EFFECT OF IRRIGATION AND FERTILIZATION ON SELECTED PHYSICAL AND MECHANICAL PROPERTIES OF LOBLOLLY PINE (*PINUS TAEDA*)

Julia Kao Hsu[1] and *C. S. Walters*[2]

Graduate Assistant and Professor of Wood Technology, respectively,
University of Illinois at Urbana-Champaign, Urbana, IL 61801

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ABSTRACT

A study of the interacting effects of irrigating and fertilizing a loblolly pine plantation showed that soil moisture and ammonium nitrate fertilizer significantly affected fiber stress at proportional limit and modulii of rupture and elasticity. The effects of irrigation and fertilization on work to proportional limit were not significant and work to maximum load was affected only by irrigation. The percentage of latewood in the annual rings was found to range from 36 for wood grown on medium wet, heavily fertilized (100 lbs/acre) plots to 57 for wood grown on nonirrigated, heavily fertilized plots. The best growth rate (6.8 rings/inch) was obtained for wood taken either from the south sides of trees grown on the wettest and medium-wet plots, or from the north side of trees grown on the medium-dry plot. The strongest and stiffest wood was taken from trees grown on unirrigated plots that had received 100 pounds of ammonium nitrate per acre.

There was a positive linear correlation between percent of latewood and specific gravity, growth rate, bending strength, and stiffness. There was a similar relationship between specific gravity and the bending strength and stiffness of wood.

Maintaining soil moisture in the range of 30 to 60% of field capacity and providing a moderate amount (50 lbs/acre) of nitrate fertilizer are recommended for increasing the bending strength and stiffness of loblolly pine. Such a silvicultural practice would accelerate the growth of poles of superior strength and stiffness or pulpwood of higher fiber yield. The cost of such practices was not included in the study.

Additional keywords: Earlywood, latewood fertilization, irrigation, water deficits, specific gravity, growth rate, fiber stress at proportional limit, modulus of rupture, modulus of elasticity, work to proportional limit, work to maximum load.

INTRODUCTION

Within the past two decades, forest fertilization and, to a limited extent, irrigation, have become of interest as the management of selected forested land has become more intensive. While these interests generally have been focused upon the possibility of improving wood yield (Tappi 1962; Weiner and Roth 1966), some reports have referred to the individual effect of fertilization or irrigation on wood properties. Practically nothing has been said about the interacting effects of irrigation and fertilization on the properties of wood.

It is well known that there is a relationship between water supply and wood formation. Soil moisture often becomes a limiting factor in tree growth because of its effects on internal water balance, which in turn affects processes controlling growth. Either an excess or a deficiency of soil moisture can produce a water deficit (Kramer and Kozlowski 1960). Water deficit usually reduces enlargement more than cell division or cell differentiation. As a result, cells in plants subjected to water deficits tend to differentiate earlier and to a greater extent than those which do not suffer from water deficits. Stems are shorter and more

[1] Present address: Dept. Materials Science and Engineering, Washington State University, Pullman, WA 99163.

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lignified, and annual rings are narrower Kramer and Kozlowski 1960).

Since soil moisture content and nitrogen play highly effective roles affecting stem growth, we designed this study to measure the interacting effects of irrigation and fertilization on latewood percentage, wood density, growth rate, and five mechanical properties.

Erickson and Lambert (1958) examined the effect of fertilization on young Douglas-fir [(*Pseudotsuga menziesii* Mirbr) Franco]. They found that the percentage of latewood and specific gravity decreased significantly after fertilization. However, the increased volume increment of the fertilized stands, in terms of pulp utilization, more than compensated for the decrease in specific gravity.

Williams and Hamilton (1961) obtained essentially the same results for slash pine (*Pinus elliottii*) grown in the deep sands of Georgia. They reported that trees receiving supplemental fertilizers produced 26% wider annual diameter-increments with a 3 to 7% reduction in both percentage of latewood and specific gravity. These changes were primarily due to the addition of nitrogen. It was indicated that no significant difference existed in the cell-wall thickness of longitudinal tracheids from fertilized and control trees.

Zobel et al. (1961) studied the effects of high and moderate levels of fertilization on 25-year-old loblolly pine (*Pinus taeda*). Three consecutive, annual fertilizer applications were made, starting when the trees were 16 years old. Wood formed in the 7 years prior to fertilization was compared to that formed in the 7 years following the first fertilization. Heavy rates of fertilization resulted in wood of considerably lower specific gravity than did moderate fertilization. Fertilizers caused a trend to shorter tracheid lengths and slight trend of increased diameter growth, but these were not statistically significant.

In most of the studies cited above, an increase in total ring width and a decrease in specific gravity and tracheid length have been observed in wood samples from fertilized trees. Generally, cell-wall thickness seems to have been unaffected by fertilization, although exceptions have been noted. Larson (1963) found that the formation of large-diameter tracheids in red pine was associated with high auxin levels in actively elongating shoots. However, his results concerning the influence of fertilization on wood properties (Larson 1962) were not clear. The confusion has been attributed, in some cases, to inconsistent sampling procedures, such as sampling at a fixed height above ground rather than at a specific internode. Inconsistent results also could be caused by not taking into account the differences between stem-formed and crown-formed wood (Brunden 1964).

Several studies (Paul and Marts 1954, Rudolph, 1957, Zahner et al. 1964) have demonstrated a correlation between favorable soil moisture conditions with an increase in percentage of latewood. Earlywood was favored when soil water was abundant during the early part of the growing season.

Zahner (1962) examined 5-year-old loblolly pine grown under two contrasting soil-moisture regimes. One group of trees was grown in soil maintained near its field capacity throughout the growing season, whereas the other group was grown in dry soil to simulate summer drought. He found that radial growth was more than twice as great in wet-grown as in dry-grown trees, although the net latewood band was equal for both treatments. No difference due to moisture treatment was found beween the specific gravities of the earlywood portions of the annual rings. However, the dry treatment produced a somewhat more dense summerwood than did the wet treatment.

Zahner and associates (1964) studied red pine grown under simulated drought and irrigation. They found that low, internal moisture stress during the entire growing season resulted in prolonged formation of springwood tracheids, which they attributed to vigorous crown activity. The initiation of drought conditions, however, produced a rapid transition to latewood tracheids and growth curtailment.

Howe (1968) found that anatomical responses to irrigation in mature ponderosa pine (*Pinus ponderosa* Laws.) were more pronounced for trees receiving a single irrigation than those receiving a double irrigation. He stated that the major effect of irrigation was to produce a much more gradual transition from typically thin-walled springwood tracheids to typically flat, thick-walled latewood tracheids. The change in tracheid form produced significant increases in the width of latewood, width of annual increment, and in specific gravity. His study seemed to indicate that the effect of irrigation on wood properties may depend upon the time of irrigation during the growing season.

Murphey and Brisbin (1970) found that irrigation with sewage-plant effluent at the rate of 2 inches per week apparently affected the specific gravity-mechanical property relationship of red pine (*Pinus resinosa* Ait.), whereas a one-inch-per-week rate did not. They concluded that any detrimental effect on the mechanical properties of the crown wood was due to a high soil-moisture level. When a large amount of effluent must be disposed of, they recommend that a species tolerant of wet sites should be chosen if maintenance of satisfactory wood-property characteristics is an objective.

A study by Paul and Marts (1954) was the only one that could be found on the combined effects of fertilization and irrigation. They examined the proportion of latewood formed as a result of various levels of fertilization and irrigation on longleaf pine (*Pinus palustris* M.) in Florida. Irrigation alone increased the percentage of latewood and total ring width to the greatest extent. Irrigation plus a nitrate fertilizer application ranked next in importance, followed by irrigation plus an NPK fertilizer application. The application of fertilizer without irrigation produced only half as much total growth as did irrigation alone.

In Southern Illinois, Boggess (1956) found that summer droughts that deplete the moisture from the upper three feet of the soil caused shortleaf pine and white oak to cease diameter growth. Loblolly pine subsequently was found (unpublished) to react similarly. Thus, theoretically, if by fertilizing and irrigating loblolly pine the species could be made to grow longer into the season when latewood is produced, the specific gravity of the wood would be increased. Not only more wood fiber could be produced each year, but also the wood would be stronger and stiffer as a result of the greater percentage of dense latewood.

The question concerning effect of cardinal direction on the properties of loblolly pine becomes of interest at the time bolts are cut from trees. Although Sellers (1962) concluded that there was no significant difference between the specific gravity of wood taken from the north side of plantation-grown slash pine trees (*Pinus caribaea*, M.) and that on the south side, Walters and Bruckmann (1965) had found the mean difference (N-S) in specific gravity to be significantly larger for wood from female cottonwood (*Populus deltoides* L.) than that for males. Cardinal direction, therefore, was included in this study.

EXPERIMENTAL DESIGN

This investigation was designed as a factorial problem with a 4 × 3 × 2 split-plot design, replicated once. The 12 plots were split among four levels of soil moisture content, to which two cardinal directions of within-tree sampling were applied, with a further division into three subplots with regard to different rates of fertilization. Table 1 shows that a total of 48 specimens were used in the tests.

THE PLANTATION

Wood test specimens were cut from loblolly pine following completion of a growth study in a plantation established in 1947 on Grantsburg silt loam at the Dixon Springs Agricultural Center in southern Illinois. The trees were grown from 1-0 seedlings supplied from an unknown seed source by the Illinois Division of Forestry. The initial spacing of trees in the plantation was approximately 6 × 6 feet (1.83 × 1.83 m).

Two of the three 1/20 acre (0.02 ha) plots within each of the four irrigation treatments (Table 3) received an initial

TABLE 1. *Number of specimens used in determining the properties of loblolly pine*

Supplemental Fertilizer Application, Pounds	Irrigation level: None--Control Driest		60% [a] of F.C. Medium Dry		30% [a] of F.C. Medium Wet		Field Capacity Wettest		TOTAL
	N[b]	S[b]	N	S	N	S	N	S	
0	2	2	2	2	2	2	2	2	16
50[c]	2	2	2	2	2	2	2	2	16
100[c]	2	2	2	2	2	2	2	2	16
TOTAL	6	6	6	6	6	6	6	6	48

[a] percentage prior to irrigation

[b] Cardinal direction in tree

[c] A supplement to 200 lb/acre 4-16-16 NPK fertilizer applied to each fertilized plot.

application of 4-16-16 NPK fertilizer at the rate of 200 pounds per acre (224 kg/ha) in March 1965. Supplemental applications of ammonium nitrate of either 50 or 100 pounds per acre (56 or 112 kg/ha) were added to the fertilized plots on May 1 and again July 1, following the initial application. The same amounts of fertilizer were applied to the plots each of six consecutive years. Table 3 shows only the supplemental applications that will be used in subsequent references to fertilization. The check plots ("0" supplemental fertilization) received no fertilizer.

Plot irrigation throughout the year was by surface watering of the soil. The wettest plots were maintained near "field capacity," which is the amount of water held in the soil after the gravitational water has drained and the downward capillary movement has materially decreased. In the "medium wet" and "medium dry" plots, the soil was recharged to field capacity whenever 30% and 60% of available moisture in the top 24 inches had been used, respectively. Thus, hereafter, in the graphs and text, "60% of F.C.," etc. will refer to soil moisture level at the time irrigation was initiated; i.e., the driest level attained by the respective plots. Only normal rainfall was available to the trees in the control or driest plots. Precipitation (Denmark 1971) for the Dixon Springs Agricultural Center is shown in Table 2. The plots were covered with plastic during the winter of 1963–1964 and spring of 1965 to protect trees from frost. Irrigation was applied from 1964 through 1970.

Average height of the sample trees was 63 feet (19.2 m) and average diameter at breast height was 8.7 inches (22.1 cm) at age of 25 years. The average diameter of the bolts from which test specimens were cut was 8.9 inches (22.6 cm).

PROCEDURES AND MATERIALS

Test specimens

Two sample trees were randomly selected from each of the 12 plots. Only codominant, straight trees with no evidence of terminal damage, relatively defect-free, not located within the outer two rows or columns, or within 20 feet of ground instrumentation, were considered for selection. Two-foot bolts taken 42″ above ground were split along the pith into "north" and "south" portions. The half-bolts were air-dried for 18 months before they were cut into test samples.

The ends of one-inch (2.5 cm)-thick, air-dried boards, cut from each half bolt so the boards were oriented due north and due south of the pith, were double-coated with resorcinal-resin glue and kiln-dried on a mild schedule (Rasmussen 1961) to 12% moisture content, before they were machined into specimens 1 × 1 × 16 in. (2.5

TABLE 2. *Monthly precipitation recorded at the Dixon Springs Agricultural Center, inches*

	Month of the year												
Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	TOTAL
1931 (ave) 1960	4.40	3.57	4.77	4.02	3.97	3.07	3.65	3.37	3.16	2.58	3.75	3.39	44.30
	--	--	--	--	--	--	--	--	--	--	--	--	--
1966	3.58	4.37	0.98	9.62	7.45	1.38	2.68	4.37	3.72	1.48	2.39	5.99	48.10
1967	1.27	2.93	3.01	3.10	6.67	3.67	5.68	2.46	3.16	4.12	3.17	6.28	45.52
1968	2.80	1.88	5.99	5.23	5.10	4.07	1.48	2.59	3.75	1.22	6.23	5.86	46.20
1969	9.55	1.25	2.24	4.65	2.81	9.18	3.70	2.22	1.66	4.77	3.25	4.17	49.45
1970	0.80	2.82	5.73	8.25	8.12	5.01	0.54	1.97	2.54	5.00	2.35	2.45	45.58
1971	4.23	4.71	1.51	2.01	4.39	2.44	5.62	2.95	2.38	0.97	1.71	4.38	37.30

× 2.5 × 40 cm). The square specimens were cut from the outer sapwood that had been formed during the period the trees were fertilized and irrigated. Each specimen was free of visible defects and had a grain slope of less than 1:15 (ASTM 1972). The actual height and width at center, and the length of the specimens were measured before they were conditioned at a temperature of 80° ± 2° F (27° ± 1° C) and 70 ± 4% relative humidity for three weeks.

Measurement of wood properties

Before static bending tests were made, each specimen was wrapped in Saran film to maintain its conditioned weight. The wrap remained on the specimen during the bending tests, but weights taken at time of testing were corrected for it.

The specimens were center-loaded as a simple beam over a span length of 14 inches (35 cm). Test procedures followed Designation D 143-52 (Reapproved 1972), American Society for Testing and Materials (1972).

Work to proportional limit (WPL) and work to maximum load (WML) were measured with a planimeter. Fiber stress at proportional limit (FSPL), modulus of rupture (MOR) and modulus of elasticity (MOE) were calculated by standard formulae. The five mechanical properties were adjusted to 12% moisture content to correct for any differences in moisture content that may have existed at time of test, using the procedures and average values for the adjusting equation from Wangaard (1950).

After testing, a moisture section approximately ½ inch (1.27 cm) in length was cut near the failure and weighed immediately. The samples were dried in a vacuum oven at 100 C and 25 inches Hg vaccum for four days. Specific gravity of each sample was calculated from oven-dry weight and oven-dry volume measurements.

Ring width and width of the earlywood and latewood portions of each annual ring were measured with a De Rouen dendrochronograph instrument along a one-inch (2.54 cm) line drawn perpendicular to the growth rings. Growth rate and percent latewood were calculated from these measurements.

RESULTS AND DISCUSSION

Effect of treatment on physical properties of wood

Latewood percentage

The mean percentage of latewood for all specimens was 46 ± 10 percent (Table 3). Table 4 is an analysis of variance for percentage-of-latewood data. Table 5 presents coefficients for correlation of latewood percentage and seven other properties. None of the main effects of irrigation, fertilization, or cardinal direction significantly influenced percentage of latewood.

Only the interacting effects of irrigation and fertilization on latewood percentage

TABLE 3. *The properties of loblolly pine when grown under various combinations of irrigation and fertilization treatments*

	0			Irrigation										
	Control (driest)			60% of F.C. [a] (medium dry)			30% of F.C. [a] (medium wet)			Field Capacity (wettest)				
	Supplemental Fertilization, pounds per acre [b]													
Properties of wood	0	50	100	0	50	100	0	50	100	0	50	100	*Mean*	Stand dev.
Latewood percentage, %	44	49	57	48	53	44	40	54	36	48	43	37	46	10
Specific gravity, OD/OD	.481	.532	.570	.529	.553	.499	.534	.576	.497	.547	.526	.512	.530	.006
Growth rate, rings/inch	9.1	8.8	9.5	7.9	7.8	6.8	7.3	8.8	6.9	7.8	7.1	7.4	7.9	2.1
Fiber stress at proportional limit x 10, psi	482	659	712	531	698	500	501	661	379	616	495	397	552	151
Modulus of rupture x 100, psi	96	119	130	102	131	91	99	125	68	108	91	86	104	25
Modulus of elasticity x 1000, psi	780	1002	1253	679	1026	669	674	1170	482	888	546	613	815	332
Work to proportional limit, in-lb/cu. in.	1.75	2.33	2.31	2.31	2.76	2.34	2.23	2.11	1.72	2.56	2.54	1.59	2.36	0.81
Work to maximum load, in-lb/cu. in.	15.0	19.8	19.7	23.7	28.4	22.1	21.8	21.0	14.8	19.9	22.3	19.3	20.7	4.29

[a] Percentage prior to irrigation.

[b] A supplement to 200 lb/acre 4-16-16 NPK fertilizer applied to each fertilized plot.

were significant (0.05 level, Table 4). Table 3 and Fig. 1 show that the two lowest latewood percentages, 36% and 37%, were for wood grown in the wetter plots with heavy applications of fertilizer; the highest percentage (57) was obtained for the driest plots with heavy application of fertilizer. Although Paul and Marts (1954) reported that the application of nitrate fertilizer alone to poor sandy soils increased latewood more than earlywood, our data failed to agree (Table 4). The main effect (fertilizer) had no significant effect on percent of latewood. It was only when moisture and fertilizer were applied together that the effect of treatment became significant.

Specific gravity

Table 3 shows the mean specific gravity for all treatments and all trees was 0.530 ± 0.006 (OD/OD). Neither irrigation, fertilization, the cardinal direction from which the wood samples were taken from the trees, nor their interactions, had a significant effect on specific gravity (Table 4). One might reasonably expect some change in density to occur. Williams and Hamilton (1961) found that applications of nitrogen decreased specific gravity from 3 to 7%. On the other hand, Paul and Marts (1954) found that the application of nitrate fertilizer alone increased latewood more than earlywood, thus probably increasing specific gravity. Our results revealed no effect on latewood percentage unless fertilization was accompanied by irrigation. The relationship between latewood and specific gravity was significant ($r = 0.773$, Table 5).

Growth rate

Mean growth rate was 7.9 ± 2.1 rings/inch. There are contradictory reports concerning the relationship between growth rate and density of wood. Kollman (1951) concluded that as ring width increases, the density of pines at first increases and then decreases again. The correlation coefficient for specific gravity and growth rate was only 0.435 (Table 5), indicating poor correlation. However, the correlation coefficient of 0.764 in Table 5 shows that there was a significant linear relationship be-

TABLE 4. *Analysis of variance for percent of latewood, specific gravity, and growth rate of loblolly pine*

Source of variation	Degrees of freedom	Percent Latewood Mean Square	Percent Latewood F Value	Specific Gravity Mean Square	Specific Gravity F Value	Growth Rate Mean Square	Growth Rate F Value
TOTAL	47						
Irrigation (A)	3	166.894	2.412 N.S.	0.0002	0.061 N.S.	8.019	2.566 N.S.
Fertilization (B)	2	177.271	2.562 N.S.	0.0036	1.184 N.S.	0.984	0.315 N.S.
A X B	6	175.785	2.541*	0.0049	1.646 N.S.	1.811	0.580 N.S.
Direction (C)	1	0.255	0.004 N.S.	0.0003	0.110 N.S.	1.880	0.602 N.S.
A X C	3	36.172	0.523 N.S.	0.0001	0.020 N.S.	11.894	3.806*
B X C	2	135.146	1.953 N.S.	0.0008	0.252 N.S.	4.630	1.482 N.S.
A X B X C	6	93.438	1.351 N.S.	0.0016	0.535 N.S.	6.832	2.186 N.S.
Sampling error	24	69.185	--	0.0030	--	3.125	--

N.S.--not significant.
*--0.05 significance level.

tween growth rate and latewood percentage.

Table 4 shows that none of the independent variables (irrigation, fertilization, or cardinal direction of the sample in the tree) had a significant effect on growth rate. Of the four interactions, only irrigation with cardinal direction, was significant (0.05 level).

Note in Table 6 that growth rate (rings/inch) was slowest on the south side of the trees growing on the driest site, but it was fastest on the south side of trees growing on the wetter sites, or on the north side of trees grown on the medium-dry plot. The combination of adequate moisture and warmth appears to have aided growth, but the evidence is not distinctly clear.

Effect of treatment on mechanical properties of wood

Table 3 shows the treatment means for fiber stress at proportional limit, moduli of rupture and elasticity, work to proportional limit, and work to maximum load.

The various properties will be compared to averages for loblolly pine published in the Wood Handbook (U.S. For. Prod. Lab. 1974). The average specific gravity for the test specimens was 0.530 ± 0.006 (Table 3), based on oven-dry weight and oven-dry volume. The value presented in the Wood

TABLE 5. *The correlation coefficients for latewood percentage and specific gravity of loblolly pine*

	Latewood percentage Regression equation	Latewood percentage r	Specific gravity r
Specific gravity	$\hat{Y}$ = 0.371 + 0.00344 X	0.773 **	1.000 **
Growth rate	$\hat{Y}$ = 2.533 + 0.115 X	0.764 **	0.435 N.S.
Fiber stress at proportional limit	$\hat{Y}$ = 162.3 X - 1970	0.945 **	0.808 **
Modulus of rupture	$\hat{Y}$ = 2229 + 273.56 X	0.936 **	0.816 **
Modulus of elasticity	$\hat{Y}$ = 775,000 + 34,507 X	0.916 **	0.773 **
Work to proportional limit	---	0.586 *	0.532 *
Work to maximum load	---	0.216 N.S.	0.483 N.S.

*--0.05 significance level
**--0.01 significance level
N.S.--not significant

TABLE 6. *Growth rate in rings per inch*

Soil Moisture Level	Cardinal Direction North	Cardinal Direction South
	(rings/inch)	
Driest	7.8	10.4
Medium dry	6.8	8.4
Medium wet	8.1	6.8
Wettest	8.1	6.8

Handbook, based on volume at 12% moisture content, is 0.51, a very close comparison. In making the comparisons it will be assumed that the relationship between a mechanical property of wood and its specific gravity is:

Mechanical Property = A x (specific gravity)^B, with each property having its unique coefficient "A." In the Western Wood Density Survey (U.S. For. Prod. Lab. 1965), it was found that in most cases the exponent B was not different from one; therefore, an assumption of a linear relationship between strength and specific gravity is justified.

Tables 7 and 8 show that fiber stress at proportional limit, modulus of rupture, modulus of elasticity, work to proportional limit, or work to maximum load were not significantly affected by the cardinal direction of sample location.

Fiber stress at proportional limit (FSPL)

The average FSPL was 5,520 ± 1,510 psi (Table 3). Treatment averages ranged from 3,790 psi for wood from the medium-wet plot with a heavy amount of fertilizer to 7,120 psi for the driest plot with a heavy amount of fertilizer. Table 7 indicates that although the effect of fertilization on FSPL was significant (0.01 level), the interaction of fertilization with irrigation also had a significant, and more important, effect. Figure 2 shows that increased amounts of fertilizer resulted in a decrease in FSPL of wood grown on the wettest plots; however, FSPL increased with increasing increments of fertilizer for the driest plots.

Table 5 shows that FSPL was positively correlated, not only with specific gravity (r = 0.808) but also with percentage of latewood (0.945). Specific gravity also was correlated with the percentage of latewood. A lower latewood percentage means more earlywood, which has weaker, thin-walled tracheids (Williams and Hamilton 1961); earlywood tracheids, therefore, fail more readily than latewood.

TABLE 7. *Analysis of variance for fiber stress at proportional limit, modulus of rupture, and modulus of elasticity of loblolly pine wood*

Source of variation	Degrees of freedom	Fiber stress at proportional limit Mean Square	Fiber stress at proportional limit F Value	Modulus of rupture Mean Square	Modulus of rupture F Value	Modulus of elasticity Mean Square	Modulus of elasticity F Value
TOTAL	47						
Irrigation (A)	3	3,501,702	2.836 N.S.	10,435,232	2.876 N.S.	233,554	4.963 **
Fertilization (B)	2	7,412,246	6.004 **	21,588,629	5.951 **	174,470	3.708 *
A X B	6	5,278,818	4.276 **	15,219,945	4.195 **	283,193	6.018 ***
Direction (C)	1	316,736	0.257 N.S.	3,357,447	0.925 N.S.	36,645	0.779 N.S.
A X C	3	603,466	0.489 N.S.	430,168	0.119 N.S.	28,585	0.607 N.S.
B X C	2	1,008,215	0.817 N.S.	823,297	0.227 N.S.	13,854	0.294 N.S.
A X B X C	6	200,886	0.163 N.S.	1,359,175	0.375 N.S.	29,996	0.637 N.S.
Sampling error	24	1,234,562		3,628,030		47,057	

N.S.--not significant
*--0.05 significance level
**--0.01 significance level
***--0.001 significance level

TABLE 8. *Analysis of variance for work to proportional limit and work to maximum load for loblolly pine wood*

Source of variation	Degrees of freedom	Work to proportional limit		Work to maximum load	
		Mean Square	F Value	Mean Square	F Value
TOTAL	47				
Irrigation (A)	3	0.4446	0.280 N.S.	99.90	3.025 *
Fertilization (B)	2	0.2850	0.179 N.S.	66.21	2.005 N.S.
A X B	6	0.6934	0.434 N.S.	25.58	0.775 N.S.
Direction (C)	1	0.0000	0.000 N.S.	41.63	1.261 N.S.
A X C	3	0.1841	0.116 N.S.	29.45	0.892 N.S.
B X C	2	0.8168	0.513 N.S.	27.76	0.841 N.S.
A X B X C	6	1.2521	0.787 N.S.	12.87	0.390 N.S.
Sampling error	24	1.5916		33.03	

N.S.--not significant
*--0.05 significance level

Modulus of rupture (MOR)

The average MOR for all specimens was 10,400 ± 2,500 psi (Table 3), about 81% of the average shown in the Wood Handbook. Table 7 shows that only fertilization and the interaction of fertilization and irrigation had significant effects on the bending strength of the wood. The MOR averages ranged from 6,800 psi for wood from the medium-wet plot with a heavy treatment of fertilizer to 13,100 psi for wood from the medium-dry plot with a moderate amount (50 lbs/A) of fertilizer (Table 3). Figure 3 shows that an increase in fertilizer brought about little change of MOR for loblolly pine wood grown on the wettest plots. On the other hand, the effect on MOR was positive when increasing increments of fertilizer were applied on the driest plots (Fig. 3).

The equation for the positive and significant linear relationship between MOR and latewood percentage is given in Table 5 ($r = 0.936$). A significant linear relationship also was found when MOR ($\hat{Y}$) was correlated with specific gravity (X), $\hat{Y} = 44160X - 13000$ ($r = 0.816$, Table 5).

Modulus of elasticity (MOE)

The average MOE for all the sample wood was 815,000 ± 332,000 psi (Table 3), or about 46% of the average shown in the Wood Handbook. Both irrigation and fertilization, and their interaction, had an effect on the stiffness of the wood (Table 7).

The relatively low stiffness is attributed to thin cell walls. Table 3 shows that specific gravity (OD/OD) ranged from 0.481 to 0.576, averaging 0.530 ± 0.006. If we correct specific gravity to account for the extractive content, thereby producing a more realistic estimate of the amount of material available to absorb energy, i.e. stiffness, we find that the mean specific gravity becomes 0.450 (OD/green), low when compared to the 0.492 value determined by Taras and Saucier (1967). They provide the following regression equation for making the correction for loblolly pine: $\hat{Y} = 0.119 + 0.713X$, where X is the specific gravity (OD/green) of unextracted cores taken at breast height. Although the test specimens were taken about 12 inches below breast height, the difference due to sampling height is believed to be unimportant as far as the analysis is concerned. A further explanation for the relatively low MOE is that the specific gravity of loblolly pine gradually decreases from the southern to the northern part of its range (Gilmore 1967). Thus, wood grown in southern Illinois is lower than average in specific gravity, and it also would likely be relatively low in stiffness.

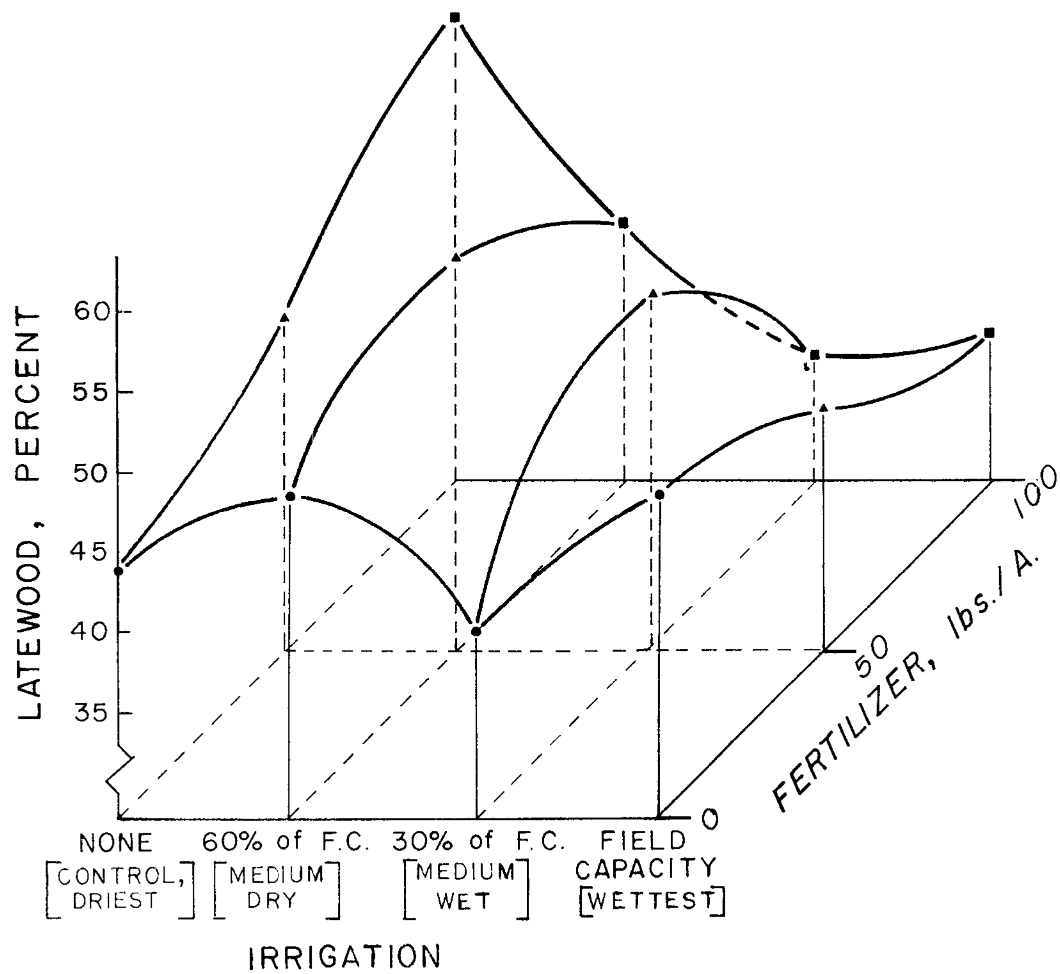

FIG. 1. The interacting effects of irrigation with fertilization on percent of latewood in annual rings of loblolly pine. The references to irrigation are the amounts of available moisture used before irrigation; fertilizer refers to supplemental increments.

The average MOE's ranged from 482,000 psi for wood from the medium-wet plot with a heavy amount of fertilizer to 1,253,000 psi for wood from the driest plots with a heavy amount of fertilizer (Table 3). Figure 4 shows that the increase in MOE was positive for increasing increments of fertilizer applied to the driest plots. However, for the wettest plots it dropped from 888,000 psi to 546,000 psi when the amount of fertilizer was increased from none to 50 lbs/A; then it slightly increased to 613,000 psi when 100 lbs/A of fertilizer were applied.

The linear relationship between MOE and latewood percentage was positive and significant ($r = 0.916$, Table 5), as was the correlation of MOE and specific gravity ($r = 0.773$, Table 5).

Work to proportional limit

The average work to proportional limit was 2.36 ± 0.81 in-lb/cu inch (Table 3). Table 8 shows that none of the main effects of irrigation, fertilization, cardinal direction, or their interactions significantly affected work to proportional limit.

Work to proportional limit was positively correlated with specific gravity ($r = 0.532$,

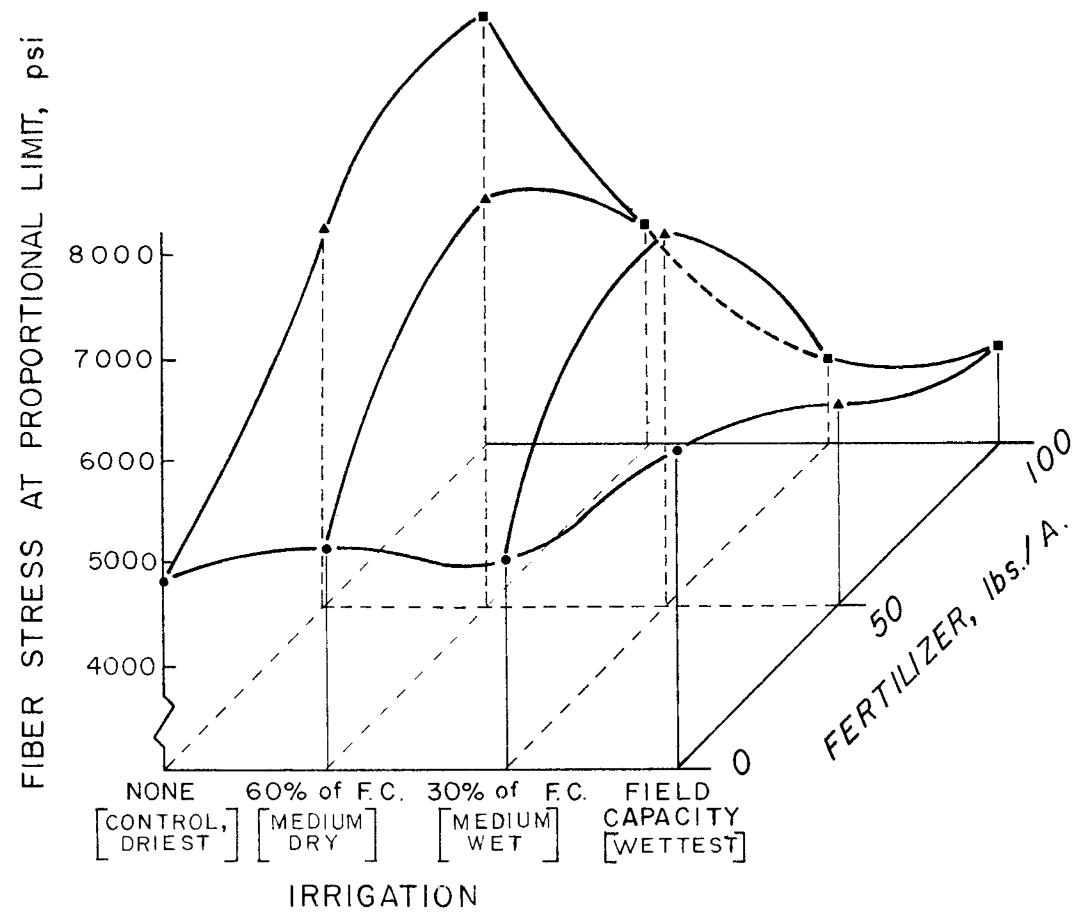

FIG. 2. The interacting effects of irrigation with fertilization on fiber stress at proportional limit of loblolly pine wood. The references to irrigation are the amounts of available moisture used before irrigation; fertilizer is supplemental increments.

Table 5), however, and with percentage of latewood (r = 0.586, Table 5).

Work to maximum load

The average work to maximum load for all specimens, a measure of the amount of energy absorbed by the beam when stressed to maximum load, was 20.7 ± 4.3 in-lb/cu inch (Table 3). Table 8 shows that only irrigation had a significant effect (0.05 level) on work to maximum load. The highest value, 24.7 in-lb/cu inch, was obtained for the medium dry plot (Fig. 5).

Work to maximum load was not correlated with either percent latewood or specific gravity (Table 5).

SUMMARY AND CONCLUSIONS

The effects of a six-year period of irrigation and fertilization on some properties of loblolly pine wood grown on an old field in southern Illinois were studied.

Two sample trees were randomly selected from each of 12 plots, and two static-bending specimens were obtained from both the north and south sides of each tree.

In the "medium wet" and "medium dry" plots, the soil was recharged to field capacity whenever 30% and 60% of the available moisture in the top 24″ had been used, respectively. Only normal rainfall was available to the trees in the control (driest) plots.

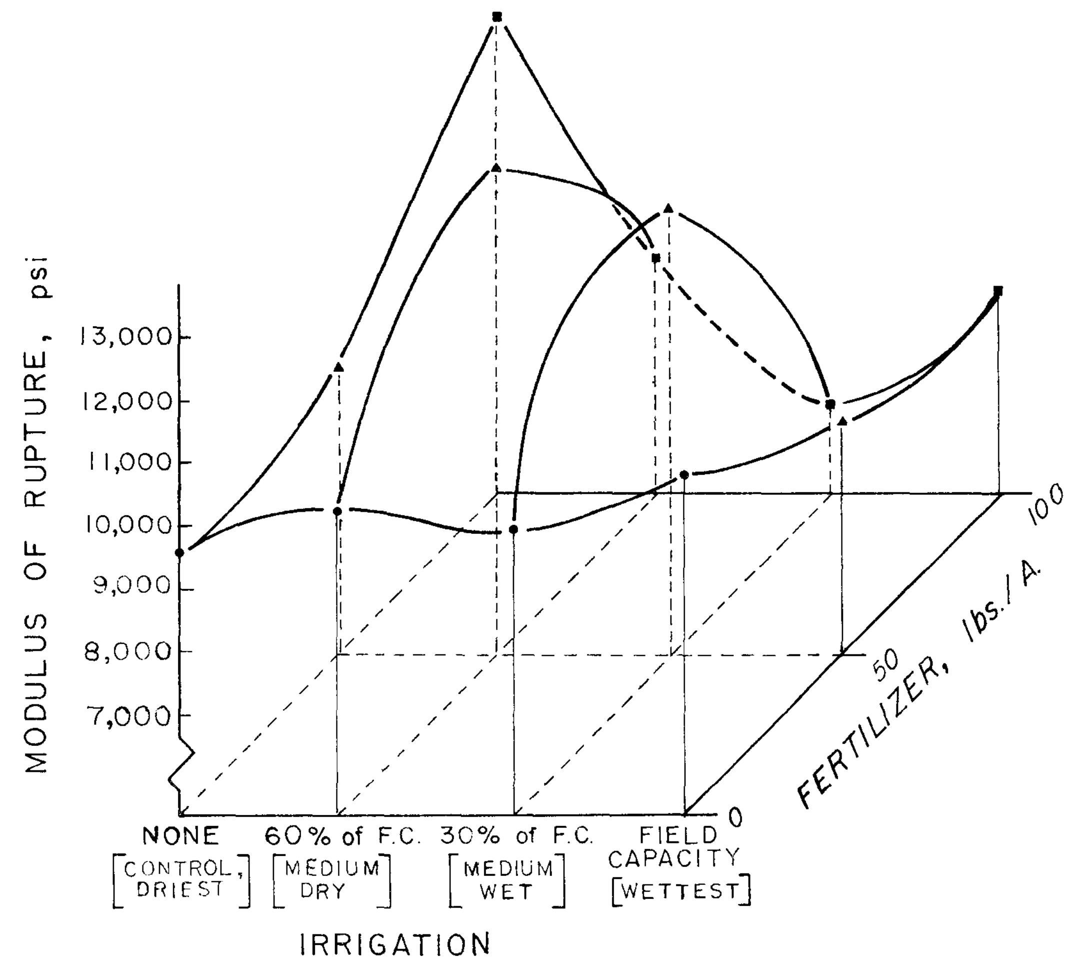

FIG. 3. The interacting effects of irrigation with fertilization on modulus of rupture of loblolly pine wood. The references to irrigation are the amounts of available moisture used before irrigation; fertilizer is supplemental increments.

Fertilized plots annually received an initial application of 4-16-16 NPK at the rate of 200 pounds per acre; two supplemental applications of ammonium nitrate of either 50 or 100 pounds per acre were added later. Control plots received no fertilizer and they were not irrigated.

The results were:

1. The interaction of moisture and fertilizer had a significant effect on percent latewood, the highest percentage being 57 for annual rings produced on nonirrigated plots that annually had received 200 lbs/acre of 4-16-16 NPK fertilizer and two 100 lbs/acre increments of ammonium nitrate. Neither cardinal direction nor its interactions with irrigation or fertilization had significant effects on percent of latewood.

2. None of the three independent variables, or their interactions, had a significant effect on specific gravity. There was a significant, positive correlation of specific gravity with percent of latewood.

3. The correlation between growth rate (rings/inch) and specific gravity was not significant at the 0.05 level of probability.

4. Mean growth rate ranged from 6.8 to 9.5 rings/inch, averaging 7.9 rings. The

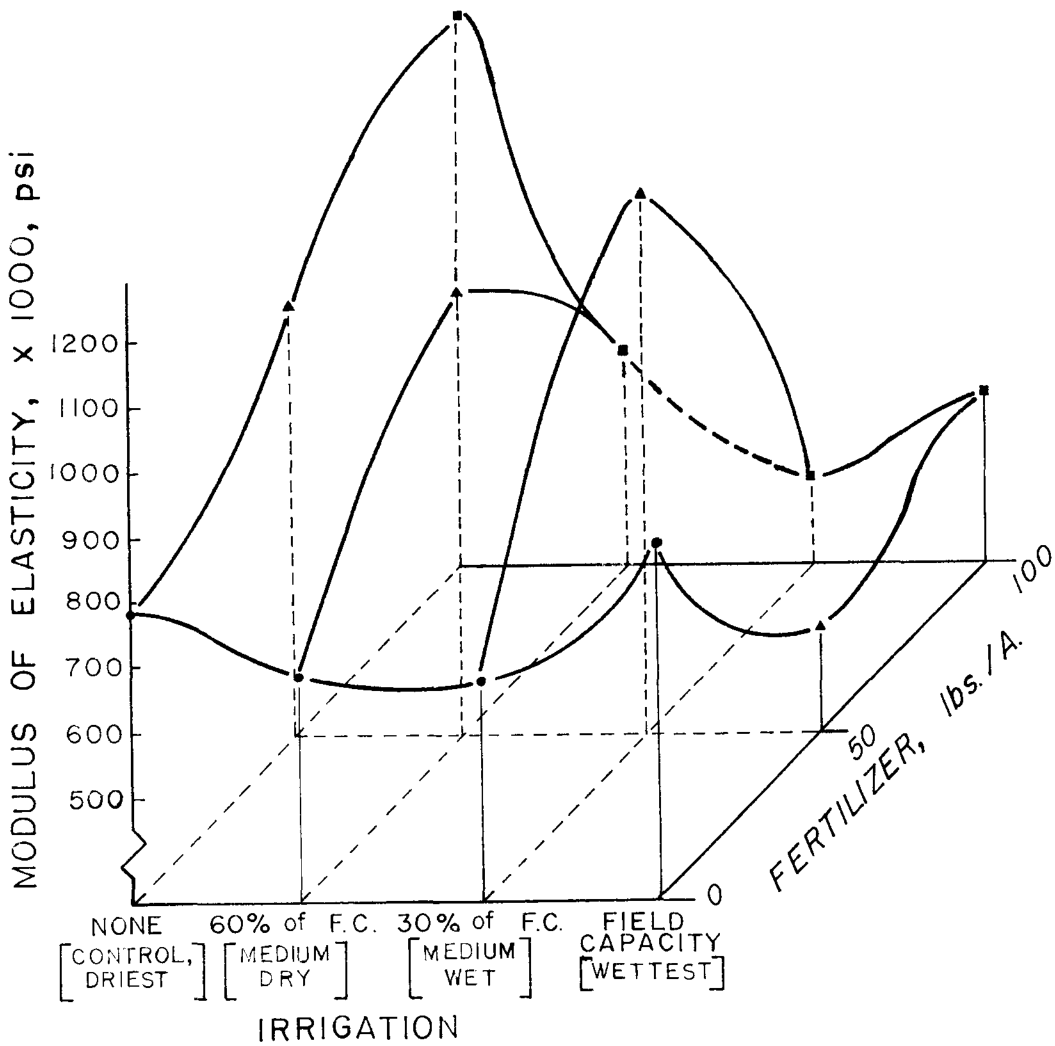

FIG. 4. The interacting effects of irrigation with fertilization on modulus of elasticity of loblolly pine wood. The references to irrigation are the amounts of available moisture used before irrigation; fertilizer is supplemental increments.

interaction of irrigation with cardinal direction had a significant effect on growth rate. The best rate of growth of 6.8 rings/inch was for wood taken either from the south sides of trees grown on the wettest plot, for wood from the south sides of trees grown on the medium wet plot or from the north sides of trees grown on the medium dry plot. The poorest rate of growth was for wood taken from the south sides of trees grown on the driest plot (10.4 rings/inch).

5. Mean fiber stress at proportional limit (FSPL) was 5,520 psi. The interacting effect of moisture level and fertilizer on FSPL was significant (0.01 level). The highest FSPL (7,120 psi) was for wood grown on the unirrigated plots which had received 200 lbs/acre of 4-16-16 NPK fertilizer plus two increments of ammonium nitrate, each increment at the rate of 100 pounds/acre. Wood taken from medium-dry plots fertilized with the supplemental ammonium nitrate increments of 50 lbs/acre had nearly the same FSPL, 6,980 psi.

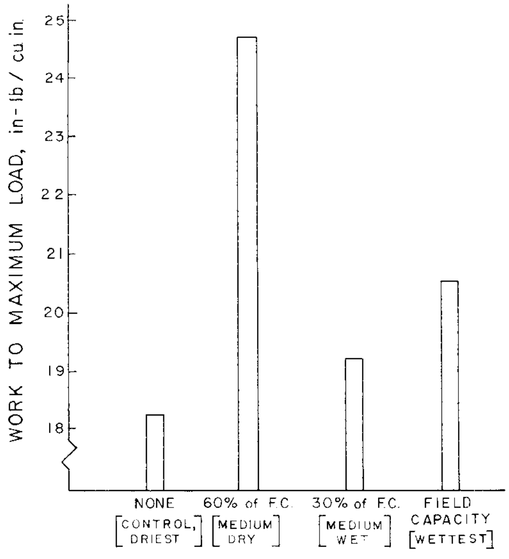

FIG. 5. Histogram showing relationship between soil-moisture levels and average work to maximum load of loblolly pine wood. The references to irrigation are the amounts of available moisture used before irrigation.

6. Essentially the same results were obtained for modulus of rupture (MOR) and modulus of elasticity (MOE) as for FSPL. The highest MOR (13,100) was for wood obtained from trees grown on the medium-dry plots (60% of field capacity used) and fertilized annually with the standard 200-lb/acre application of 4-16-16 NPK fertilizer, plus two increments of ammonium nitrate at the rate of 50 lbs/acre. However, the wood from nonirrigated plots receiving the 100-lb/acre increments had an MOR nearly as high, 13,000 psi.

7. The stiffest wood (MOE 1,253,000 psi) came from the nonirrigated plots with the standard application of NPK fertilizer, plus the two 100-lb/acre nitrate applications. The relatively low mean value, 815,000 ± 332,000 psi, was attributed to thin cell walls.

8. Neither cardinal direction nor its interactions with irrigation or fertilization had significant effects on MOR or MOE.

9. The mean value for work to proportional limit was 2.36 ± 0.81 in-lb/cu inch. Neither the effects of irrigation, fertilization, nor cardinal direction, nor their interactions, had a significant effect on work to proportional limit.

10. The mean value for work to maximum load (WML) was 20.7 ± 4.3 in-lb/cu inch. The highest value of significance for WML was for wood grown on the medium-dry plots (60% of field capacity used), 24.7 in-lb/cu inch. The irrigation effect was significant at the 0.05 level of probability. No other main effect or the interactions among them, were significant.

11. There was a significant (at least 0.05) and positive linear correlation between percentage of latewood in loblolly pine and the following properties: specific gravity, growth rate, fiber stress at proportional limit, modulus of rupture (bending strength), modulus of elasticity (stiffness), and work to proportional limit. There was no significant linear correlation between latewood percentage and work to maximum load, a measure of a beam's ability to store energy.

12. There was a significant (at least 0.05) and positive linear correlation between specific gravity and the following properties: fiber stress at proportional limit, modulus of rupture, modulus of elasticity, and work to proportional limit. The correlation between work to maximum load and specific gravity was not significant at the 0.05 level of probability.

The conclusions drawn from the study were these:

1. The use of 4-16-16 NPK and nitrate fertilizers and irrigation would be useful silvicultural tools in changing certain physical and mechanical properties of loblolly pine grown in southern Illinois. However, maintaining soil moisture at levels above the point where 60% of field capacity was used and applying annual supplemental increments of ammonium nitrate in quantities above 100 lbs/acre, plus 200 lbs/acre of 4-16-16 NPK, probably would not be justified as a means of growing substantially denser, stronger, and stiffer wood.

2. Replenishing soil moisture when 60% of the field capacity has been used, and annually providing an initial application of

200 lbs of 4-16-16 NPK fertilizer per acre in March, plus a 50-lb/acre increment of ammonium nitrate in May and again in July, appears to give the best combination of growth rate and percentage of latewood for the treatments studied. The irrigation-fertilization schedule is recommended for increasing the fiber stress at proportional limit, modulus of rupture, and modulus of elasticity (i.e., bending strength and stiffness of loblolly pine). Such a silvicultural practice would accelerate the growth of poles or produce more pulp per cubic foot of wood grown in southern Illinois. The cost of such practices, however, was not included in this study. Since the main effects of fertilization and irrigation also were significant, the individual effects of these variables might be considered when evaluating the cost:benefit ratio.

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