The Effects of Irrigation and Fertilization on Specific Gravity of Loblolly Pine

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Abstract: The effects of two treatments, irrigation and fertilization, were examined on specific gravity (SG)-related wood properties of loblolly pine trees (*Pinus taeda* L.) grown in Scotland County, North Carolina. The effects on the core as a whole, on the juvenile core, on the mature core, and from year to year were all analyzed. The results indicate that fertilization significantly lowered latewood SG, overall SG, and percent latewood and did so consistently throughout the period of study. Irrigation significantly lowered earlywood SG during the phase of juvenile wood production but significantly raised latewood SG during the period of mature wood production. Significant interaction between fertilization and irrigation indicated that irrigation helped overall SG and percent latewood of fertilized trees to increase to the level of untreated trees. Therefore, this study provides evidence that although fertilization significantly affects several SG-related properties, water availability is beneficial to the fertilization process; over time, an adequate water supply may help fertilized trees to maintain SG levels similar to those of unfertilized trees. FOR. SCI. 56(5):484–493.

Keywords: water availability, optimal fertilization, specific gravity, wood properties

PRESENTLY MULTIPLE SILVICULTURAL PRACTICES are used to increase the productivity of plantation-grown trees, including fertilization and irrigation (Haygreen and Bowyer, 1996). Several studies have confirmed the effects of fertilization on tree growth and other properties related to productivity. Studies have shown that both annual fertilization and one-time applications result in increased productivity in southern pines (Borders et al. 2004, Jokela and Stearns-Smith 1993). In particular, a recent study from the North Carolina State Forest Nutrition Cooperative (FNC) suggested that fertilization with nitrogen and phosphorus led to significant growth gains (Forest Nutrition Cooperative 2006). Growth and yield models by Amateis et al. (2000) support the empirical conclusions of the FNC study, demonstrating that tree height and basal area can respond significantly to applications of nitrogen and phosphorus.

Studies that examine the link between irrigation and stand productivity have not demonstrated results that are as clear as or universal as the responses to fertilization. Some studies performed on very dry sites, for example, those of Linder et al. (1987) and Pereira et al. (1994) have shown quite significant growth-related results from the addition of irrigation in several species. Other studies, however, have not demonstrated a clear link between irrigation and stand growth. Jokela et al. (2004) found that the irrigation of trees in a moderately water-deprived stand did not provide significant growth benefits in loblolly pine (*Pinus taeda* L.); the conclusion of this study was that nutrient availability was the primary contributor to stand productivity.

Over several decades, the forest products industry has become more concerned about the effects of intensive silvicultural management on wood quality. Of the many factors associated with wood quality, there is often a focus on density-related properties, including within-ring measures of earlywood and latewood specific gravity (SG) and their corresponding percentages. Density-related properties are popular because they are easy to measure, are positively associated with the strength and stiffness of solidwood products (Nyakuengama 1991), and can be used to predict the yield and quality of pulp produced for paper products (Morling 2002).

Several studies have revealed that although fertilization does lead to significant growth gains for treated trees, it can lead to a decrease in the SG and percentage of latewood in those trees as well, which is undesirable for many solidwood products. Clark et al. (2004) indicated that annual fertilization led to a significant decline in the latewood SG of fertilized trees and also led to a significant decrease in the percentage of latewood (probably because the accelerated growth due to fertilization occurs in the earlywood growth phase). Studies of mid-rotation fertilization indicate that this effect is transient, and treated trees generally return to a density and latewood percentage comparable to that of untreated trees within 5 years (Nyakuengama et al. 2002). In a recent study, Love-Myers et al. (2009) observed that loblolly pine and slash pine (*Pinus elliottii* Engelm. var. elliottii) returned to untreated density and percent latewood levels within 2–3 years of a one time mid-rotation fertilization.

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The effects of irrigation on wood quality have been studied to a limited extent in hardwoods, and in blue gum (*Eucalyptus globulus*) and shining gum (*Eucalyptus nitens*) irrigation was found to significantly lower the basic density of the wood produced compared with severely water-deprived control trees (Downes et al. 2006). However, an older study of white oaks (*Quercus alba* L. and *Quercus stellata* Wang) and red oaks (*Quercus coccinea* Muenchh. and *Quercus velutina* Lam.) showed that sewage effluent irrigation led to higher SG in red oak but did not affect the SG of white oak (Szopa et al. 1977). The factors that may influence SG responses to irrigation are not known, as few studies have concentrated on the relationship between wood quality and irrigation, particularly for softwoods. In addition, very little is known about the interaction of fertilization and irrigation with regard to wood quality properties. By studying various combinations of fertilization and irrigation, it may be possible to determine whether irrigation alters the expected wood quality response to fertilization.

The Southeast Tree Research and Education Site (SETRES) study was developed by the FNC to learn about the combined effects of irrigation and fertilization on growth properties and facilitated an examination of the effects of these treatments on wood properties. Early analysis of growth data from the SETRES site revealed that there was a large growth response associated with fertilization (e.g., basal area was 71% greater on fertilized plots). The increase in growth response due to irrigation was relatively small, with no significant increase in basal area (Albaugh et al. 2004). In this study, the questions we attempted to answer were whether the growth gains experienced from fertilization resulted in lower SG and percent latewood, as expected from previous studies; whether SG properties were affected by irrigation, implying the importance of water availability despite limited growth gains; and whether irrigation had an impact on the wood quality of fertilized trees different from that of unfertilized trees.

Materials and Methods

Origin of Samples

This study was conducted on a subset of loblolly pine trees from the SETRES experiment, grown on the same site in Scotland County, North Carolina. The trees were planted in 1985 on an excessively drained sandy soil; this minimized the water and nutrients naturally available to the trees. The trees received one of four treatments: a control treatment with no artificial irrigation or fertilization, optimal irrigation only, optimal fertilization only, or optimal irrigation and fertilization, which ranged from 735 to 990 mm/year during the course of the study (for more specific information on rainfall, see Albaugh et al. 2004). In addition, to account for geographic orientation within the site, the site was divided into four blocks, and each block was divided into four plots so that each block received all four treatments.

Fertilization began in 1992 and included additions of nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, and boron. The primary requirement was that trees maintain a foliar nitrogen concentration of 1.3%; for additional details of optimum fertilization and monitoring of the study site, the reader is referred to Albaugh et al. (1998, 2004). Irrigation treatments began in 1993 and were originally designed to maintain soil water content of at least 30 mm in the surface 500 mm of soil. In 1999 new equipment allowed irrigation to occur continuously, but the soil moisture target could not be achieved even with daily irrigation; therefore, in the year 2000 the irrigation target goal was changed to applying 650 mm of additional water evenly distributed during the growth season to each irrigated plot (Albaugh et al. 2004).

In July 2004, for each of the four treatment combinations of fertilization and irrigation, increment cores (12 mm in diameter) were collected from seven standing trees at breast height (1.37 m) in proportion to the dbh distribution across each plot (a total of 112 cores). The increment cores were dried, glued to core holders, and sawn into radial strips (12 mm tangentially, 2 mm longitudinally) using a twin-blade saw. To perform a complete analysis, each tree was required to have measurements from 1991 as well as measurements from all rings between 1993 and 2000.

Eight of the samples did not contain measurements from the 1991 ring and therefore could not be used in the analysis; hence, not all block/treatment combinations included the maximum of seven trees. This did not create difficulty in the analysis, because the analytical methods used were fairly robust to these differences in sample size among treatments. Radial growth and SG of earlywood and latewood of each annual ring for each radial strip was determined at 0.006-mm intervals using a direct-scanning X-ray densitometer (Quintek Measurement Systems). Earlywood and latewood in each ring were distinguished using a SG threshold of 0.48 (this is an established threshold for determining transition; e.g., see Clark et al. 2006). The densitometer was calibrated to express SG on a green volume and oven-dry weight basis.

Statistical Analysis and Model Development

First, to get an overview of the effects of fertilization and irrigation on the selected wood properties, the averages of the properties were analyzed over several different sections of the core grown during the treatment years (1993–2000). This core was divided into a juvenile section grown between 1993 and 1995 and a mature section grown between 1996 and 2000. The juvenile and mature sections of the core were separated based on evidence that wood properties typically develop differently in the two stages (Burdon et al. 2004, Clark et al. 2006). The division was based on a ring-specific gravity threshold of 0.50 (see Clark et al. 2006), and 1996 was the first year this value was reached. The complete core was analyzed as well. The average response of each property for a core was calculated as an estimated basal area-weighted average of the response measured on its individual rings.

The statistical model used separately on the juvenile, mature, and entire study sections of the core for earlywood SG, latewood SG, overall SG, and percent latewood was

$$y_{ijkl} = \mu + B_i + I_j + F_k + IF_{jk} + e_{ijk} + \beta C_{ijkl} + f_{ijkl}, \quad (1)$$

where y_{ijkl} is the response of interest (earlywood SG, latewood SG, overall SG, or percent latewood), μ is the overall mean, B_i is the random effect of the ith block, I_j is the effect of the jth level of irrigation (a value of 0 means no irrigation and 1 means irrigation was applied), F_k is the effect of the kth level of fertilization (a value of 0 means no fertilization and 1 means fertilization was applied), IF_{jk} is the interaction effect of the jth level of irrigation and kth level of fertilization, e_{ijk} is the error associated with measuring the jth level of irrigation and kth level of fertilization in the ith block, and f_{ijkl} is the observational error that was separated by measuring the lth tree with irrigation level j and fertilizer level k in the ith block. The additional term C_{ijkl} is the response property measurement from the year before any treatment (the 1991 ring), multiplied linearly by the parameter to be estimated β; including this helped isolate which part of the effect was due to the individual tree and which part was due to the treatments.

Next, a ring-level model to explore responses over time involved repeated measures on each tree, one measurement for each response for each of the eight rings after the start of treatment (1993 through 2000). To account for the autocorrelation between repeated measurements taken from the same tree, a spatial exponential covariance structure was included in each model. This structure was chosen because in each case it resulted in the lowest Akaike information criterion of several covariance structures tested.

The basic ring level model was

$$y_{ikjlm} = \mu + B_i + I_j + F_k + IF_{jk} + e_{ijk} + \beta C_{ijkl} + f_{ijkl} + R_m + IR_{jm} + FR_{km} + IFR_{jkm} + g_{ijklm}, \quad (2)$$

where terms through f_{ijkl} are similar to those listed in the core level model in Equation 1; in addition, R_m is the effect of ring m, IR_{jm} is the interaction effect of the jth level of irrigation and the mth ring, FR_{km} is the interaction effect of the kth level of fertilization and the mth ring, IFR_{jkm} is the three-way interaction effect of the jth level of irrigation, the kth level of fertilization, and the mth ring, and g_{ijklm} is the error associated with measuring the lth tree with irrigation level j and fertilizer k in the mth ring in block i.

In addition to the ring-level analysis of variance model in Equation 2, which does not consider the sequential nature of the rings, a polynomial model accounting for the continuity of the years was developed. The full quadratic regression mixed model was

$$y_{ij} = \beta_0 + b_{0i} + \beta_1 x_{1ij} + \beta_2 x_{2ij} + \beta_3 x_{3ij} + \beta_4 x_{4ij} + \beta_5 x_{4ij}^2 + \beta_6 x_{1ij} x_{4ij} + \beta_7 x_{2ij} x_{4ij} + \beta_8 x_{3ij} x_{4ij} + \beta_9 x_{1ij} x_{4ij}^2 + \beta_{10} x_{2ij} x_{4ij}^2 + \beta_{11} x_{3ij} x_{4ij}^2 + \beta_{12} x_{5ij} + e_{ij}, \quad (3)$$

where y_{ij} is the response (earlywood SG, latewood SG, overall SG, or percent latewood) from measurement j from the ith tree, β_0 is the intercept, b_{0i} is a random factor allowing the intercept of the model to vary consistently for all observations from tree i, x_1 is an indicator variable for the irrigation factor (1 when irrigation is present, 0 when irrigation is absent), x_2 is an indicator variable for the fertilization factor (1 when fertilizer is present, 0 when fertilizer is absent), x_3 indicates that both irrigation and fertilization are present (1 when both are present, 0 otherwise), and x_4 is equal to the ring number after the start of treatment (for the 1993 ring $x_4 = 1$, for the 1994 ring $x_4 = 2$, and so on). The variable x_5 is the appropriate value measured on the ring from 1991, before treatment. The term e_{ij} is the random error resulting from the individual measurement.

No random term was included to account for an observation's block or plot of origin, as the variance among the four blocks was estimated to be zero, but a spatial exponential autocorrelation structure between repeated measurements was included. The final variables for each model were selected using a stepwise process in which factors were added in order of significance and were required to remain significant at the 0.05 level to remain in the model after each addition. A polynomial model was developed for each of the SG properties in this study but only added considerable information in the case of percent latewood; this is the only result for which this model will be discussed. All tests were conducted using the MIXED procedure available in SAS version 9.1 (SAS Institute, Inc. 2004).

Results

Effects of Fertilization

Fertilization had a significant effect on latewood SG, overall SG, and percent latewood in the portion of the core grown during this study; in addition, fertilization was found to interact with irrigation for latewood SG (Table 1). Latewood SG was lower by 0.0361 for fertilized trees in the juvenile core and by 0.0504 for fertilized trees in the mature core (Table 2). The effect of fertilization to lower overall SG can probably be attributed to this effect on latewood SG. Percent latewood was lower by 4.41% in the complete core due to fertilizer (Table 2).

When examined from year to year, fertilization interacted with ring number for earlywood SG, latewood SG, and whole ring SG, meaning it had different effects on those properties in different years; in addition, fertilization was shown to have a significant three-way interaction with irrigation for whole ring SG (Table 3). Figure 1 demonstrates that the interaction between fertilization and ring number for earlywood SG arises because fertilization is associated with higher earlywood SG in certain years and lower earlywood SG in other years. However, this difference is not significant in any given year (Table 4). This result indicates that the trend was not related to the maturity of the trees and may be related instead to factors outside the scope of this study.

In each year of the study, latewood SG was significantly lower for fertilized trees than for unfertilized trees (Table 4). The interaction between fertilization and ring number exists

Table 1. Analysis of variance for average wood properties at the core level for the juvenile, mature, and complete sections of the core formed during the study

Property and core	Source	Numerator df	Denominator df	*F*	*P*
Earlywood SG					
Juvenile	I	1	8.94	13.95	0.005
	F	1	9.03	0.19	0.675
	I × F	1	8.91	0.15	0.708
Mature	I	1	9.15	0.48	0.504
	F	1	9.29	4.01	0.075
	I × F	1	9.11	0.55	0.479
Complete	I	1	9.01	5.74	0.040
	F	1	9.12	1.72	0.222
	I × F	1	8.97	0.48	0.505
Latewood SG					
Juvenile	I	1	10.6	3.48	0.090
	F	1	9.95	59.4	<0.001
	I × F	1	10.3	1.39	0.264
Mature	I	1	9.42	10.49	0.010
	F	1	9.10	52.17	<0.001
	I × F	1	9.20	1.96	0.194
Complete	I	1	9.80	21.00	0.001
	F	1	9.13	136.55	<0.001
	I × F	1	9.56	5.92	0.036
Overall SG					
Juvenile	I	1	8.86	5.00	0.053
	F	1	8.74	15.38	0.004
	I × F	1	9.02	0.06	0.806
Mature	I	1	8.96	2.64	0.139
	F	1	8.86	24.57	0.001
	I × F	1	9.10	2.47	0.150
Complete	I	1	8.29	0.29	0.603
	F	1	8.25	18.39	0.003
	I × F	1	8.44	1.13	0.317
Percent latewood					
Juvenile	I	1	8.74	1.90	0.203
	F	1	9.00	6.82	0.028
	I × F	1	9.21	0.16	0.701
Mature	I	1	8.42	0.89	0.371
	F	1	8.66	9.57	0.013
	I × F	1	8.84	1.54	0.247
Complete	I	1	5.88	0.05	0.837
	F	1	6.03	7.39	0.035
	I × F	1	6.14	0.24	0.640

I, irrigation; F, fertilization.

Table 2. Estimated wood property means for juvenile, mature, and complete sections of study core by treatment, accompanied by Tukey's honestly significant difference pairwise comparisons

		Irrigation		Fertilization	
Property	Core	No	Yes	No	Yes
Earlywood SG	Juvenile	0.360a	0.341b	0.351a	0.349a
	Mature	0.331a	0.327a	0.334a	0.324a
	Complete	0.345a	0.334b	0.343a	0.336a
Latewood SG	Juvenile	0.647a	0.656a	0.670a	0.633b
	Mature	0.693a	0.716b	0.730a	0.679b
	Complete	0.677a	0.695b	0.709a	0.663b
Overall SG	Juvenile	0.463a	0.448a	0.469a	0.443b
	Mature	0.508a	0.523a	0.538a	0.492b
	Complete	0.488a	0.4923a	0.509a	0.472b
Percent latewood	Juvenile	35.8a	33.8a	36.7a	32.8b
	Mature	48.7a	50.1a	51.7a	47.1b
	Complete	43.0a	43.4a	45.4a	41.0b

Treatments in the same row under each treatment with the same letter indicate no significant difference at $\alpha = 0.05$.

because fertilization resulted in relatively lower latewood SG in some years than others; for example, fertilized trees experienced a drop in latewood SG from 1995 to 1996 and a rise from 1996 to 1997 that unfertilized trees did not (Figure 2).

Table 3. Analysis of variance for average wood properties at the ring level

Property	Source	Numerator df	Denominator df	*F*	*P*
Earlywood SG	I	1	9.06	2.90	0.123
	F	1	9.15	2.01	0.189
	I × F	1	9.02	0.45	0.518
	R	7	700	74.23	<0.001
	I × R	7	700	10.93	<0.001
	F × R	7	700	6.42	<0.001
	I × F × R	7	700	1.03	0.406
Latewood SG	I	1	9.27	17.73	0.002
	F	1	8.66	128.12	<0.001
	I × F	1	9.02	3.68	0.087
	R	7	700	114.44	<0.001
	I × R	7	700	2.51	0.015
	F × R	7	700	2.97	0.005
	I × F × R	7	700	0.85	0.548
Whole ring SG	I	1	8.22	0.62	0.452
	F	1	8.19	17.91	0.003
	I × F	1	8.41	1.78	0.218
	R	7	700	182.87	<0.001
	I × R	7	700	11.08	<0.001
	F × R	7	700	4.09	0.002
	I × F × R	7	700	2.11	0.041
Percent latewood	I	1	8.14	0.05	0.832
	F	1	8.37	6.63	0.032
	I × F	1	8.52	0.59	0.463
	R	7	700	190.49	<0.001
	I × R	7	700	3.79	<0.001
	F × R	7	700	1.47	0.174
	I × F × R	7	700	1.92	0.064

I, irrigation; F, fertilization; R, ring number.

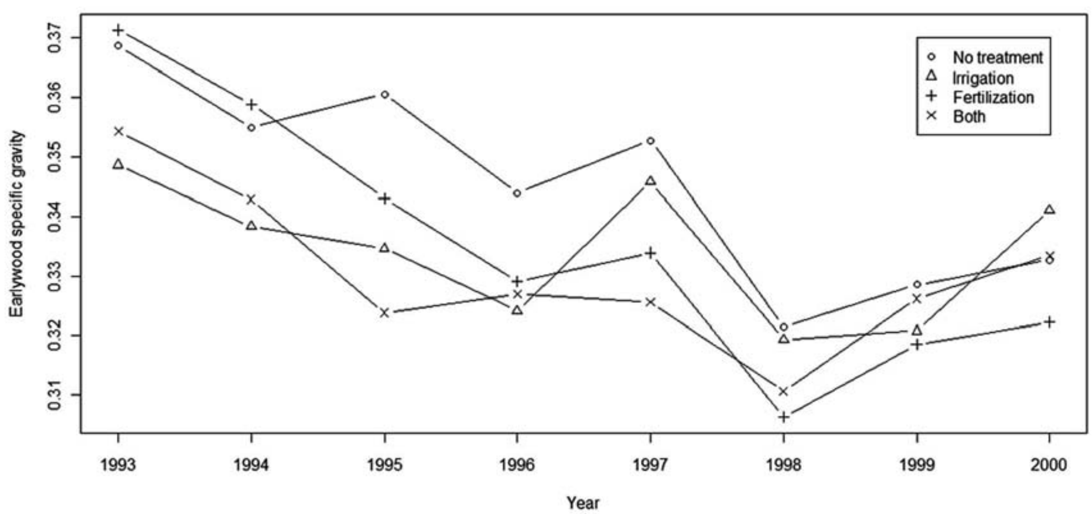

Figure 1. Average earlywood SG by treatment and year.

Effects of Irrigation

Irrigation affected earlywood SG in the juvenile core and latewood SG in the mature core (Table 1). The effect on juvenile earlywood SG was to lower it by 0.0188, but the effect on mature wood latewood SG was the opposite, raising it by 0.0228 (Table 2). There were no significant effects on percent latewood from irrigation in any part of the core (Table 1).

When the effects of irrigation were considered on a yearly basis, there was an interaction between irrigation and ring number for all properties (Table 3). Earlywood SG was lower for irrigated trees particularly during the juvenile years of the study (significantly lower in 1995), but when the trees were older, differences were less pronounced and not consistent in direction (Table 4). Figure 1 shows consistently lower earlywood SG for irrigated trees in the beginning of the study period but no clear pattern based on irrigation as the trees developed mature wood.

In opposition to this effect on earlywood SG, latewood SG was higher each year during the study for irrigated trees than for nonirrigated trees; this difference was significantly higher for several years during the period of mature wood

Table 4. Estimated wood property means by irrigation and fertilization, accompanied by pairwise comparisons with the Bonferroni adjustment

Property and Treatment	Year							
	1993	1994	1995	1996	1997	1998	1999	2000
Earlywood SG								
Irrigation								
No	0.370a	0.357b	0.352b	0.337c	0.343c	0.314d	0.324de	0.328e
Yes	0.352a	0.341ab	0.329c	0.326c	0.336c	0.315d	0.324d	0.337e
Fertilization								
No	0.359a	0.347b	0.348bc	0.334d	0.349e	0.320f	0.325fg	0.3368h
Yes	0.363a	0.351b	0.334c	0.328cd	0.330ce	0.309f	0.322g	0.328g
Latewood SG								
Irrigation								
No	0.621a	0.645b	0.675c	0.673c	0.694d	0.702de	0.687d	0.712g
Yes	0.621a	0.650b	0.686c	0.690c	0.721f	0.727ef	0.713f	0.738h
Fertilization								
No	0.640a	0.668c	0.698e	0.717e	0.730e	0.737e	0.720e	0.748h
Yes	0.602b	0.626d	0.664f	0.646f	0.685g	0.692g	0.680g	0.703i
Whole ring SG								
Irrigation								
No	0.447a	0.466b	0.474b	0.507c	0.473d	0.511e	0.513e	0.542f
Yes	0.426a	0.456b	0.464b	0.505cg	0.492dg	0.540e	0.531e	0.569f
Fertilization								
No	0.445a	0.475b	0.483b	0.531c	0.502e	0.552g	0.538g	0.572h
Yes	0.428ab	0.447b	0.455b	0.482d	0.462f	0.500i	0.505gi	0.539h
Percent latewood								
Irrigation								
No	31.1a	37.6b	38.0b	50.7c	37.0d	50.8e	52.1e	55.5e
Yes	26.7a	36.8b	37.4b	48.7c	40.3d	54.5e	53.1e	57.8e
Fertilization								
No	30.7a	40.1b	38.9b	51.4c	40.4d	55.7e	54.3e	57.1ef
Yes	27.0a	34.2b	36.5b	48.0c	36.9d	49.5e	50.9e	56.2f

Treatments in the same column for the same property and treatment OR the same row in adjacent columns with the same letter indicate no significant difference at $\alpha = 0.05$; comparisons between treatments not in the same column or the same row in adjacent columns were not tested for significance.

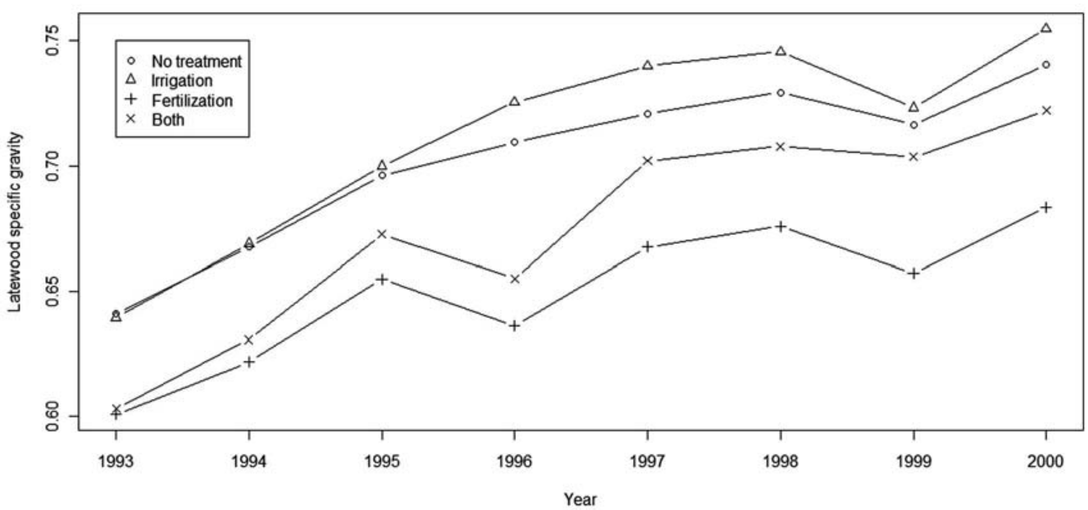

Figure 2. Average latewood SG by treatment and year.

production (Table 4). Figure 2 shows how the difference between the latewood SG of irrigated and nonirrigated trees became generally larger throughout the period of study. This result implies that irrigated trees gradually developed higher latewood SG than nonirrigated trees over time.

Interaction of Fertilization and Irrigation

Although there was no significant difference between the estimated average latewood of control trees (0.7045) and trees that were irrigated only (0.7134), there was a significant difference in the whole core SG ($P = 0.0046$, using Tukey's honestly significant difference pairwise comparisons) between trees that were fertilized (0.6485) and trees that were both fertilized and irrigated (0.6768). This result indicates that irrigation probably raised the latewood SG of fertilized trees (which had lower latewood SG to begin with because of fertilization), but it did not raise the latewood SG of unfertilized trees. This result can be seen in Figure 2, where the latewood SG of fertilized and irrigated trees seems to be very similar to that of the control trees toward the end of the study period, but trees with fertilization only still have much lower latewood SG in these years.

The interaction between irrigation and fertilization for whole ring SG over time can be seen in Figure 3. During the period of juvenile wood production, when irrigation resulted in low earlywood SG and fertilization resulted in low latewood SG, irrigated and fertilized trees had the lowest whole ring SG. When the trees were producing mature wood, however, and irrigation resulted in higher latewood SG for fertilized trees and no longer affected earlywood SG, trees with both treatments approached whole ring SG levels of unfertilized trees. Fertilized trees that were not irrigated, however, continued to have low latewood SG and therefore low whole ring SG.

Finally, a significant interaction was found between fertilization and irrigation for the effect on percent latewood. This interaction was not quite significant at the 0.05 level in the analysis of variance model and is difficult to discern in Figure 4 because all trees experienced significant fluctuations in percent latewood from year to year (Table 4). However, when time was modeled as a continuous phenomenon using the polynomial regression model Equation 3, making these yearly fluctuations less influential, a significant interaction between fertilization and irrigation was detected (Figure 5). Interestingly, irrigation only affected those trees that had been fertilized. Fertilization significantly lowered percent latewood consistently throughout the study period, but irrigation, which began 1 year after fertilization, gradually raised the percent latewood level of these fertilized trees to the level of the control trees.

Discussion

There are several important results of this study. As expected from previous related studies, fertilization did significantly lower latewood SG. This effect was prevalent enough to affect both whole core and ring SG. Also as reported in previous studies, fertilizer treatments significantly lowered the percentage of latewood found in a ring. Irrigation, however, had diverse effects over time, based on the age of the tree and the presence of fertilization. Irrigation significantly lowered earlywood SG during the juvenile phase of development. On the other hand, irrigation was also found to significantly raise latewood SG, mainly during the mature phase of development. This effect was especially strong when fertilization was applied, so that by the end of the study it appeared that fertilized and irrigated trees were nearly on par with unfertilized trees in terms of latewood and overall SG. In addition, although irrigation alone did not affect percent latewood, there was also evidence that a similar interaction took place between irrigation and fertilization over time for percent latewood, in which the percent latewood of fertilized and irrigated trees approached the percent found in unfertilized trees toward the end of the study.

The effects of annual fertilization alone on properties related to SG have been explored in previous studies, and the outcomes here generally agree with those studies (e.g., Clark et al. 2004). Love-Myers et al. (2009) included an extended discussion of the possible physiological reasons for the effect on latewood SG and conjecture that fertilization causes increased auxin production and an extended crown formation period, resulting in less latewood production and reduced secondary wall thickening.

The effects of irrigation and water availability on SG and related characteristics are not well-known and have been shown to vary among studies. As mentioned previously, a study by Downes et al. (2006) showed that irrigation lowered density in two eucalyptus species, but an earlier study by Szopa et al. (1977) showed that irrigation raised SG in red oaks. Interestingly, the Downes et al. (2006) study involved trees treated up until 8 years after planting, indicating that these trees would have been producing juvenile wood at that time. The Szopa et al. (1977) study involved trees that had at least 15 and up to 35 years of growth before the start of the study indicating that these trees would have been producing mature wood throughout the study. Although comparisons between different tree species, particularly between softwoods and hardwoods, cannot be made conclusively, results of these studies appear to agree with

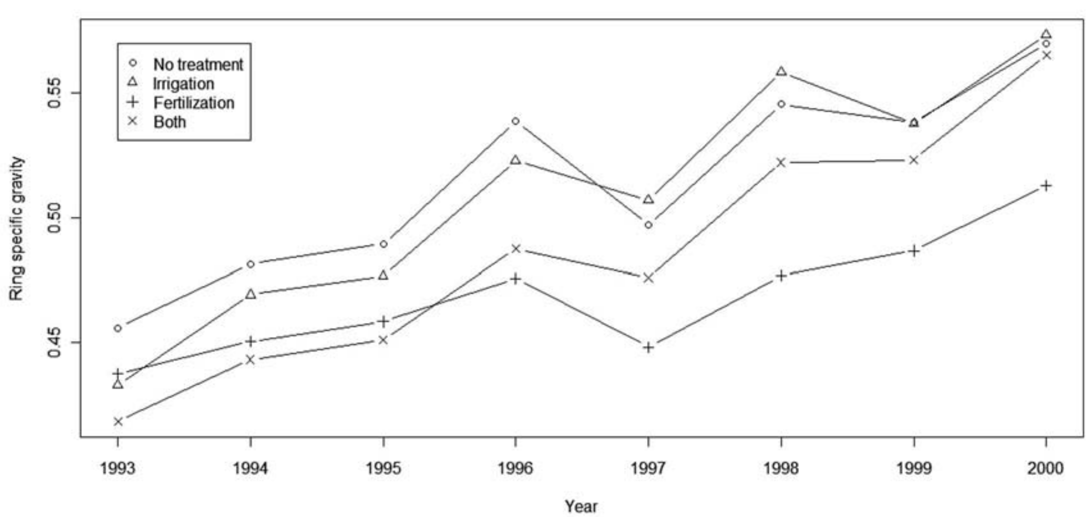

Figure 3. Average whole ring SG by treatment and year.

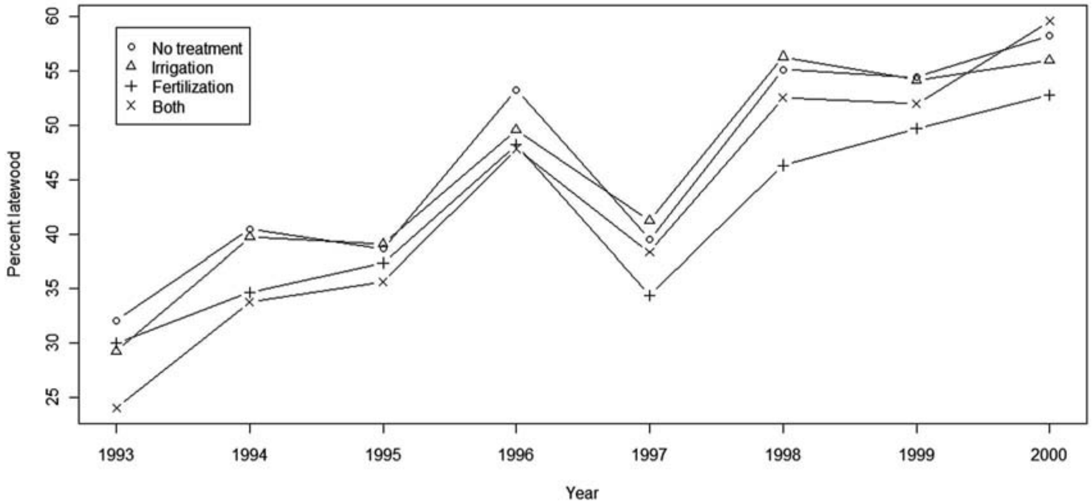

Figure 4. Average percent latewood by treatment and year.

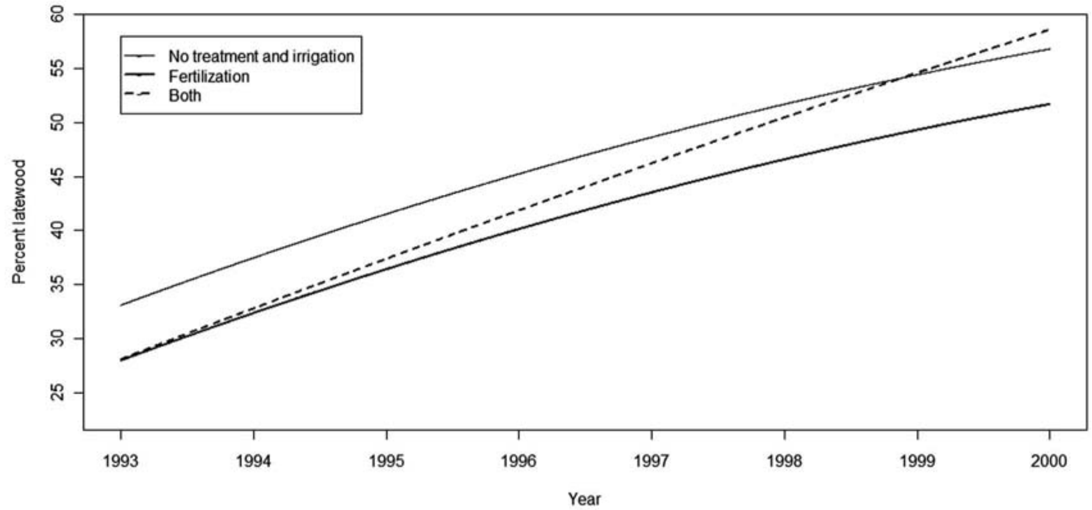

Figure 5. Regression equations for average percent latewood by treatment.

the current results (irrigation lowers earlywood SG during juvenile wood production and raises latewood SG during mature wood production).

In one study (Cregg et al. 1988) conducted on loblolly pine over 2 years one high-rainfall growing season (746 mm) and one low-rainfall growing season (256 mm) were coincidentally experienced. When the data were analyzed, it was found that percent latewood and ring SG from the drier year were significantly lower. The trees in this study were 10 years old when the study began, implying that they were probably transitioning into mature wood production during the study. Although the difference in ring SG agrees with the current results, irrigation in the current study was not found to result in a change to the percentage of latewood found in any ring. However, other factors could have caused the change in percent latewood, because the water availability in the previous study was observed only and not experimentally manipulated.

Fertilization and irrigation interacted significantly in relation to latewood SG and percent latewood. Although fertilization alone has been shown to lower latewood SG and percent latewood, trees that were both fertilized and irrigated approached control levels by the end of the study period. One interpretation of this phenomenon is that when trees are fertilized in dry conditions, increased growth takes place early in the season (assuming sufficient soil moisture is available), and this growth causes the stand to deplete available water. Once trees begin to produce latewood, generally considered to be later in the growing season, the available water that remains can no longer support extensive growth, possibly resulting in both lower percent latewood and less secondary cell wall thickening of latewood tracheids (causing lower latewood SG). Research on the SETRES site by Albaugh et al. (1998) supports this theory, because fertilized trees increased leaf area index by 101% after 4 years compared with unfertilized trees. Needle growth occurs early in the growing season and latewood production tends to coincide with the maturation of needles (Megraw 1985). Once needles have matured, photosynthate becomes available to thicken cell walls; however, if water availability is low because of increased needle and earlywood production, photosynthesis cannot take place efficiently, and both the amount and SG of the latewood produced will be low. When trees are irrigated as well as fertilized, the increased water availability may allow latewood production to continue at control levels while producing the increased radial growth typically associated with fertilization. More support for this idea comes from research by Wimmer and Downes (2003) on Norway spruce (*Picea abies* [L.] Karst.) trees. Their research indicated that irrigation in summer and early fall after latewood production began increased the density of trees, whereas heavy rainfall in the early part of the growing season was associated with longer production of earlywood and lower density.

Laviner (1997) provided further insight into the relationship between fertilization, irrigation, and the growth process of loblolly pines. In 9-year-old loblolly pine trees, fertilization was found to generally lower stomatal conductance of the trees, whereas irrigation was found to raise stomatal conductance during dry periods. An increase in water availability in the upper 500 mm of soil was also found to cause an increase in net photosynthesis. In addition, whereas fertilization was shown to lower stomatal conductance, fertilization did increase water use efficiency by increasing the slope of the relationship between stomatal conductance and net photosynthesis. This finding implies that if irrigation were supplied to keep stomatal conductance higher during fertilization, fertilization and irrigation together could raise the amount of net photosynthesis that occurs and could explain why trees in the current study that were both fertilized and irrigated reached near-control levels of percent latewood and latewood SG, whereas trees that were fertilized alone experienced lower levels of each. However, this effect was only apparent in the mature wood not the juvenile wood. A possible explanation for the different behavior observed in the two wood zones is related to differences in the properties of latewood in the juvenile and mature wood. For juvenile wood the majority of the ring is earlywood (Figure 4), and the latewood that does form has lower specific gravity than mature latewood (Figure 2). Hence, juvenile latewood may not have as much opportunity as mature latewood to recover from the effects of fertilization. In addition, as the tree begins to produce latewood, water stresses on the tree are increased owing to increased leaf area, which may create more potential for a visible effect due to irrigation.

Although commercial irrigation is generally impractical because of logistics and expense, knowledge of how water availability and fertilization work together is important. The results of this study imply that stands on water-deprived and drought-prone sites will be affected most significantly by fertilization in terms of SG and latewood production. The quality of trees on sites that receive regular rainfall well-distributed throughout the growing season is less likely to be affected. Also important are soil characteristics; sites that have good water holding capacity in the B-horizons (e.g., clay and other fine texture components as opposed to sandy, well-drained soils) are more likely to produce high-quality wood when fertilized.

Conclusion

In summary, irrigation can have a significant impact on the results of fertilization with regard to wood properties. Specifically, it appears that irrigation can, over time, help fertilized trees (which have significantly lower and less desirable latewood SG) to reach SG and percent latewood levels similar to those of unfertilized trees. This discovery could prove to be very important with fertilization practices continuing to gain popularity among wood producers, as it could allow them to produce a large volume of wood quickly without sacrificing significant wood quality by using sites that receive regular well-distributed rainfall and have good water-holding capacity.

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