
Count	**138**	**138**	**138**

Without considering seasonal variation between coniferous and deciduous tree species, statistical analyses show less throughfall allowed by loblolly (Tables 5-8) than for sweetgum. Looking at the respective figures (11-18), loblolly intercepts a greater volume of water than sweetgum. For all plots during the growing season, when sweetgum have significant basal leaf area, it was expected that during precipitation events under a threshold of volume, a higher value of interception should occur. In a report by Herwitz and Slye, 1994, the heterogeneity and extreme differences in canopy height and basal area caused many problems with measurements due to natural but unpredictable patterns, vertical changes in wind speed, and as a result highly variable throughfall direction. In a monoculture environment such as the one in this experiment where age, genetics, and growing conditions are extremely similar, if not identical, those problems are not present.

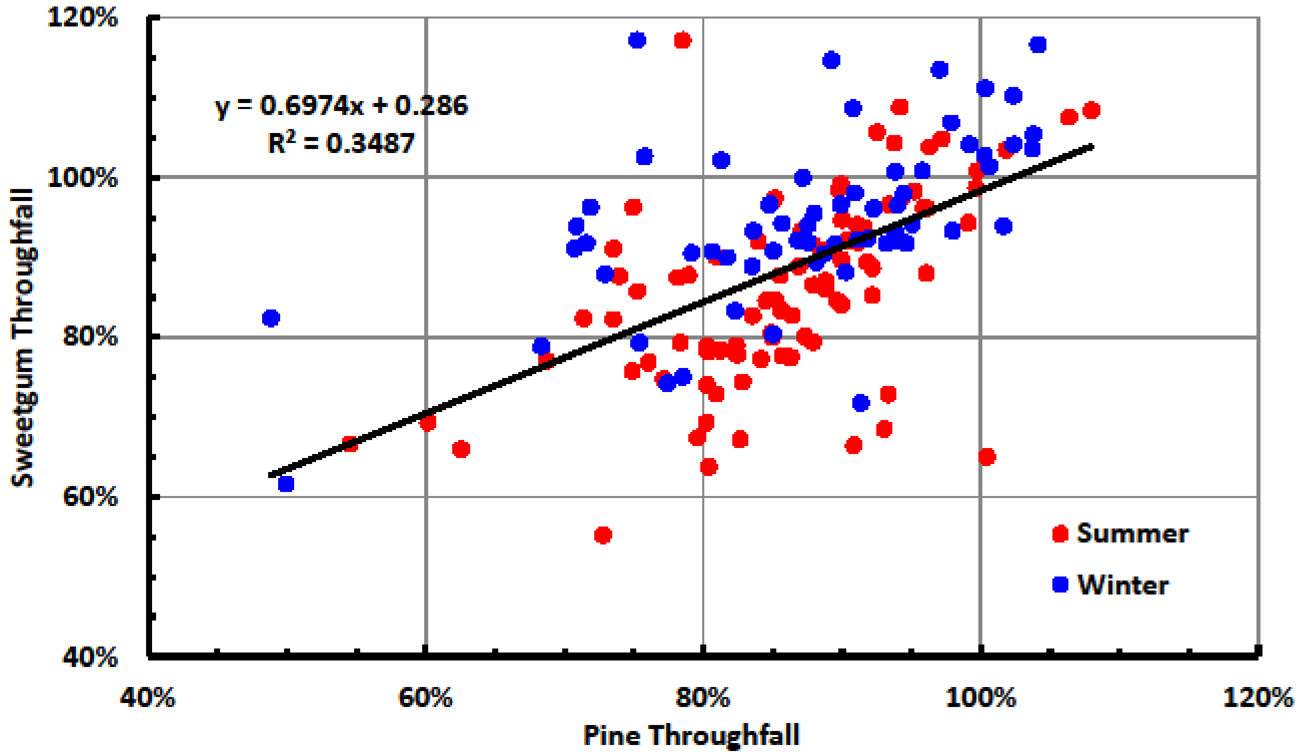

Figure 19. Distribution of the variance of means as a percentage of total interception.

Figure 19 illustrates the variance of throughfall between the forested plots in each season. The dates correspond to the active (summer) and dormant (winter) periods used throughout the results. During the active period, higher volumes of throughfall were observed in the loblolly plots. During the dormant period, coinciding with leaf off for the deciduous species, higher volumes of throughfall were evident among the sweetgum plots.

Table 9. Statistical analysis of the variance of means in seasonal throughfall among all Blocks. SD represents the standard deviation. SE represents the standard error.

	Winter	Summer
Mean	-0.073	0.001
SD	0.102	0.095
SE	0.013	0.011
T-stat	-5.692	0.053
Count	63	75

The statistical findings from the seasonal variance among forested plots show zero difference in throughfall during the active growing period in the summer and a 7% difference during the winter, or dormant period.

The comparison of variance in plot interception by season in Figure 19 shows the clear difference between the species due to seasonality. In summer the throughfall was greater in the loblolly plots and in winter the throughfall was greater in the sweetgum plots. Some difference may be due to outliers from the bigger storms in each season increasing the effect of leaf on and leaf off in the deciduous sweetgum, but this analysis allows for equal consideration of all compared values, no matter the depth of precipitation. The statistical analysis of variance (Table 9) shows 0% difference in the throughfall between species over summer. However, a 7% difference in winter illustrates that loblolly pine intercepted 7% more precipitation than sweetgum during that time.

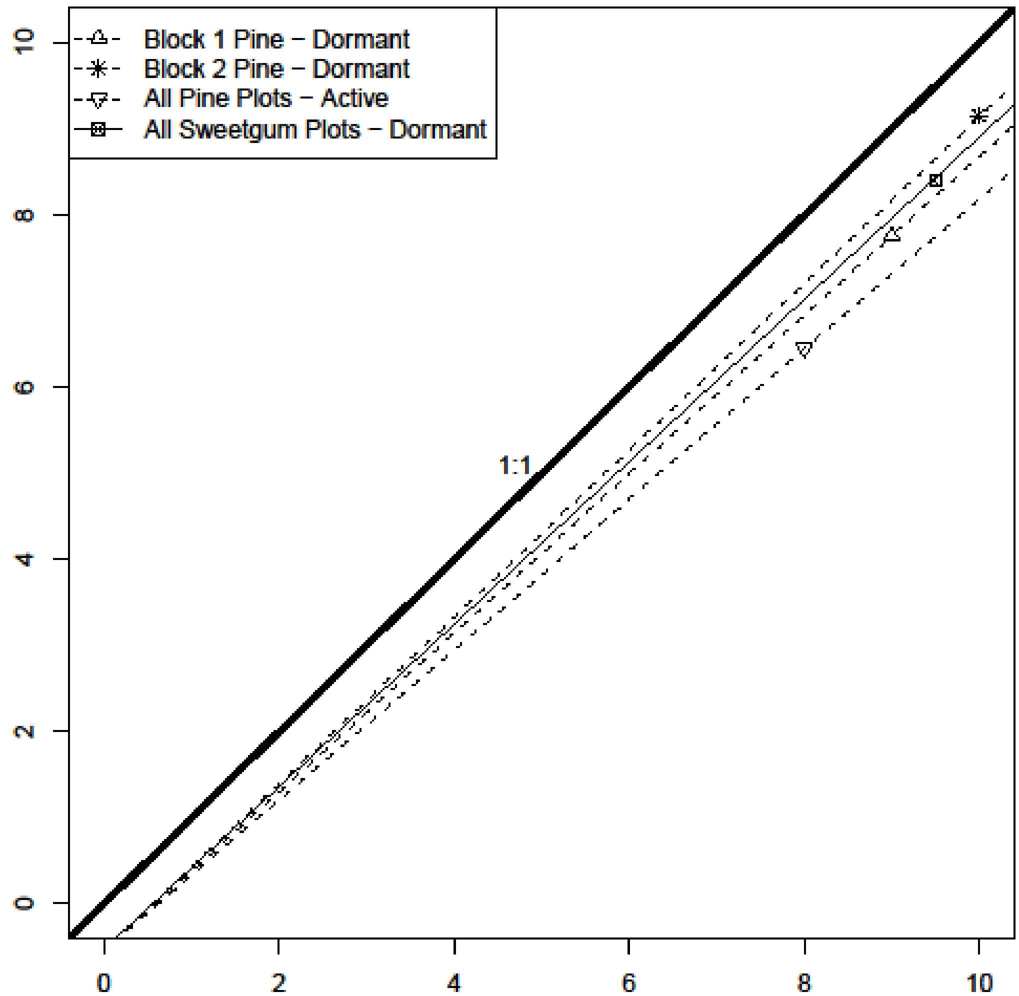

Figure 20. Results of the linear regression using ordinary least squares with indicator variables.

Results from this are listed in Table 10. The test returned a reported R^2=0.9726. The base argument was loblolly in block 1 over the dormant season (slope and const). Results were also returned for loblolly plots in block 2 (Blk2) and block 3 (Blk3) during the dormant season, all loblolly plots during the active season (Act), all sweetgum plots during dormant season (D+gum), and all sweetgum plots during the active season (A+gum). Dormant pine in block 1 was reported to intercept 7.9% of precipitation. Dormant pine in block 2 was reported to intercept only 3.3% of precipitation. Dormant pine interception in block 3 was not significantly different from block 1. Dormant sweetgum in all blocks were reported to intercept 5.7% of precipitation. Active loblolly pine was reported to intercept 12.8% of precipitation. Active sweetgum interception was not significantly different from active loblolly.

Table 10. Results from linear regression using ordinary least squares with indicator variables. Coef= coefficient, SE refers to the standard error.

A + gum	D + gum	Act	Blk3	Blk2	slope	const	
0.013	0.022	-0.049	0.004	0.046	0.921	-0.536	Coef
0.007	0.007	0.007	0.006	0.006	0.006	0.118	SE
1.819	3.106	-7.047	0.623	7.542	142.081	-4.548	T-Stat

The same test was done for interception and returned the same results. The same test was performed while omitting the insignificant factors of block 3 pine plots in dormant season and active gum with the same results.

Measurements of loblolly throughfall from our collectors averaged from all plots for the entirety of the experiment gave a total collection depth of 1048.9 mm. This means that by simple calculation, 11.1% of precipitation was lost to loblolly interception. Measurements of sweetgum throughfall from our collectors averaged from all plots for the entirety of the experiment gave a total collection depth of 1055.9 mm. This means that 10.6% of precipitation was lost to sweetgum interception.

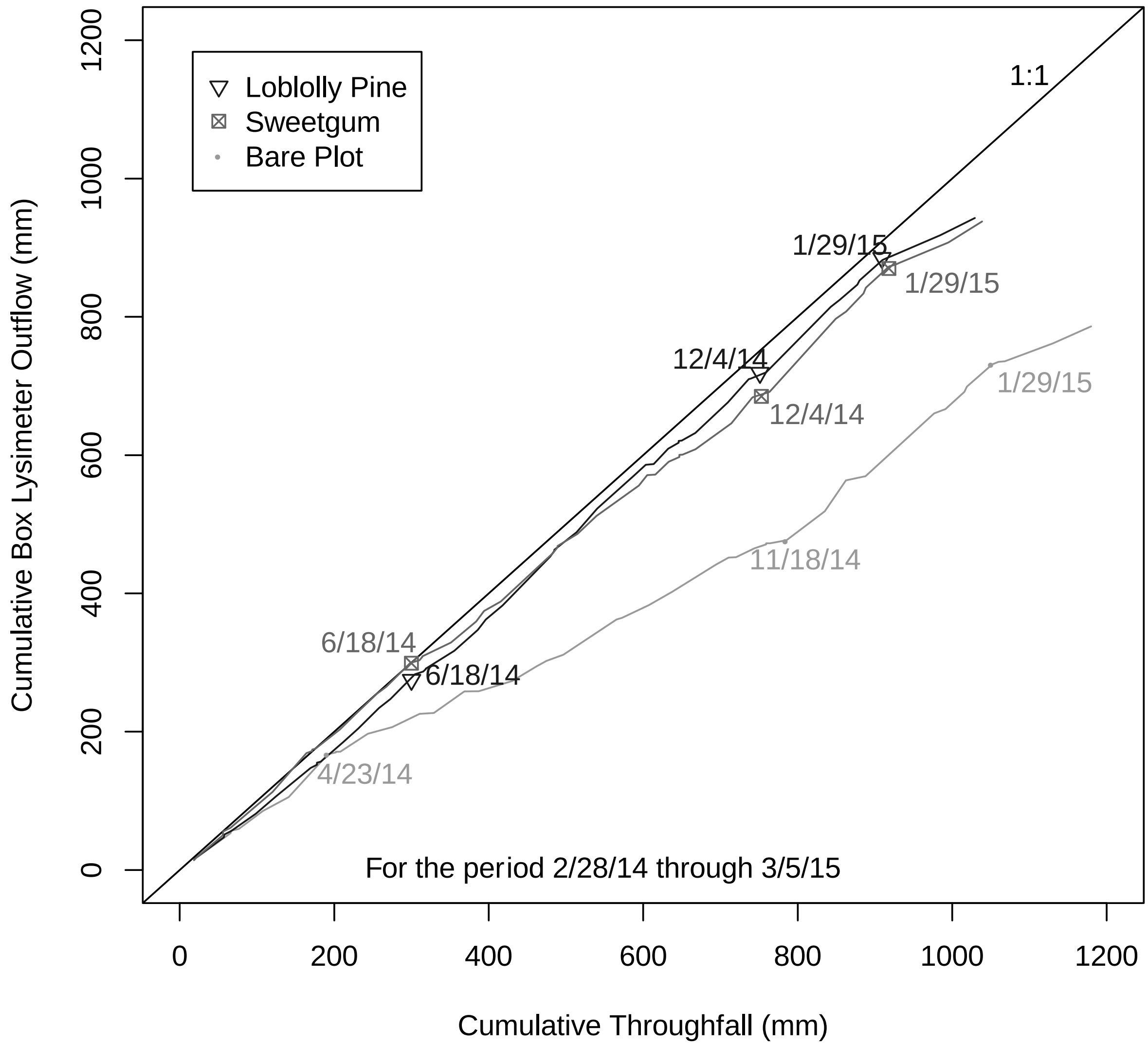

Figure 21. Double mass curve of cumulative lysimeter outflow as compared to cumulative throughfall in Block 3. Precipitation used as throughfall for bare plot.

The difference seen in Figure 21 between the respective lines and the 1:1 aspect is assumed to be the loss of throughfall to storage and evaporation. The sweetgum plot did not see much loss until 6/18/14. The lines of loss in the sweetgum and loblolly plots intersect, or equal each other, on 9/5/2014. From 9/5/14 to the end of the experiment, 3/5/15, the loss from the loblolly plot is less than that from the sweetgum plot.

Outflow from loblolly was 942.7 mm, or 89.9% of throughfall. Outflow from sweetgum was 937.8 mm, or 88.8% of throughfall. Outflow from the bare plot was 786.2 mm, or 66.6% of precipitation.

The lines of loss in Figure 21 can be attributed primarily to evaporation if soil moisture storage is considered to be negligible over time. Figure 22 shows just that. The moisture content, or storage, from the volumetric moisture content (VMC), remains within $\pm$20mm of the initial values over the course of the experiment for each plot type. Looking at the DMC in Figure 21, we notice the intersection of the loblolly and sweetgum values on September 5, 2014. It is very likely if these measurements were continued, the lines would continue to intersect each other biannually due to changes in leaf coverage and associated changes in throughfall depth, primarily. Evaporative loss from soil in these forested plots does not seem to reach levels that would result in a sustained wilting point under normal precipitation patterns. Loss to evaporation from the bare plot is of greater volume when compared to either forested plot.

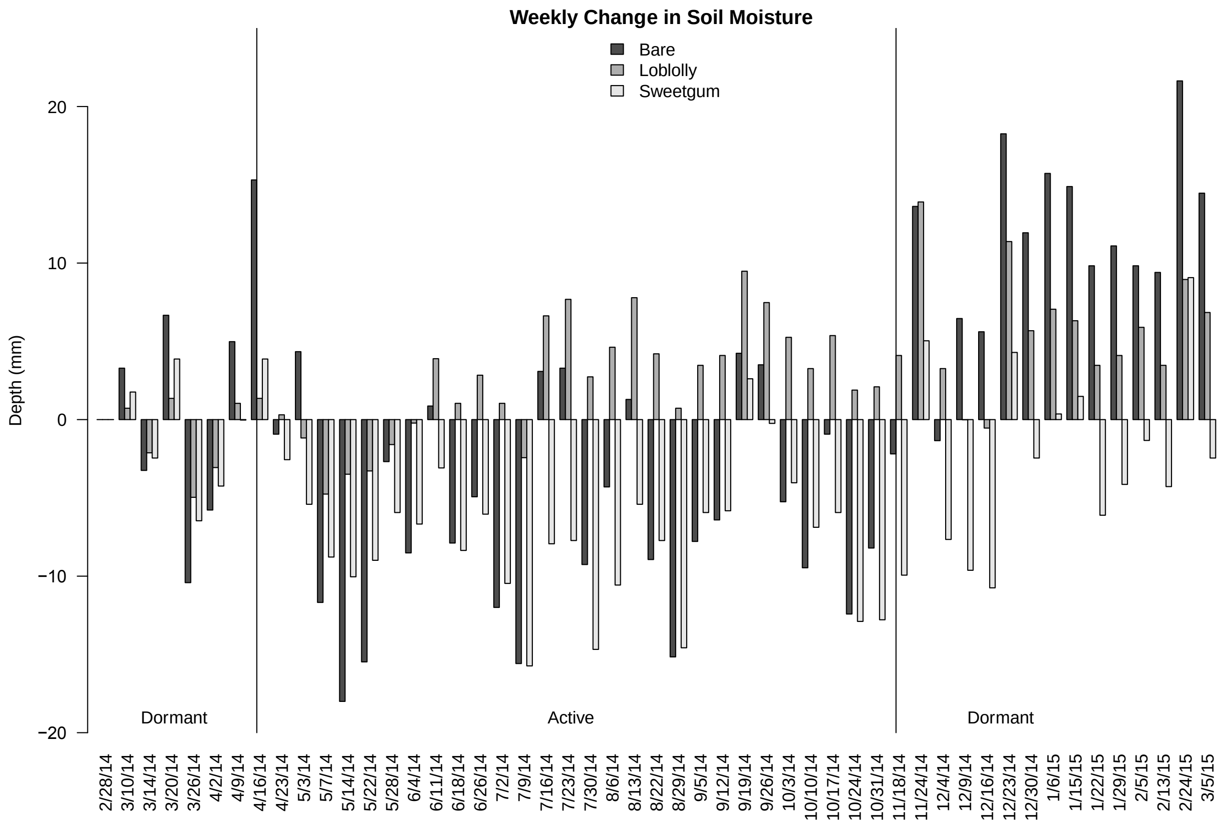

Figure 22. Weekly change in soil moisture storage within each box lysimeter.

In figure 22, the two bold vertical lines depict the active and dormant seasons. The data show how the storage of soil moisture varied with the seasons. The loss of soil moisture in the forested plots was likely dampened by the combination of forest cover along with the mulching effect of leaf litter, which is not present in the bare plot. The source of this variation in available soil moisture is a lack of near ground cover. In a bare plot, there is no shelter from the addition of energy from solar irradiance and the effects of wind speed on relative humidity. This is a direct cause of increased evaporation as the near surface potential evaporation rate remains high due to wind effects. Similarly, the latent heat of vaporization is achieved much faster and for a more prolonged period of time due to solar irradiance.

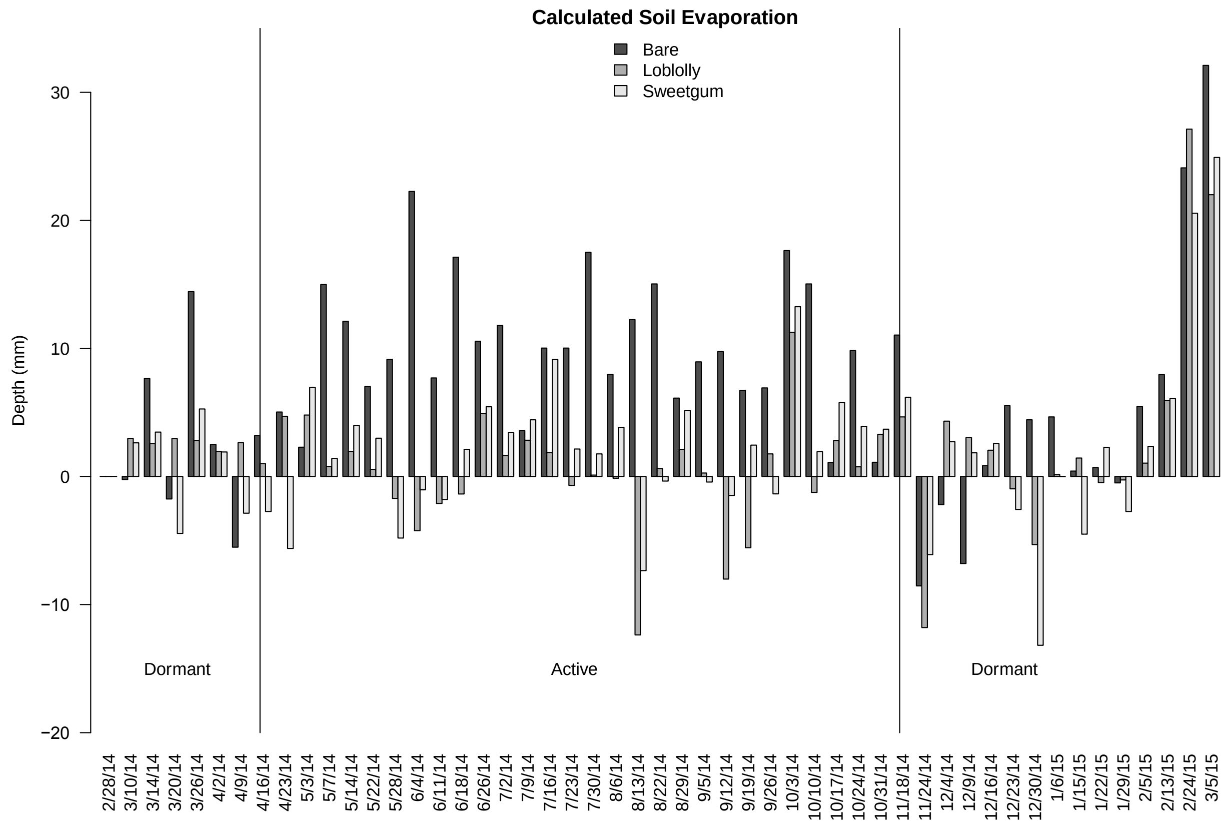

Figure 23. Result of our water balance equation for each plot.

Data for Figure 23, above, were calculated using precipitation or throughfall data, soil volumetric moisture data, and box lysimeter outflow data. A simple water balance equation involving all measured components from the experiment was used to find respective plot evaporation values. The figure shows seasonal effects on evaporation between the forested and bare plots. Of particular interest is the difference in height between the bare and forested plots, easily seen in the growing season when bare-soil evaporation rates are highest, is attributed to the volume of drainage through each box lysimeter. This would be equivalent to the volume of water gained to the forested watershed via infiltration. Using this information, we were able to measure evaporation for each species in each plot much more accurately than other previous studies have accounted for.

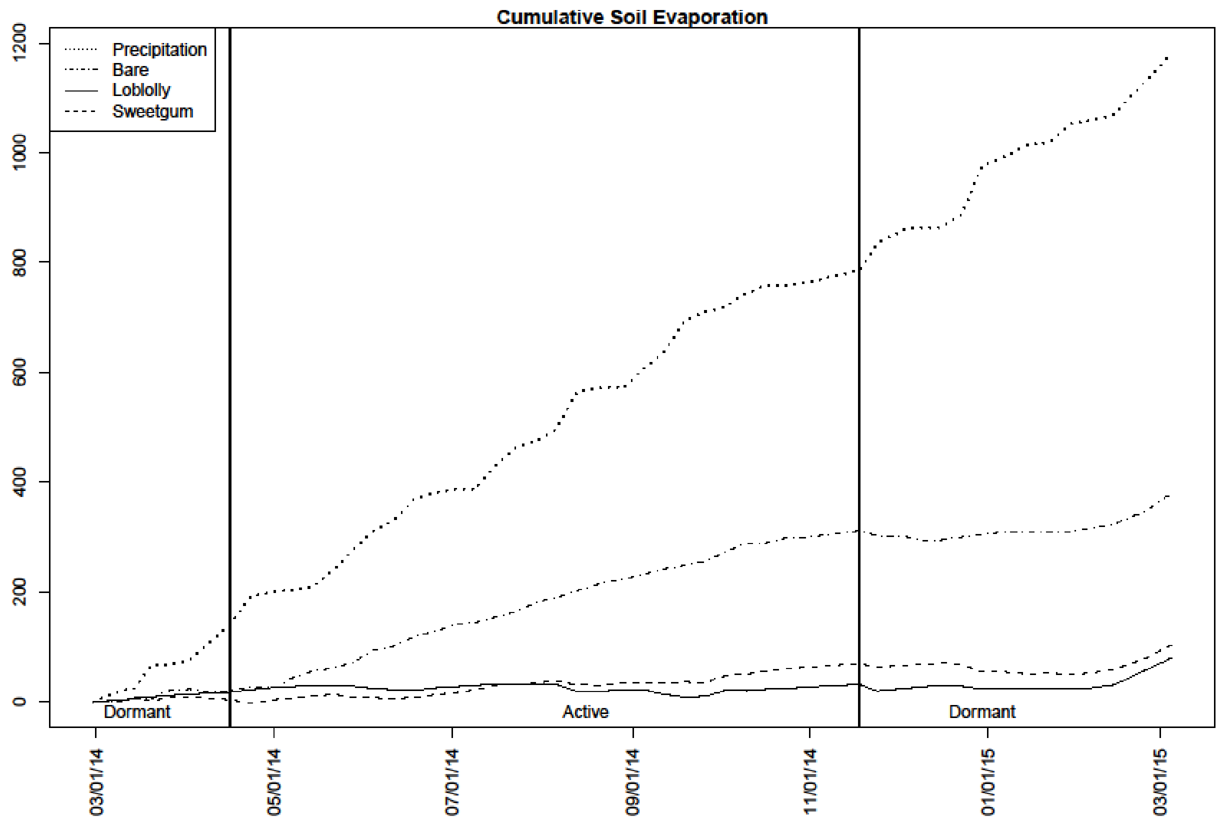

Figure 24. Cumulative changes of calculated evaporation (mm) within each plot using all measured data. The bold vertical lines represent the separation of dormant and active seasons.

Figure 24 displays the cumulative sum of the calculated evaporative data. Over the course of the experiment, very little loss was observed from either the sweetgum or the loblolly plots. The bare plot, on the other hand, demonstrated continual evaporative loss during the growing season. This loss eventually ceased over winter, before continuing an upward trend as the growing season began again. Precipitation remained relatively constant over the experiment. During this experiment, loblolly has lost 79.6 mm, or 7.6%, of precipitation to calculated evaporation. Sweetgum has lost 103.4 mm, or 9.8%, of precipitation to calculated evaporation. The bare plot has lost 379.2 mm, or 32.1%, of precipitation to calculated evaporation.

The graph above, Figure 24, resembles that of the DMC (Figure 21) in that the levels of evaporation in the sweetgum and loblolly plots both stay near each other, but also intersect in the growing season. Though the dates differ by roughly a month (7/30/14 and 9/5/15) they show that seasonal variation was clearly affecting the hydrologic systems here. The level of evaporation taking place during the dormant season when the sweetgum has no foliage was greater than the loblolly plot. The depth of throughfall in the sweetgum plots over that time period was also greater than for loblolly. As the temperature shifts, and the growing season continues, the greater basal coverage of the sweetgum reduced throughfall while evaporation rates increased in the loblolly plots in relation to sweetgum. Eventually, the decrease of evaporation in the sweetgum plot due to interception and reduction of solar irradiance allowed the increased rate of evaporation in the loblolly plots to again equal that of sweetgum.

Errors

During the course of the experiment, some probes became dislodged or damaged by debris or animal action (Table 10). Decagon® ECH2O probes are also listed with an accuracy of +/- 3%.

Table 11. Dates of error related to Decagon® VMC probes.

Plot in Block 3	**Dates in Question**	**Number of Functioning Probes**
Loblolly	2/28/14 – 3/31/15	All 4
Sweetgum	11/29/14 – 3/31/15	Only 3
Bare	5/7/14 – 5/28/14	Only 3
	12/1/14 – 3/31/15	Only 1

The tipping-bucket rain gauges also had wiring problems likely caused by animal damage. Block 2 precipitation were the average of Blocks 1 and 3 for the dates 2/28/14 through 4/23/14. The values for Block 3 precipitation were the average of Blocks 1 and 2 for the dates

5/14/14 through 6/18/14. Precipitation data from the Savannah River Site weather station was also used in the averaging.

For the double mass curve (Figure 21), we averaged the throughfall data from the three present collectors in each forested plot for the missing data from the collectors which were added later. This was for the timeframe of 3/10/14 to 4/9/14.

There was also the possibility of runoff from the surface of the box lysimeters where the soil was filled very near to the inside edge of the box. The loblolly lysimeter had 5.1-7.4 mm of space, but the sweetgum lysimeter had only 0.8-2.3 mm and the bare lysimeter had only 1.0-1.2 mm of space. During heavy precipitation events, it is possible that rainfall overflowed the surface capacity of the boxes.

CHAPTER 5

CONCLUSIONS

Freshwater demands are increasing, placing greater importance on basin water budgeting. Tree production for biofuel and paper pulp affects several components of the water budget in an area and any relative impact can be difficult to measure. With water budgeting being a fundamental aspect for evaluating the potential effects of land use change, accuracy in measurements are critical. This study investigated and quantified commonly overlooked aspects of a water budget; interception and soil evaporation. As a large component of calculations for the soil-water balance, evaporation is used in equations analyzing groundwater recharge, catchment stream flow, pasture production models, and crop irrigation scheduling. No known studies have considered the combination of these measurements among the expanse used in this experiment. This study was designed to highlight the distinct differences, if any, between loblolly pine stands and American sweetgum stands in terms of water use, soil evaporation, throughfall, and infiltration. Knowing the actual variation present between these two species of short rotation woody crop and how they change seasonally, gives researchers, planners, and foresters the ability to determine the best use of timberland in water sensitive areas.

The average volume of annual precipitation during this 53 week study was 1151 mm, between the 2014 annual value from NOAA of 1039 mm (Appendix C) and the long-term site average from Kilgo and Blake (2005) of 1225 mm. Interception between seasons among each species in each Block were found to not be significant from simple linear regression. Analysis of variance in block 2 by seasons returned loblolly intercepts 4% more precipitation than sweetgum annually. Analysis of variance of all blocks by seasons returned loblolly intercepts 3% more. . However, when all blocks were combined, the statistical analysis of variance (Table 9) showed a 0% difference in the throughfall between species over summer and a 7% difference in the throughfall between species over winter. A further analysis of linear regression using ordinary least squares with indicator variables returned that dormant loblolly intercepts 7.9% of precipitation, dormant sweetgum intercepts 5.7% of precipitation, and active plots intercept 12.8% of precipitation regardless of the species.

Overall, the significance of the seasonal variation among the species is important, but not as important as the presence of ground cover in general. The water lost to bare-soil evaporation observed in this study area was calculated to be 379 mm compared with 103 mm for sweetgum and 79 mm for loblolly. Even in the dormant season for sweetgum, the effect on leaf litter to restrict soil evaporation is impressive. The use of unvegetated lysimeter’s combined with measurements of soil moisture content allowed for the calculation of specific values assigned strictly to evaporation as well as the direct comparison to throughfall and infiltration.

Evaporation from a forested area differs greatly from that of open pasture or bare-soil. A forested area offers the ground shelter from intense and direct irradiance. It also prevents penetration of the interior by high winds which aid in higher evaporation rates. In maintained short rotation woody crop plantations such as those featured in this study, the ground cover is restricted to leaf litter. The leaf litter in this fashion acts as an impediment to water loss through a mulching effect, further protecting the soil water from evaporation. It is not just evaporative demand that determines evaporation rate. The rate and timing of rainfall, the soil properties and dynamics, and the age and type of vegetation also play important roles.

Further research should investigate stem flow differences between the species, but focusing on leaf structure and branch arrangement. Seasonal differences in loblolly interception exist the same as with deciduous trees. Loblolly experience a noticeable needle drop similar to the leaf-off period of sweetgum. It is also possible that the physical structure of the pine needle groupings allow for greater amounts of precipitation to be held by each branch and for directed stem flow along the bark. This would explain some of our findings with regard to leaf area index having little to no effect on interception between these two species. LAI should be measured in the winter to further quantify seasonal differences in interception. It may also be of interest to quantify needle drop within the stands.

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APPENDIX A

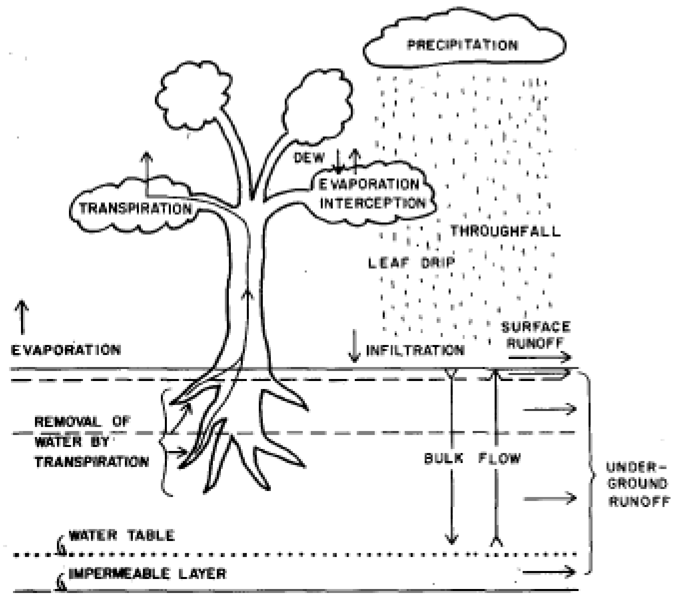

FIG. 1. Schematic of processes included in improved ground hydrology calculations.

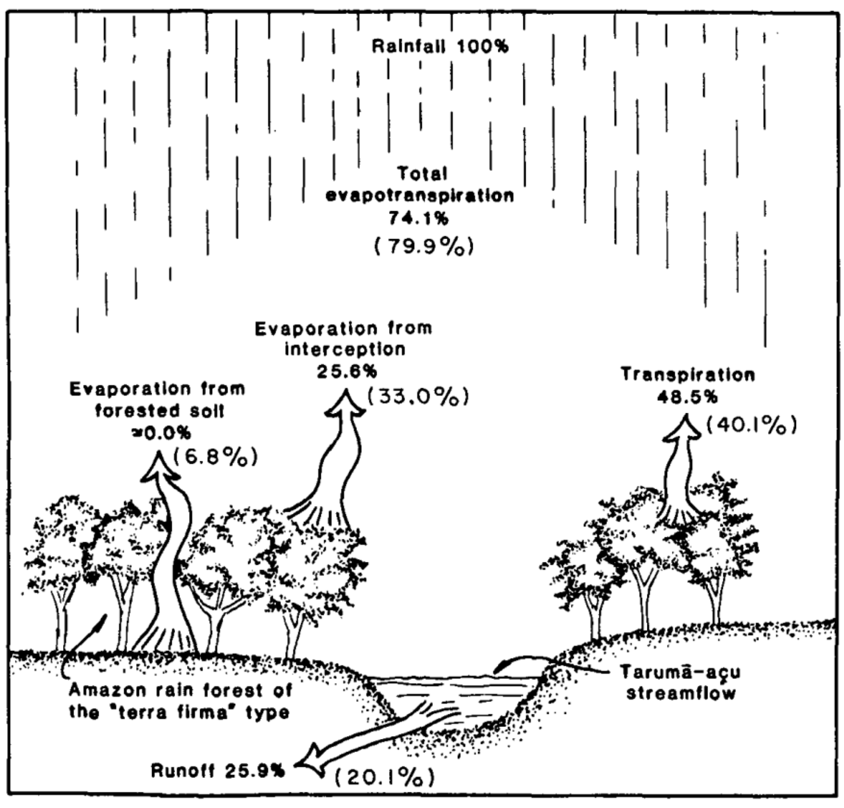

FIG. 17. Water balance from a study of a model basin near Manaus (Salati and Vose 1984). Water balance values for Brazilian rainforest from ground hydrology model are in parentheses.

APPENDIX B

TABLE 7-9
Annual Canopy Interception Loss as a Fraction of Gross Precipitation for Various Plant Communities

Latitude	Location	Community	Annual Pptn. (cm)[a]	Ec/*R*
	Tropics	Lowland forest		0.22
	Tropics	Montane forest		0.18
3.0	Manaus, Brazil	Amazonian rain forest	281	0.09
4.0	Malaysia	Lowland forest		0.23
5.9	Ivory Coast	Evergreen hardwoods		0.09
6.5	W Java	Lowland tropical rain forest		0.21
7.0	Ghana	Semideciduous moist forest		0.16
10.0	Nigeria	Forest-savannah boundary		0.05
11.3	Kottamparamba, India	Cashew	300	0.31
18.3	Mts., E Puerto Rico	Tabonuco et al.	575	0.42
18.3	Mts., E Puerto Rico	Dwarf forest		0.09
34.5	Mts., AR, U.S.	Pine-hardwood		0.13
35.0	W NC, U.S.	60-yr-old white pine	203	0.09
35.0	W NC, U.S.	Mixed hardwoods	203	0.12
35.0	W NC, U.S.	35-yr-old white pine	203	0.19
35.0	W NC, U.S.	10-yr-old white pine	203	0.15
42.2	S Is. New Zealand	Mixed evergreen hardwood	260	0.24
43.9	Mts., N NH, U.S.	Mixed hardwoods	130	0.13
~45.0	NW U.S.	Douglas fir		0.24
~45.0	NW U.S.	Douglas fir et al.		0.32
~45.0	NW U.S.	Sitka spruce-hemlock et al.		0.35
~45.0	NW U.S.	Mature Douglas fir		0.34
~45.0	NW U.S.	White pine-hemlock		0.21
~45.0	NW U.S.	Douglas fir-hemlock		0.24
51.4	SE U.K.	Corsican pine	79	0.35
51.4	Hampshire, U.K.	Hornbeam		0.36
51.4	Hampshire, U.K.	Douglas fir		0.39
51.4	Hampshire, U.K.	Oak		0.18
51.4	Hampshire, U.K.	Oak—defoliated		0.12
51.4	Hampshire, U.K.	Norway spruce		0.48
51.4	Hampshire, U.K.	Corsican pine		0.35
52.3	Norfolk, U.K.	Scots & Corsican pine	60	0.36
52.5	Wales, U.K.	Sitka spruce	187	0.27
52.5	Castricum, Holland	Oak forest	31	0.22
55.0	S Scotland, U.K.	Sitka spruce	160	0.30
55.0	Northumberland, U.K.	Sitka spruce—mature	100	0.49
55.0	Northumberland, U.K.	Sitka spruce—pole timber	100	0.29
55.2	S Scotland, U.K.	Sitka spruce	97	0.32
56.4	Scotland, U.K.	Sitka spruce	213	0.28
57.7	NE Scotland, U.K.	Scots pine	64	0.42
58.3	SE AK, U.S.	Hemlock-Sitka spruce		0.25

[a] Annual precipitation during period of measurement or climatic average, as given in source.
Data from published sources.

APPENDIX C

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Environmental Satellite, Data, and Information Service

Annual Climatological Summary
(2014)
Generated on 10/01/2015

National Centers for Environmental Information
151 Patton Avenue
Asheville, North Carolina 28801

Elev: 542 ft. Lat: 33.550° N Lon: 81.697° W
Station: **AIKEN 2 E, SC US COOP:380072**

Date	Temperature (F)														Precipitation (inches)									
Elem->	MMXT	MMNT	MNTM	DPNT	HTDD	CLDD	EMXT		EMNT		DT90	DX32	DT32	DT00	TPCP	DPNP	EMXP		TSNW	MXSD		DP01	DP05	DP10
Month	Mean Max.	Mean Min.	Mean	Depart. from Normal	Heating Degree Days	Cooling Degree Days	Highest	High Date	Lowest	Low Date	Number Of Days Max >=90	Max <=32	Min <=32	Min <=0	Total	Depart. from Normal	Greatest Observed Day	Date	Snow, Sleet Total Fall	Max Depth	Max Date	Number Of Days >=.10	>=.50	>=1.0
1	50.7	28.2	39.5		784	0	66	21	10	07	0	3	19	0	2.97		1.83	11	2.0X			6	1	1
2	61.3X	37.0X	49.1			0	80	22	19	01	0	0	6	0	3.98A		0.39	27	0.0			4	0	0
3	61.4X	38.3X	49.8			0	79	12	26	05	0	0	8	0	3.02A		1.22	17	0.0			5	3	1
4	77.5X	50.5X	64.0				86	28	35	17	0	0	0	0	4.87A		1.45	15	0.0			5	2	2
5	85.8X	61.3X	73.5				93	25	49	16	11	0	0	0	4.03X		1.20	16	0.0			6	3	2
6	89.5	68.1	78.8		0	419	96	21	55	03	16	0	0	0	3.20		1.02	12	0.0			5	4	1
7	90.6X	70.1X	80.4		0		98	10	66	30	18	0	0	0	2.04A		0.63	22	0.0			5	1	0
8	89.5X	68.7X	79.1		0		98	24	64	28	17	0	0	0	1.62A		0.61	03	0.0			3	1	0
9	82.5	65.7	74.1		5	284	95	05	53	25	6	0	0	0	6.22		1.63	17	0.0			10	4	2
10	78.5	52.7	65.6		81	107	88	12	41	05	0	0	0	0	0.53		0.37	15	0.0			2	0	0
11	60.5	36.5	48.5		486	0	77	13	20	20	0	0	10	0	3.81		1.03	23	0.0			8	4	1
12	60.1X	37.1X	48.6			0	72	06	18	13	0	0	5	0	4.62A		2.50	24	0.0			4	2	2
Annual	74.0*	51.2*	62.6		1356*	810	98	Aug	10	Jan	68*	3*	48*	0*	40.91		2.50*	Dec*	2.0*			63*	25*	12*

Notes

(blank) Data element not reported or missing.

+ Occurred on one or more previous dates during the month. The date in the Date field is the last day of occurrence. Used through December 1983 only.

A Accumulated amount. This value is a total that may include data from a previous month or months or year (for annual value).

B Adjusted total. Monthly value totals based on proportional available data across the entire month.

E An estimated monthly or annual total.

X Monthly means or totals based on incomplete time series. 1 to 9 days are missing. Annual means or totals include one or more months which had 1 to 9 days that were missing.

T Trace of precipitation, snowfall, or snowdepth. The precipitation data value will equal zero.

Elem Element types are included to provide cross-reference for users of the NCDC CDO system.

Station Station is identified by: COOP ID, Station Name, State

S Precipitation amount is continuing to be accumulated. Total will be included in a subsequent monthly or yearly value. Example: Days 1-20 had 1.35 inches of precipitation, then a period of accumulation began. The element TPCP would then be 00135S and the total accumulated amount value appears in a subsequent monthly value.

* Annual value missing; summary value computed from available month values.