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Wood properties of loblolly pine grown under intensive management in the Upper Coastal Plain of southwest Georgia

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Abstract

Loblolly pine (*Pinus taeda* L.) productivity over the past century has increased significantly from genetic improvements and more intensive management practices. The current study concludes a series of assessments of loblolly pine growth/physiological responses to continuous resource management treatments of weed control (W), weed control plus irrigation (WI), and weed control plus irrigation and fertigation (WIF). Increment cores were analyzed by X-ray densitometry to assess treatment impacts on wood properties. Plotting the wood property data against assigned years allowed results to be compared with available weather data. Mean values for all wood property determinations were similar between the W and WI treatments. Increased ring width for the WIF treatment was consistent with other studies demonstrating substantial increases in loblolly pine productivity by fertilization. Since decreases in ring specific gravity (SG) from fertilization can be offset by increases in ring SG from irrigation, gains in productivity were achieved without reducing wood quality.

Key words: earlywood, fertilization, irrigation, latewood, southern pine, specific gravity

Résumé

Au cours du siècle dernier, la productivité du pin Loblolly (*Pinus taeda* L.) a augmenté de manière significative grâce aux améliorations génétiques et aux pratiques de gestion plus intensives. L'étude actuelle conclut une série d'évaluations de la croissance et des réactions physiologiques du pin Loblolly aux traitements de gestion continue des ressources : désherbage (D), désherbage plus irrigation (DI), et désherbage plus irrigation et fertigation (DIF). Des carottes d'accroissement ont été analysées par densitométrie aux rayons X pour évaluer l'impact des traitements sur les propriétés du bois. Le tracé des données sur les propriétés du bois en fonction des années attribuées a permis de comparer les résultats aux données météorologiques disponibles. Les valeurs moyennes pour toutes les déterminations des propriétés du bois étaient similaires entre les traitements D et DI. L'augmentation de la largeur des cernes pour le traitement DIF était conforme à d'autres études démontrant une augmentation substantielle de la productivité des pins Loblolly par la fertilisation. Étant donné que les diminutions de la largeur des cernes en fonction de la gravité spécifique (GS) dues à la fertilisation peuvent être compensées par les augmentations de la largeur des cernes en fonction de la gravité spécifique dues à l'irrigation, les gains de productivité ont été obtenus sans réduire la qualité du bois. [Traduit par la Rédaction]

Mots-clés : bois précoce, fertilisation, irrigation, bois tardif, pin du sud, gravité spécifique

1. Introduction

The productivity of southern pine plantations throughout the southeastern United States has increased 4-fold within the past century through genetic tree improvement initiatives along with intensive management treatments such as fertilization and competition (hardwood/weed) control (Fox et al. 2007). Combining annual fertilization with multiple herbicide applications for young loblolly pine (*Pinus taeda* L.) stands gave mean annual increments averaging 27 m^3·ha^{-1}·year^{-1} that rival the 26 m^3·ha^{-1}·year^{-1} achieved in exotic environments such as in Hawaii (Harms et al. 2000; Borders and Bailey 2001). In terms of the carrying capacity — the maximum number (or biomass) of a plant that can be sustained on a long-term basis under finite site resources (Yang and Burkhart 2017) — a loblolly pine plantation on a dry site in Georgia was reported to reach a maximum basal area of

48 $m^2 \cdot ha^{-1}$ with annual fertilizer additions and weed control treatments (Jokela et al. 2004); note that a loblolly pine plantation in Hawaii can achieve levels (100 $m^2 \cdot ha^{-1}$) twice that value (Harms et al. 2000; Samuelson et al. 2010, 2013). Accordingly, while impressive productivity gains for loblolly pine have been achieved on mainland plantations, exotic environments (e.g., Hawaii) still have higher carrying capacities, attributable to favorable climate/environmental conditions such as mild year-long temperatures, longer day lengths, and low evaporative demand (Harms et al. 2000; Samuelson et al. 2010, 2013).

Intuitively, leaf area dictates the growth rate of loblolly pine, with gains in leaf area/mass from fertilization on nutrient-limited sites leading to dramatic gains in growth (Albaugh et al. 2004, 2006; Jokela et al. 2004; Fox et al. 2007). Fertilization is not without risk since it can reduce the root-to-leaf area ratio and thereby increase the vulnerability of a tree to drought stress (Ewers et al. 2000); however, increases in water use efficiencies from fertilization can ameliorate this issue for loblolly pine under mild or moderate drought conditions (Maggard et al. 2017; Samuelson et al. 2018). Overall, loblolly pine productivity across the southeastern United States is most influenced by soil nutrients (Jokela et al. 2004). Productivity gains can also be achieved by irrigation (Albaugh et al. 2004) or competition control (Will et al. 2006) treatments, but these gains are usually less than those achievable by fertilization. Note that the benefit to stand productivity with each additional treatment is not completely cumulative, with said productivity ultimately being constrained by the maximum carrying capacity for loblolly pine in the southeastern United States (Jokela et al. 2004; Samuelson et al. 2004, 2008).

An economic benefit of high loblolly pine productivity is the ability to obtain merchantable material such as pulpwood in as early as 10 years (Dahlen et al. 2018). Loblolly pine wood properties have been widely studied to gain an understanding of the impacts of a wide spectrum of influences including genetics, planting density, and region (Roth et al. 2007; Jordan et al. 2008; Dahlen et al. 2018). Fewer studies have been conducted to investigate the influence of irrigation and intensive management treatments on wood properties. Although there are exceptions (see Antony et al. 2015), studies reported in the literature tend to show values for % latewood and ring specific gravity (SG) to decrease with competition control (Antony et al. 2011) and fertilization (Albaugh et al. 2004; Love-Myers et al. 2009, 2010), while irrigation can have the opposite effect on these wood properties (Gonzalez-Benecke et al. 2010) by promoting greater latewood formation through greater moisture availability.

The current study brings closure to a series of assessments of growth/physiological responses to continuous resource management treatments (e.g., irrigation) applied at a loblolly pine study site near Bainbridge, Georgia (Samuelson et al. 2004, 2008; Johnsen et al. 2013). Increment cores were collected at a stand age of 15 years and analyzed by X-ray densitometry to assess the possible impacts of these treatments on selected SG-based measures of wood properties. Of specific interest was whether increased water availability via irrigation would manifest in a significant gain in ring SG by promoting greater latewood formation. Furthermore, if any gain in ring SG was indeed realized from irrigation, the study design allowed us to determine whether it would be sufficient to compensate for the reduction in ring SG that can accompany increases in productivity from fertilization.

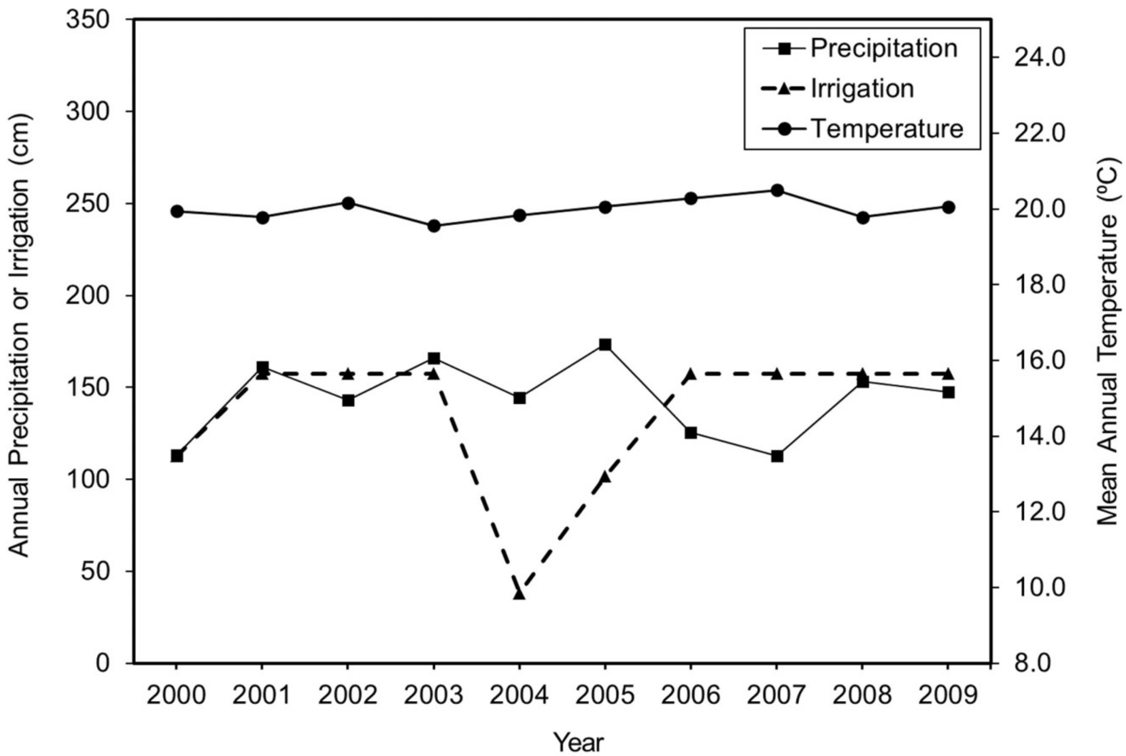
2. Materials and methods

2.1. Study design and treatments

The 15 ha study site, established in 1995 by International Paper, Inc., was located 22 km west of Bainbridge, Georgia (30°48 N, 84°39 W). Numerous reports discuss the specifics of the establishment of the study site and the maintenance of the treatments; only a few of the reports are cited herein (Samuelson et al. 2004, 2008; Johnsen et al. 2013). Briefly, site preparation began in August 1994, and continued until the loblolly pine seedlings were hand-planted in January 1995 using a 2.4 m × 3.7 m spacing. Treatment plots were arranged in a randomized complete block design with four treatments and three blocks. The treatments, applied continuously since plantation establishment, were as follows: (*i*) complete weed control (W); (*ii*) weed control plus drip irrigation (WI); (*iii*) weed control plus irrigation and fertigation (WIF), with fertigation being the addition of a fertilizer solution to the irrigation water; and finally, (*iv*) weed control plus irrigation, fertigation, and pest control (WIFP). Trees subjected to the most intensive treatment (WIFP) were not used in the current study involving wood property determinations because of stand damage that prevented us from sampling two of the three blocks. Although this long-term study was designed without an untreated control, it allowed for an assessment of the continuous resource management treatments added in series to the W treatment.

Key aspects of the three treatments used in the current study are briefly discussed below. In the W treatment, complete weed control was maintained with herbicide applications throughout the summer months. The WI treatment used weed control plus drip irrigation from drip lines that ran along tree rows. The irrigation system applied water daily, March through December. The drip system, which began operation in 1995, did not function for most of 2004, but resumed functioning in early July 2005. The WIF treatment included weed control, irrigation (4 months; March, April, November, and December), and fertigation (6 months; May through October). Annual water balances, and fertilizer additions in WIF treatment, are reported in the literature up to age 10 (Samuelson et al. 2008; Johnsen et al. 2013). Temperature and precipitation data (Fig. 1) were from the Georgia Automated Environmental Monitoring Network (www.GeorgiaWeather.net) for a weather station at Attapulgus, Georgia, located approximately 21 km from the study site. The 12-month Palmer Drought Severity Index (PDSI) data (Fig. 2) were obtained from the National Oceanic and Atmospheric Administration's Climate Data Online website (www.ncdc.noaa.gov/cdo-web/), state = 9, climate division =

Fig. 1. Estimated annual precipitation and irrigation amounts, along with mean annual temperature for the study site. **Note:** Weather data are from the Georgia Automated Environmental Monitoring Network (www.GeorgiaWeather.net) for Attapulgus, Georgia, approximately 21 miles from the study site; irrigation levels are based on amounts programmed for daily distribution for the months of March through December.



7. As a meteorological index, the PDSI classifies soil moisture conditions, using precipitation and temperature data along with soil type (Palmer 1965); the magnitude of the negative PDSI values coincides with the severity of the drought (e.g., −1 to −2 = mild drought; −2 to −3 = moderate drought; −3 to −4 = severe drought).

2.2. Densitometry

Increment cores (12 mm in diameter) were removed from the study trees at breast height (1.37 m) with an increment borer in mid-September 2010 (stand age = 15 years), taking five cores from each of three blocks, and from each of the three treatments described above except for five cores belonging to block 1 of the WIF treatment that were excluded because of stand damage also sustained for that treatment. Trees were randomly selected among those within 1 standard deviation of the mean diameter at breast height for each plot. Mean stand characteristics are reported in Samuelson et al. (2008). Mean core lengths and standard deviations (in parentheses) for each treatment were as follows: W, 9.3 (1.1) cm; WI, 10.4 (1.0) cm; and WIF, 12.8 (1.8) cm.

All cores collected in the field were refrigerated to prevent microbial growth until prepared for X-ray densitometry using established processes for our laboratory (Eberhardt and Samuelson 2015). Briefly, unextracted cores were prepared to have the transverse surface of each core to be orthogonal to the X-ray beam; densitometry was performed in an air-conditioned laboratory. The densitometer (Model QTRS-01X, Quintek Measurement Systems, Knoxville, TN, USA), using a 0.06 mm radial step resolution and a threshold SG value of 0.48 to differentiate latewood from earlywood, was calibrated to a green volume and oven-dried mass basis. Percent latewood, earlywood SG, latewood SG, and ring SG values for the growth rings of interest in each increment core were weighted by the corresponding ring basal areas to obtain the mean basal-area-weighted wood property values for each tree sampled. To eliminate variability in total ring counts, and excessive influence of the growth rings closest to the pith, the data set was restricted to 10 growth rings, assigned to years 2000–2009; the outermost growth ring for each increment core, assigned to year 2010, was excluded because it was incomplete. Plotting the wood property data against assigned years, as opposed to cambial age, allowed us to compare our results to available weather data (e.g., precipitation).

2.3. Statistical analysis

Analysis of variance (ANOVA) for a randomized complete block design with three blocks was performed using the SAS general linear methods procedure to test for treatment effects (SAS version 9.1; SAS Institute Inc., Cary, NC). In all tests, treatment effects were considered significant at $\alpha < 0.05$, and differences between treatments were determined using Duncan's multiple comparison procedure.

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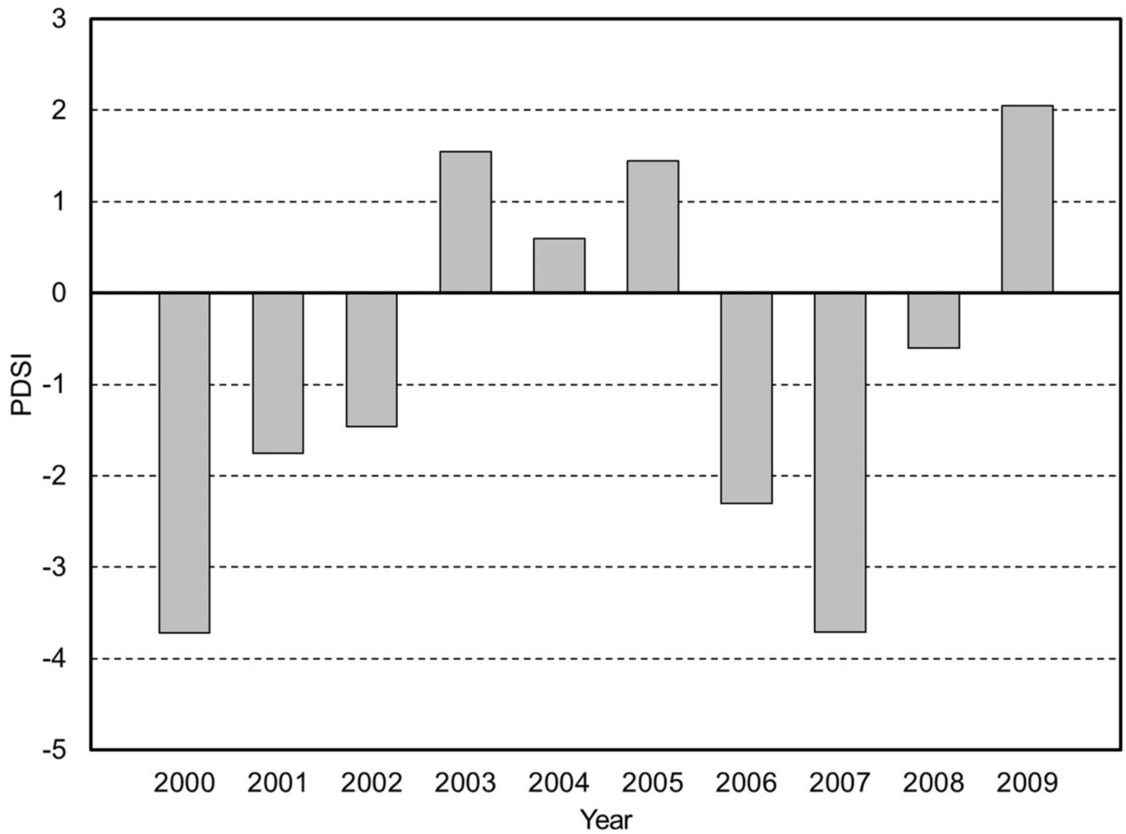
Fig. 2. Annual Palmer Drought Severity Index (PDSI) for the study site. **Note:** Data are from the National Oceanic and Atmospheric Administration, Climate Data Online website (www.ncdc.noaa.gov/cdo-web/), state = 9, climate division = 7. Magnitude of a negative PDSI value is indicative of drought severity (e.g., −1 to −2 = mild drought; −2 to −3 = moderate drought; −3 to −4 = severe drought).



3. Results and discussion

3.1. Ring width

Comparing the ring width data (Table 1) between treatments by ANOVA showed that there was a significant treatment effect ($P = 0.0017$). The mean ring widths for the W and WI treatments (5.36 and 5.61 mm, respectively) showed no difference by Duncan's multiple comparison procedure, whereas the mean ring width for the WIF treatment (6.73 mm) was at least 20% greater than that for either the W treatment or the WI treatment. Samuelson et al. (2008) reported productivity data (volume, stem mass, etc.) for the study trees at a stand age of 11 years (in year 2006) that increased in a stepwise manner with each additional treatment, resulting in significant differences between the W and WI treatments, and between the WI and WIF treatments. Focusing on the abovementioned higher ring width value for the WIF treatment, as a proxy for productivity, supports the assessment from a synthesis study that found soil nutrient levels to be the dominant factor in loblolly pine productivity across its natural range (Jokela et al. 2004).

Figure 3 shows the mean annual ring widths for each continuous resource management treatment plotted against the years assigned to the growth rings. As expected for these relatively young trees, the ring width values declined with each additional year of growth. Calculating and plotting the mean annual ring basal areas across the years assigned to the growth rings (Fig. 4), the downward trends are less pronounced given the increased weighting of the growth rings over time, or more explicitly, with increased distance from the pith (i.e., for two growth rings having equal ring widths, that which is further from the pith will have a greater basal area). Figures 3 and 4 show that the values for each assigned year are equal or higher for the WIF treatment than those for the W and WI treatments, and thereby demonstrate a sustained higher productivity imparted by fertilization.

The sudden decreases in both mean annual ring width and mean annual ring basal area at year 2007 are the most pronounced with the W treatment. Upon reviewing the climate data, we can see years 2006 and 2007 had lower annual precipitation amounts (see Fig. 1). This is clearly shown in the plot of the PDSI values for the area (southwest Georgia) where year 2006 was classified as moderate drought and year 2007 was classified as severe drought (see Fig. 2). Note that a technical glitch with the irrigation system, which was not fully operational in 2004 and 2005, likely exacerbated the unfa-

Table 1. Effects of management treatments on ring width, percent latewood, and specific gravity (SG) values for loblolly pine trees and associated ANOVA *P* values.

Treatment	Ring width (mm)	Percent latewood	Earlywood SG	Latewood SG	Ring SG
W	5.36 (0.20)a	51.0 (1.3)a	0.327 (0.005)a	0.718 (0.009)a	0.529 (0.009)ab
WI	5.61 (0.17)a	54.7 (1.4)a	0.336 (0.004)ab	0.715 (0.009)a	0.548 (0.009)a
WIF	6.73 (0.40)b	51.1 (2.3)a	0.344 (0.006)b	0.657 (0.011)b	0.507 (0.012)b
P >F					
Treatment	0.0017	0.0974	0.0544	0.0002	0.0178
Block	0.7099	0.0050	0.0231	0.4215	0.0091

Note: Values are means and standard errors (in parentheses). Values with different letters for a given wood property are significantly different ($\alpha = 0.05$) by Duncan's multiple comparison procedure. W, weed control; WI, weed control plus irrigation; WIF, weed control plus irrigation and fertigation.

Fig. 3. Annual mean ring width for loblolly pine increment cores from weed control (W), weed control plus irrigation (WI), and weed control plus irrigation and fertigation (WIF) treatments.

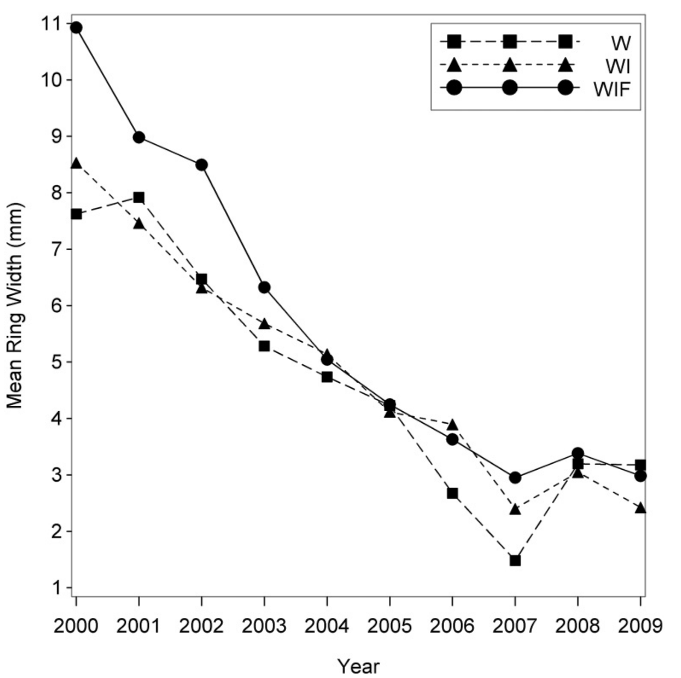
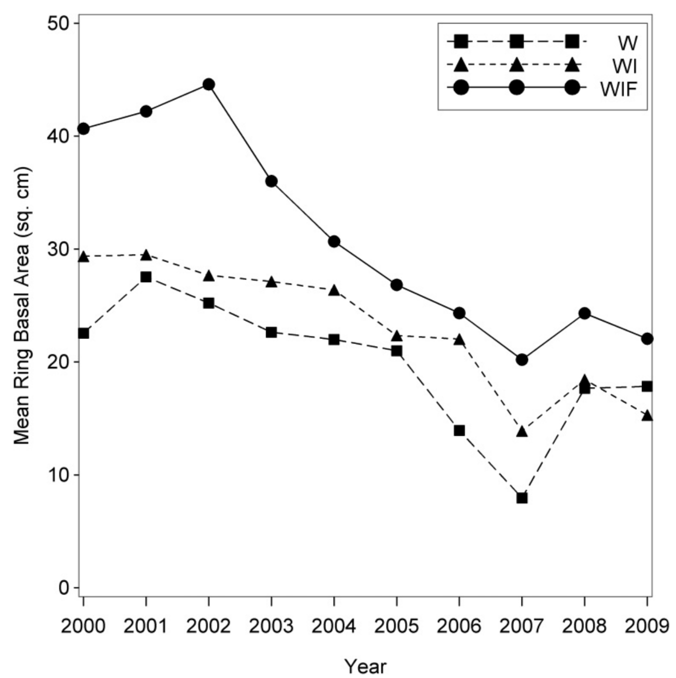


Fig. 4. Annual mean ring basal area for loblolly pine increment cores from weed control (W), weed control plus irrigation (WI), and weed control plus irrigation and fertigation (WIF) treatments.

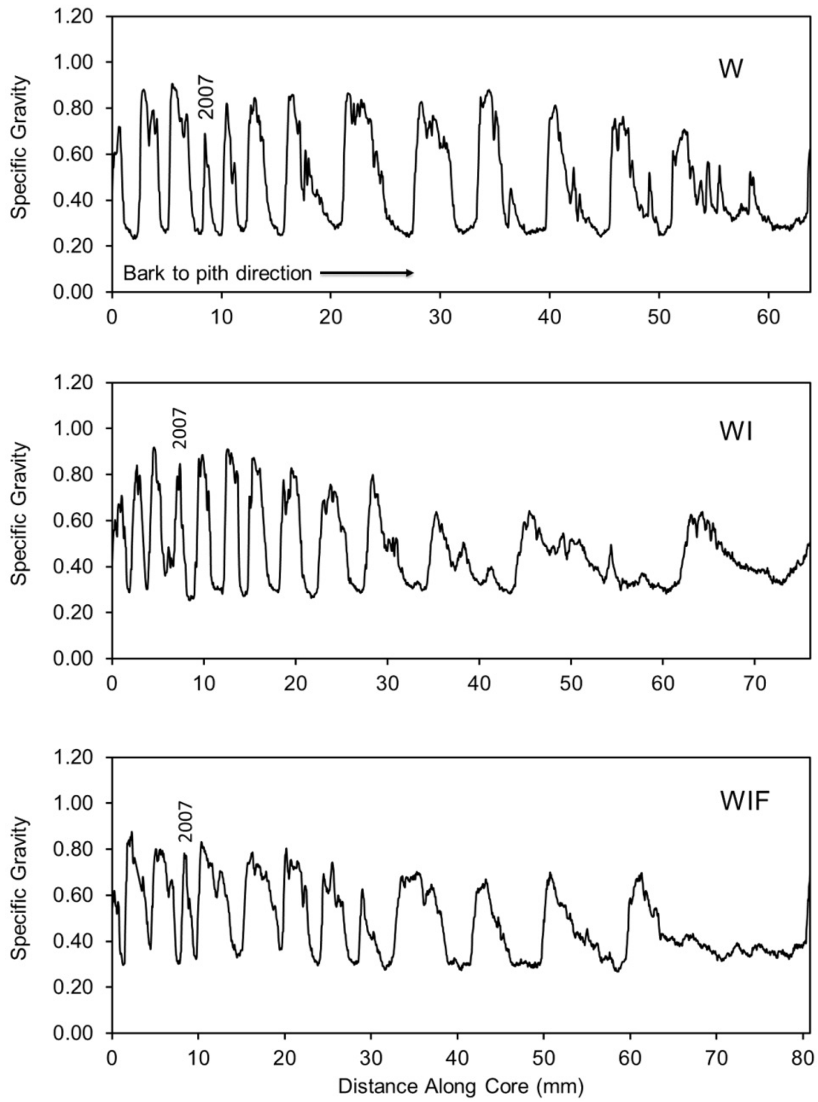


vorable climate conditions in the following years. Representative densitometry scans of individual increment cores from each treatment are shown in Fig. 5. Keeping in mind that the distance scales are different to include the same number of growth rings in each plot, the density traces illustrate the generally wider growth rings for the WIF treatment, and the distinctly narrow rings for year 2007 with all treatments that coincide with the drought conditions during that period.

3.2. Percent latewood

For loblolly pine, increased water availability, either naturally by precipitation (Cregg et al. 1988), or by irrigation (Gonzalez-Benecke et al. 2010; Love-Myers et al. 2010), has been shown to augment latewood formation at the end of the growing season resulting in higher values for % latewood (or latewood SG), although there are exceptions (Albaugh et al. 2004). Our findings gave a % latewood of 54.7% for the WI treatment that was seemingly higher than the 51.0% for the W treatment, but neither the ANOVA nor the Duncan's multiple comparison results supported a conclusion of a significant difference; factoring into this was the limited sample size and significant block effect. Competition control, in itself, can increase water (and nutrient) availability for all treatments (Antony et al. 2011), thereby attenuating increases in % latewood from additional moisture made available through irrigation. Interestingly, Love-Myers et al. (2010) showed irrigation helped to offset reductions in % latewood from fertilization, demonstrated by the % latewood for trees receiving both treatments to approach that determined for trees receiving neither treatment. Given the design of the present study, we cannot make the same comparison since we do not

Fig. 5. Representative densitometry scans for individual loblolly pine increment cores from weed control (W), weed control plus irrigation (WI), and weed control plus irrigation and fertigation (WIF) treatments. A total of 12 growth rings are shown along with the incomplete growth ring from 2010, the first growth ring on the left.



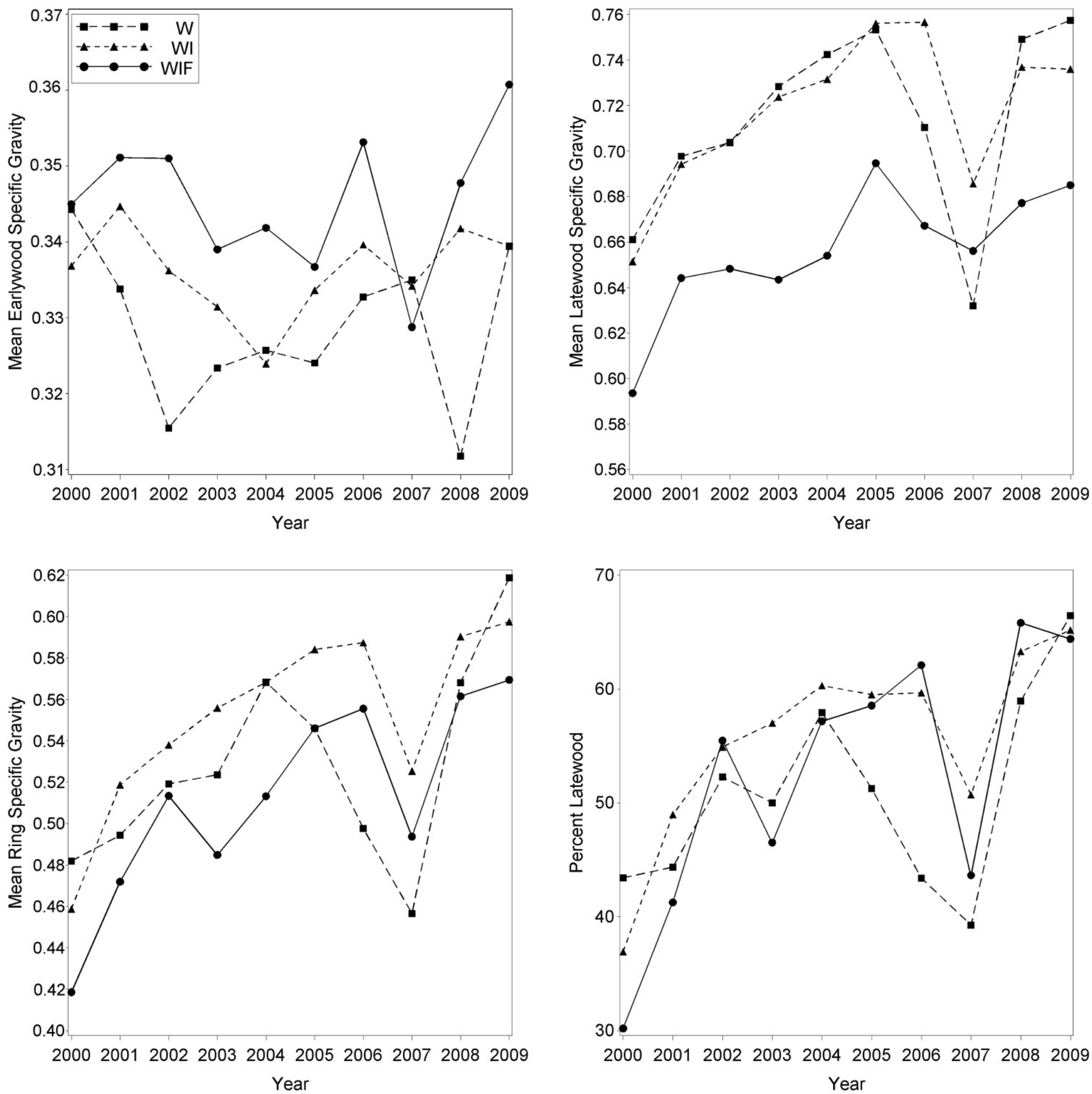
have a fertilization treatment without irrigation. Our results do show that the % latewood values between the W and WIF treatments are the same, supporting the conclusion of Love-Myers et al. (2010) that the combination of irrigation with fertilization, in our case being fertigation, can provide increased productivity without undesirable reductions in wood quality as would be indicated by reductions in values for % latewood.

3.3. Specific gravity

It is well established that % latewood and ring SG trend together for the southern pines (Eberhardt and Samuelson 2015; Eberhardt et al. 2019). Accordingly, like the % latewood results, ring SG seemed to increase with the WI treatment, but again showed no difference by Duncan's multiple comparison procedure. Whereas Gonzalez-Benecke et al. (2010) demonstrated an increase in ring SG for an irrigation treatment in young (11-year-old) loblolly pine, Albaugh et al. (2004) found no significant impact for slightly younger (9-year-old) trees of the same species. Direct comparison of our results to those in the literature cannot be done since our study did not have an untreated control. It is plausible that any increase in ring SG from irrigation may have been obscured by increased water availability (and nutrients) afforded by the complete weed control treatment (W).

Regarding the ANOVA for ring SG, significant effects were observed for both treatment ($P = 0.0178$) and block ($P = 0.0091$). Whereas the mean ring SG for the WIF treatment (0.507) was significantly lower than that for the WI treatment (0.548), it was not significantly different from that for the W treatment (0.529). Given the findings by Love-Myers et al. (2010), it can be rationalized that increases in ring SG from irrigation could be offset by decreases in ring SG from fertilization. The net result herein being higher productivity, as indicated by higher ring width for the WIF treatment, without undesirable reductions in wood quality, as indicated by

Fig. 6. Annual mean earlywood, latewood, and ring SG, and percent latewood for loblolly pine increment cores from weed control (W), weed control plus irrigation (WI), and weed control plus irrigation and fertigation (WIF) treatments.



the lack of a significant ring SG difference between the W and WIF treatments.

Narrowing down our analysis to the impacts on the earlywood and latewood zones within each growth ring, we found neither earlywood SG nor latewood SG to be significantly different between the W and WI treatments. In the study by Love-Myers et al. (2010), earlywood SG decreased in the juvenile wood and latewood SG increased in the mature wood of irrigated loblolly pine. Aside from working with a larger set of wood cores, the trees used in that study were from slightly older trees (19 years), affording more mature wood for the analysis. It is commonly accepted that the juvenile wood to mature wood transition in loblolly pine occurs at a cambial age of about 10 years (Larson et al. 2001; Clark et al. 2006). Since our data set was selected to encompass segments of both juvenile and mature wood, differences in the SG of the earlywood and (or) latewood may be reduced below the level of statistical significance; however, like Love-Myers et al. (2009, 2010), we observed a reduction in latewood SG with fertilization (WIF treatment).

Plots of the annual mean for each SG-based wood property by treatment are shown in Fig. 6. As to be expected, the wood properties for the three treatments (W, WI, and WIF) show similar trends, often overlapping, the exception being instances where significant differences were observed in the mean values shown in Table 1. For example, each annual mean latewood SG for the WIF treatment is about 0.05 units lower than each annual mean latewood SG for both the W and WI treatments, the exception being for year 2007. The plots for latewood SG, ring SG, and % latewood show values that trend upward over time (i.e., by year), typical within the juvenile wood zone of the southern pines (Clark et al. 2006; Jordan et al. 2008; Antony et al. 2011; Eberhardt and Samuelson 2015). The earlywood SG plot is also typical, usually being flat with values varying within a narrow range. As before, the sharp drop in the values at year 2007 is attributed mainly to the drought conditions experienced by these relatively young trees.

4. Conclusions

Mean values for all wood property determinations did not show any significant differences with irrigation (W versus WI treatments). Using the ring width as a proxy for productivity, our results confirmed that fertilization provided the most substantial impact on loblolly pine growth. Plots of the annual means for all wood property determinations showed them to follow similar trends, especially an abrupt drop in the wood properties that could be attributed to a period of severe drought. Finally, reductions in ring SG from fertilization could be offset by increases in ring SG from irrigation, with the net result being higher productivity without undesirable reductions in wood quality as indicated by a mean ring SG value for the WIF treatment being similar to that obtained from trees receiving neither irrigation nor fertigation (W treatment).

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The authors have declared that no competing interests exist.

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