Canopy Rainfall Interception Measured over Ten Years in a Coastal Plain Loblolly Pine (*Pinus taeda* L.) Plantation

evapotranspiration monitoring & modeling in multiple land uses

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Abstract. *The area of planted pine in the southern U.S. is predicted to increase by over 70% by 2060, potentially altering the natural hydrologic cycle and water balance at multiple scales. To better account for potential shifts in water yield, land managers and resource planners must accurately quantify water budgets from the stand to the regional scale. The amount of precipitation as rainfall intercepted by forest canopies is an important component of evapotranspiration in forested ecosystems, yet there is little information about intra- and inter-annual canopy interception variability in southern pine plantations. To address this knowledge gap, canopy rainfall interception was measured between 2005 and 2014 in a North Carolina coastal plain loblolly pine (*Pinus taeda *L.) plantation to quantify the range of annual and seasonal variability in interception rates (IRs) as influenced by stand thinning and natural variation in rainfall rates and intensities. Over the study period, biweekly measured canopy IRs averaged 19% across all years, with a range of 14% to 23%. However, at the annual scale, IRs averaged 12% and ranged from 2% to 17%. Thinning resulted in a 5% decrease in rainfall interception, but IRs quickly returned to pre-thin levels. Across years, the amount of annual rainfall intercepted by the canopy averaged 15% of total evapotranspiration, with a range of 2% to 24%. The decade-long data indicate that inter-annual variability of canopy interception is higher than reported in short-term studies. Local and regional hydrological models must describe the variability of canopy interception to accurately predict the hydrologic impacts of forest management and climate change.*

Keywords. *Canopy interception, Evapotranspiration, Loblolly pine,* Pinus taeda*, Throughfall.*

Forest ecosystems intercept precipitation via foliage, branches, stems, and forest floor litter. Rainfall interception is recognized as a fundamental component of the forest hydrologic cycle and as a critical parameter when estimating total ecosystem evapotranspiration (ET) and developing water balances at stand to watershed scales (McCarthy et al., 1991; Xiao et al., 2000; Sun et al., 2002). Therefore, the development of robust hydrologic models must include accurate estimates of canopy interception rates to allow for partitioning of rainfall between ET and runoff (Wang et al., 2007; Pitman et al., 1990).

Rainfall (R) can be partitioned into canopy interception (I), throughfall (TF, the amount of rainfall that falls through the canopy and reaches the forest floor), and stemflow (the amount of rainfall that falls through the canopy and down the stems of trees). Canopy interception is often estimated as the difference between total rainfall and throughfall since stemflow is often small (<5% of precipitation). Forest canopy interception rate (IR) is the ratio of canopy interception divided by total rainfall measured above the canopy at certain time intervals. Interception rates (IRs) are influenced by meteorological conditions such as wind speed and direction, evaporation rate, rainfall rate and duration, and canopy structure, which is influenced by vegetation composition and age (Horton, 1919; Helvey, 1974; Crockford and Richardson, 2000).

In the early 20th century, Horton (1919) presented one of the first detailed analyses of rainfall interception across species and found that conifers intercepted more rainfall than hardwoods, but only hardwoods exhibited seasonal differences. The percentage of rainfall intercepted decreased as rainfall rate increased. The storage capacity of foliage was between 0.5 to 1.8 mm per storm. Interception rates averaged 25% during heavy rains of long duration but could be as high as 100% during light rainfall events when total rainfall did not exceed the storage capacity.

Studies since Horton (1919) have confirmed the early

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basic understanding of factors that influence interception rates. While rates have exhibited high variability between and across species, the spruce-fir-hemlock forest type has been shown to have the highest canopy IR, followed by pines and then hardwoods (Helvey, 1974). The difference between hardwood and conifer forest IRs has important management implications. Delfs (1967) reported higher streamflow rates in beech (*Fagus* sp.) versus spruce (*Picea* sp.) dominated watersheds, and Swank and Miner (1968) found that reductions in streamflow could be attributed to greater rainfall interception following the conversion of a hardwood watershed to white pine (*Pinus strobus* L.).

Helvey and Patric (1965) summarized canopy IRs for hardwood forests in the eastern U.S. and found that summer rates ranged from 8% to 33%, with a mean of 17%, and winter rates ranged from 5% to 22%, with a mean of 12%. In western Georgia, Bryant et al. (2005) measured annual IRs of 18% for wetland sites, 20% for hardwood sites and a longleaf pine (*Pinus palustus* Mill.) plantation, and 23% for pine-dominated forests. In a summary of conifer forests in the U.S., Helvey (1974) reported annual canopy IRs of 17% for red pine (*Pinus resinosa* Ait.), 16% for ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws.), 19% for eastern white pine, and 28% for the spruce-fir-hemlock forest type.

In one of the first studies to examine IRs in loblolly pine forests, Hoover (1953) found that annual canopy interception was approximately 28% of total rainfall. Later research showed that annual canopy IRs in unthinned stands were influenced by stand age and basal area and ranged from 14% to 28% (Rogerson, 1967; Swank et al., 1972; McCarthy et al., 1991). Reducing basal area and subsequent leaf area through thinning has been shown to decrease canopy interception by 3% to 14% (Rogerson, 1967; McCarthy et al., 1991). Canopy IRs for individual storm events are often not reported, but in a hydrologic balance study on drained wetlands, McCarthy et al. (1991) estimated that IRs during individual storms ranged from 10% to 35% and from 5% to 25% for unthinned and thinned loblolly pine stands, respectively.

The southern U.S. produces more timber than any other region in the U.S. or country in the world, with planted pine comprising over 15 million ha (Wear and Greis, 2012). The Southern Forest Futures Project estimates that this acreage could grow by over 70% by 2060 even though the total forest area in the southern U.S. is expected to decrease (Wear and Greis, 2012). This increased demand for planted pine could have a significant impact on the hydrologic cycle due to the intensive management practices often employed in pine plantation silviculture. This is especially true in the southeastern coastal plains, where planted pine plantations are most common (Wear and Greis, 2012). Forest management activities that increase pine productivity such as fertilization, ditching, bedding, and thinning have been associated with reduced infiltration and increased nutrient export, flow events, and drainage (Richardson and McCarthy, 1994; Lebo and Herrmann, 1998; Amatya and Skaggs, 2001; Sun et al., 2002; Checheir et al., 2003; Sun et al., 2010).

Loblolly pine (*Pinus taeda* L.) is the primary species employed in southern pine plantation management. Due to its economic importance, management implications such as growth, yield, genetic improvement, and carbon sequestration potential have been well studied (Shultz, 1997; Johnsen et al., 2004). However, the hydrological impacts of plantation management are not well understood (Amatya and Skaggs, 2001; Domec et al., 2009; Sun et al., 2010). The potential for droughts and altered rainfall patterns and intensities under a changing climate necessitates further study of rainfall partitioning in plantation forests to improve hydrologic modeling and efficiency. While research has been conducted on loblolly pine plantation canopy IRs, there has been little examination of their intra- and inter-annual variability and the influence of management on interception rates. This article presents the findings from ten years (2005 to 2014) of throughfall data collection in a coastal plain loblolly pine plantation and estimates the contribution of canopy interception to annual ET estimates.

MATERIALS AND METHODS

This research was conducted in the lower coastal plain near the town of Plymouth, North Carolina. Locally known as Weyerhaeuser's Parker Tract, the study area is located at 35° 48′ N and 76° 40′ W in the outer coastal plain mixed forest province (Bailey, 1980). Annual precipitation, almost entirely in the form of rainfall, averages approximately 1321 mm (1945 to 2014), with a high of 1845 mm and a low of 854 mm (NCDC, 2014). The study area is a 90 ha loblolly pine plantation, planted in 1992 at an estimated planting density of 1400 trees ha^{-1} (TPH) and managed for timber production. The soil type is classified as a Belhaven series histosol and characterized by deep, well drained organic soil. The water table is managed with a perimeter ditch and a series of open field ditches approximately 90 m apart that drain the watershed through an outlet weir. Detailed descriptions of the site and associated research in water quality, hydrology, and carbon, water and energy fluxes are found in Checheir et al. (2003), Domec et al. (2009), Noormets et al. (2010), and Sun et al. (2010).

Eddy fluxes and canopy interception measurements at the study site began in 2005 when the stand was 13 years old, stand density was 655 TPH, and site index was approximately 70 (Amateis and Burkhart, 1985). The stand was thinned in 2009 to remove approximately 50% of the basal area by removing every fourth row and selectively thinning from the remaining rows. Mean stand basal area for woody plants greater than 2.5 cm diameter at breast height was 34.2 m^2 ha^{-1} before the thin and 14.9 m^2 ha^{-1} afterward. Mean loblolly pine height and percent of the total basal area were approximately 16.5 m and 95%, respectively, before and after the thin. The remaining stand basal area was composed primarily of red maple (*Acer rubrum* L.). The understory biomass before and after the thin was dominated by red maple, blackberry (*Rubus* spp.), grape vine (*Vitis* spp.), and giant cane (*Arundinaria gigantean* (Walter) Muhl.). The number of understory stems per hectare decreased by 40% immediately after the thinning but has increased by approximately 60% per year since.

Precipitation was measured using a TE525 tipping-bucket rain gauge (TBRG) (Campbell Scientific, Inc., Logan, Utah) mounted above the forest canopy on a fixed scaffold tower. Precipitation was recorded during each rainfall event and summed every 30 min using a CR5000 datalogger (Campbell Scientific, Inc., Logan, Utah). An RG-2 tipping bucket (Onset Computer Corp., Bourne, Mass.) was also installed 2 m from the TE525 to act as a backup and early indicator of equipment error. Gaps in data from the TE525 were filled with data from the RG-2 tipping bucket. When precipitation data were not available for either instrument, such as during a five-month period when the tower blew over during Hurricane Irene in August 2011, data from a micrometeorological research station approximately 4 km away were used for gap filling.

Throughfall was measured using Stratus 6330 manual rain gauges (MRG) (Scientific Sales, Inc., Lawrenceville, N.J.) mounted 1 m above the ground. Ten MRGs were installed 3 m apart along a transect perpendicular to the planted pine rows, and throughfall was collected weekly to biweekly during site visits. Prior to stand thinning, the canopy was nearly closed based on ocular estimates, and all of the MRGs were under varying degrees of canopy cover. Following thinning, the MRG design resulted in eight of the MRGs being under some degree of canopy cover, and two of the MRGs having no canopy cover directly above. However, rainfall from an angle of more than few degrees would have been at least partially intercepted by the canopy. The post-thin MRG design was in general agreement with the post-thin stand conditions where every fourth row had been removed, leaving four MRGs in thinned areas for every one MRG within a gap. TBRG data were aggregated to the MRG measurement periods. Precipitation data from the micrometeorological station 4 km from the site and the National Climate Data Center's Plymouth weather station, located approximately 8 km from the tower, were also aggregated to the MRG measurement periods to assess the influence of different precipitation data sources on estimated throughfall rates.

To assess the annual contribution of I to ET, ET was calculated using the eddy covariance method from 2006 to 2009 and the watershed balance method from 2010 to 2013. Two separate methods of ET estimation were necessary due to missing measurement components needed by each method to cover the entire range of the study period. For example, gaps in data from the eddy covariance tower prevented a complete estimate of ET after 2009, and streamflow data were missing before 2010 to estimate ET using the watershed balance equation. While using only one approach to calculate ET was the preferred method, Domec et al. (2012) and Tian et al. (2015) showed that differences are small (<5%) between the two methods at the seasonal and annual scales.

Annual eddy covariance based ET estimates were derived from canopy latent heat fluxes measured in the middle of the watershed. A more detailed explanation of how the data were processed can be found in Noormets et al. (2010), Sun et al. (2010), and Domec et al. (2012). Annual ET estimates from the watershed balance method were calculated using the following equation:

$$ET = R - Q + WS \tag{1}$$

where ET is stand evapotranspiration (mm), R is total rainfall (mm), Q is total drainage flow (mm), and WS is the change in water storage (mm).

Drainage outflow (Q) from the stand was measured at the outlet weir using an ultrasonic datalogger (Infinities USA, Port Orange, Fla.) to record the water level every 12 min above a 120° V-notch and calculated with the following equation from Grant and Dawson (2001):

$$Q = 0.1225H^{2.5} \tag{2}$$

where Q is flow rate ($m^3\ s^{-1}$), and H is the height of the water stage above the V-notch (m).

Changes in water table depth and soil moisture content were used to calculate annual changes in soil water storage (Sun et al., 2010). The groundwater table depth was measured every 30 min in the center of the site between two drainage ditches by mounting an ultrasonic datalogger (Infinities USA, Port Orange, Fla.) on top of a PVC well. Soil moisture content was measured every 30 min with two 30 cm CS616 water content reflectometers (Campbell Scientific, Inc., Logan, Utah) inserted vertically into the soil profile. In 2010, five more CS616 water content reflectometers were installed horizontally into the soil profile at 10, 20, 40, 60 and 80 cm. Repeated measures analysis of variance was used to analyze time series data with an autoregressive covariance structure and Bonferroni adjustment (PROC MIXED; SAS Institute, Inc., Cary, N.C.). Means were considered significantly different if $p < 0.05$.

RESULTS AND DISCUSSION

CANOPY INTERCEPTION AS A FUNCTION OF RAINFALL

Annual canopy IR as a function of total annual rainfall and total annual throughfall averaged 12% and ranged from 2% to 17% (table 1). These rates were lower than expected, and an analysis of the aggregated data indicated that throughfall exceeded rainfall during a few measurement periods. This result has also been reported in previous studies (Horton, 1919; Valente et al., 1997; Abrahamson et al., 1998; Crockford and Richardson, 2000; Chang, 2013) and is likely caused by equipment errors (in the case of the tipping buckets installed above the tree canopy), human error when recording throughfall, canopy characteristics, or natural variability in rainfall amounts around the area.

To better quantify intra- and inter-annual canopy interception, IR was calculated for each measurement period, and measurement records were removed from the analysis whenever TF exceeded R, thereby removing negative IRs. Using this approach, the average annual IR across measurement periods was 19% and ranged from 14% to 23% (table 1); however, the effect of year on IR was not significant ($p = 0.055$). The IR in the years preceding the thin averaged 18% and ranged from 14% to 23%. The year following the thin, IR decreased by 5%, or 4% based on the average of all five pre-thin years. The 5% reduction in IR following thinning was similar to the 8% reduction reported by McCarthy et al. (1991) in a similar aged loblolly pine plantation following thinning. The mean IR two years post-thin and forward averaged 20%, with a range of 16% to 22%. The high variability in IR within and between years was likely due to natural variability in rainfall rates and intensities, as well as changes

Table 1. Stand characteristics and canopy interception rates based on annual and measurement period means.

						Canopy Interception Rate (%)		
Year[a]	Basal Area[b] (m^2 ha^{-1})	No. of Trees[b] (ha^{-1})	LAI[c] max/min (m^2 m^{-2})	Rainfall (mm)	Throughfall (mm)	Annual Mean[d]	Measurement Period Mean[e]	Measurement Period Range
2005	27	655	3.9/2.4	1206	1062	12	23 (3)	4 to 51
2006	29	650	4.0/2.7	1425	1216	15	21 (2)	7 to 100
2007	31	624	4.3/2.8	897	825	8	14 (3)	1 to 37
2008	33	624	4.3/2.9	1016	891	12	14 (3)	2 to 35
2009	34	630	4.3/1.2	1326	1306	2	19 (4)	2 to 67
2010	15	400	1.8/1.2	1422	1225	14	14 (3)	0 to 40
2011	17	631	1.7/1.1	1307	1119	14	22 (3)	9 to 47
2012	18	1009	2.9/1.5	1328	1200	10	16 (3)	1 to 40
2013	20	1686	3.8/1.7	1270	1052	17	21 (3)	3 to 57
2014	23	2140	4.1/1.9	1071	895	16	22 (3)	9 to 32
Mean[e]				1227	1079	12 (1)	19 (1)	

[a] Measurements began in May 2005.

[b] Calculated from all trees >2.5 cm diameter at breast height.

[c] Leaf area index (LAI) measured with an LAI2000 Plant Canopy Analyzer (LI-COR Biosciences, Lincoln, Neb.): max = maximum LAI during the growing season, and min = minimum LAI during the dormant season.

[d] Annual mean calculated as 100 × (total annual rainfall – total annual throughfall) / total annual rainfall.

[e] Values in parentheses are standard errors of the mean.

in leaf area index throughout each year.

The annual IRs as a function of TPH compared reasonable well with other studies in loblolly pine stands, and the IRs associated with the lowest and highest TPH in this study corresponded very well with the regression line developed from other studies (fig. 1). The poor fit of the regression line through the other studies ($R^2 = 0.46$) indicates a high level of variability between TPH and IR. Little research was found in the literature that reported multi-year IRs in loblolly pine plantations, and this study shows that annual variability can be high (14% to 22%) despite minimal variability in annual tree density. While the results from this study initially indicated that IRs were low compared to IRs reported elsewhere, figure 1 shows that our estimates may be higher when based on TPH alone. The results also highlight the important role that land managers have in manipulating water availability through management and vegetation control. Decreasing TPH, and by association leaf area, results in lower ecosystem IRs and higher water availability. While decreased IRs may only last a year or two, the potential for flooding and runoff may increase and lead to decreased water quality in affected areas. Conversely, appropriately designed channels of managed water flow could allow land and water resource managers to increase water availability to areas experiencing water stress and better manage increases in water supply.

Canopy IR as a percentage of R has been shown to follow a logarithmic relationship in which IR decreases with increasing R (Horton, 1919; Hoover, 1953; Crockford and Richardson, 1990). When the data in this study were plotted across all years, there was a poor but significant relationship ($R^2 = 0.14$, $p < 0.001$), with the low R^2 likely due to using data from measurement periods that predominantly included multiple rain events of varying intensities and amounts (fig. 2). By aggregating data to measurement periods, the relationship between R and IR was likely underestimated in some cases and overestimated in others.

To better assess this relationship, throughfall data from multiple rainfall events were removed from the analysis so that only measurement period data with one rainfall event were included. A rainfall event was defined as a period of rain followed by at least 6 h with no measurable rainfall (Swank et al., 1972). This restriction resulted in a much

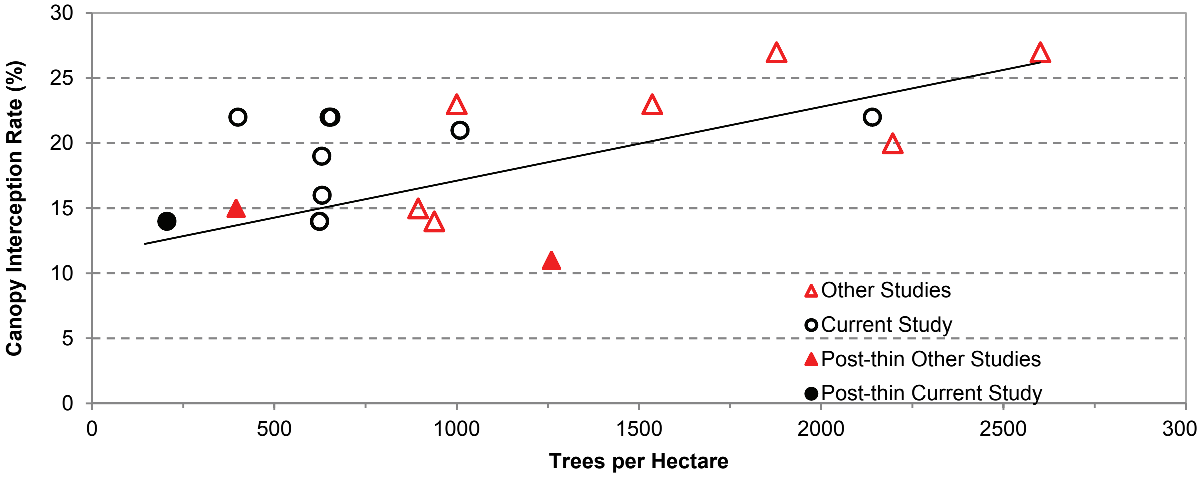

Figure 1. Canopy interception rates as a function of trees per hectare reported for loblolly pine in this study and by Hoover (1953), Rogerson (1967), Swank et al. (1972), McCarthy et al. (1991), and Abrahamson et al. (1998). Trend line applies to other loblolly pine studies only (R^2 = 0.46)

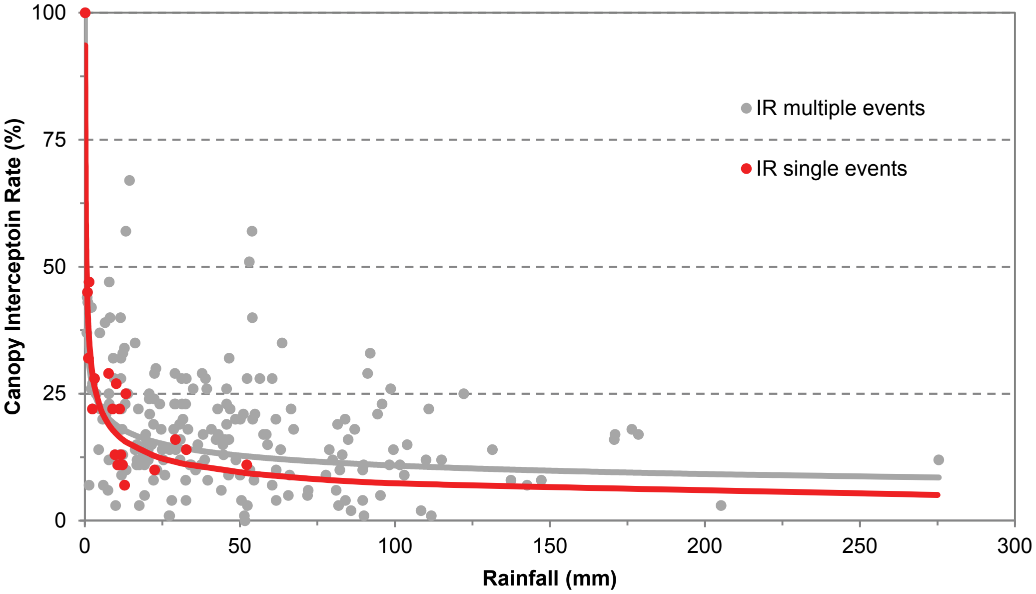

Figure 2. Canopy interception rates as a percentage of rainfall across all years for multiple rainfall events during a measurement period (gray) and only one rainfall event during a measurement period (red). The trend line for single rain event IRs ($R^2 = 0.78$) was extended beyond the last measured data point to better contrast with the trend line for multiple rainfall event IRs ($R^2 = 0.10$).

smaller dataset ($n = 21$) but a stronger logarithmic relationship ($R^2 = 0.78$, $p < 0.001$) between R and IR that can be expressed as:

$$\log(\mathrm{IR}) = 3.69 - 0.37\,\log(\mathrm{R}) \qquad (3)$$

where log(IR) is the natural log of the interception rate (%), and log(R) is the natural log of rainfall (mm). To eliminate bias when back-transforming the logarithmic predictions, a correction factor, as described by Sprugel (1983), should be applied as:

$$\log(\mathrm{IR}_{\mathrm{corrected}}) = \log(\mathrm{IR}) \times 1.06 \qquad (4)$$

While this approach resulted in a stronger relationship based on the R^2 values, the two curve fits are very similar. Both produce a steep decline from an IR of 100% to 22% during the first 5 mm of rainfall. When R reaches 10 mm, the IRs begin to stabilize around 18% and decrease approximately 1% for every additional 5 mm of R. For rainfall events greater than 10 mm, the IR estimated from multiple measurement periods remains approximately 2% to 3% higher than the IR measured from single rain events. The curves have a steeper initial slope than those reported in the literature but agree with the lower IRs reported in this study.

Pooled measurement period canopy throughfall and rainfall were strongly related (fig. 3; $R^2 = 0.98$, $p < 0.001$) and can be estimated as:

$$\mathrm{TF} = 0.88\mathrm{R} - 1.27 \qquad (5)$$

where TF is canopy throughfall (mm) and R is rainfall (mm).

The strong linear relationship was expected, as Rogerson (1967) found that R was the only significant variable correlated with TF, and Swank et al. (1972) found that gross R accounted for 98% to 99% of the variation in TF. The slope of the regression (0.88) was similar to the slopes reported by Rogerson (1967) but higher than those reported by Hoover (1953) and Swank et al. (1972). Annual regression slopes ranged from 0.87 to 0.93 before the thin and from 0.82 to 0.95 after the thin. Variability around the mean was lowest up to approximately 50 mm of rainfall, after which TF variability increased as measurements became more scattered about the mean. Some of this variability was likely due to the increased variability associated with larger storm events of varying intensities and durations. Heavy storms of short duration and light storms of long duration will have high spatially variability. Solving equation 5 for TF = 0 resulted in an estimated canopy storage capacity equal to 1.44 mm of R and indicated that canopy throughfall will not occur during events that produce less than 1.45 mm of rainfall. This estimate is just slightly higher than the average storage capacity of 1.35 mm reported by McCarthy et al. (1991) for thinned and unthinned coastal plain loblolly pine plantations.

SEASONAL CANOPY INTERCEPTION

The mean dormant season (October through March) IR was 21% and significantly greater ($p = 0.015$) than the mean growing season (April through September) IR of 17% (fig. 4). Mean dormant and growing season IRs ranged from 11% to 33% and from 10% to 23% across all years, respectively. While there was some variability across seasons, adding year to the model showed that there was no significant interaction ($p = 0.241$), so tests between individual seasons were ignored. Higher measured IRs during the dormant season compared to the growing season was a surprising result, as the opposite trend was expected. Pre-thin leaf area was approximately 35% lower during the dormant season than during the growing season on this site, so it seemed reasonable that IRs would also be lower. While higher growing season IRs have been reported in hardwood forests, results have been inconclusive in loblolly pine and other conifer forests (Hoover, 1953; Helvey and Patric, 1965; Helvey, 1974; Bryant et al., 2005). The 2009 dormant season IR of 11% was the lowest dormant season IR measured and likely resulted

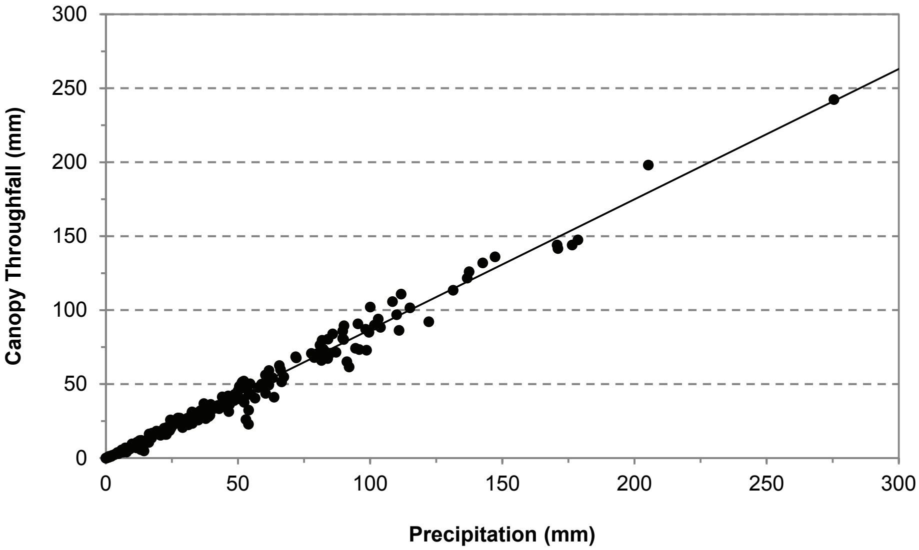

Figure 3. Relationship between pooled measurement period rainfall and canopy throughfall ($p < 0.001$).

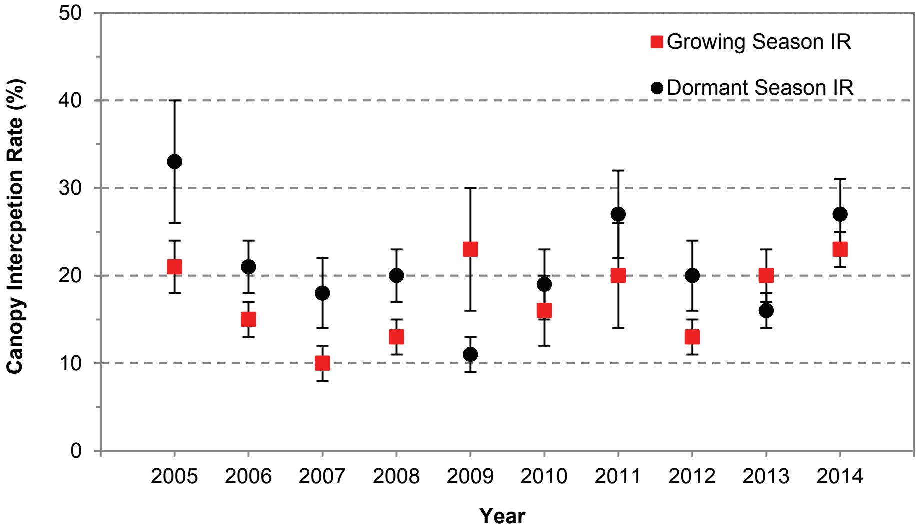

Figure 4. Growing and dormant season loblolly pine canopy interception rates over ten years in a coastal plain loblolly pine plantation. The growing season is April through September, and the dormant season is October through the next year's March. Vertical bars are standard errors of the mean. For the 2005-2014 growing season measurement periods, n = 16, 17, 14, 14, 8, 12, 6, 11, 14, and 12, respectively. For the 2005-2014 dormant season measurement periods, n = 12, 13, 11, 10, 12, 10, 7, 11, 10, and 8, respectively.

from the 2009 fall thinning.

A least part of the reason for the lack of significant differences between individual years and seasons is likely the higher variability recorded for TF by the manual rain gauges during the growing season. The standard deviation between these gauges was much higher during the growing season compared to the dormant season (fig. 5) and was likely due to heavier, more intense rainstorms during the growing season. Heavy spring and summer storms with greater spatial variability in rainfall are typical of coastal plain weather patterns (Bosch et al., 1999; Robinson and Fishel, 2006). A Brown-Forsythe test was conducted to determine if the variance between MRG measurements was equal, and the results indicated that both seasons exhibited heteroscedasticity ($p < 0.001$). Based on the regression line and variance of predicted values for each season, the MRG data had unequal variances, and the dormant and growing season variance splits occurred at approximately 25 and 37 mm of R, respectively.

Increases in both climate variability and extreme weather events have been proposed as likely scenarios in future climate forecasts. Under these conditions, land and water resource managers will need a thorough understanding of the hydrologic cycle and its component parts to better predict water availability and use. This study has shown that there is already high inherent variability in IRs within and between years under current climate conditions. It is important that land and water resource managers understand and consider this variability when making decision that impact hydrologic budgets, as overestimation of IRs can lead to flooding and underestimation of IRs can lead to water stress.

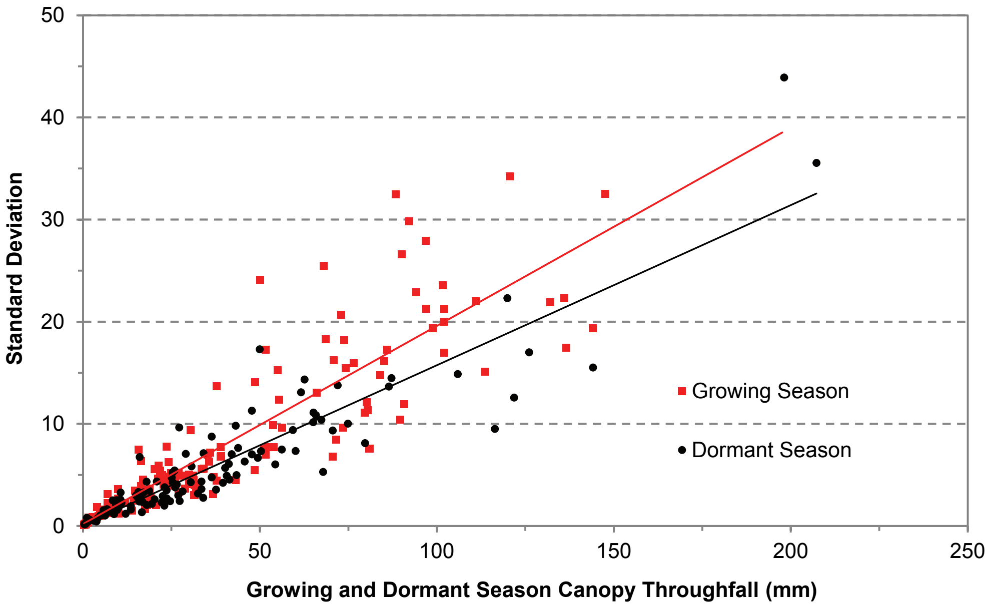

Figure 5. Growing and dormant season mean canopy throughfall and standard deviations between manual rain gauges for each measurement period over ten years in a coastal plain loblolly pine plantation.

Canopy Interception as Influenced by Calculation Method and Rainfall Data Source

The mean annual IR and the range of IRs across years was influenced ($p < 0.001$) by the method used to calculate IRs and the source of rainfall data (table 2). The lowest annual IR was 2% when subtracting total annual TF from total annual R. As stated earlier, the data used in this calculation included pooled measurement period events in which TF exceeded R, and this contributed to a lower annual IR. Measurements in which TF exceeded R, while not uncommon in the literature, indicate that we may not have captured the variability in R patterns around the MRGs and underestimated R. Since these events mostly occurred during the growing season, it has been proposed that TF amounts could have been inflated due to pooling and redirecting of TF along leaves of the deciduous understory. While not tested, the highest measured TF during the summer measurement periods were often recorded beneath areas with a dense deciduous understory.

When the difference between annual R and TF (site: annual mean) were used to calculate annual IRs, there was no significant difference ($p = 0.117$) compared to using annual measurement period means from the site. IRs using both methods from the site were significantly lower ($p \leq 0.032$) than annual IRs calculated with R data from the sites 4 and 8 km from the study area. Assuming that calculating IRs using measurement period means from the site is the most appropriate method to estimate annual IR, using R data from sites farther away from the study area would overestimate IR from 42% to 121%. This has important implications for larger-scale studies of water supply and use, in which NCDC rainfall data are often used as a surrogate for unavailable site-level rainfall data.

Table 2. Comparison of 2007 to 2012 annual canopy interception rate (IR) estimated with different methods and rainfall sources.[a]

Rainfall Data Source	Distance from Site (km)	Mean IR Across Years[b] (%)	Annual IR Range (%)
Site: Annual mean	0	10 (2) a	2 to 14
Site: Measurement period mean	0	17 (2) a	14 to 22
Local micrometeorological station	4	25 (2) b	21 to 31
NCDC Plymouth 5E	8	33 (2) c	26 to 40

[a] Years were selected to include all data from the micrometeorological station 4 km from the research site.

[b] Means followed by the same letter are not significantly different. Values in parentheses are standard errors of the mean.

Canopy Interception as a Percentage of ET

Canopy interception as a percentage of ET averaged 15% across all years and ranged from 2% to 24% (fig. 6). These rates were lower than those reported by McCarthy et al. (1991), who found that rainfall interception contributed 25% and 36% to annual ET in thinned and unthinned coastal plain loblolly pine stands, respectively. TPH in the unthinned stand was over 50% greater in the McCarthy et al. (1991) study compared to this study, which may explain the lower I and I/ET estimates in this study. Ford et al. (2007) found that rainfall interception in white pine stands was 44% to 47% of ET. These rates indicate there is high variability in the contribution of interception to ecosystem ET, a major pathway by which rainfall is returned back to the atmosphere (Ford et al., 2007; Sun et al., 2010). Canopy interception (I) and I/ET were both lowest in 2009 at 20 mm and 2%, respectively. These low values can be at least partially explained by the thinning in the fall of 2009 that removed approximately 50% of the stems. Otherwise, 2009 was a normal year in terms of annual R and ET.

The low annual 2009 interception rate in this study was due to TF exceeding or nearly equaling R during several summertime measurement periods before the thin (data not shown). Rainfall measurements at the study site and the nearby micrometeorological station were in good agreement

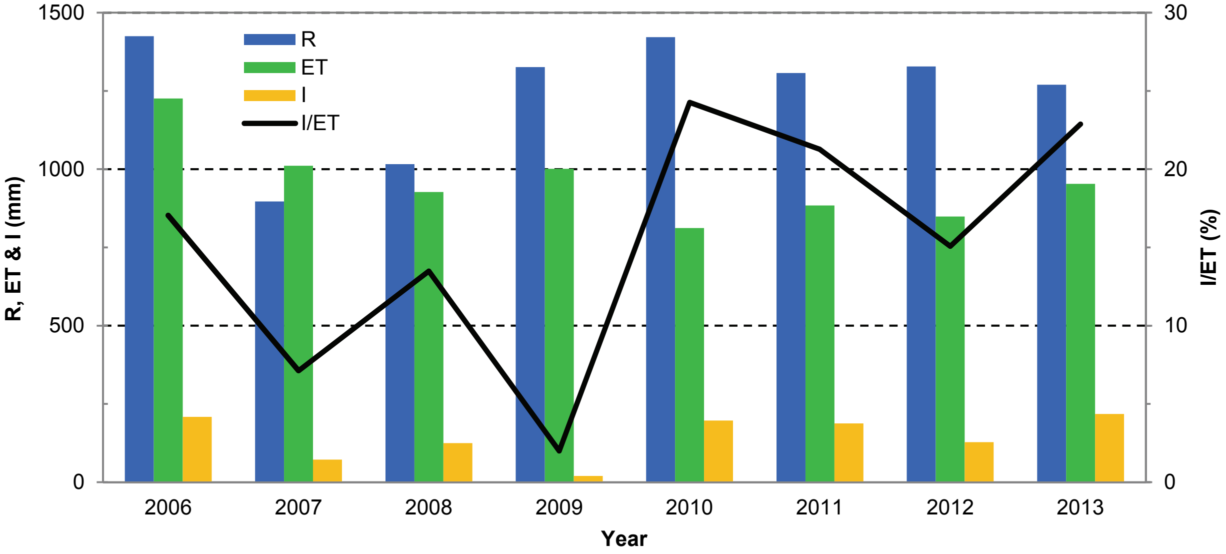

Figure 6. Annual rainfall (R), evapotranspiration (ET), canopy interception (I), and the contribution of I to ET (I/ET). ET from 2006-2009 was calculated using the eddy covariance method. ET from 2010-2013 was calculated using the watershed balance equation.

during this period (data not shown), indicating that rainfall estimates were reasonable. However, accuracy of the TBRGs is reduced at rainfall rates over 10 mm h^{-1} (CSI, 2000), so it is possible that the rain gauges underestimated rainfall during heavy rain events, resulting in lower estimated interception. It has been reported that TBRGs positioned on towers above a canopy are subject to undercatch, possibly as a result of aerodynamic turbulence (Gash et al., 1980; Valente et al., 1997). A nearly 1:1 relationship was found between an MRG and TBRG mounted side-by-side, 1.5 m above the ground, in a nearby clearcut (data not shown), indicating that errors between the two gauges can be minimal closer to the ground. The MRGs were assumed to be the most reliable instruments because they used a simple, non-mechanical method to catch throughfall and were less prone to equipment malfunction. However, measurement errors were possible when recording rainfall above the canopy, and it is also possible that the MRGs overestimated throughfall.

Canopy interception and its relationship to watershed ET are fundamental components of the hydrological cycle and have important implications for water resource management, especially as they relate to climate change and variability. The impacts of elevated atmospheric carbon dioxide (CO_2) and changing rainfall patterns and intensities on ecosystem services have been studied for many years (Weltzin et al., 2003; Backlund et al., 2008; Vose et al., 2012), but a high level of uncertainty remains regarding ecosystem response (Makino and Mae, 1999; Cramer et al., 2001; Battipaglia et al., 2013). Higher water use efficiency and lower ET as a result of a predicted decrease in stomatal conductance for plants growing under elevated atmospheric CO_2 could result in greater ecosystem water availability (Drake et al., 1997; Wullschleger et al., 2002; Battipaglia et al., 2013) if the forest leaf area remains constant. However, the response of stomatal conductance in CO_2 fertilization studies has been inconsistent (Field et al., 1995; Ellsworth, 1999; Kergoat et al., 2002; De Kauwe et al., 2013; Battipaglia et al., 2013). Predicted increases in tree biomass and leaf area index under elevated CO_2 (Kimball et al., 1993; Ellsworth, 1999; Norby et al., 2002) would result in greater IRs and less rainfall reaching the forest floor for use during tree maintenance and transpiration, possibly increasing the susceptibility of drought-stressed species to additional stressors such as insects and diseases. While a high level of uncertainty surrounds species and ecosystem responses to future climate scenarios, the combination of predicted lower ET and higher IRs would result in higher I/ET. The implications of this result and the possibility of using the I/ET ratio as an indicator of ecosystem stress are outside the focus of this study. However, given the high variability in canopy IRs found in this study and uncertain climate-ecosystem interactions, further research is warranted.

CONCLUSIONS

Canopy interception measured over ten years in a southeastern U.S. loblolly pine planation was found to have higher annual variability compared to what has been reported in studies of shorter duration. Over the study period, annual canopy interception rates (IRs) calculated from biweekly measurement period rainfall and throughfall ranged from 14% to 23% and averaged 19%. Measurement period canopy IRs ranged from 0% to 100%, and throughfall was occasionally greater than rainfall, indicating that the study may not have always captured the spatial variability in rainfall over the study area. The southeastern U.S. coastal plain is characterized by highly variable rainfall rates and intensities, and it was shown that using rainfall data collected 4 to 8 km away from the research site resulted in overestimates of canopy interception. Thinning resulted in a 5% decrease in rainfall interception, but the IRs quickly returned to post-thin levels, likely due to the rapid growth of the understory. While there were no significant differences, the variability between annual IRs was higher than expected compared to IRs reported for loblolly pine stands with comparable stocking levels. The mean dormant season interception rate was significantly higher than the mean growing season interception rate, but not across all years. Canopy interception was found to be quite variable and a smaller percentage of estimated total annual ET (15% ±3%) compared to published ratios. The uncertainties posed by future climate scenarios and the potential for altered ecosystem productivity and hydrological responses make it imperative that models accurately predict ecosystem functions such as rainfall interception at the canopy to forest scale. The data presented in this article offer a rare assessment of decade-long forest canopy interception measurements and indicates that inter-annual variability may be higher than previously thought.

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