WATER RESOURCES RESEARCH, VOL. 34, NO. 12, PAGES 3503–3513, DECEMBER 1998

Hydrological components of a young loblolly pine plantation on a sandy soil with estimates of water use and loss

Deborah A. Abrahamson
J. Phil Campbell Natural Resources Conservation Center, USDA Agricultural Research Service
Watkinsville, Georgia

P. M. Dougherty
Forest Research, Westvaco, Summerville, South Carolina

S. J. Zarnoch
Southern Research Station, USDA Forest Service, Asheville, North Carolina

Abstract. Fertilizer and irrigation treatments were applied in a 7- to 10-year-old loblolly pine (*Pinus taeda* L.) plantation on a sandy soil near Laurinburg, North Carolina. Rainfall, throughfall, stemflow, and soil water content were measured throughout the study period. Monthly interception losses ranged from 4 to 15% of rainfall. Stemflow ranged from 0.2 to 6.5% of rainfall. Rainfall, leaf area index (LAI), basal area (BA), and the interactions of rainfall with LAI or BA influenced prediction models of throughfall, but not stemflow, on a stand level. We found significant differences due to the effects of treatments in the soil water of the top 0.5- and 1-m soil layers by the beginning of the second growing season and throughout the remainder of the study period. Average daily water use and loss from a 1-m soil layer reflected the low water-holding capacity of the sand. Soil water in a 1-m layer was rapidly depleted to within 10% of available water during periods of little or no rainfall. Irrigation did not significantly affect productivity and created a greater potential for loss of water to drainage below 1 m. On the basis of *Zahner*'s [1966] method of soil water depletion in a sandy soil under forest cover, total drainage to below 1 m was 55% of evapotranspiration in unirrigated plots and 150% of evapotranspiration in irrigated plots.

1. Introduction

Loblolly pine (*Pinus taeda* L.) is a major commercial species in the southeastern United States. Water stress is one of the factors that imposes limits to forest productivity. *Teskey et al.* [1987] reported unexplained declines in loblolly pine productivity in the southeast and found that productivity of intensively managed loblolly pine stands is reduced by summer temperatures and droughts in the spring and fall in east central North Carolina. *Swank et al.* [1972] found that rainfall interception ranged from 10 to 35% as loblolly pine stands developed unless management practices reduced stocking and tree canopy. *Jackson et al.* [1983] have found that managing water availability by thinning or reducing initial planting density can compensate for rainfall during dry periods when balanced nutrient applications are made. However, *Mitchell and Correll* [1987] found that rapid increases in canopy cover and basal area of radiata pine at an early age as a result of intensive management practices such as irrigation and fertilization may result in early depletion of water and nutrients. Irrigation and fertilization can rapidly increase canopy cover, basal area, and other stand characteristics such as tree height. These characteristics affect throughfall, stemflow, and soil water [*Swank et al.*, 1972; *Murphy and Knoerr*, 1975; *Spittlehouse and Black*, 1981; *Stogsdill et al.*, 1989; *Whitehead and Kelliher*, 1991; *Myers and Talsma*, 1992; *Amatya et al.*, 1996]. The productivity of pine stands must then depend in part on the ability of the stand to acclimate to changes in water availability, especially to water deficit periods during the growing season.

Understanding how the hydrological components are affected by fertilization and irrigation and how the growth induced by these treatments affects water availability in young pine stands was the objective of the hydrological component of this study. This study should also help us understand how loblolly pine responds to water deficit periods on soils with low water-holding capacities under conditions of high evaporative demand.

We quantified monthly throughfall, stemflow, and soil water in a young loblolly pine stand on a sandy soil under irrigation and fertilization treatments; tested for differences between the amounts of water reaching the soil under control, irrigated, fertilized, and irrigated + fertilized treatments; and compared treatment water use and loss by the water balance method using the measured components, and *Zahner*'s [1966] method of soil water depletion for sandy soils.

Paper number 98WR02363.

2. Site Description and Characterization

The study area is in the Sandhills of Scotland County, North Carolina. The Sandhills are more elevated (300–650 feet above sea level) than the rest of the coastal plain of North Carolina. Sandhills vegetation consists of longleaf pine (*Pinus palustris* Mill.), loblolly pine, slash pine (*Pinus elliottii* Engelm.) and oak species such as blackjack oak (*Quercus marilandica* Muenchh.) and turkey oak (*Quercus laevis* Walt.) [*Lee*, 1955;

Natural Resources Convervation Service, 1972]. Forty-five-year mean annual rainfall at Laurinburg, North Carolina, which is located 16 km south of the site, is 1220 mm; mean maximum air temperature is 24°C, mean minimum air temperature is 10°C, and mean daily temperature is 17°C (National Climatic Data Center, Asheville, North Carolina). Rainfall from November through February typically recharges the soil profile by the following March.

The soil in the study area was mapped as a Lakeland series in 1942 but was remapped as a Wakulla series in 1972 because it was found to have a variable clay and silt component after observations that various hardwoods were growing in the area (Natural Resources Conservation Service, personal communication, 1994). The Wakulla series (sandy, siliceous, thermic Psammentic Hapludults) is highly permeable and somewhat excessively drained. The soil contains 91% sand at depths of 0–30 cm, 93% at 30–60 cm, 89% at 60–120 cm, and 95% at 120–150 cm and at 150–200 cm in the study area. Bulk density ranges from 0.92 to 1.5 g cm^{-3} at depths of 0–15 cm and from 1.2 to 1.7 g cm^{-3} at depths greater than 15 cm. Gravimetric water content ranged from 0.02 to 0.20 with a mean of 0.05 to the 2-m soil depth on the basis of data collected on two consecutive days without rain at the beginning of the study period. Regressions of soil water release for each depth as determined with pressure plate and tempe pressure cell equipment resulted in soil water release curves characteristic of sand where depletion is approximately linear between 0 and 0.2 MPa. Depletion was related exponentially to increasing pressure in the range from 0.2 to 1.5 MPa for each depth. Regressions of soil water on pressure using the combined data from the first four depths resulted in this same characteristic curve for sand in the top 1-m layer. Equilibrium pressure was 0.5–0.7 MPa on the basis of predicted values of soil water release between 0.5 and 1.5 MPa. Water-holding capacity of the top 1 m based on laboratory analysis was 0.09 cm^3 cm^{-3}, and wilting point, the point at which greater pressure results in no further decrease in soil water content, ranged from 0.02 to 0.03 cm^3 cm^{-3} for individual depths and for the 1-m layer. On the basis of the 1-m layer, the average plant available water (PAW = $\theta_{0.01} - \theta_{0.5}$) was 6.7 cm in 1 m of soil.

The site has a flat topography and is located in an elevated position, so there is no lateral flow onto it. The flat topography and the excessively high infiltration rate of the soil (152–508 mm h^{-1}) ensure that no overland runoff will occur, and surplus water is lost through deep seepage. The area was planted with loblolly pine in March 1985. Planting was by machine at a spacing of 2.4 by 2.4 m. In 1992 the stand was thinned to 1260 trees ha^{-1}. Four to five longleaf pines that developed from seed or seedlings in place at the time of harvest occupy a dominant or codominant position in the developing canopy of each treatment plot. The remaining understory vegetation consists of wire grass (*Aristida stricta*), poison oak (*Rhus toxicodendron*), and various annuals that are sprayed with glyphosate to minimize or eliminate competition for water and nutrients.

The study has a randomized complete block design in a 2 × 2 factorial combination of irrigation and nutrition treatments replicated four times. Each treatment was randomly assigned to one of four plots in each of four blocks. Irrigation treatments were (1) no irrigation and (2) irrigation to maintain soil water above 70–80% of PAW in the top 0.5-m layer of soil. Fertilization treatments were (1) no fertilization and (2) fertilizer applied to maintain optimum foliar nutrient levels established for loblolly pine by the North Carolina State University Fertilizer Cooperative. Each treatment plot measured 50 × 50 m and contained a 30 × 30 m sample plot (0.09 ha). The four treatments were designated control (C), irrigated only (I), fertilized only (F), and irrigated + fertilized (IF). The irrigation system was installed during the second year of the study (April, 1993), and the treatments designated C (unfertilized) and F (fertilized) until irrigation was begun. Basal area and the number of loblolly and longleaf trees per hectare were standardized across all plots before main treatments were applied. Pretreatment foliage N concentration in the dormant season (December–February) was 0.98% of dry mass, less than the critical concentration of 1.15% of dry mass established for loblolly pine [*Allen*, 1987]. We used site measurements of leaf area index (LAI) and basal area (BA) in the regression models of throughfall and stemflow that were measured throughout the study period. LAI ranged from 0.2 to 1.3 m^2 m^{-2} for the C and I treatments and from 0.2 to 2.5 m^2 m^{-2} for the F and IF treatments over the study period. Measured BA used in the regression models ranged from 0.01 to 13.0 m^2 ha^{-1} for the C and I treatments and from 0.02 to 21 m^2 ha^{-1} for the F and IF treatments over the study period.

3. Methods

3.1. Rainfall and Irrigation

Rainfall was measured with tipping bucket rain gages. One gage was placed 2 m above the soil surface at a weather station in a 60 m × 60 m clearing located adjacent to the study area. Instrument error of the tipping bucket gages was ±0.5 mm, and the gages were recalibrated twice a year. A second gage was located 2 m above average canopy height in a control plot and was used to determine whether rainfall above the canopy differed from rainfall in the clearing. The irrigation system consisted of a head sprinkler system with nozzles located below the canopy and controlled by a central timing system in the center of the study site. Irrigation was scheduled according to daily measurements of soil water in the top 0.5-m layer using time domain reflectometry (TDR) with a 0.5-m three-conductor probe. From 2 to 2.5 cm of water were applied to all irrigated treatment plots when soil water content dropped to 3–3.5 cm available water (70–80% PAW).

3.2. Throughfall

Throughfall was collected daily, except during multiday periods of continuous rain when as much as 80 mm fell during a 3-day period. Four throughfall collectors, 150 cm × 10 cm troughs, were located randomly in each treatment plot. There were 16 collectors per treatment, which enabled us to achieve <5% sampling error at the 80% confidence level for rainfall events greater than 25 mm [*Helvey and Patric*, 1969]. Each trough was positioned 0.75 m above the ground and drained into a 75-L plastic container with a locking lid. The collector locations were rerandomized once a year on each plot. We calibrated the collectors by placing three of them near the rain gage in the clearing adjacent to the study area. Tipping bucket data were regressed on throughfall collector data for eight events for rain samples from 4 to 22 mm. Plot throughfall measurements throughout the study period were adjusted by means of this calibration before analysis.

We used GLM procedures [*SAS Institute*, 1989] for throughfall analysis by rain event with block and treatment as classification variables. Multiple linear regression was used to regress throughfall data on rainfall with leaf area index or basal area and the interaction of rainfall with each to determine whether these characteristics influenced our ability to predict throughfall. Throughfall data were also divided into classes by size of rain event (0–12, 12–25, 25–50, and 50–100 mm) and regressed on rainfall similar to the method of [*Singh and Szeicz* [1979]. This method defines the interception capacity of the stand for low- to high-intensity rains and the amount of evaporation that occurs during rainfall. Models for predicting throughfall were developed based upon the results of these analyses.

3.3. Stemflow

Stemflow was collected from four randomly selected trees in each plot during the first three growing seasons (1992–1994). Plastic tubing was spirally wrapped near the base of the tree to complete one full circumference around the stem. Each tree's stemflow drained into a funnel, which then drained through tubing into a 40-L container with locking lid.

The four stemflow sample amounts for each plot were averaged, multiplied by the number of trees in the plot, and then converted to millimeters per hectare[1] per plot. This method assumes that the average of the four stemflow volumes per plot represents the stemflow volume of each tree in the plot. We analyzed the stemflow data in the same way we analyzed throughfall, testing for significant treatment differences on an event basis, examining the effects of LAI and BA on stemflow, and developing prediction models for stemflow.

3.4. Soil Water Content

Soil water content was measured biweekly using TDR and a Tektronix 1502-C cable tester (Tektronix, Inc., Beaverton, Oregon). The probes were three conductor, 20 cm in length, and placed horizontally in the soil at depths of 10, 25, 50, 100, 150, and 200 cm at two random locations in each of the C and F plots the first year. In April 1993, after the irrigation system was in place, probes were placed also in each of the I and IF treatment plots. One probe location included all six depths, and the second included the first four depths. We used the programs TACQ and TRAD (S. R. Evett, TACQ.EXE (software for IBM PC/AT compatible computers), and Time Domain Reflectometry System Manual (File TACQ-WPD.ZIP), USDA Agricultural Research Service, Bushland, Texas; available at http://www.cprl.ars.usda.gov/programs, last updated December 5, 1997) to collect TDR waveform data and to analyze the data for volumetric water content, respectively. TACQ uses an algorithm to find the time it takes the signal to traverse the length of the TDR probe and converts this time to the dielectric constant. The program then uses Topp's equation [*Topp et al.*, 1980] to calculate volumetric water content. The probes were calibrated with soil core samples from the site, and each soil water measurement throughout the study period was adjusted by reference to the calibration before analysis.

PAW in the top 1 m was estimated by multiplying the volumetric water content of each of the first four depths by 15, 15, 20, and 50 cm, respectively, corresponding to the depth of the horizon at each probe to obtain centimeters of water, summing them, and averaging that sum for a plot. GLM procedures [*SAS Institute*, 1989] were used to test for significant differences due to treatments using block and treatment as classification variables on each day we measured soil water content.

3.5. Water Balance Estimates

A monthly water balance was calculated using the water balance equation in the form

$$\mathrm{Net}P\ (+I) - \Delta S - \mathrm{ET} - D = 0 \qquad (1)$$

where Net$P$ = throughfall × stemflow, I is irrigation, ΔS = soil water$_{\mathrm{time}\,2}$ − soil water$_{\mathrm{time}\,1}$, ET is actual evapotranspiration, and D is drainage to below 1 m. A 0.5-m TDR probe was used to measure soil water vertically from the surface before and after irrigation at 15–20 locations in each plot over a 4-month period in 1995. The proportion that reached the soil layer was calculated by subtracting pre-irrigation soil water measurements from postirrigation measurements on the same day, and then dividing by the total amount of irrigation applied. These values were averaged for each irrigated plot over the 4-month period and analyzed for significant differences. This revealed how much water was lost by evaporation or intercepted by the understory and the litter layer.

Net$P$ was predicted from total monthly rainfall by means of prediction models developed for throughfall and stemflow. We used predicted values rather than measured ones because it was not practical to measure all events during the 47-month study period. The prediction models were based on measurements for 20 months of rain events (105 events) that produced from 2 to 100 mm of rainfall.

ΔS was calculated by subtracting the current amount of soil water from the previous amount and summing the differences from month to month. Since ET and D were not measured, the term (ET + D) was referred to as water use and loss and was divided by the number of days in the month to estimate the daily water use and loss rate (mm d^{-1}). This method gave us a reasonable estimate of average daily water use and loss, but since we did not specifically measure ET and drainage, we used the method of *Zahner* [1966] to estimate these two components. Zahner's method provides depletion or recharge amounts of soil water on a daily basis by adding daily input (rainfall minus PET) to the current soil water content. According to Zahner, soil water depletion in a sandy soil under forest cover occurs at a rate equal to PET as long as measured soil water stays above 25% of field capacity, and depletes at a rate of (1/2 current soil water/total potential storage) × PET when soil water falls below 25% of field capacity. Drainage is the amount of (rain − PET) that exceeds field capacity after the layer is recharged. Water use and loss by Zahner's method is then the sum of the actual evapotranspiration term, either PET or reduced PET (PET when soil water drops below 25% field capacity) and the drainage term up to the time of a field soil water measurement. This method showed excellent agreement with measured soil water regimes on a sandy soil in a uniformly stocked upland forest. Zahner concluded that the method has application to growing season water regimes in upland forests with good surface infiltration and good internal drainage. Though our stand was not upland, the basis of Zahner's method seemed well suited to our study because it was uniformly stocked (planted), and the method depends mainly on the soil water release characteristic of the specific soil texture and the rooting distribution and depth that would develop relative to those soil properties [*Zahner*, 1966]. In addition, the amount of available energy in the form of PET calculated from site measurements and measured rainfall are strong drivers in this method.

PET was calculated using the method of *Thornthwaite et al.* [1957] and air temperature 2 m above the canopy height in a control plot. Values were then adjusted by regressing Penman combination PET [*Penman*, 1948] on Thornthwaite PET after instrumentation was installed in a control plot (August 1993)

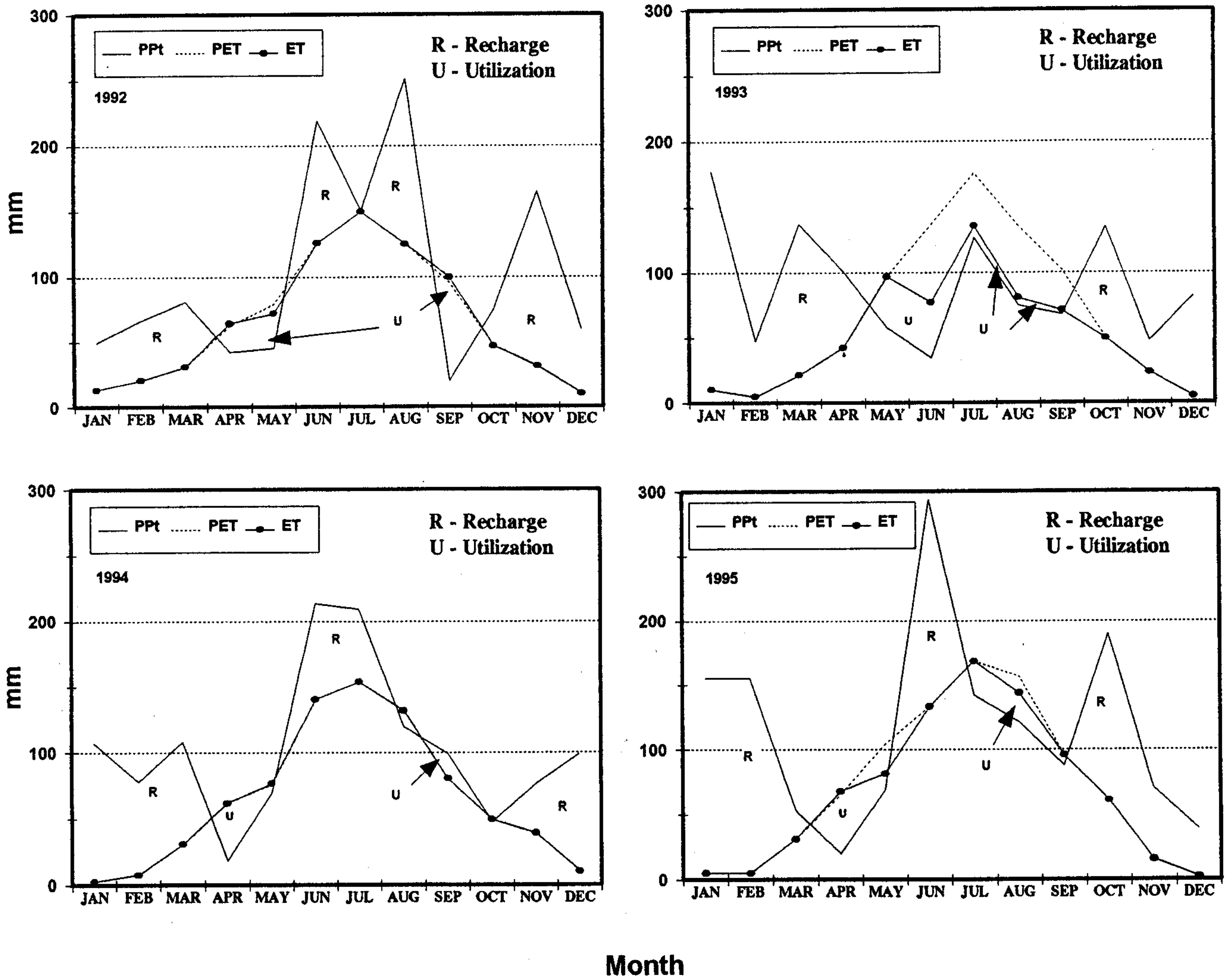

Figure 1. Total monthly precipitation (PPt), potential evapotranspiration (PET), and actual evapotranspiration (ET). PET and ET were calculated using site temperature and rainfall [*Thornthwaite et al.*, 1957] for Scotland County, 1992–1995.

to measure the required canopy inputs for Penman. Zahner used Thornthwaite PET to develop his method empirically, but the Penman combination method is based on the vegetative microclimate rather than just air temperature, and thus represents fluctuations in radiation, vapor pressure deficit, and air movement as well as temperature. We began daily soil water depletion or recharge by Zahner's method beginning with field capacity (10.5 cm) in the top 1-m layer in January of the first year of the study (1992) and continued until the study period ended in August 1995. We subtracted measured ΔS from measured rainfall and compared water use and loss with water use and loss calculated by Zahner's method. The advantage of using rainfall rather than Net*P* in this case is that free surface evaporation of water can be accounted for by the water use and loss term, i.e., any change in soil water storage not reflected by measured ΔS must end up in the water use and loss term. By Zahner's method, PET, as an upper limit of available energy, is subtracted from rainfall before it affects current soil water storage, and it also becomes a part of the water use and loss term.

4. Results

4.1. Rainfall and PET Trends

Peak rainfall occurred during the summer months of 1992, 1994, and 1995. Seasonal distribution was similar in 1992, 1994, and 1995; in those years there were dry periods each spring and fall, and heaviest rainfall occurred from June through August. Total rainfall in 1992 (1224 mm) and 1994 (1245 mm) was near the 45-year mean of 1220 mm, while 1993 was drier than average with 1090 mm of rainfall. Total rainfall in 1995 was 1395 mm, greater than the 45-year mean. Thornthwaite PET exceeded rainfall (PPt) immediately before (April–May) and immediately after (September–October) the summer season during the study years (Figure 1), but PET was generally less than rainfall during the summer months of years that had average rainfall. In 1993, however, Thornthwaite PET exceeded rainfall from May through September. Penman PET was similar to Thornthwaite PET, but Penman estimates were 8–36 mm higher than Thornthwaite estimates in the cooler months (October–May) and 11–25 mm lower in the warmest months (June–September). The regression of daily calculated values of Penman PET on Thornthwaite PET had a slope of 0.68 and an intercept of 1.05, both highly significant.

4.2. Throughfall

Measured throughfall ranged from 43 to 125% of rainfall over the study period (Figure 2). The calibration regression for the throughfall collectors had a slope of 1.08 and a very small intercept (0.5 mm) that was not significant ($p = 0.23$); this indicates that the collectors accurately sampled rainfall through the canopy in the plots. The percentage of throughfall that exceeds 100% of rainfall for very small rain events represents the higher sampling error for events <25 mm [*Helvey and Patric*, 1966].

Analysis of variance with block and treatment classification variables revealed significant differences due to treatment effects in 3 of 105 events measured. Sampling error for rain events when the contents of all throughfall collectors in a treatment plot were measured ranged from 1 to 19%, and average sampling error for the stand was 7%. Canopy storage capacity as calculated by the Rutter method [*Rutter et al.*, 1975] increased from 0.3 mm in 1992 to 1.1 mm by April 1995 (IF). In Rutter's method, canopy storage capacity is interpreted as a 0.2-mm layer of water a leaf can hold × total leaf area. Differences in canopy storage capacity between treatments based on measured leaf area ranged from 0.06 mm in 1992 to 0.6 mm in 1995 (C and IF). Detection of such small differences even over a period of several rain events or where there is higher sampling error for small events would require an impractically large number of collectors and more than could reasonably be maintained. As an alternate method of determining the influence of canopy cover on interception, we regressed throughfall on rainfall with rainfall divided into event sizes of 0–12, 12–25.4, 25.4–50, and 50–100 mm similar to the method of *Singh and Szeicz* [1979]. The regression slopes ranged from 0.74 to 0.96. Predicted throughfall based on these regressions ranged from 85 to 96% of rainfall and averaged 90%. According to these analyses, canopy interception ranged from 4 to 15% of rainfall throughout the study period. This amount represents the rainfall that was subject to evaporation during the event.

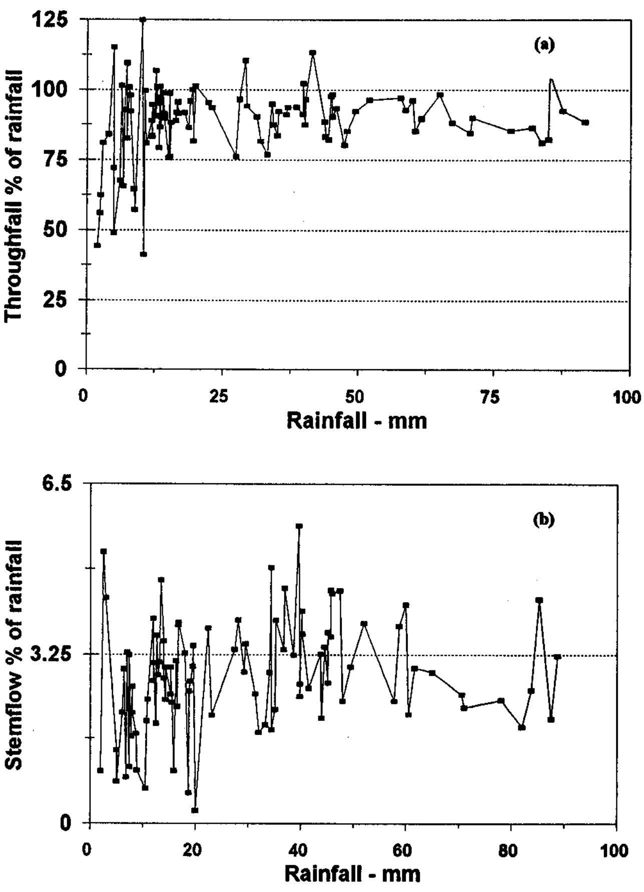

Figure 2. Mean measured (a) throughfall and (b) stemflow for the stand as a percent of rainfall, June 1992 through August 1995.

Table 1. Prediction Models of Throughfall T with Rainfall and LAI or BA, and Prediction Model for the Square Root of Stemflow (rootS), 1992–1995

Model	r^2	MSE	C.V.	$C(p)$	n
$T = 0.47 + 0.89$ (Rain)	0.95	41.9	21	56.9	6234
$T = 1.56 + 0.89$ (Rain) -1.2 (LAI)	0.95	40.3	21	2.1	6163
$T = 1.0 + 0.89$ (Rain) -0.13 (BA)	0.95	41.4	21	2.7	6172
rootS = 0.36 + 0.02 (Rain)	0.64	0.08	33	na	5053

Differences in LAI and BA were significant between the fertilized and unfertilized treatments the first 3 years [*Albaugh et al.*, 1998]. Multiple linear regression analysis of throughfall on rainfall with LAI or BA showed that LAI and BA were significant in the model but did not improve the r^2 or covariance and therefore our ability to predict throughfall. However, Mallow's $C(p)$ statistic indicated the model would be very biased if rainfall alone were used (Table 1). Since there was very little difference in predicted throughfall using the models with rainfall versus the models with rainfall and LAI or BA, total monthly Net$P$ was predicted using the regression with rainfall alone in the monthly water balance.

4.3. Stemflow

Measured stemflow ranged from 0.3 to 6.5% of rainfall over the study period (Figure 2). The average sampling error was 16% using an 80% confidence level and ranged from 7 to 31%. Variability and sampling error of stemflow data were low compared with similar studies measuring stemflow [*Durocher*, 1990; *Helvey and Patric*, 1966].

Analysis of variance using block and treatment classification variables revealed significant differences due to treatment effects for 3 events out of 99 measured. Multiple linear regression did not improve when LAI or BA was included as prediction variables for stemflow on a stand level. Stemflow increased gradually as rainfall increased, and graphs of the residuals from the regression analysis indicated that a transformation was needed. The best model for predicting stemflow used the square root of stemflow as the dependent variable and rainfall alone as the independent variable. The model had an r^2 of 0.63, a slope of 0.02 and an intercept of 0.36.

4.4. Soil Water

PAW was 4.3 cm in the top 0.5 m and 6.7 cm in the top 1 m on the basis of maximum and minimum values of all field measurements and from analysis of soil water release data. Field measurements showed that wilting point was 3.8 cm in the top 1 m. This value corresponded with soil water release

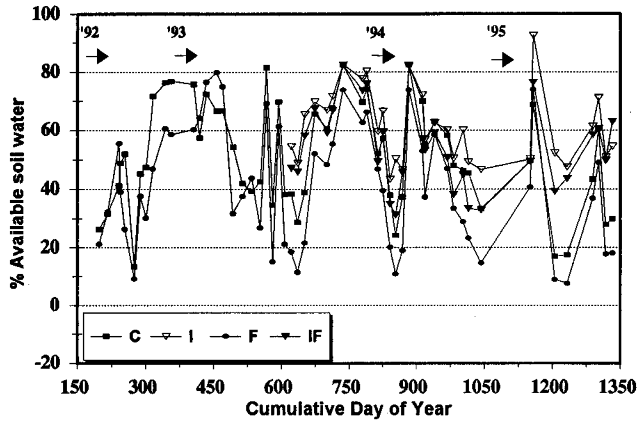

Figure 3. Percentage of available soil water from measurements in the top 1-m layer using field capacity of 10.5 cm and wilting point of 3.8 cm.

curve values (0.02–0.03 cm^3 cm^{-3}) at 0.5–0.7 MPa tension. Soil water in the F treatment plots reached a minimum of 10% PAW at the end of the first growing season (fall, 1992) and a minimum of 7% PAW in the spring of 1995 (Figure 3). Soil water measurements taken after irrigation as well as the computed effective irrigation (the amount that actually entered the soil) indicated that the remaining understory (wire grass) and litter layer intercepted ~1–1.5 cm of the irrigation water, with no significant difference between plots. Some portion of the loss from irrigation water as it was applied may have been due to evaporation. However, based on the fact that the spray of water from the sprinklers was at or below midcanopy, where the air is cooler and where minimal energy is available for evaporation, most of the loss during application was probably intercepted by the understory and the litter layer.

In 1993, average annual rainfall was 1092 mm, or 128 mm less than normal. The departure from normal occurred from May to September. Significant differences in available soil water due to treatments began to occur in September 1993 and continued through the remainder of the study period in the top 0.5- and 1-m layers. In 1994, a normal rainfall year, differences in available water between treatments became significant in mid-February, and soil water depletion peaked during the spring and fall. Differences in the amount of available water remained significant through December 1994 for main effect treatments. In 1995, differences in amounts of available water for irrigated treatments and unirrigated treatments were significant from March through August, when final measurements were made. Available water in fertilized plots differed significantly from available water in unfertilized plots in April and July 1995 only. Although available water in the F treatment plots was depleted to low levels in each year of the study period, BA for the F treatment plots never differed significantly from BA for the IF treatment plots, and LAI for the F treatment plots never differed significantly from LAI for the IF treatment plots.

4.5. Water Balance and Estimates of Water Use and Loss

Three to four days were required to irrigate all of the plots, based on the capacity of the well and the amount of water the holding tanks could cycle during this period. During dry periods, when one cycle of irrigation was completed and no rainfall had occurred, irrigation was begun again to bring soil water back to capacity. On the basis of pre-irrigation and post-irrigation measurements of soil water in the top 0.5 m, we deduced that the irrigated treatment plots were using approximately 5 mm of water per day from the top 0.5-m layer. This rate is consistent with the adjusted mean PET rates of 4.3, 4.1, and 4.3 mm in the summer months (June, July, and August) of 1993–1995. A 0.5-m layer of soil could hold 43 mm of available water. At a PET rate that ranged from 1 to 6 mm d^{-1} during the growing season, the unirrigated treatment plots could be depleted within 7 days if soil water in a sandy soil is depleted at a rate equal to PET as long as measured soil water stays above 25% of field capacity [*Zahner*, 1966]. Periods of 6 or more days without rain occurred from March through October an average of 12 times per year from 1992 to 1995, and available soil water was depleted to zero in the top 0.5-m layer and to near zero in the top 1-m layer in the most productive unirrigated (F) treatment plots by the fall of the second growing season. Average daily water use and loss for June (total water use and loss/30 days) in 1993 was 1.4 mm with the C treatment and 0.79 mm with the F treatment, and average daily PET was 4.28 mm. There was a large depletion of soil water in all of the plots during the hot, dry April of 1994. In April 1995, however, when figures for rainfall and temperature were almost identical to those for April 1994, average daily water use and loss with irrigated treatments reached PET levels when irrigation was begun by mid-April. During the 1994 and 1995 growing seasons, water use and loss was greater than PET during the summer months but was not equal to PET during the spring and fall. This pattern was similar to the one originally calculated with Thornthwaite's monthly equation (Figure 1). Total water use and loss was slightly greater with the F than with the C treatment during the same periods when soil water was more depleted with the F treatment than with the C treatment (June 1993 and March 1995).

Water use and loss in the I and IF treatment plots equalled or exceeded PET from the time irrigation was begun and was equal to and slightly less than PET during periods of water stress in the spring and fall of 1994 and 1995, typical rainfall years. Patterns of water use and loss in the 1995 growing season resembled those in the 1994 season with water use and loss, with the C and F treatments meeting or falling slightly below PET in the spring and with the I and IF treatments meeting or exceeding PET beginning in May after irrigation was begun.

Predicted values of soil water content in the unirrigated plots, calculated using [*Zahner*'s [1966] method of soil water depletion, dropped below 25% of field capacity in the top 1 m during dry periods in fall 1992, summer and fall 1993, June 1994, and May and August 1995, when water use and loss was less than PET (Figure 4) but measured ΔS was generally smaller than predicted ΔS (Figure 5). An exception to this pattern occurred in May 1994, when the soil in all plots actually showed recharge in the top 1 m during periods of small rain events while Zahner's method showed depletion. Predicted and measured values were checked for accuracy during this period, and no errors in the time step were found. Comparison of predicted and measured ΔS (Figure 5) revealed that in the unirrigated plots, the top 1-m layer did not consistently discharge and recharge according to rates of PET and rainfall as the predicted values would indicate, but discharged at reduced rates of PET during dry periods, i.e., summer, 1993. Recharge then occurred to less than field capacity when rainfall was light to moderate until the layer was recharged and water was avail-

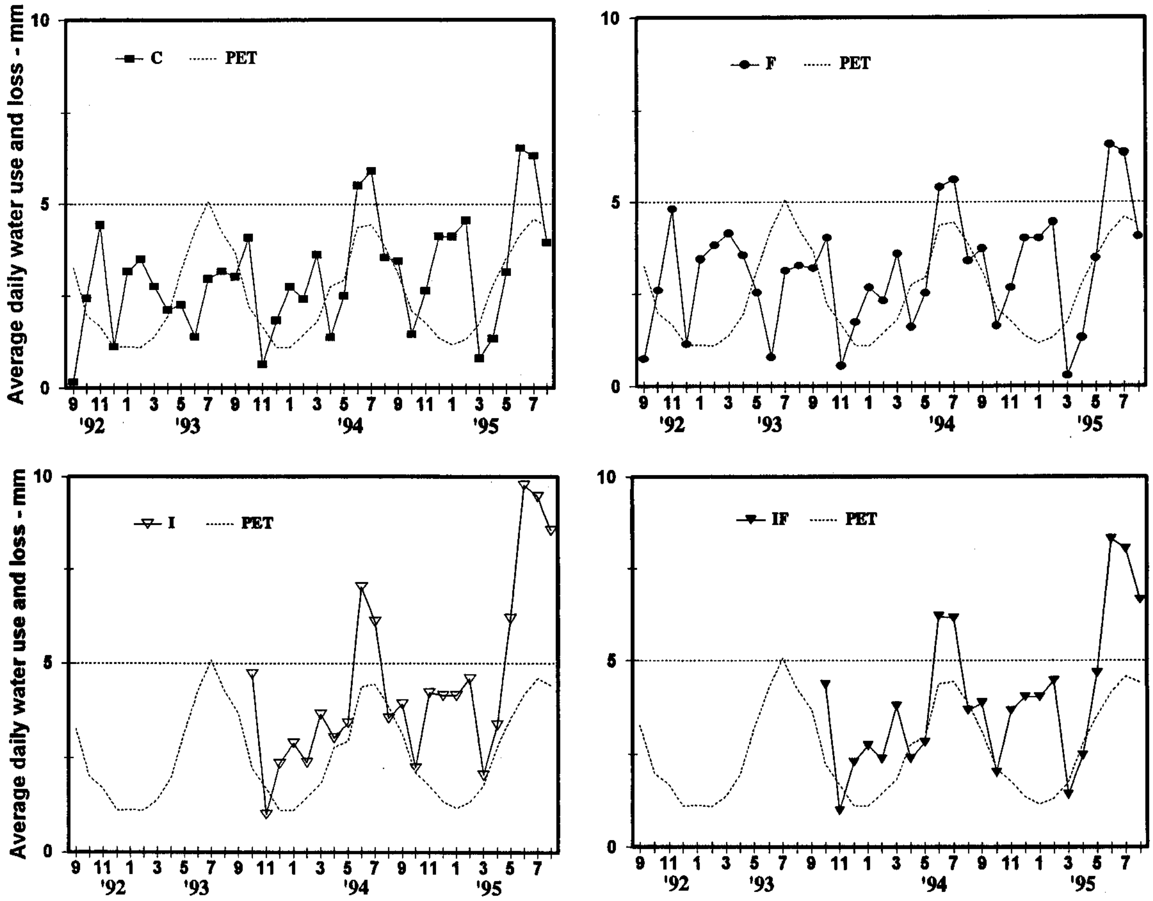

Figure 4. Average daily water use and loss from monthly water balance using predicted Net$P$ from regression analysis and measured ΔS. Average daily PET (adjusted) is shown for comparison.

able for PET. In addition, when adequate recharge was followed by heavy rainfall, ΔS from measured soil water content indicated depletion in the top 1 m of soil and infiltration to depths greater than 1 m, while predicted ΔS indicated that the layer was recharged to field capacity.

Measured ΔS in the irrigated plots was smaller than measured ΔS in the unirrigated plots. Measurements indicated that recharge and discharge were close to predicted values in the irrigated plots. Periods of heavy rainfall again showed greater-than-predicted changes in soil water, and it appeared that water infiltrated before it was used as ET. As in the unirrigated treatments, the top 1-m layer of soil recharged during periods of light rainfall when water was available for PET and then appeared to discharge according to rates of PET.

Cumulative water use and loss, based on measured rainfall and ΔS with the unirrigated treatments, was equal to cumulative water use and loss predicted by Zahner's method (Figure 6). Average daily water use and loss computed with measured rainfall and ΔS based on the monthly water balance indicates that depletion of soil water by ET occurred at rates of PET when rainfall was adequate (Figure 4). However, ΔS in Figure 5 indicates that the 1-m layer did not consistently recharge or discharge at rates predicted by Zahner's method. By Zahner's method, total predicted drainage was 55% of total predicted ET over the study period in the unirrigated plots (Table 2). Zahner's method overpredicted water use and loss in the irrigated treatments (Figure 7). When it was calculated by Zahner's method, soil water in the 1-m layer never fell below 25% of field capacity and was always available for PET, and total predicted drainage was 150% of total predicted ET from September 1993 through August 1995. By February 24, 1995, after 279 mm of rainfall since January 1, 1995, cumulative predicted drainage began to exceed cumulative predicted ET. This trend continued through the remainder of the study period. Mean monthly predicted ET was 70 mm with the unirrigated and 72 mm with the irrigated treatments. Measured water use and loss in the irrigated plots exceeded that in the unirrigated plots by 1211–1491 mm, an amount that could be attributed to drainage (Figure 8 and Table 2).

5. Discussion

Regression analysis of throughfall and stemflow shows that the canopy intercepted water in a manner typical of loblolly pine [*Swank et al.*, 1972; *Stogsdill et al.*, 1989]. We carefully analyzed treatment sampling error for throughfall and stemflow to insure that the effects of any potentially critical increases or decreases in the soil water content would be accounted for if differences due to treatments did exist. Significant differences in amount of water reaching the soil did not occur as a result of treatments, but LAI and BA influenced throughfall on the basis of Mallows $C(p)$ statistic and the fact

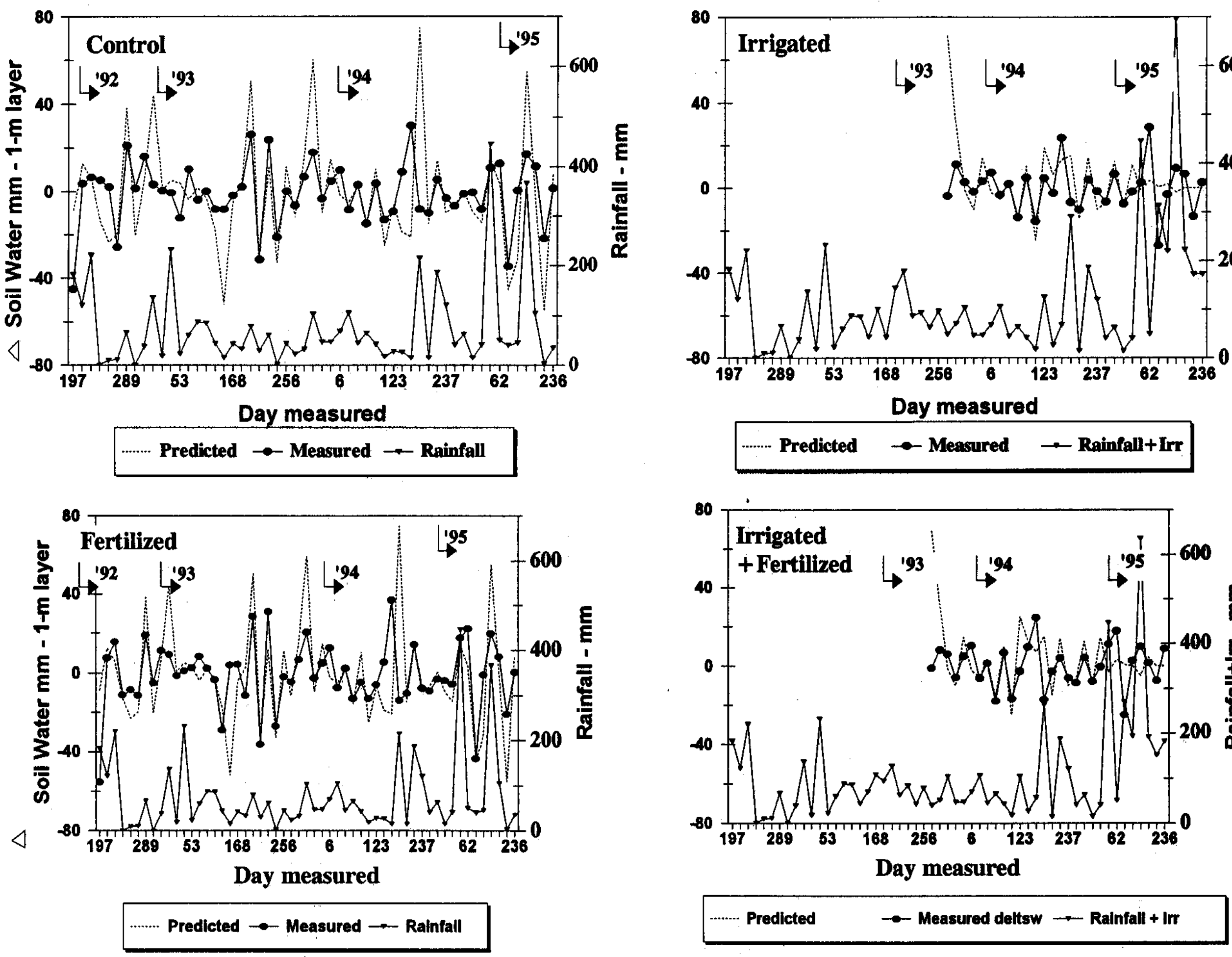

Figure 5. Measured and predicted (*Zahner*, [1966] method, 1957) ΔS in the top 1-m layer of soil, and cumulative measured rainfall up to day of soil water measurement.

that they were highly significant in the model. Regression analysis of throughfall on rainfall by rain size classes showed that interception ranged from 4 to 15% of rainfall. This indicates that rain event size and duration (larger events occurred over a period of several days) influenced the intercepted amount. This also suggests that LAI and BA, which represent canopy cover and tree size, influence the amount of throughfall and, when enhanced by management practices such as fertilization and irrigation, will affect the amount of rainfall that reaches the soil.

Calculated PET from March through October ranged from 1 to 6 mm d^{-1}. Figures for average daily water use and loss, based on a monthly water balance and 1 m of available soil water, indicate that enough water was available to meet daily PET requirements with the unirrigated treatments in years of normal rainfall distribution during the summer months of the growing season (1994 and 1995). PET normally exceeded average daily rainfall in the spring and early fall. The seasonal distribution pattern of rainfall was inverted in 1993 when PET exceeded rainfall from May through October. During that period, soil water in the top 1 m of soil was near depletion, and trees in unirrigated treatment plots were using water at a much reduced rate relative to PET. Water in the soil profile rapidly increased as rainfall increased and PET decreased in the late fall and winter. Water may have been withdrawn from below 1 m until recharge occurred in that layer, but ΔS from measured values of soil water content in 1 m of soil and the rapid drainage rate to depths greater than 1 m that occurred during periods of moderate to heavy rainfall when unirrigated treatments did not use water at potential rates of evapotranspira-

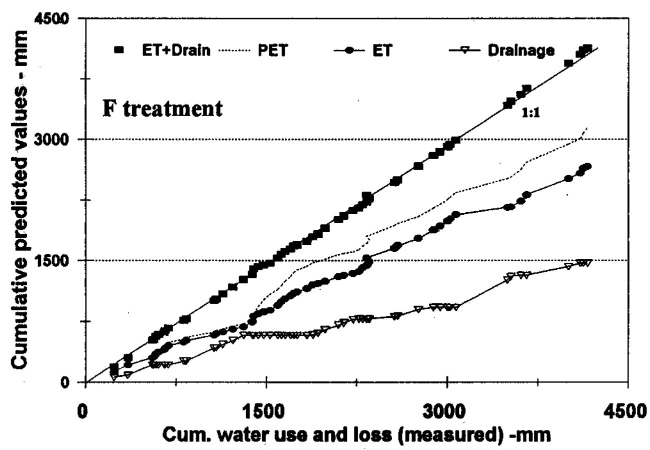

Figure 6. Cumulative predicted water use and loss (ET + Drain), ET, and drainage versus cumulative water use and loss (ET + Drain) from measured values of soil water, rainfall, and cumulative adjusted PET. July 1992 through August 1995, fertilized-only treatment.

Table 2. Predicted and Measured Cumulative Water Balance by Treatment for the Study Period Indicated

Treatment	Rainfall mm	Irrigation mm	Predicted ET	Predicted Drain	Predicted ET + Drain	Predicted ΔS	Measured ET + Drain	Measured ΔS
July 1992 through August 1995								
C	4105	...	2670	1468	4138	−33	4147	−42
F	4105	...	2670	1468	4138	−33	4162	−57
September 1993 through August 1995								
C	2459	...	1601	888	2489	−30	2464	−5
I	2459	1987	1645	2402	4047	399	3950	496
F	2459	...	1601	888	2489	−30	2459	0
IF	2459	1584	1645	2193	3838	205	3675	368

tion show that available water was not used to meet PET as often as Zahner's model predicted. Instead, drainage to below 1 m in the soil occurred simultaneously with ET at reduced rates of PET and suggests that actual drainage was similar to predicted drainage with the unirrigated treatments.

When ET was calculated by Zahner's method, predicted ET for the irrigated treatments was almost exactly equal to predicted ET for the unirrigated treatments. Zahner's method predicted greater water use and loss with the irrigated treatments than with the unirrigated ones, possibly because in calculations made according to that method, soil water was always depleted first according to PET rates and drainage was the remaining water surplus, but in reality, according to measured ΔS, soil water that was available was not always used at rates of PET. This may have been due to a lower demand for water in a young versus a mature forest. Since there were no significant differences in LAI and BA between the F and IF treatments, there must have been enough soil water in the top 1-m layer to meet growth demands without irrigation. At the same time, increased water input through irrigation maintained greater pressure heads in the top meter, ultimately creating maximum infiltration rates in the IF treatment plots. The net effect of irrigation along with moderate to heavy rainfall therefore produced a "flushing" effect in the sand. The recurrence of flushing is also supported by the fact that by Zahner's method, while soil water was always available at rates of PET in the irrigated plots, when rainfall exceeded PET, drainage to below 1 m was 1.5 × PET.

From a production standpoint, irrigation was not required in this young stand even though depletion of water in the top 1-m soil layer was greater with the F treatment than with the IF treatment. The most productive unirrigated (F) treatment, though it resulted in depleting soil water to a lower level than any other treatment, did not require more water for greater production than its irrigated counterpart, and excess water in the irrigated treatment plots evaporated as free surface water, drained to depths below 1 m, or was used for energy exchange as a cooling mechanism, i.e., transpiration and sensible heat flux.

Because soil water was depleted in the top 0.5-m layer during dry periods, and soil water in a 1-m layer with the F treatment was depleted to 7% available water early in the fourth growing season since fertilization began, irrigation may become important in the next few years. As canopy cover increases, both interception of rainfall and net radiation will increase, making more energy available for PET. Losses of intercepted water to evaporation could begin to represent a critical loss of effective rainfall. The rate of evaporation of intercepted rainfall can be 2–5 times as great as the rate of transpiration [*Murphy and Knoerr*, 1979]. Increased interception may eliminate the flushing effect of high intensity or continuous rain events in the sandy soil but could begin to induce even greater water deficits needed for growth.

Mitchell and Correll [1987] and *Myers and Talsma* [1992], who investigated soil water regimes for radiata pine growing on a sand soil, found that recharge of soil water in the top 1-m

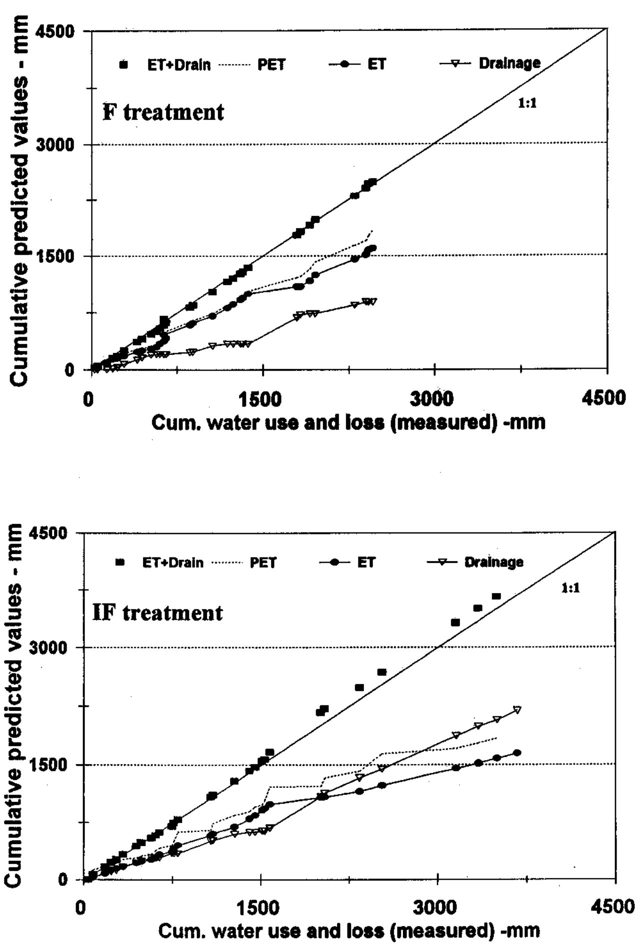

Figure 7. Cumulative predicted water use and loss (ET + Drain), ET, and drainage versus cumulative water use and loss (ET + Drain) from measured values of soil water, rainfall, irrigation, and adjusted cumulative PET. August 1993 through August 1995, F and IF treatments.

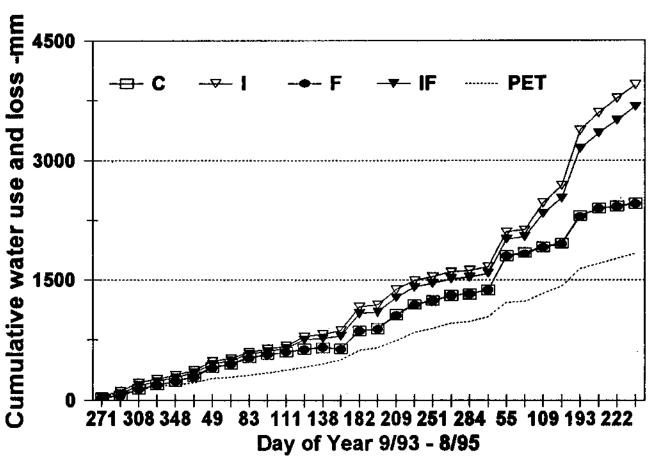

Figure 8. Cumulative water use and loss (ET + Drain) by treatment from measured values of soil water, rainfall, and cumulative adjusted PET. August 1993 through August 1995.

layer decreased over time. They proposed that the absence of significant differences in soil water content due to treatments in the first meter of soil was probably a result of the efficient uptake by the root mass with water supplied to some extent by the clay layer beneath. We found consistent differences throughout the 1-m profile due to treatments throughout the course of our study, but the Wakulla soil does not have an established clay layer beneath the main rooting zone, and loblolly pine does not have a dense root mass extending throughout 1 m of soil. This study suggests that loblolly pine growing in a sandy soil may have to acclimate to a decrease in soil water availability as it matures and demands more water, and that optimization of nutrient and water supplies in young stands of loblolly pine on sandy soils could lead to depletion of soil water and reduced growth rates after canopy closure.

6. Appendix:

Physical Characterization of the Soil

Because the clay and silt components of the Wakulla soil are variable, we measured soil texture, bulk density, and gravimetric water content the first year (1992) and soil water release in 1994 to accurately characterize the soil environment.

Bulk density was determined by analysis of six soil samples from each of 12 plots and seven depths. To determine texture, we combined three of these samples from each plot and depth to form two samples per depth per plot, and used the standard hydrometer method [*Weil*, 1986]. We collected 12 gravimetric samples per depth on four C plots and four F plots (total of eight plots) and used them to calculate the range of water content as an additional check on the variability of the clay and silt component. We collected six samples 1 m from and in a circle around each set of TDR probes in all of the plots.

To measure soil water release, we collected one soil sample at each of seven depths in each of eight plots (a total of 56 samples). We only used eight of the sixteen in the study because texture analysis showed that the amount of sand did not differ significantly among plots or among depths. We used tempe pressure cells [*Soil Moisture Equipment Corporation*, 1993; *Klute*, 1986] to measure water release from 0.01 MPa (water-holding capacity) to 0.1 MPa. We wet samples to saturation, weighed, then weighed after each exposure to pressure from 0.01 to 0.1 MPa. We used standard pressure plates [*Soil Moisture Equipment Corporation*, 1993; *Klute*, 1986] to measure water release from 0.1 MPa to 0.5 MPa, weighed the samples, and calculated the bulk density. We then developed regressions of pressure on volumetric water content for soil water release curves at each depth and for the top 1-m soil layer. Analysis for the 1-m layer was based on the average soil water content and pressure at the first four depths (10, 25, 45, and 75 cm) (Figure 9).

We found significant differences ($p < 0.05$) in bulk density among depths of 90–120 cm. At those depths, bulk density ranged from 1.48 to 1.52 g m^{-3}. Plot mean bulk density increased at depths from 10 cm to 100 cm, then gradually decreased at a depth of 165 cm. Plot mean percentage of sand decreased at a depth of 75 cm, and plot mean percentage of clay and silt increased at that depth; this is consistent with the higher bulk density values we found at 100 cm (Figure 10).

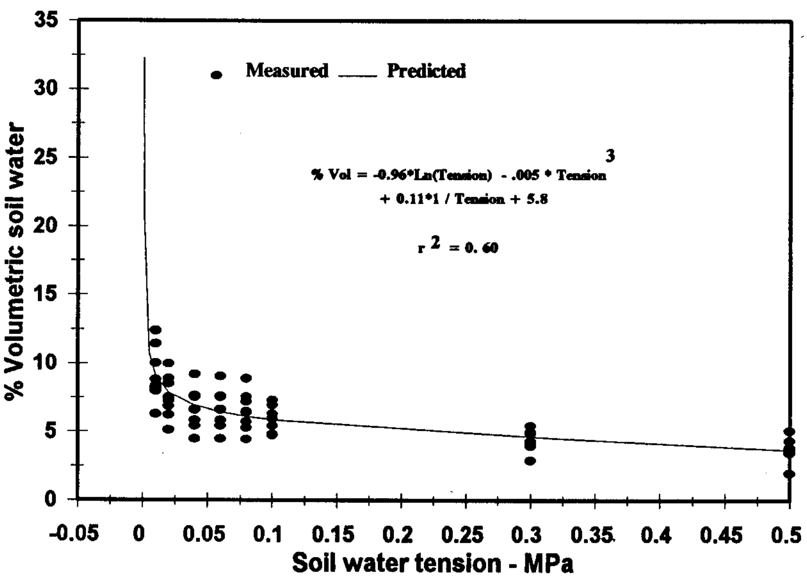

Figure 9. Measured and predicted soil water release in the top 1-m layer, 1995.

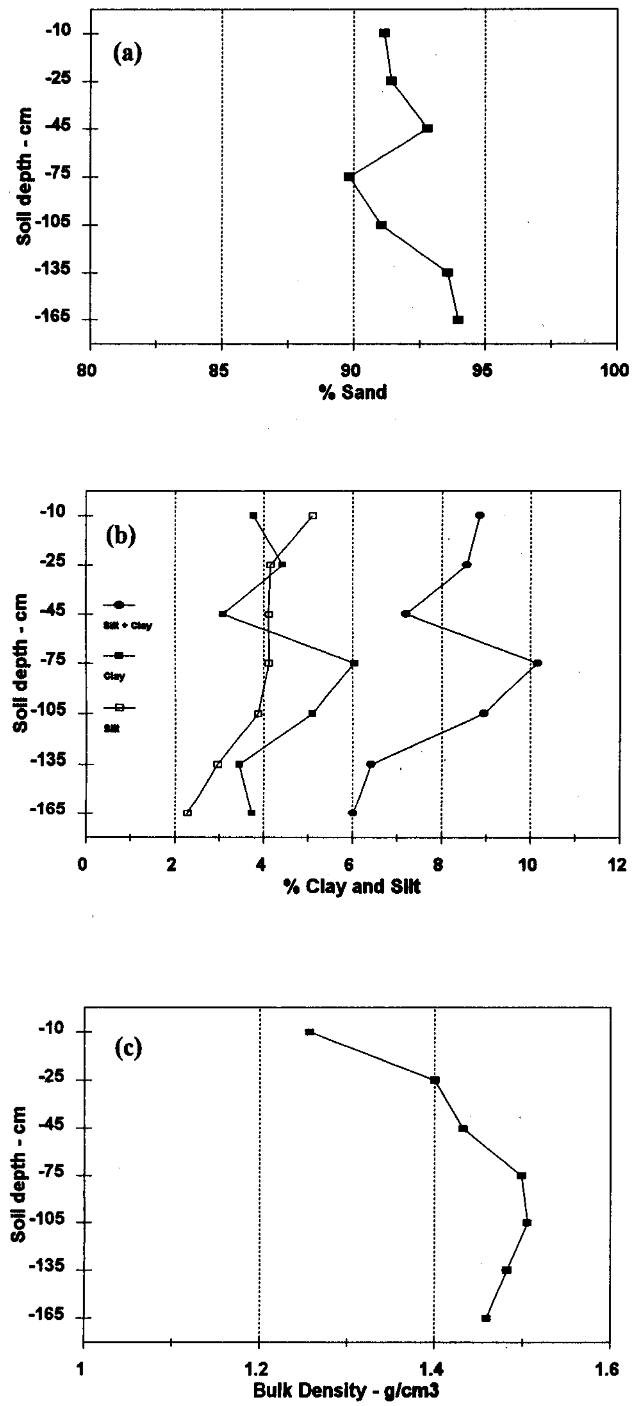

Figure 10. Texture analysis: (a) sand component, (b) clay and silt components, and (c) bulk density. Means of all plot samples.

Acknowledgments. We would like to thank Andy Laviner, Michelle Canick, Karen Sarsony, and David Josepheus for their excellent and reliable field and lab work, and Lee Allen and Tim Albaugh for their use of leaf area index and basal area data. This project was funded by the USDA Forest Service Southern Global Climate Change Program.

References

Albaugh, T. J., H. L. Allen, P. M. Dougherty, L. W. Kress, and J. S. King, Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions, *For. Sci.*, *44*(2), 317–328, 1998.

Allen, H. L., Forest fertilizers, *J. For.*, *85*, 37–46, 1987.

Amatya, D. M., R. W. Skaggs, and J. D. Gregory, Effects of controlled drainage on the hydrology of drained pine plantations in the North Carolina coastal plain, *J. Hydrol.*, *181*, 211–232, 1996.

Durocher, M. G., Monitoring spatial variability of forest interception, *Hydrol. Processes*, *4*, 215–229, 1990.

Helvey, J. D., and J. H. Patric, Design criteria for interception studies, *Bull. Int. Assoc. Sci. Hydrol.*, *67*, 131–137, 1966.

Jackson, D. S., E. A. Jackson, and H. H. Gifford, Soil water in deep pinaki sands: Some interactions with thinned and fertilised *Pinus radiata*, *N. Z. J. For. Sci.*, *13*(2), 183–196, 1983.

Klute, A., Water retention: Laboratory methods, in *Methods of Soil Analysis Agron. Monogr.*, vol. 9, part 1, 2nd ed., edited by A. Klute, pp. 635–662, Soil Su: Soc. of Am., Madison, Wis., 1986.

Lee, W. D., *The Soils of North Carolina*, *Tech. Bull.*, *115*, N. C. Agric. Exp. Stn., Raleigh, 1955.

Mitchell, B. A., and R. L. Correll, The soil water regime in a young radiata pine plantation in southeastern Australia, *New For.*, *1*(4), 273–289, 1987.

Murphy, C. E., and K. R. Knoerr, The evaporation of intercepted rainfall from a forest stand: An analysis by simulation, *Water Resour. Res.*, *11*(2), 273–280, 1975.

Myers, B. J., and T. Talsma, Site water balance and tree water status in irrigated and fertilised stands of *Pinus radiata*, *For. Ecol. Manage.*, *52*, 17–42, 1992.

Natural Resources Conservation Service, Soil survey NC0068, Wakulla series, U.S. Dep. of Agric., Raleigh, N. C., 1972.

Penman, H. L., Natural evaporation from open water, bare soil and grass, *Proc. R. Soc. London. Ser. A*, *193*, 120–145, 1948.

Rutter, A. J., A. J. Morton, and P. C. Robins, A predictive model of rainfall interception in forests, II, Generalisations of the model and comparisons with observations in some coniferous and hardwood stands, *J. Appl. Ecol.*, *12*, 367–380, 1975.

SAS Institute Inc., *SAS/STAT User's Guide, Version 6* 4th ed., vol. 1, 943 pp., Cary, N. C., 1989.

Singh, B., and G. Szeicz, The effect of intercepted rainfall on the water balance of a hardwood forest, *Water Resour. Res.*, *15*(1), 131–138, 1979.

Soil Moisture Equipment Corporation, Operating instructions for No. 1400 Tempe cell, Santa Barbara, Calif., 1993.

Spittlehouse, D. L., and T. A. Black, A growing season water balance model applied to two douglas fir stands, *Water Resour. Res.*, *17*(6), 1651–1656, 1981.

Stogsdill, W. R., R. F. Wittwer, T. C. Hennessey, and P. M. Dougherty, Relationship between throughfall and stand density in a *Pinus taeda* plantation, *For. Ecol. Manage.*, *29*, 105–113, 1989.

Swank, W. T., N. B. Goebel, and J. D. Helvey, Interception loss in loblolly pine stands of the South Carolina piedmont, *J. Soil Water Conserv.*, *27*, 160–164, 1972.

Teskey, R. O., B. C. Bongarten, B. M. Cregg, P. M. Dougherty, and T. C. Hennessey, Physiology and genetics of tree growth response to moisture and temperature stress: An examination of the characteristics of loblolly pine (*Pinus taeda* L.), *Tree Physiol.*, *3*, 41–61, 1987.

Thornthwaite, C. W., J. R. Mather, and D. B. Carter, Instructions and tables for computing potential evapotranspiration and the water balance, *Publ. Climatol.*, *10*(3), Drexel Inst. Technol. Lab. Climatol., Centerton, N. J., 1957.

Topp, G. C., J. L. Davis, and A. P. Annan, Electromagnetic determination of soil water content: Measurements in coaxial transmission lines, *Water Resour. Res.*, *16*(3), 574–582, 1980.

Weil, R. W., *A Laboratory Manual for General Soils*, 3rd ed., Ginn Press, Lexington, Mass., 1986.

Whitehead, D., and F. M. Kelliher, Modeling the water balance of a small radiata catchment, *Tree Physiolo.*, *9*, 17–33, 1991.

Zahner, R., Refinement in empirical functions for realistic soil-moisture regimes under forest cover, in *International Symposium on Forest Hydrology*, edited by W. E. Sopper and H. W. Lull, pp. 261–274, Pergamon, Tarrytown, N. Y., 1966.

D. A. Abrahamson, USDA Agricultural Research Service, 1420 Experiment Station Road, Watkinsville, GA 30677. (dstark@arches.uga.edu)

P. M. Dougherty, Forest Research, Westvaco, Summerville, SC 29484.

S. J. Zarnoch, Southern Research Station, USDA Forest Service, Asheville, NC 23302.

(Received July 29, 1997; revised July 6, 1998;
accepted July 14, 1998.)