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A Method to Study Response of Large Trees to Different Amounts of Available Soil Water[1]

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Abstract

A method was developed to manipulate available soil water on large trees by intercepting thrufall with gutters placed under tree canopies and irrigating the intercepted thrufall onto other trees. With this design, trees were exposed for 2 years to either 25 percent less thrufall, normal thrufall, or 25 percent additional thrufall. Undercanopy construction in these plots moderately affected patterns of thrufall entry onto the forest floor when compared to a plot without construction. In this pilot study, a variety of aboveground and belowground measurements were recorded from trees over the 2-year period. Additional amounts of thrufall increased circumference growth, litter fall, fine-root biomass, ectomycorrhizal development, and number of fruiting bodies of ectomycorrhizal fungi. Intercepted thrufall decreased amounts of ergosterol, a surrogate for soil and root-origin fungal biomass. Recommendations are made to improve and simplify the design, including arranging gutters to intercept more or less thrufall at any time of year.

Keywords: Ectomycorrhizae, global climate change, root-ingrowth cores, thrufall.

Introduction

General circulation models suggest that the earth's climate may be changing at an unprecedented rate in history (Hansen and others 1987, Schneider 1989). Mean annual global temperature is projected to rise 2 to 6 °C by the middle or end of the 21st century. Increasing temperatures in the United States are predicted to change both the atmospheric supply of moisture (precipitation) and the atmospheric demand for moisture (potential evapotranspiration). Significant increases in drought in the United States are predicted if precipitation decreases by as little as 10 percent (Rind and others 1990, Waggoner 1989).

Few models agree on the direction of change in seasonal patterns of temperature or precipitation in any area of the United States. Some models predict decreases in precipitation for the Southeastern United States, and others predict increases (McCabe and others 1990). Contradictions between circulation models became more controversial after examining historic precipitation records. For example, precipitation in 38 of the 48 contiguous States of the United States has actually increased significantly since 1955 when compared with the period 1895-1954. Idso and Balling (1991) suggest that this increase is caused by increasing emissions of SO_2 from industry since 1955. Air pollution and its contribution to cloud and haze formation and cooler daytime temperatures would tend to increase rainfall and ameliorate drought trends. However, the impact of air pollution on global warming has not been factored into most circulation models.

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Precipitation is the component of climate change likely to have the greatest effect on the composition, structure, and productivity of forests (Wigley and others 1984, Winjum and Neilson 1989). This effect is primarily made possible through controls on soil supply of available water. Available soil water is determined by the differences between gains from precipitation and soil storage and losses from evapotranspiration. Most forest scientists agree that availability of soil water is a primary factor limiting productivity of natural ecosystems (Brown 1978, Kramer 1983) and plantations. Unfortunately, most of our knowledge concerning the effect of available soil water on forest trees is based on studies of seedlings (Lee and others 1990, Seiler and Cazell 1990, Seiler and Johnson 1988), stand modifications by thinning (Brown 1978, Donner and Running 1986, Langdon and Trousdell 1978, Zahner and Whitmore 1960), or the relationship between historic rainfall amounts and tree diameter growth (Bassett 1964, Bay 1963, Marx and others 1988, Zahner and Myers 1986).

Because climate modeling has not provided credible regional predictions of precipitation, how do we study the effects of precipitation on forest trees? Obviously, we need to create long-term experimental scenarios that mimic both increasing and decreasing precipitation. Recent studies on elevating soil water by irrigation (Jarvis 1985, Linder 1987, Persson 1980, Whitehead 1985) provide the only knowledge we have about how large trees respond in the field to different experimental levels of available soil water. The future development of reliable simulation models for whole trees or stands depends on testing with real field data. Information obtained from experimental treatments that mimic rainfall changes should be obtained from aboveground and belowground components of large trees grown where manipulative field designs provide above and below normal precipitation levels (i.e., available soil water).

In this report, we describe a method that provides above normal, normal, and below normal amounts of available soil water by controlling thrufall in plantation-grown loblolly pine (*Pinus taeda* L.). Intercepting thrufall with gutters under tree canopies produces below normal amounts, while irrigating the intercepted thrufall onto other trees produces above normal amounts. We also present preliminary data from aboveground and belowground measurements that reflect tree response to the different amounts of available soil water.

Study Description

Plantation Characteristics

A closed canopy, loblolly pine plantation (planted in 1980) with good 2.4 x 2.4-meter (m) stocking on a 5-percent, smooth slope was selected at the Department of Energy's Savannah River Site (SRS), Savannah River Forest Station (USDA Forest Service), Aiken, SC. Soil is Troup (site index 25 m) classified as well-drained, loamy, siliceous, thermic Grossarenic Paleudults. Trees ranged from 7 to 20 centimeters (cm) in diameter and from 5 to 9 m in height.

In October 1990, soil core sampling protocols were developed for estimating the standing crop of live fine-root (roots $\leq$ 2 millimeter (mm) diameter) biomass on the trees in the plantation (Zarnoch and others 1993). The results showed that 5.7-cm outside diameter (OD) soil cores were as statistically representative as 7.9-cm diameter cores and better than 2.9-cm diameter cores. Using 5.7-cm diameter cores, no spatial patterns resulting from distance from tree, tree diameter, or a void caused by a missing tree were found in fine-root biomass. The lack of spatial patterns in this plantation indicated that no statistical basis for spatial stratification in sampling existed; therefore, random sampling could be used to estimate live fine-root biomass.

In April 1991, all understory woody vegetation was removed with hand tools and nonwoody vegetation was killed with a herbicide. Branches lower than 3 m were removed from all trees. Debris was removed from the site.

Before the soil water treatments were installed, the dimensions of the root systems of trees were measured. The forest floor and upper 10 cm of mineral soil were removed from around the base of several trees to expose lateral roots. Lateral roots (to 0.5-cm diameter) radiated up to 8 m from the base of the trees, with the majority (90 percent) radiating 4 to 5 m, or within two tree rows of each tree. The distance that lateral roots radiated suggested that a two-tree border was necessary around interior measurement trees in study plots.

Chemical analyses of soil collected from the upper 0 to 20 cm in the study area showed the soil to be low in nutrients. It contained 7, 5, 15, and 80 micrograms per gram (g) of available P, K, Mg, and Ca, respectively; pH 4.9; 1.4 percent organic matter content; and 1.0 cation exchange capacity of 1.0 meq per 100 g.

Construction of Study Plots

Four study plots, each with seven rows of six to seven trees, were selected in the plantation and randomly designated as the intercepted thrufall, irrigated thrufall, control, or site-control-treatment plot. Each plot had three rows of three trees in the interior for measurement trees; two trees bordered measurement trees on all sides (table 1). Plots were approximately 17-m square. Treatments were not replicated in this pilot study.

Table l-Tree characteristics in study plots

Treatment	Total plot		Measurement trees	
	No. trees	DBH	No. trees	DBH
		cm		cm
Intercepted thrufall	43	13.8	9	14.6
Study control	48	14.2	9	14.2
Irrigated thrufall	42	14.7	9	14.4
Site control[1]	47	14.1	9	13.7

DBH = Diameter at breast height.

[1] No construction plot.

No construction occurred on the site-control plot, while lumber to support gutters or plastic pipe framed the other three plots (figs. 1 and 2). All lumber was pressure-treated, and all hardware (nails, bolts, nuts, etc.) was galvanized steel. Posts (10 cm x 10 cm x 2.5 m) were placed upright, 45-cm deep into the soil. They were spaced 4 to 5 m apart and centered between trees. Lumber (5 x 20 cm) was bolted to those posts to create a frame with a roof effect. The frames ran perpendicular to tree rows with a l-m slope from plot center to plot ends. Frame height was 1.5 m at plot ends and 2.5 m at the center. Either half or full rings of stainless steel were fastened to the top side of the lumber to hold gutters or plastic pipes in place. The holders were spaced so gutters or pipes placed parallel to tree rows would occupy 25 to 30 percent of the area under tree canopies.

Gutters made of 2-mm (11-gauge) thick sheet aluminum were placed in the intercepted thrufall plot. They were half-round, 10-cm wide x 10-cm deep x 10 m in length and painted with white oil based paint. Their end view was six sided with a pointed bottom. Gutters were turned in their ring holders to empty out pine needles and other debris shed by the canopies. The low ends of all gutters on both sides of the plot were fitted into a manifold that transferred the collected thrufall to a reservoir. Two manifolds were prefabricated from 20-cm diameter, thick-walled, white polyvinyl chloride (PVC) pipe. Slits, 10-cm wide and of various lengths running parallel to the run of the pipe, were cut from the PVC pipe to hold the ends of the gutters. Aluminum screens (0.6-cm mesh) were placed at the ends of the gutters to collect debris. Both manifolds had screen filters at their low ends and were connected to a common 10-cm diameter PVC pipe that drained collected thrufall into a reservoir 15 m from the plot. The reservoir was a 3.7-m diameter x 0.9-m deep, commercially available, round, children's wading pool (8800 liter capacity). The estimated required capacity of the reservoir (pool) was based on the highest weekly rainfall at the site in the past 30 years. The pool had metal sheet sidewalls covered on the inside with a heavy duty plastic liner. It was placed 0.8 m into soil to create a drainage angle from the manifolds and to help keep the water cool. A low roof was constructed over the reservoir (pool) to protect it from debris and sunlight.

In the irrigated thrufall plot, 10-cm diameter PVC pipes, instead of gutters, were placed on the frames. Manifolds and other components of water collection and interception were not constructed in this plot. To standardize shade and thrufall patterns, the PVC pipes were the same size as the gutters. Six irrigation lines (1.9-cm diameter, thick-walled, white PVC pipe) were placed on the forest floor approximately 2.4 m apart and perpendicular to the tree rows. Each line had six irrigation nozzles (Micro-bird spinner

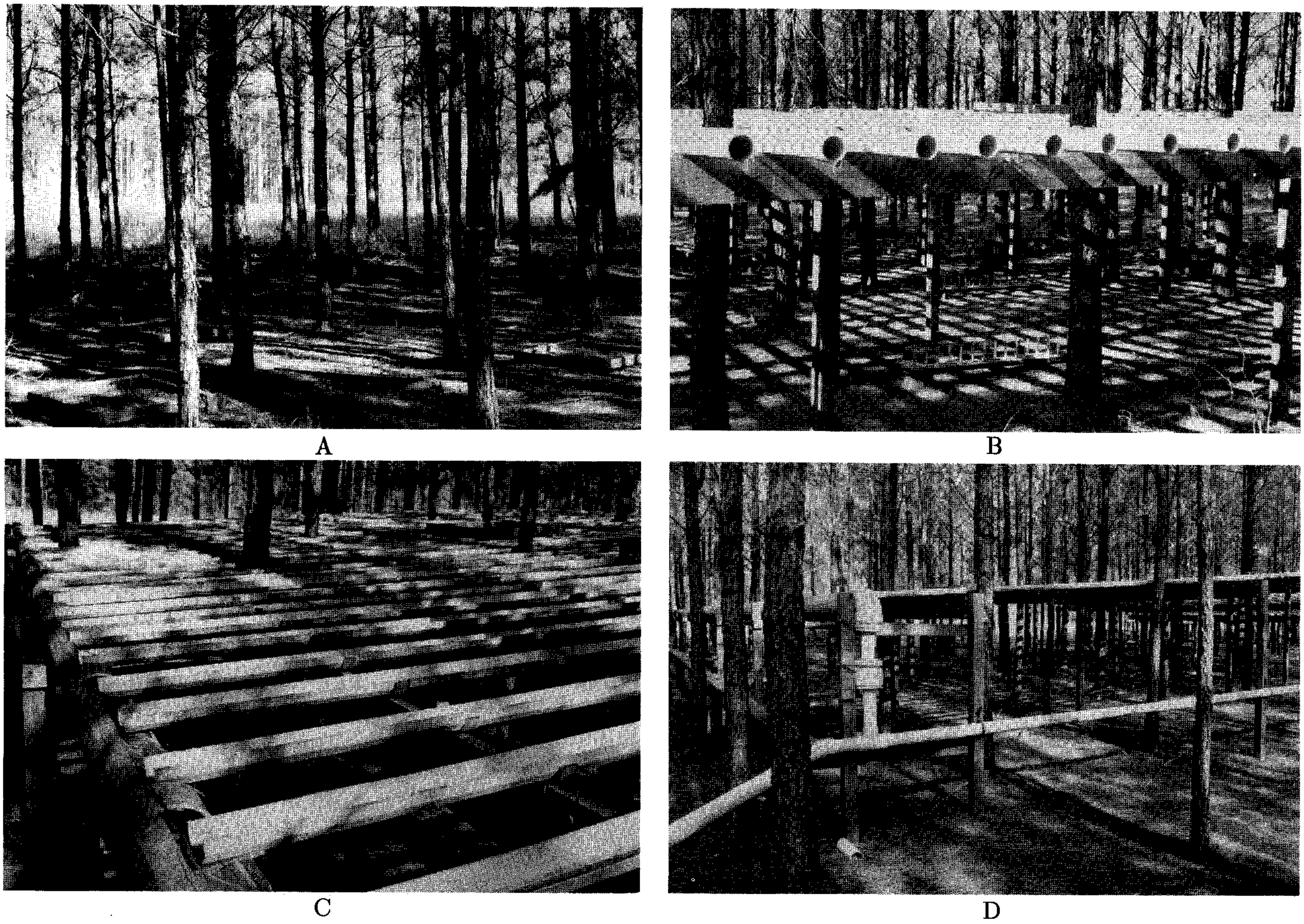

Figure 1-Plots in the loblolly pine plantation used in the intercepted, normal, and irrigated thrufall study. Site-control plot without construction (A), study control plot with under canopy construction (B), gutter array under canopy to intercept thrufall (C), and a manifold that transferred collected thrufall from gutters to water reservoir (D). Note rain gauges, litter collectors, and uniform shade on forest floor.

SP-30-340 nozzle, Rain Bird Sprinkler Manufacturing Corporation, Tampa, FL); one nozzle was placed 1 m from each end of the line, and the remaining four nozzles were equally spaced on the line about 2.4 m apart. Nozzles were mounted on 1.3-cm diameter PVC pipe 15 cm from the forest floor, and the radius of irrigation for each nozzle was 1.3 m. Cut-off valves were placed on the low end of each line to facilitate maintenance and to drain the pipes for winterization. The six irrigation lines were connected to a pumping system by a common PVC pipe (3.8-cm diameter). An electric pump (3 horsepower, 109-liter per minute capacity) powered by a gas-powered generator pumped water to the plot from the reservoir 20 m away. Water in the reservoir was first filtered through a gravel-coated, filtration pipe (17-cm diameter by 1.5-m length) that lay on the bottom of the reservoir, and then through a 100-mesh, in-line filter.

Ten-centimeter PVC pipes were placed on the frames in the control plot to duplicate the shade and thrufall patterns of the other two treatment plots. To determine the possible effects of the construction on tree response, no construction occurred on the site-control plot.

Physical properties of the soil in each plot were determined by driving the sharpened ends of 1.3-m long PVC pipe (10-cm diameter) 1 m into the soil at each plot corner when soil water was high. After soil was dug from around the pipe, it was removed. Soil horizons (color changes) were identified and measured from the hole created by the pipe; these depths were marked on the pipe. Ends of the pipes were closed; pipe:soil columns were brought to the laboratory and frozen at -3 °C for 96 hours. While still frozen, pipe:soil column disks (5-cm thick) were cut from each horizon with a power saw. Soil in the pipe was thawed and processed for soil properties. Located up-slope, the soil properties of the site-control plot differed from those of the three treatment plots, while the treatment plots had similar horizon depths, water flow rates, and water holding capacity (table 2).

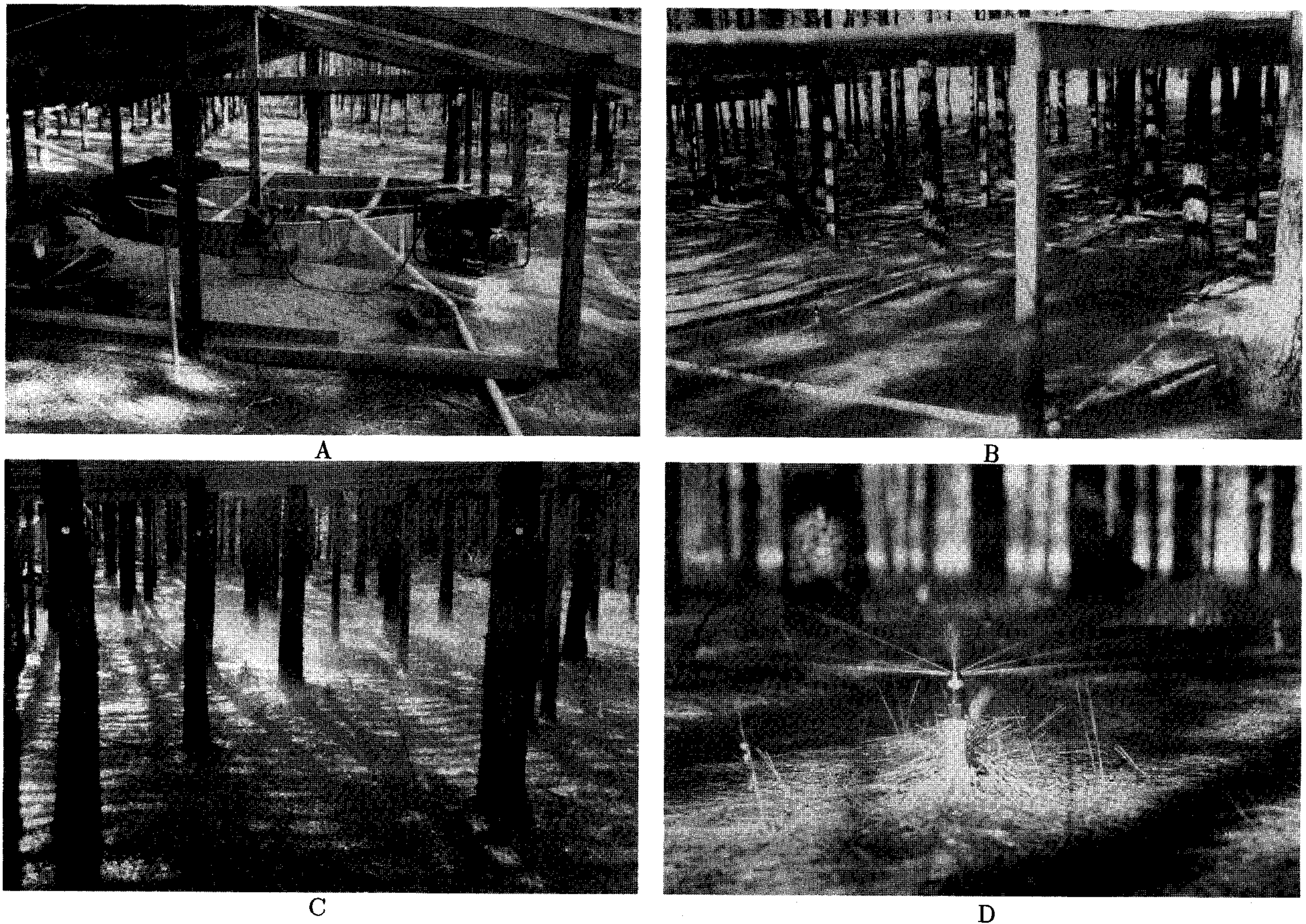

Figure 2-Water reservoir used to hold collected thrufall for irrigation (A), irrigated thrufall plot with irrigation system (B and C), and nozzle irrigating collected thrufall onto forest floor (D). Note rain gauges and pans used to measure volume of irrigation in B and C.

Table 2-Weighted averages of saturated hydraulic conductivity (K) and water holding capacity (WHC) of soil horizons in study plots

Plots	Horizon	Depth	K	WHC	Total profile K	Total profile WHC
		cm	*m/day*	*pct*	*m/day*	*pct*
Intercepted thrufall	A	4.25	16.89	24.5		
	E1	13.75	16.93	20.7	14.29	21.6
	E2	15.50	11.23	21.5		
Study control	A	5.50	18.58	29.3		
	E1	13.50	14.70	22.5	14.86	23.1
	E2	15.50	13.67	21.4		
Irrigated thrufall	A	6.25	14.29	30.4		
	E1	14.75	8.22	21.2	10.44	22.9
	E2	12.50	11.06	20.9		
Site control[1]	A	5.25	6.88	22.9		
	E1	13.50	8.37	18.8	8.29	20.4
	E2	15.25	8.70	20.9		

[1] No construction plot.

Monitoring Thrufall and Tree Measurements

Fifteen glass rain gauges (1.9-cm diameter by 12.5-cm depth) were attached 15 cm apart to 1.5-m long, 5- by 20-cm lumber to create an array of rain gauges. Four arrays were placed level on the forest floor and perpendicular to the overhead gutters or PVC pipes at random in each plot. These arrays were used to measure volume and pattern of thrufall as it passed through the canopies and overhead construction. Measurements were made after significant rain (> 4 mm) and measured to the nearest 1 mm.

Dendrometers were prefabricated (Liming 1957) and placed 1.4 m from ground level on stems of each of the nine measurement trees in each plot. Diameters were measured monthly. Four 1- by l-m litter baskets with screen (6 mm) bottoms were placed on top of the gutters or PVC pipes in the interior five rows of five trees (interior 25 trees) of the treatment plots, Litter baskets were placed on the forest floor in the site-control plot. Litter was measured yearly.

In June 1992, the standing crop of live fine roots was determined on each plot by removing 7.9- by 20-cm deep soil cores from 25 random locations within the area of the 25 interior trees. Fine roots were separated from soil over a 4-mm mesh wire screen. Soil was further examined by hand sorting for roots passing through the screen. Fine roots were transported to the laboratory in coolers and processed within 24 hours. Roots were placed in 250-milliliter (mL) beakers containing 200 mL water with three to four drops of wetting agent, and sonification was performed for 12 minutes to loosen soil and organic matter. Soil and debris were removed by hand with forceps over a No. 10 wire sieve. After cleaning, roots were suspended in water and visually assessed at 4X magnification for ectomycorrhizal development using an arbitrary scoring scale of 0 to 3 in 0.5 increments. Roots were then dried at 65 °C for 24 hours and weighed to the nearest 0.1 milligram.

Root-ingrowth cores were used to measure soil water effects on fine-root-growth potential. The root-ingrowth cores were made 20-cm long from 7.5-cm diameter perforated, rigid plastic tubing (RN-7480, R-L plastic tubing from Internet Inc., 2730 Nevada Avenue North, Minneapolis, MN 55427) with 5- by 5-mm holes in the walls (nine holes per 4 cm^2). Cores were put into the 7.9-cm diameter holes made during sampling (June 1992) for standing live fine-root biomass. After removal of the fine roots, the soil was used to refill each core; all cores were covered with the forest floor.

At monthly intervals from September to December 1992, five cores were removed from each plot and fine roots were collected from the cores (fig. 3). Cores were removed from soil by first vertically cutting along the outside of the core walls with a 25-cm long knife and carefully lifting them from the core hole. Fine roots were screened from soil as described for the June 1992 sample. Cores and screened soil were returned to their respective holes. The September sample represented 3 months of fine-root ingrowth, and the December sample represented 6 months.

In March 1993, soil and roots from all cores were removed and processed; all cores and screened soil were returned to their respective holes. At this time, 5 additional cores were randomly placed in each plot, raising the total to 30 cores per plot. At monthly intervals (September to December), six cores were removed from each plot. Three were processed for live fine-root biomass, and three were processed for ergosterol analyses. Ergosterol, a fungus-origin sterol, is used as a surrogate to estimate living ectomycorrhizal fungal biomass (Nylund and Wallander 1992). After on-site soil screening, both the fine roots and screened soil were placed in separate plastic bags, transported on ice to the laboratory, and processed within 24 hours. Soil was partially dried for 2 hours in a 60 °C oven and screened over No. 10 and No. 25 mesh screen to remove organic matter. Quick partial drying of soil did not quantitatively affect ergosterol. Total fresh weight of screened soil was recorded. Hyphal masses retained on screens were collected and processed separately. After visual evaluation for ectomycorrhizal ratings, the ectomycorrhizae were removed from lateral roots and analyzed separately.

Ergosterol was determined for soil, hyphal masses, and ectomycorrhizae using a modified version of techniques developed by Nylund and Wallander (1992) and Davis and Lamar (1992). This method involved extraction with ethanol:dithiothreitol:KOH and hexane. High-performance liquid chromatography with a Cl8 reverse phase column and an ultraviolet detector at 282 nanometers (nm) was used to detect and quantify ergosterol dissolved in methanol. Hyphal

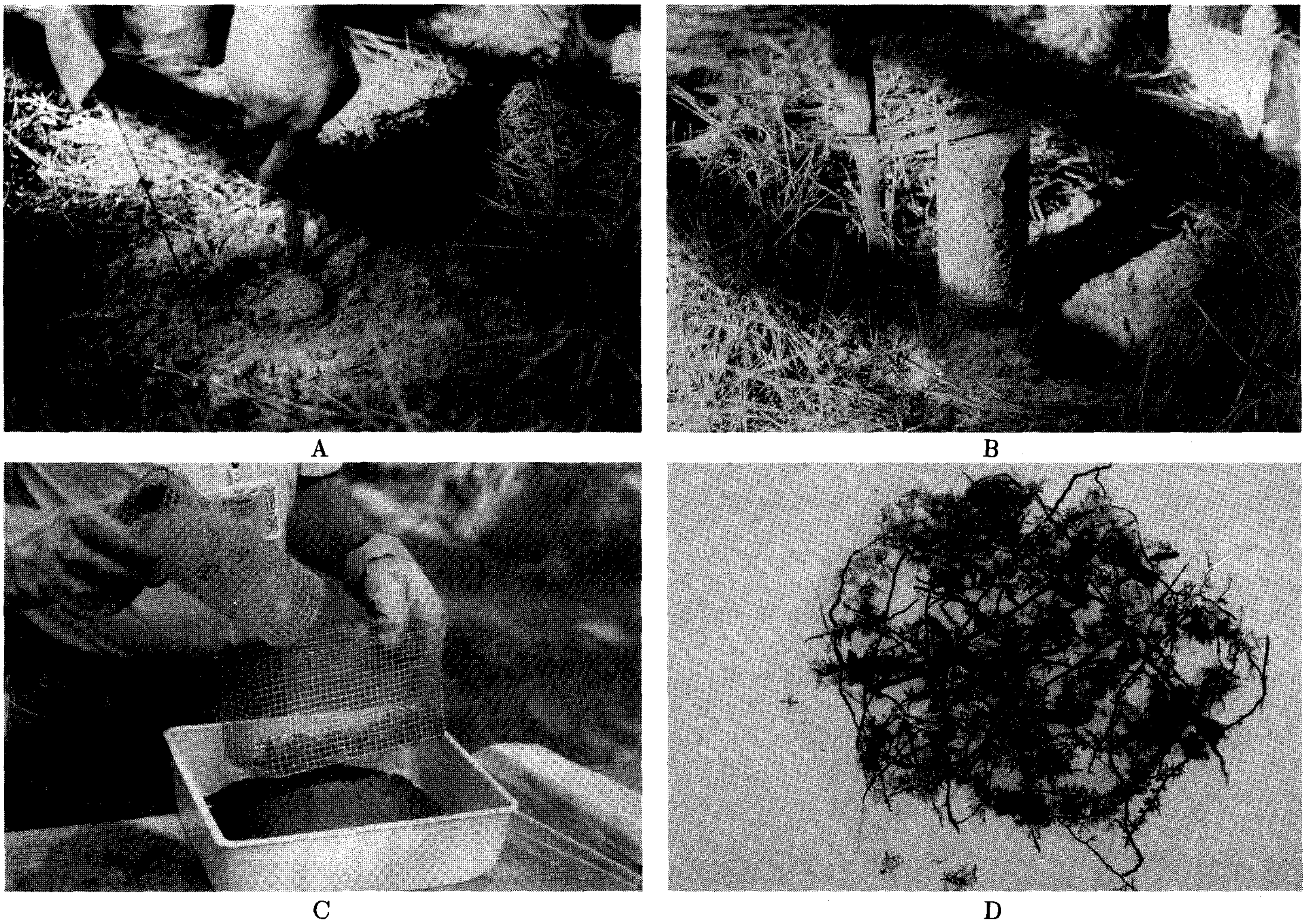

Figure 3—Measurement of fine roots in root-ingrowth cores. Knife is used to cut lateral roots grown into soil in the cores (A), core removed (B), removal of fine roots by screening soil from cores (C), and example of fine roots produced in 4 months within a core (D).

masses and ectomycorrhizae were processed like soil with one exception-before extraction, they were homogenized with mortar and pestle in the extract solution. Fine-root-ingrowth biomass was determined for each of these samples by combining the dry weights of all processed root tissue. A series of control tests to determine extraction efficacy were performed by adding known amounts of reagent-grade ergosterol to soil and roots. The recovery of ergosterol in these quality control tests was $>$ 95 percent.

Irrigation

The study began in May 1992 by turning gutters upright to begin intercepting thrufall. Irrigation was done when $>$ 4 mm of thrufall was detected in rain gauge arrays under the PVC pipes. The volume of each irrigation was measured with the four rain gauge arrays and four 60- by 60- by 5-cm deep pans randomly placed in the irrigated thrufall plot (fig, 2). At each irrigation, fruiting bodies of fungi, mainly those of ectomycorrhizal fungi, were counted and removed from all plots.

In 1992, treatments began in late May and ended in mid-December when the gutters were turned over to stop thrufall interception. Litter samples were collected and the irrigation system was winterized by draining all pipes and the pump. In 1993, treatments were maintained from early April to mid-December.

Results and Discussion

Patterns of tree growth, aboveground and belowground, and litter fall in the site-control plot (no construction) were similar to those in the control plot. Therefore, tree growth data from the site-control plot will not be included in this report. Because thrufall treatments were not replicated in this pilot study, the data can only be used to show trends and not statistical probabilities.

Analyses of rain volumes in the rain gauges in each plot indicated that the construction changed thrufall patterns by about 15 to 20 percent when compared to those from the site-control plot. The coefficient of variation (CV) for thrufall collected in the site control, intercepted thrufall, irrigated thrufall, and the control plots was 15.5, 19.1, 34.9, and 31.1, respectively. The CV of rainfall collected in the open was 6.9. Plots with PVC pipes showed the greatest variation. The pipes tended to collect thrufall on their undersides, which dripped irregularly along the pipe lengths, and the rain gauges measured the irregular pattern. The aluminum gutters dripped considerably less than the PVC pipes and thrufall patterns for the site-control plot differed little from the plot with gutters (intercepted). Other than the dripping under the PVC pipes, no significant rain shadows resulted from the construction. Apparently, the height (1.5 to 2.5 m) of the construction allowed enough wind-mixing of thrufall between the construction and the forest floor to minimize rain shadows. Visual examination of mineral soil in a few locations in each plot showed that after 10- to 12-mm rains, the soil was wetted evenly. Obviously, the 1- to 1.5-cm deep forest floor helped disperse the thrufall.

Using data from 15 rain events ranging in volume from 9 to 109 mm, amounts collected in the open were compared to amounts of thrufall collected in the site-control plot. The comparison showed that the tree canopies intercepted an average of 30 percent (range from 9 to 50 percent) of rainfall allowing 70 percent to penetrate as thrufall to the forest floor. The degree of canopy interception did not appear to be related to volume of rainfall; canopies retained about 4 to 6 mm of rainfall regardless of final volume of the rain event.

In 1992, treatments were applied for 6½ months and involved 17 irrigations, equaling 1 every 10 days (fig. 4). Based on rainfall records dating back to 1952, the rainfall at the SRS in these months in 1992 was 15 percent above average. The gutters intercepted 24.3 percent of thrufall when compared to the average thrufall in the irrigated and control plots. The irrigated plot received 24.8 percent additional water. The amount of thrufall affected the percent of thrufall intercepted by the gutters. Thrufall more than 15 mm was intercepted at the designed rate more consistently than thrufall less than 15 mm. Interception of thrufall less than 15 mm was erratic.

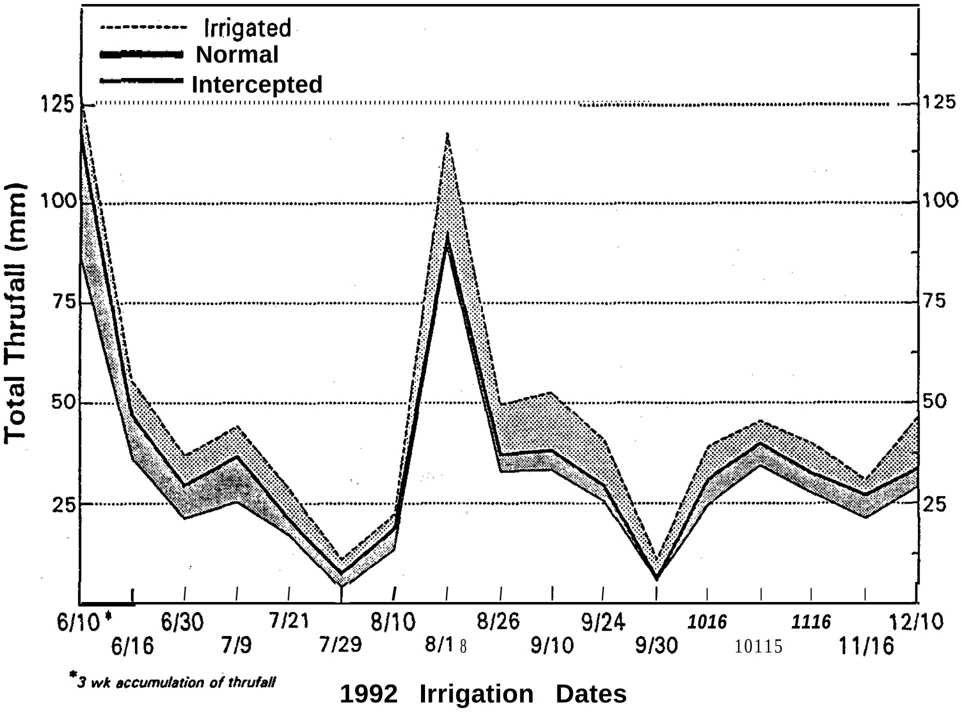

Figure 4—Amount of thrufall in millimeters received by trees in intercepted, normal, and irrigated thrufall plots in 1992. Amount recorded on June 10 represents a 3-week accumulation.

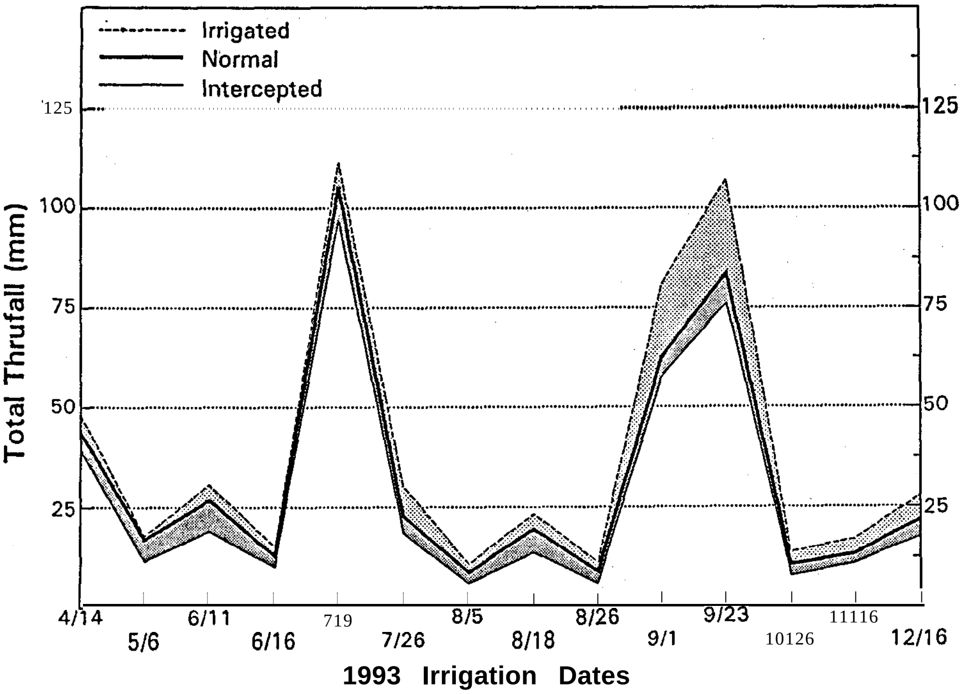

Figure 5-Amount of thrufall in millimeters received by trees in intercepted, normal, and irrigated thrufall plots in 1993.

In 1993, treatments were applied for 8½ months and involved 14 irrigations equaling 1 every 17 days (fig. 5). In contrast to 1992, the rainfall in this period in 1993 was 18 percent below normal. Over 5 months in this period, less than 125 mm of total thrufall was measured in the site-control plot. The gutters intercepted 25.4 percent of thrufall, and the irrigated plot received 24.2 percent additional thrufall.

Tree circumference growth between trees in the control plot and the intercepted thrufall plot did not differ (fig. 6). Trees in the irrigated plot, however, showed 30 percent more circumference growth midway into the treatment period. These differences persisted through the winter (December to March), and stem growth differences in 1993 were similar to those found in 1992 (fig. 6). Additional thrufall from irrigation stimulated stem circumference growth, but less thrufall did not decrease stem growth when compared to control.

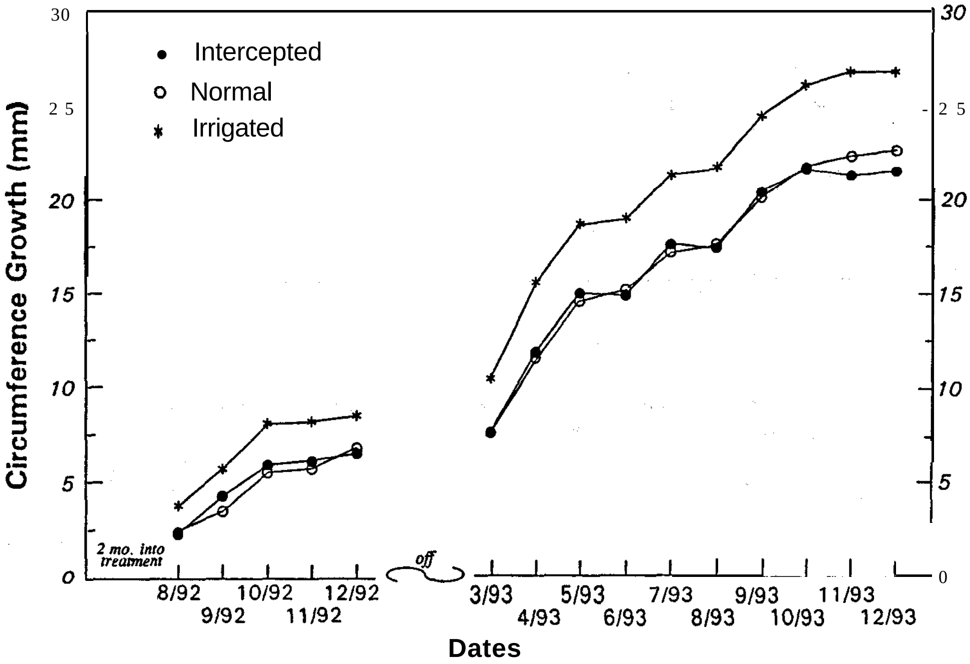

Figure B-circumference growth of trees in millimeters in plots with intercepted, normal, and irrigated thrufall in 1992 and 1993.

The initial standing crop of live fine-root biomass, removed from soil cores before ingrowth cores were installed in June 1992 ranged from 328 to 340 g per m^2 of soil 20-cm deep for all plots. Ingrowth of fine roots was stimulated by irrigation as early as October 1992 (fig. 7); however, a sharp decrease in fine-root ingrowth occurred in November 1992. This decrease was most evident in the control and irrigated thrufall plots. High thrufall in August preceded high ingrowth in October, and low thrufall in September preceded low ingrowth detected in November, which suggests that a large amount of fine roots died between October and November. Rates of ingrowth increased in all plots following increased thrufall. By December, irrigation had produced twice as much ingrowth as the other treatments. This pattern continued through 1993, but overall fine-root ingrowth was much less than in 1992 (probably due to less soil water). Ingrowth after 3 months in 1992 was as large as ingrowth after 6 months in 1993. Neither in 1992 nor in 1993 did fine-root-ingrowth biomass approach that found in the original standing crop of fine roots. This suggests that some fine roots persist from year to year and do not die and regenerate within the same growing season.

Ingrowth that occurred after replacement of cores each month from September to December 1992 was assessed in March 1993. Results indicated that regardless of thrufall treatments, only modest amounts of ingrowth occurred after September, and biomass decreased sharply each month thereafter (fig. 8). It is possible that no growth occurred or growth occurred and died (turnover) before assessments in March 1993. These findings also suggest that most fine-root development in loblolly pine takes place in the spring and early summer.

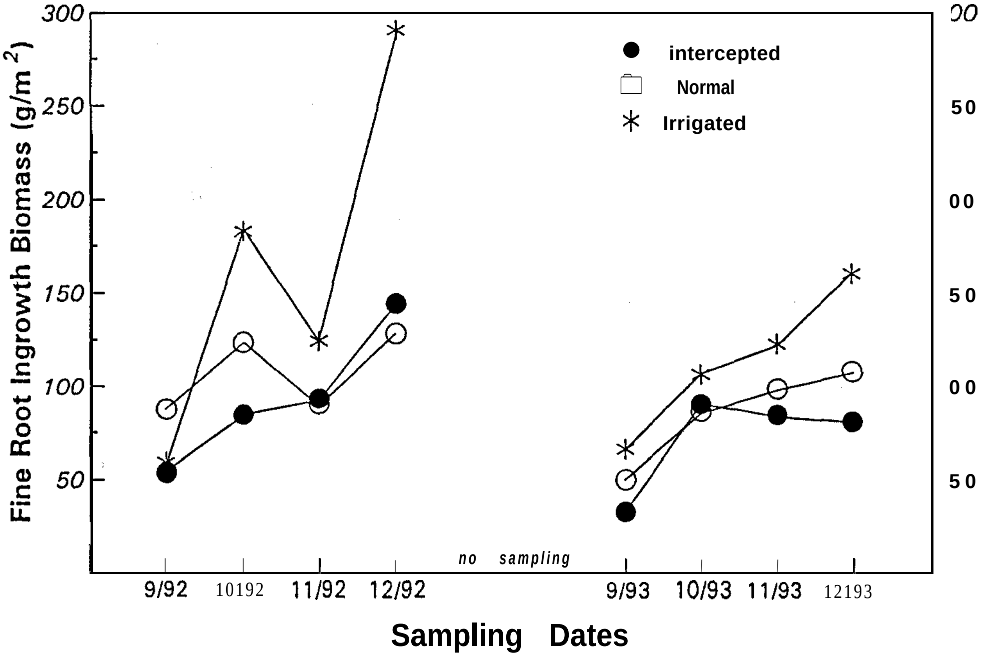

Figure 7—Production of fine-root biomass in grams per square meter after different thrufall treatments in 1992 and 1993.

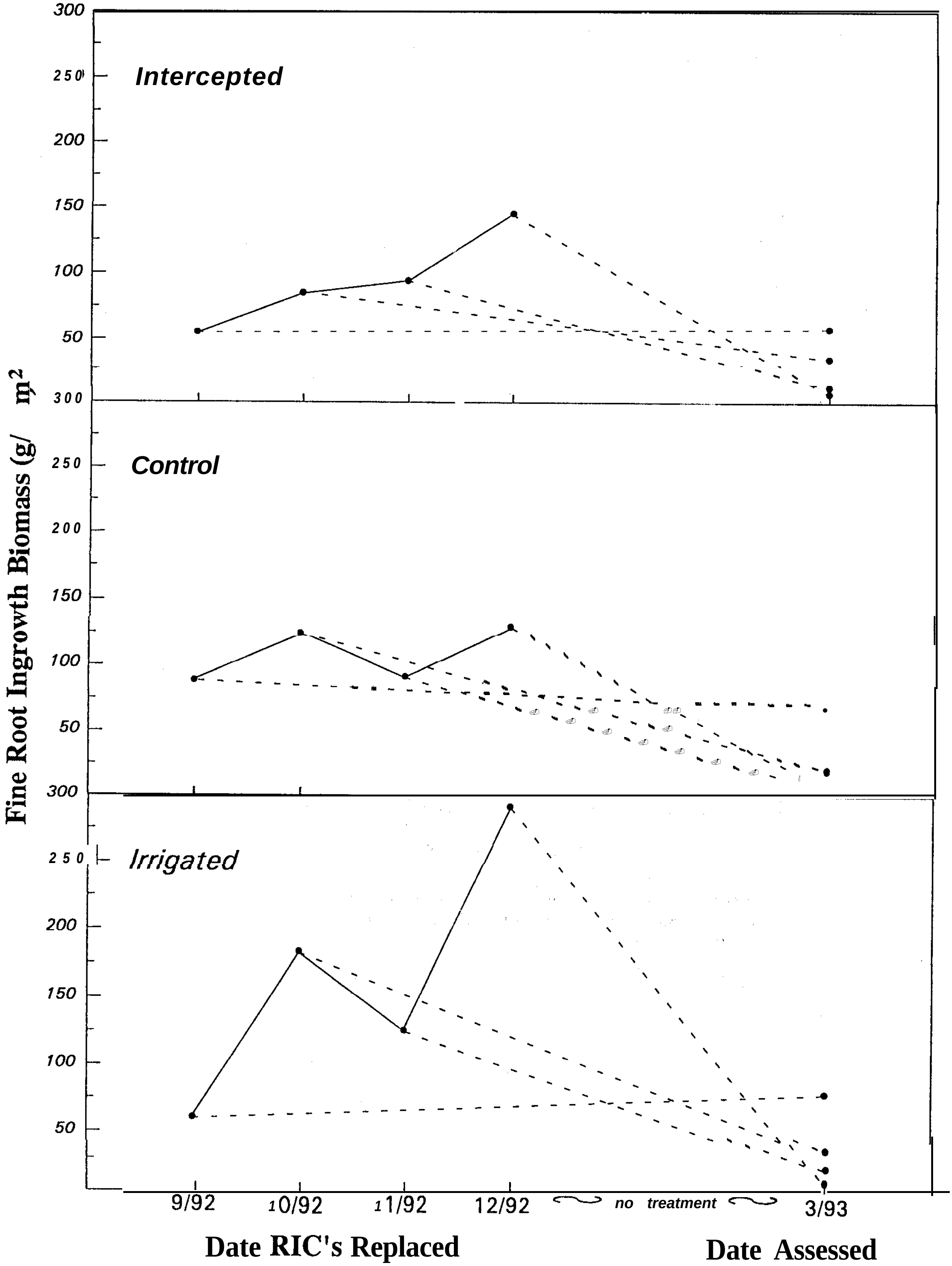

Figure 8—Production of fine-root biomass in grams per square meter after different thrufall treatments in ingrowth cores emptied and replaced at different times and then sampled in March 1993.

Assessments of ectomycorrhizal development on lateral roots from the ingrowth cores showed the effects of thrufall (fig. 9). A strong and consistent trend for increasing ectomycorrhizal development with increasing thrufall appeared in most months of both years. Black ectomycorrhizae formed by *Cenococcum geophilum*, a droughty soil, root-symbiont, were common in all samples but appeared most frequently in high numbers in samples from the intercepted thrufall plot. Considerably fewer fruiting bodies of known genera (*Amanita*, *Suillus*, *Lactarius*, *Tricholoma*, and *Cantharellus* spp.) of other ectomycorrhizal fungi occurred in the intercepted thrufall plot. In 1992, the number of fruiting bodies in the intercepted, normal (control), and irrigated thrufall plots were 317, 400, and 649, respectively; 84, 149, and 343 appeared in the same plots in 1993. These data show both the effects of increased thrufall in 1 year and the effects of different amounts of thrufall between years on fruit body production. Over 80 percent of the fruiting bodies were observed in November and December each year.

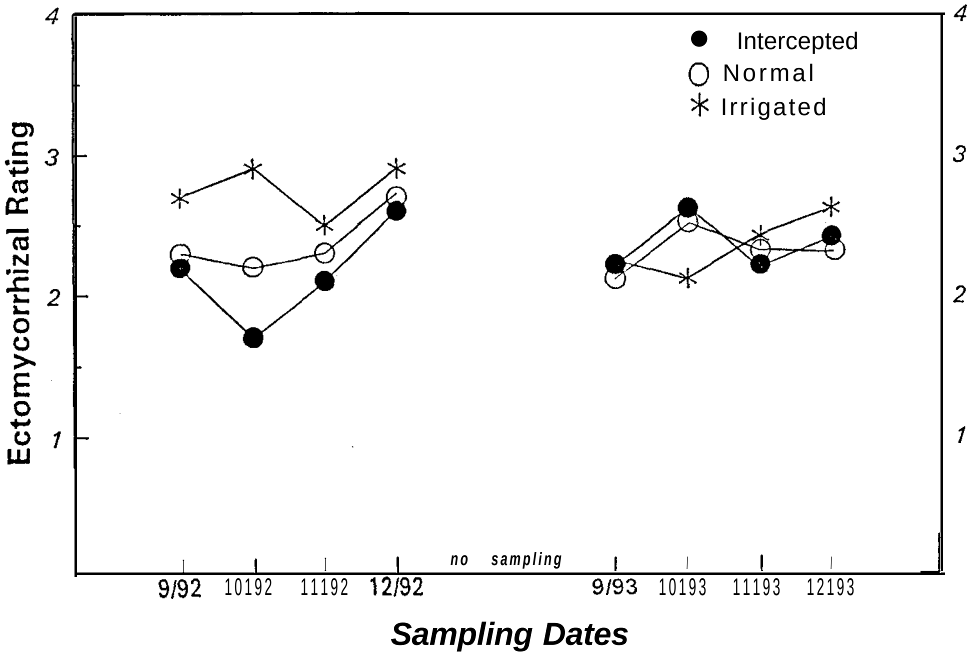

Figure 9—Rating for ectomycorrhizae produced on roots collected from ingrowth cores after different thrufall treatments in 1992 and 1993.

Visual quantitative estimates of ectomycorrhizal development have several limitations. First, these estimates do not consider the quantity of lateral roots supporting ectomycorrhizae; they only estimate the relative proportion of ectomycorrhizal to nonmycorrhizal roots on the lateral roots. This, limitation can be overcome by using a derived parameter-feeder root potential obtained from live fine-root-ingrowth biomass (a) and the ectomycorrhizal rating (b) data in the formula (a x b) divided by 100. These derived values (fig. 10) show more succinctly the response of fine roots and ectomycorrhizae to different amounts of thrufall. Trees in irrigated thrufall plots had more than twice the feeder root potential than those receiving less thrufall each year.

A second limitation of visual estimates involves the lack of accounting for the amount of fungal tissue in the ectomycorrhizae, which is related to the relative size of the ectomycorrhizae. This limitation can be overcome by using ergosterol analyses. Results from the ergosterol analyses showed large differences in the location of fungal biomass and its response to thrufall treatment and sampling period. With thrufall treatments combined, ergosterol (fungal biomass) in soil exceeded the combined biomass in ectomycorrhizae and hyphal masses by nearly two times from September through November and by more than two times (fig. 11A) in the December sample. Normal and irrigated thrufall showed sharp increases in soil and total fungal biomass in the December sample (figs. 11B and 11C), suggesting there was insufficient soil water in the intercepted thrufall plot to stimulate fungal growth either in soil or elsewhere. Little difference in fungal biomass in any samples from September through November indicated a steady state for fungal growth during this period. Increased ergosterol, both total and in soil, found in the December samples correlated well with increased production of fruiting bodies of ectomycorrhizal fungi.

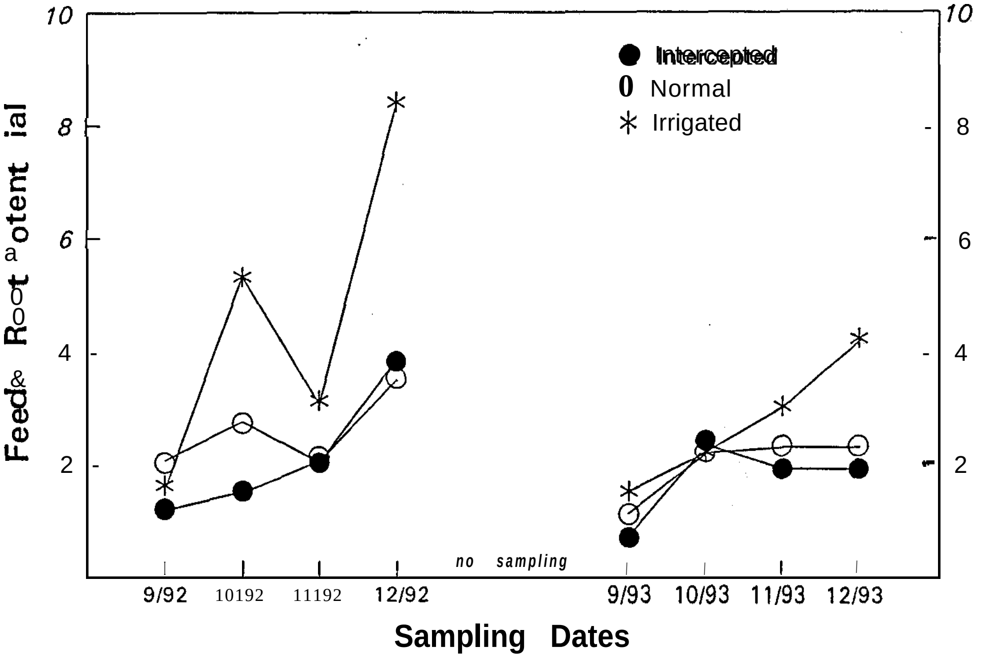

Figure IO-Feeder root potential derived from tile-root biomass and ectomycorrhizae rating after different thrufall treatments in 1992 and 1993.

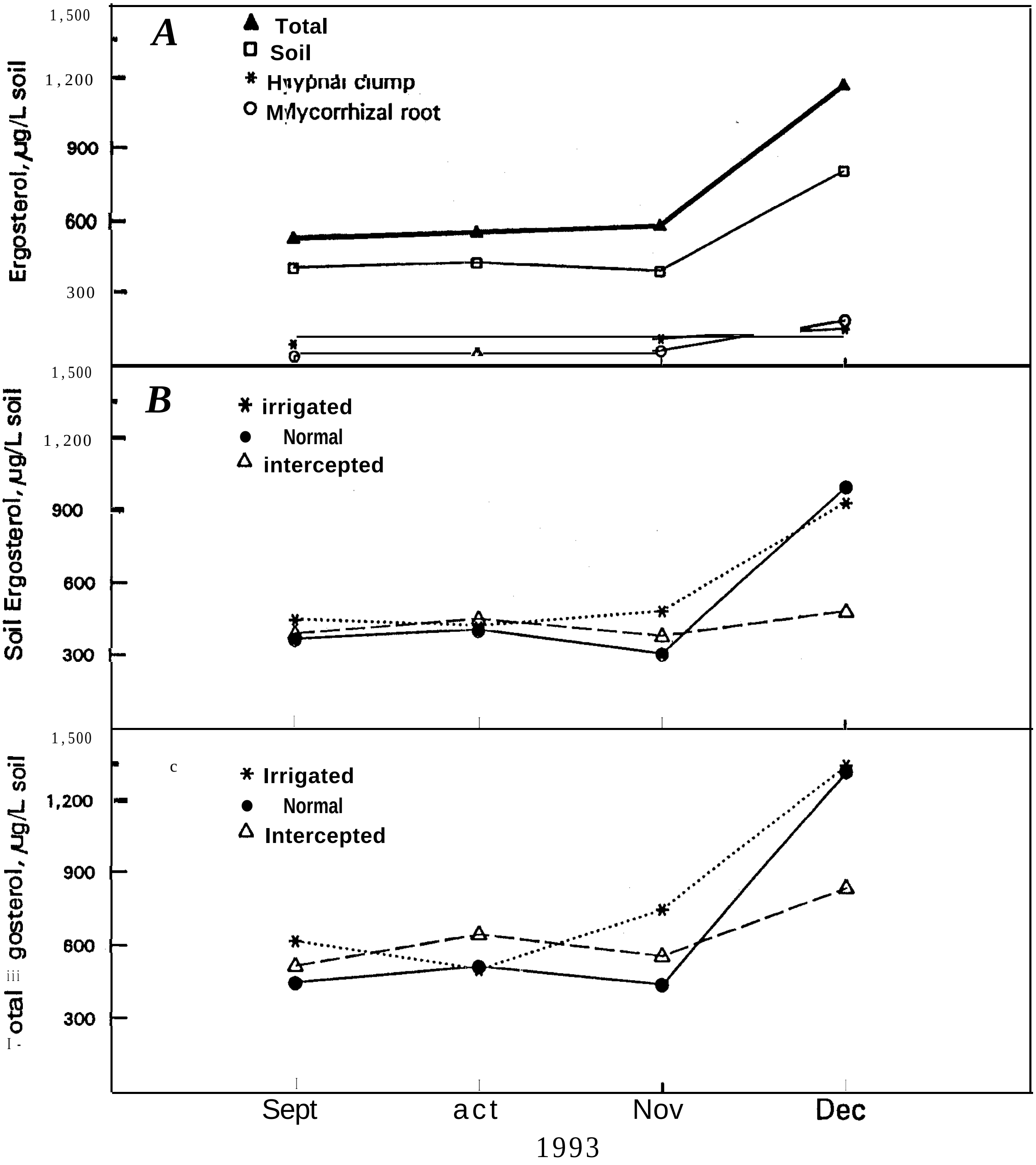

Figure 11—Ergosterol analyses of soil and roots from root-ingrowth cores after different thrufall treatments in 1993. Ergosterol in combined thrufall treatments (A), from soil as affected by thrufall treatments (B), and as total from soil, ectomycorrhizae and hyphal masses as affected by thrufall treatments.

In both years, litter fall in the intercepted thrufall plot was less than in the other treatment plots. The 1992 and 1993 accumulations of litter biomass were 254 and 248 g per m^2 in the intercepted thrufall plot, 276 and 412 g per m^2 in the control (normal) thrufall plot, and 300 and 353 g per m^2 in the irrigated thrufall plot.

Conclusions and Recommendations

The system of gutters arranged under tree canopies in this pine plantation consistently intercepted predicted quantities of thrufall without seriously affecting thrufall patterns on the forest floor. The physical area of the gutter surfaces was between 25 and 30 percent, and they intercepted an average of 25 percent thrufall over 31 treatment periods during the 2 growing seasons. The arrangement of manifolds, screen filters, drain pipes, water reservoir, and the pump/irrigation system was also effective. The system intercepted nearly 100 percent of the thrufall during the 31 irrigations. The simple wooden frames supporting the light weight gutters and PVC pipes had no obvious invasive effects on aboveground and belowground tree growth. The construction design in this pilot study successfully created thrufall treatments of 25 percent below normal, normal (control), and 25 percent above normal.

Several improvements could be made in construction design:

1. PVC pipes should not be used to mimic physical effects of the gutters. They create identical shade but, unfortunately, dripping of thrufall from their undersides has significant and undesirable effects on thrufall patterns.

2. The gutter shape should be changed from the half-round six-sided, pointed bottom design to a simple tray shape with 2-cm high walls and a flat bottom 10-cm wide. Less expensive to construct, the flat gutters would allow easier emptying of debris. The half-round gutters would not easily lay flat in their rings in the wooden frames after turning to empty the debris. With tray gutters, properly placed wooden blocks mounted in the wooden frames would simplify emptying and repositioning. Tray gutters should be made of the same 11-gauge aluminum to assure sufficient strength to support their weight and the weight of thrufall and debris over the 4- to 5-m span between supports.

3. The drainage angle (3-cm fall for each l-m length) of the current design was too severe. Intercepted thrufall drained rapidly to the manifolds as did all the debris. Collecting this debris from the manifold screens and replacing it in the plot was time consuming. Tray gutters with a drainage fall of 1 cm per meter length would suffice. Intercepted thrufall would still drain effectively but most litter would remain approximately where it landed and not wash to the manifold. Turning these gutters to empty them periodically would allow more normal deposition of litter on the forest floor. To reduce drainage angle, the current 1.5 cm-high wooden frames on plot-ends should be raised so they are only 10 cm shorter than frames in the plot center.

4. All treatment plots should have tray-shaped gutters. On intercepted thrufall plots, gutters would be turned to intercept thrufall. On other treatment plots, gutters would be inverted so they did not intercept thrufall. Because gutters would be constructed on all treatment plots, thrufall patterns, shade, etc. would be the same for all treatment plots. Using gutters on all plots would also allow for different treatments, such as intercepting thrufall during only parts of the year or intercepting thrufall on alternate years. The number of gutters could be increased to intercept more thrufall or decreased to intercept less.

5. All construction components in contact with intercepted and irrigated thrufall must be noncorrosive. The gravel filter used in the water reservoir had steel parts that began to rust by the second year. Such components must be made of plastic, stainless steel, or other noncorrosive material.

Measurements of tree response in this pilot study were kept simple because our main objective was to develop reliable methods to intercept a specific amount of thrufall from one plot of trees and to irrigate this same amount of thrufall onto another plot of trees. Certain trends in tree response to thrufall amounts, however, were observed. In both test years, 25 percent below normal thrufall did not have obvious effects on tree growth, but 25 percent above normal thrufall did. Stem growth, ingrowth of fine roots, ectomycorrhizal development, feeder root potential, and number of fruiting bodies of ectomycorrhizal fungi were greater on the irrigated plot than on the control plot. The only measurement to show an effect of below normal thrufall was the ergosterol assay. Ergosterol amounts were lower, indicating less live fungus biomass, in soil and ectomycorrhizae in the 25 percent below normal thrufall plot than in the control plot and higher in the 25 percent above normal thrufall plot than in the control plot.

This pilot study shows how simple construction can manipulate thrufall amounts (available soil water) for extended periods on large, field grown trees. This gutter and irrigation system for controlling available soil water could be used to create a range of available soil water regimes in well-replicated studies on a variety of forest sites. With data obtained from aboveground and belowground measurements, a reliable simulation model on tree response to changes in precipitation patterns could be created. This model would be useful in predicting tree, stand, and ecosystem response to future climate changes.

Literature Cited

Bassett, J.R. 1964. Diameter growth of loblolly pine trees as affected by soil-moisture availability. Res. Pap. SO-9. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 7 p.

Bay, R.R. 1963. Soil moisture and radial increment in two density levels of red pine. Res. Note L-30. St. Paul, MN: U.S. Department of Agriculture, Forest Service. 4 p.

Brown, C.L. 1978. The physiological role of water in tree growth and development. In: Balmer, W.E., ed. Proceedings of the soil moisture . . . site productivity symposium; 1977; November 1-3, Myrtle Beach, SC. Atlanta, GA: U.S. Department of Agriculture, Forest Service, Southern Region: 22-29.

Davis, M.W.; Lamar, R.T. 1992. Evaluation of methods to extract ergosterol for quantitation of soil fungal biomass. Soil Biology and Biochemistry. 24:189-198.

Donner, B.L.; **Running, S.W.** 1936. Water stress response after thinning *Pinus contorta* stands in Montana. Forest Science. 32:614-625.

Hansen, J.; **Lacis, A.; Rind, D.; Russell, G.; Fung, I.;** Ledededff, S. 1967. Evidence for future warming: how large and when? In: Shands, W.E.; Hoffman, J.S., eds. The greenhouse effect, climate change, and U.S. forests. Washington, DC: The Conservation Foundation: 57-75.

Idao, S.; **Balling, R.C.,** Jr. 1991. Surface air temperature response to increasing global industrial productivity trends: A beneficial greenhouse effect? Theoretical Applied Climatology. 44:37-41.

Jarvis, P.G. 1935. Increasing productivity and value of temperate coniferous forests by manipulating site water balance. In: Ballard, R.; Farnum, P.; Ritchie, G.A.; Winjum, J.K., eds. Forest potentials-productivity and value. Proceedings of Weyerhauser Science Symposium 4; 1984 20-24 August; Tacoma, WA: Centralia, WA: Weyerhauser Co. 39-74.

Kramer, P.J. 1963. Water relations of plants. New York: Academic Press. 469 p.

Langdon, O.G.; Trousdell, K.B. 1973. Stand manipulation: effects on soil moisture and tree growth in southern pine-hardwood stands. In: Balmer, W.E., ed. Proceedings of the soil moisture site productivity symposium. 1977; November 1-3, Myrtle Beach, SC. Atlanta, GA: U.S. Department of Agriculture, Forest Service, Southern Region: 221-236.

Lee, **W.S.; Chevone,** B.I.; **Seiler, J.R.** 1990. Growth and gas exchange of loblolly pine seedlings as influenced by drought and air pollutants. Water, Air and Soil Pollution. 51:105-116.

Liming, F.G. 1957. Homemade dendrometers. Journal of Forestry. 55: 575-577.

Linder, S. 1967. Responses to water and nutrients in coniferous ecosystems In: Schulae, E.O.; Zwolfer, H., eds. Ecological studies. Berlin, Germany: Springer-Verlag: 180-202. Vol. 61.

Marx, Donald H.; Cordell, Charles E.; Clark, Alexander III. 1988. Eight-year performance of loblolly pine with *Pisolithus* ectomycorrhiaae on a good-quality forest site. Southern Journal of Applied Forestry. 12:275-280.

McCabe, G.J., Jr.; Wolock, D.M.; Hay, L.E.; *Ayers,* **M.A.** 1990. Effects of climate change on the Thornthwaite moisture index. Water Resources Research. 26:633-643.

Nylund, J.-E.; Wallander, H. 1992. Ergosterol analysis as a means of quantifying mycorrhizal biomass. Methods in Microbiology. 24:77-88.

Persson, H. 1980. Fine root dynamics in a Scots pine stand with and without near optimum nutrient and water regimes. Acta Phytogeographica Suecica. 68:101-110.

Rind, D.; Goldberg, R.; Hansen, J.; Rosenzweig, C.; Ruedy, R. 1990. 'Potential evapotranspiration and the likelihood of future drought. Journal of Geophysical Research. 95:9983-10004.

Schneider, S.H. 1989. The greenhouse effect: science and policy. Science. 243:771-781.

Seiler, J.R.; Caeell, B.H. 1990. Physiology and growth of red spruce seedlings as influenced by water stress. 'Dee Physiology. 6:69-77.

Seiler, J.R.; Johnson, J.D. 1988. Physiological and morphological responses of three half-sib families of loblolly pine to water-stress conditioning. Forest Science. 34:487-495.

Waggoner, P.E. 1969. Anticipating the frequency distribution of precipitation if climate change alters its mean. Agricultural and Forest Methodology. 47:321-337.

Whitehead, D. 1985. A review of processes in the water relations of forests. In: Landsberg, J.J.; Parsons, W., eds. Research for forest management. Melbourne, Australia: CSIRO: 94-124.

Wigley, T.M.L.; Britts, K.R.; Jones, P.D. 1964. Predicting plant productivity and water resources. Nature. 312:102-103.

Winjum, J.P.; Neilson, R.P. 1969. The potential impact of rapid climatic change on forests in the United States. In: Smith, J.B.; Tirpak, D.A., eds. The potential effects of global climate change on the United States. Washington, DC: U.S. Environmental Protection Agency; Report to Congress: Vol. 1, Chapter 11:1-39.

Zahner, R.; Myers, R.K. 1986. Assessing the impacts of drought on forest health. In: Proceedings of annual meeting Society of American Foresters; 1936 October 5-8; Birmingham, AL. Bethesda, MD: Society of American Foresters: 227-234.

Zahner, R.; Whitmore, F.W. 1960. Early growth of radically thinned loblolly pine. Journal of Forestry. 58:628-634.

Zarnoch, Stanley **J.; Marx, Donald H.; Ruehle, John L.; Baldwin, Virgil** C. 1993. Sampling open-top chambers and plantations for live fine-root biomass of loblolly pine. Res. Note SE366 Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 19 p.

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