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Effect of early age woody and herbaceous competition control on wood properties of loblolly pine

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ABSTRACT

Early age competition control has been reported to significantly improve the growth and yield of plantation grown loblolly pine. The objective of this paper is to understand the changes in wood properties: basal area weighted whole disk SG, earlywood SG (EWSG), latewood SG (LWSG) and latewood percent (LWP) of 14 year-old trees which received early age herbaceous and hardwood competition control, using data collected from 13-sites across 4-physiographic regions in the southeastern USA. The study was laid out in a randomized complete block design and had four levels of weed control (no weed control; woody vegetation control; herbaceous vegetation control; and woody and herbaceous vegetation control), with four blocks at each site. Increment cores 12 mm in diameter were collected at breast height (1.37 m) from 9-trees in each plot and ring-by-ring SG, EWSG, LWSG and LWP measured using a X-ray densitometer. Whole disk basal area weighted SG and LWP were determined for each tree and used for analysis. A reduction in whole disk SG of 0.039 and 0.0014 and LWP of 7.38% and 3.62% was observed for trees which received total weed control compared to no weed control, for lower and upper Coastal Plain sites, respectively. For trees receiving total weed control compared to no weed control, it was observed that the diameter of the juvenile core increased by 20% on average across all physiographic regions. However, no change in the length of the juvenile period was observed among treatments other than the regional differences.

1. Introduction

Throughout the southeastern United States of America (USA) pine plantations are managed intensively with the objectives of reducing rotation age and maximizing cash-returns. The most commercially important species in this region is loblolly pine (*Pinus taeda* L.) which compared to other southern pines shows rapid growth, an ability to grow on a wide range of sites and can respond well to any silvicultural practices. The productivity of pine plantations in this region is limited by the availability of resources, such as nutrients and water (Albaugh et al., 2004; Allen et al., 2005). Herbaceous and hardwood competition may reduce the growth rate of pine stands by limiting nutrient and water availability to trees (Albaugh et al., 2003). Competition at an early age (up to 3–5 years following plantation establishment) is especially important as it can adversely affect the establishment and growth of young pine saplings and thus the yield. Managing competing vegetation in a stand at establishment, and in subsequent years, may improve the availability of water and nutrients and have a positive impact on site quality.

Significant improvement in the growth and yield of loblolly pine owing to competition control (both in early and late aged pine stands) has been reported (e.g. Cain and Mann, 1980; Nelson et al., 1981; Miller et al., 2003b; Albaugh et al., 2003; Borders et al., 2004; Allen et al., 2005; Wagner et al., 2006; South and Miller, 2007; Jokela et al., 2010). In a study that compared the effect of weed control and fertilization on the growth and yield of 15-year old loblolly pine stands in Georgia (in USA), Borders et al. (2004) observed an increase in total height, diameter at breast height and stem biomass in trees which received complete weed control compared to no weed control. However, compared to fertilization or weed control plus fertilization, the increase in growth from weed control was moderate. Most of the response to weed control was concentrated in the first 5-years of growth following treatment. In a similar study based in Florida, Jokela et al. (2010) identified significant improvement in site index (at base age 25 years) and a subsequent increase in basal area and volume growth for loblolly pine following weed control, fertilization and both weed control and fertilization compared to no treatment. Later age competition control has also been found to be effective in improving the growth of loblolly

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pine. Albaugh et al. (2003) reported a volume response of 1.1 and 4.5 m^3 ha^{-1} yr^{-1}, following a one time control of hardwood vegetation in 10–22 year old loblolly pine plantations.

The quality of wood produced following the application of various intensive silvicultural practices is of concern to the forest product industry. The study mentioned above by Borders et al. (2004) observed no difference in whole-tree weighted average specific gravity (SG) between the weed control and no weed control treatments. Clark et al. (2006a), based on their preliminary analysis of data used in this manuscript, reported no influence on individual ring SG, earlywood and latewood SG and percent latewood following early age vegetation control, but found an increase in annual ring basal area growth following the application of weed control treatments in the initial 4–6 years of growth. However, they observed differences in whole core averages of wood properties across physiographic regions. They concluded that the complete woody and herbaceous weed control in a stand significantly increases juvenile wood (a cylindrical core of wood that has low density, stiffness and strength and short tracheids with high microfibril angle, formed in the vicinity of the tree crown and found at the center of a tree) formation without changing the wood properties much. However, their analysis of competition control on wood properties were incomplete as they failed to consider the changes in wood properties on a ring basal area weighted basis and ignored the site-to-site and tree-to-tree variability in their analysis.

Our objective was to further examine changes in loblolly pine wood properties (basal area weighted whole disk SG, earlywood SG (EWSG), latewood SG (LWSG) and latewood percent (LWP)) of the trees examined by Clark et al. (2006a) and to present a complete analysis of the data.

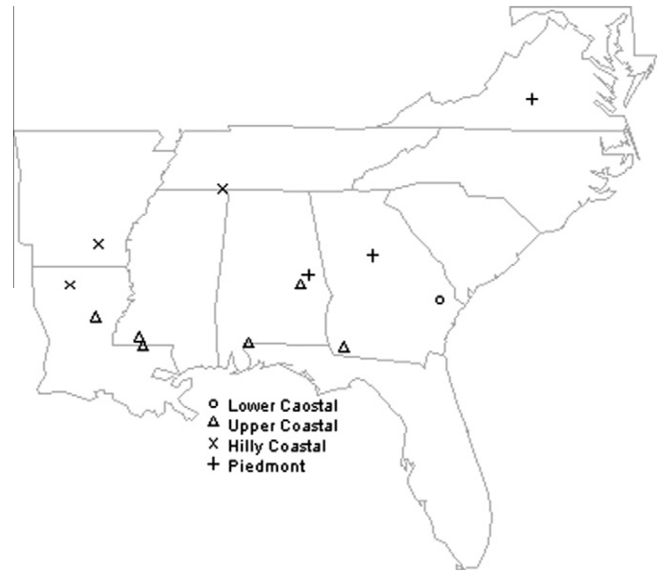

Fig. 1. Map showing the location of the 13 study sites.

2. Materials and methods

2.1. Data

Data for this study is from experimental trials that were established in 1984 at 13 sites/stands across the southeastern USA as part of the Competition Omission Monitoring Project (COMP) (for more details see Miller et al., 2003a,b; Clark et al., 2006a). The aim of the study was to examine the effect of early age herbaceous and woody competition control on growth and stand dynamics of loblolly pine. The 13-stands in this study were spread across four physiographic regions (lower, upper and Hilly Coastal Plain and Piedmont) in the southeastern USA (Fig. 1). More detailed information of each stand is presented in Table 1.

The study involved four levels of competition control: (1) no weed or competition control (C); (2) herbaceous vegetation control (H); (3) woody vegetation control (W); and (4) woody plus herbaceous vegetation control (WH). A randomized complete block design was used at each stand with each treatment replicated in four blocks (four plots in each block). Plots were 0.1 ha in size with an interior measurement plot of size 0.036 ha. One block in four stands (Bainbridge – 1H (indicates block 1 and treatment H), Jena – 4WH, Monticello – 3W and Appomattox – 4H) were incomplete with one treatment missing.

After completion of the 15th growing season, 12 mm diameter increment cores were collected at breast height (1.37 m) from nine trees within each treatment plot within a block, i.e. 36 trees per treatment per location. The increment cores were dried, glued to core holders and cut to give radial strips 1.98 mm thick (radial length varied from tree-to-tree). Ring SG, EWSG, LWSG, and LWP of each annual ring was measured using an X-ray densitometer at an interval of 0.06 mm. A SG threshold of 0.48 was used to demarcate earlywood from latewood within each ring. The X-ray densitometer measured SG on a green volume-oven dry weight basis.

Trees from 13 locations were sampled in the summers of 1999, 2000 and 2001. Each increment core carried a segment of earlywood from the sampled year. Also, trees from different stands were sampled in different years. To make the data uniform, all the rings produced after 1998 (i.e. after stand age 14) were excluded from further computation and analysis. Average basal area weighted whole disk ring SG, EWSG, LWSG and LWP was computed for each tree by weighting the individual ring-by-ring wood property values (e.g. Mora, 2003). The weight used was the ratio between individual ring basal area and whole disk basal area. The computed weighted average wood property values were used for further analysis and inference.

2.2. Juvenile – mature wood demarcation

The length of juvenile wood formation is usually determined by identifying the age or ring number at which selected wood properties become relatively constant and become typical of mature wood (Clark et al., 2006b). The age of transition can be estimated using different methods, for example the use of a threshold value for selected wood properties, segmented modeling approaches (Clark et al., 2006b) or by differentiating the function used to model wood property changes from pith-to-bark, i.e. derivative method (Mora et al., 2007; Jordan et al., 2008).

In order to compare the amount of juvenile wood produced under each region by treatment combination, the ring number at which the transition from juvenile-to-mature wood occurred and juvenile wood diameter was determined using the threshold method (Clark et al., 2006b) and the derivative method (Mora et al., 2007) for each tree in the study. The threshold method defined the transition from juvenile-to-mature wood as the ring number at which average ring SG was greater than or equal to 0.50 and percent latewood was greater than 40% for two consecutive rings (Clark et al., 2006b).

The derivative method involves fitting a model to the SG profile of each tree (or plot) with ring number as an explanatory variable and taking the first derivative of the fitted function with respect to ring number (Mora et al., 2007; Gonzalez-Benecke et al., 2010). A 4-parameter logistic function was used to explain the change in SG with ring number as presented below

Table 1
Mean diameter at breast height (DBH) and total tree height (Total Ht.) at age 15 for all the trees from 13 sampled stands, with their corresponding standard deviation in parenthesis.

Region	Stand	State	DBH (cm)	Total Ht. (m)
Lower coast	Pembroke	GA	16.87 (2.55)	14.18 (1.72)
Upper coast	Bainbridge	GA	18.58 (2.87)	17.04 (1.32)
	Liberty	MS	20.82 (3.47)	17.5 (1.72)
	Atmore	AL	17.52 (3.18)	15.18 (1.61)
	Liverpool	LA	18.34 (3.06)	15.08 (1.41)
	Jena	LA	19.31 (2.98)	15.51 (1.41)
	Tallassee	AL	17.45 (2.56)	13.77 (1.22)
Piedmont	Camp hill	AL	18.19 (2.84)	14.84 (1.42)
	Monticello	GA	19.38 (3.00)	16.24 (1.22)
	Appomattox	VA	18.93 (3.43)	13.19 (1.57)
Hilly coast	Arcadia	LA	18.77 (3.00)	14.68 (1.19)
	Warren	AR	19.42 (2.75)	14.29 (1.26)
	Counce	TN	18.31 (2.48)	13.52 (1.06)

$$y = \beta_0 + \frac{\beta_1 - \beta_0}{1 + e^{\left(\frac{\beta_2 - x}{\beta_3}\right)}} + \varepsilon$$

where y is the measured SG value from xth ring number from pith, β_0 is the lower asymptote as $x \to -\infty$, β_1 is the upper asymptote as $x \to \infty$, β_2 is the inflection point, and β_3 is the scale parameter (Pinheiro and Bates, 2000). The above model was fitted to ring-by-ring SG data collected from each plot within each stand. The plot-specific estimate of parameters were used to compute the first derivative with respect to ring number for each tree as follows

$$\frac{\mathrm{d}f(x)}{\mathrm{d}x} = \frac{\beta_1 - \beta_0}{\beta_3\left(1 + e^{\left(\frac{\beta_2 - x}{\beta_3}\right)}\right)^2} e^{\left(\frac{\beta_2 - x}{\beta_3}\right)}$$

The criteria of Mora et al. (2007) was used to demarcate the juvenile wood and mature wood of each tree, where juvenile wood is the area between ring number 1 and the ring number where the maximum rate of change in SG was observed. Transition wood is arbitrarily defined as the region between the juvenile wood boundary and the ring number at which the rate of change in SG was less than 0.01 units, i.e. the point where mature wood production begins.The inside bark diameter of the juvenile wood core using the threshold and derivative methods and the diameter of the juvenile core plus transition zone using the derivative method was estimated for each tree and subjected to further analysis.

2.3. Statistical analysis

The data in this study follows a hierarchical structure, with stands sampled at random within each region. The 9-trees sampled from each plot represent a random subsample of all the trees in the plot. In the analysis, the variability from stand-to-stand and the subsampling of trees within each plot (subsampling error) should be properly accounted for (Schabenberger and Pierce, 2002, Chapter 7.6.3). The incomplete nature of 4-blocks was taken into account by utilizing mixed models (Littel et al., 2006, Chapter 2.5; Schabenberger and Pierce, 2002, Chapter 7.6.4).

The full linear mixed model used for the analysis is represented below as

$$y_{ijklm} = \boldsymbol{\mu} + \mathbf{R}_i + \mathbf{T}_m + (\mathbf{RT})_{im} + s_j + b_l + u_{lm} + e_{ijklm}$$

where y_{ijklm} is the response measured from kth tree in lth block receiving mth treatment from jth stand in ith region; μ is the overall population mean; $\mathbf{R}_i$ is the ith fixed region effect; $\mathbf{T}_m$ is the mth fixed treatment effect; $(\mathbf{RT})_{im}$ is the interaction effect between region and treatment; s_j is the random stand effect with $s_j \sim NID(0, \boldsymbol{\sigma}_s^2)$, and is the proper error term for testing the region effect; b_l is the random block effect with $b_l \sim NID(0, \boldsymbol{\sigma}_b^2)$; u_{lm} is the random interaction between lth block effect with mth treatment effect with $u_{lm} \sim NID(0, \boldsymbol{\sigma}_u^2)$, and is the proper error term to test the treatment effect and the region by treatment interaction effect; and e_{ijklm} is the subsampling error term with $e_{ijklm} \sim NID(0, \boldsymbol{\sigma}_e^2)$.

Sliced effect tests were conducted within each region (tests for treatment differences) and within each treatment (tests for regional differences) to test for the differences across the mean for one fixed effect within each level of other fixed effects. Separate analysis of variance was conducted for each wood property and estimated juvenile wood diameter using both threshold and derivative method. Multiple comparison tests were conducted between treatments within each region using an adjusted p-value (P) from the Tukey-Kramer procedure. Of particular interest is comparison among treatments within each stand nested within each region. Estimates of stand specific random effects were utilized to test the differences across treatments within each stand (Littel et al., 2006). All the tests were conducted at a significance level of 0.05. Statistical analysis was conducted using the MIXED procedure in SAS version 9.2 (SAS Institute Inc., 2008).

3. Results

3.1. Whole disk SG

The region by treatment interaction was significant for whole disk SG, and indicates that the effect of treatments vary across regions (Table 2). Significant differences among treatment means were observed for disk SG within each region. Differences among mean regional disk SG were observed within each treatment with high disk SG values for trees from the lower Coastal Plain compared to other regions, supporting observations reported in recently published studies (Jordan et al., 2008; Antony et al., 2010).

A significant reduction in average whole disk SG for 14 year-old trees which received any weed control treatment (H, W or WH) compared to treatment C was observed in this study for the lower ($P = 0.017$) and upper Coastal Plain ($P = 0.003$). A significant decrease was also observed in the mean disk SG of treatment WH when compared with that of trees which had received either W or H weed control treatments for the Hilly ($P = 0.040$) and lower Coastal Plain's ($P < 0.001$) and the Piedmont ($P = 0.009$).

The mean disk SG of tress which received the WH treatment was significantly reduced compared to C ($P = 0.005$) and W ($P = 0.016$) for the lower Coastal Plain sites (Fig. 2). A significant decrease in whole disk SG was also observed for the WH treatment compared to C ($P = 0.048$) for the upper Coastal Plain sites (Fig. 2). No significant differences were observed between treatment means for the Hilly Coastal Plain and Piedmont.

At the stand level, differences were observed between the average disk SG of trees that received treatment C and those which received any weed control at several lower Coastal Plain sites (Pembroke, Bainbridge, and Atmore) and at Tallassee in the upper Coastal Plain. The type of weed control applied was also important

Table 2
Results from ANOVA for each wood property and juvenile wood diameter.

Property	Effect	*F*-value	*P*-value
Whole disk SG	R	15.87	0.0006
	T	14.31	<.0001
	R × T	2.04	0.0386
Whole disk LWSG	R	1.32	0.3272
	T	5.55	0.0012
	R × T	2.08	0.0337
Whole disk EWSG	R	5.91	0.0164
	T	1.85	0.1403
	R × T	3.06	0.0022
Whole disk LWP	R	13.05	0.0013
	T	17.97	<.0001
	R × T	2.57	0.0091
Juvenile core diameter – threshold method	R	9.68	0.0036
	T	20.91	<0.0001
	R × T	1.59	0.1203
Juvenile core diameter – derivative method	R	4.69	0.0312
	T	25.83	<0.0001
	R × T	1.71	0.0906
Juvenile + transition diameter – derivative method	R	0.96	0.4531
	T	31.69	<0.0001
	R × T	1.98	0.0444

R – region; T – treatment; R × T – interaction between region and treatment.

at some locations with differences observed in mean disk SG for the WH treatment compared with that of trees which received either W or H weed control treatments at several upper Coastal Plain sites (Bainbridge, Liberty, Liverpool and Jena), in addition to sites in the hilly Coastal Plain (Counce), lower Coastal Plain (Pembroke), and Piedmont (Monticello).

3.2. Whole disk EWSG

A significant interaction between regions by treatment was found for disk EWSG (Table 2). Significant effect of treatments was observed on disk EWSG for the hilly and lower Coastal Plain stands. However, differences in means across regions were absent at all treatment levels for disk EWSG.

Mean disk EWSG of trees which received treatment WH was lower than that of trees which received either W or H treatment for the lower Coastal Plain ($P = 0.019$). In addition, whole disk EWSG of trees which received WH treatment was decreased compared to trees that received W ($P = 0.034$) for the Hilly Coastal Plain (Fig. 2).

At the stand level, average disk EWSG of trees received treatment C was significantly different from that of trees which received any weed control at Warren in Hilly Coastal Plain, and at Bainbridge in upper Coastal Plain. Again, the type of weed control applied was important at some locations, with significant differences in mean disk EWSG for WH compared with that of trees which received either W or H treatments for Counce in Hilly Coastal Plain and at Bainbridge in upper Coastal Plain.

3.3. Whole disk LWSG

Regional differences in treatment effect were indicated through the significant region by treatment interaction term (Table 2). Significant differences in treatment means were observed for the Piedmont sites. Significant differences in mean disk LWSG was found across regions within each treatment levels, having high LWSG observed for trees from lower Coastal Plain.

The mean disk LWSG for trees subject to treatment C was higher than that of trees which received any weed control ($P = 0.005$) at Piedmont. A decrease in mean disk LWSG was observed for trees which received treatment WH compared to that of trees which received either W or H treatments ($P = 0.003$) at Piedmont.

At the stand level, significant differences in disk LWSG were observed for trees which received no competition control compared to those that did at two Piedmont sites: Camp Hill and Monticello, and one Hilly Coastal Plain site: Warren. We also observed significant differences in disk LWSG between WH and the average of W and H treatments at sites located in the Hilly Coastal Plain (Counce), Piedmont (Camp Hill and Appomattox) and upper Coastal Plain (Atmore).

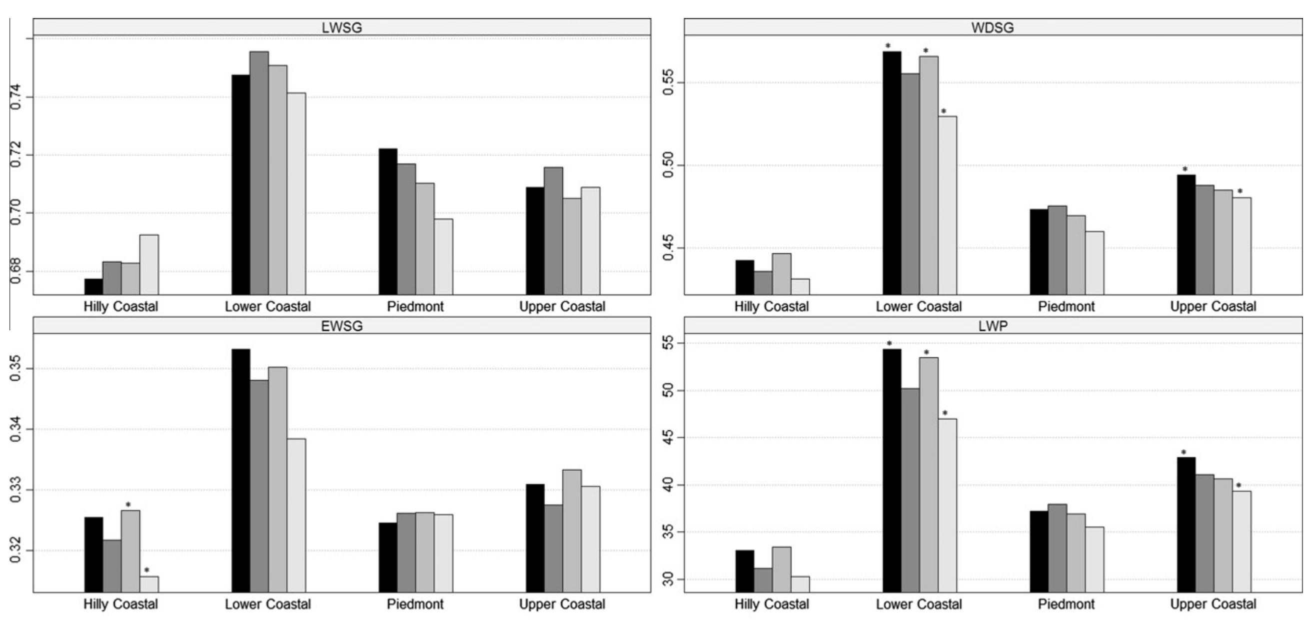

Fig. 2. Estimated whole disk wood property means by region and treatment. Whole disk average ring (WDSG), latewood (LWSG) and earlywood (EWSG) specific gravity and latewood percent (LWP); C – no weed or competition control; H – herbaceous vegetation control; W – woody vegetation control and WH – woody plus herbaceous vegetation control. The bars with an asterisk indicate significantly different treatments within a region.

3.4. Whole disk LWP

The interaction between region and treatment was significant for whole disk LWP (Table 2). Mean LWP across treatments were significantly different for all regions. Significant regional differences were observed within each treatment in whole disk LWP (Fig. 2).

Whole disk LWP followed a similar pattern to whole disk SG, with the disk LWP of trees which received treatment C being lower than that of trees which did not receive any weed control for the lower ($P = 0.002$) and upper ($P < 0.001$) Coastal Plain's. In addition, mean disk LWP of trees which received treatment WH was significantly lower than the mean disk LWP of trees which received either W or H treatments for all regions (P values of 0.017, 0.001, 0.009, and 0.022, respectively for the Hilly, lower and upper Coastal Plain's and Piedmont).

Significantly lower whole disk LWP was observed for WH compared with treatments C ($P = 0.002$) and W ($P = 0.013$) for the lower Coastal Plain (Fig. 2). Similarly for the upper Coastal Plain, significantly lower mean LWP was observed for trees which received WH compared with C ($P < 0.001$).

Significant differences in mean LWP of trees which received C compared to all weed control treatments (WH, H and W) were observed for all the stands in upper Coastal Plain and at Pembroke in lower Coastal Plain. Similarly, significant difference were observed in mean LWP for trees that received WH compared to W and H treatments at sites in each region including the Hilly Coastal Plain (Counce), lower Coastal Plain (Pembroke), Piedmont (Monticello), and upper Coastal Plain (Liberty, Liverpool, and Jena).

3.5. Juvenile-mature wood transition

3.5.1. Threshold method

Based on the threshold method, the ring number at which juvenile wood transitioned to mature wood differed by region. The longest juvenile period was for trees from the Hilly Coastal Plain (10.4 rings), while the shortest was for trees from the lower Coastal Plain (4.7 rings). Regardless of the region, the competition control treatments did not influence the length of the juvenile period (on average ranged from 8.5 to 9.2). Based on the analysis, the interaction between region and treatment on the diameter of the juvenile core was not significant. Significant differences across regions, and among treatments, were observed for the diameter of the juvenile core (Table 2). The diameter of the juvenile core of trees from the lower Coastal Plain (7.49 cm) was significantly smaller than that of trees from the Hilly (14.64 cm; $P = 0.003$) and upper (12.49 cm; $P = 0.016$) Coastal Plain and Piedmont (13.78 cm; $P = 0.006$). The juvenile core diameter for trees that received treatment C (11.06 cm) was smaller compared to trees that received the H (12 cm; $P = 0.004$); W (12.12 cm; $P = 0.001$) and WH (13.23 cm; $P < 0.001$) treatments. Whereas the juvenile core diameter of trees that received WH was higher than that of trees that received H ($P < 0.001$) and W ($P < 0.001$) treatments. The ring number and least square estimate of juvenile core diameter for each region by treatment combinations is presented in Table 3.

3.5.2. Derivative method

Based on the derivative method, the juvenile period for trees from the Hilly Coastal Plain (6.5 rings) was longer than the other regions, which ranged from 4.4 rings for the lower Coastal Plain through to 5.7 rings for the Piedmont. Differences among treatments were absent (it ranged from 5 to 5.6 rings) as was any effect owing to the interaction between region and treatment. Significant regional and treatment differences were observed in the diameter of the juvenile core, but not a region by treatment interaction (Table 2). The juvenile core diameter for trees from the lower Coastal Plain (7.52 cm, $P = 0.046$) was smaller compared to trees from the Hilly Coastal Plain (11.95 cm). The diameter of the juvenile core of trees received treatment C (8.54 cm) was smaller than that of trees which received the W (10.06 cm, $P < 0.001$) and WH (11.41 cm, $P < 0.001$) competition control treatments. A larger juvenile core was observed for trees that received treatment WH compared to trees that received H (9.28 cm, $P < 0.001$) and W ($P < 0.001$) treatments.

The ring number at which juvenile core plus transition wood zone was produced was longer for trees from the lower Coastal Plain (9.4 rings) compared to the other regions; Piedmont (7.9) and Hilly (8.3) and upper (8.4) Coastal Plain. Difference among treatments on average juvenile core plus transition wood zone across regions was marginal (ranging from 8 to 8.6), while a significant interaction between region by treatment was observed. Significant difference was observed among treatments for the Hilly ($P < 0.001$) and upper ($P < 0.001$) Coastal Plain and Piedmont ($P < 0.001$). The juvenile core plus transition zone was larger for trees that received the WH treatment compared to C ($P < 0.001$) for the Hilly Coastal Plain sites (Table 3). For the Piedmont sites, the juvenile/transition wood zone was larger for trees that received WH compared to that of C ($P < 0.001$) and H ($P < 0.001$) treatments (Table 3). For Piedmont sites trees which received treatment W had more juvenile plus transition wood than those that did not

Table 3
Juvenile-to-mature wood transition age and diameter of the juvenile wood for each region by treatment. C – No weed or competition control; H – herbaceous vegetation control; W – woody vegetation control and WH – woody plus herbaceous vegetation control.

Treatments	Lower Coastal Plain		Upper Coastal Plain		Piedmont		Hilly Coastal Plain	
	Ring number	Diameter (cm)	Ring number	Diameter (cm)	Ring number	Diameter (cm)	Ring number	Diameter (cm)
Threshold method								
C	4.7	6.23	8.1	11.26	9.8	12.71	10.3	14.03
H	4.7	7.81	8.9	12.61	9.8	12.88	10.6	14.72
W	4.8	7.45	8.0	12.47	9.9	14.13	10.1	14.42
WH	4.5	8.45	7.6	13.66	9.6	15.40	10.4	15.41
Derivative method – juvenile wood								
C	4.5	6.29	4.6	7.80	5.4	8.94	6.5	11.12
H	4.0	7.43	4.4	8.62	5.5	9.35	6.2	11.73
W	5.0	7.96	4.8	9.33	6.1	11.03	6.8	11.93
WH	4.3	8.39	5.0	11.72	5.9	12.53	6.5	13.02
Derivative method – juvenile plus transition wood								
C	9.3	10.11	8.5	11.90*c*	7.6	10.99*b*	7.9	12.38*b*
H	9.3	11.59	8.0	12.45*b*	7.6	11.28*b*	8.3	13.42*ab*
W	10.0	11.95	8.5	13.20*c*	8.3	13.15*c*	8.5	13.40*ab*
WH	9.1	11.95	8.5	14.59*a*	7.9	14.25*ac*	8.6	14.45*a*

*Values with different letter in a column are significantly different; only treatments with significant differences are letter coded.

received any weed control ($P < 0.001$) and H ($P = 0.009$) (Table 3) treatments, while for the upper Coastal Plain sites trees which received the WH treatment had a larger juvenile/transition wood zone compared to treatment C ($P < 0.001$); H ($P < 0.001$) and W ($P = 0.003$) treatments (Table 3).

3.6. Pith-to-bark profiles

The pith-to-bark profiles of ring-by-ring basal area and cumulative basal area growth are presented in Figs. 3 and 4. Ring basal area and cumulative basal area of trees which received any weed control treatment was increased considerably, especially during the early periods of growth until 3–6 years at which the treatments were applied.

The pith-to-bark profiles of ring-by-ring SG, EWSG, LWSG and LWP are presented in Figs. 5–8. Based on the pith-to-bark profiles, differences among treatments were absent for ring-by-ring wood properties. However, regional differences in pith-to-bark profiles of wood properties are present. The general form of the pith-to-bark profiles for SG and LWP agrees with those reported in

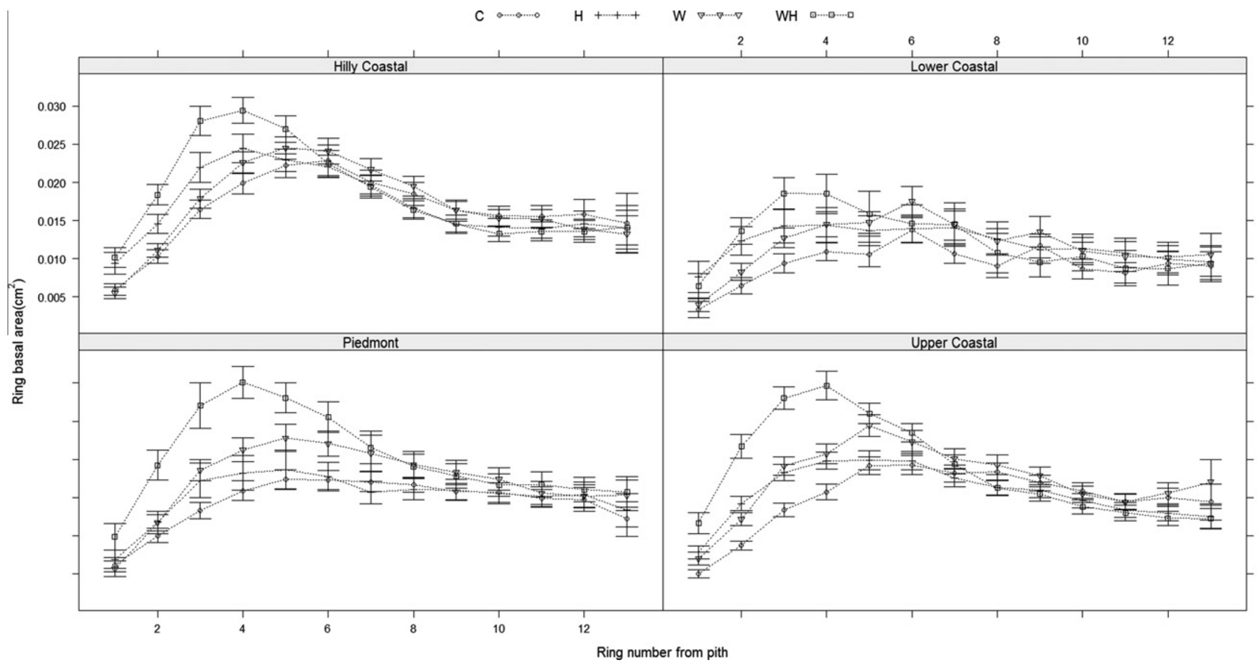

Fig. 3. Observed mean ring basal area growth from pith-to-bark for each treatment by region. C – No weed or competition control; H – herbaceous vegetation control; W – woody vegetation control and WH – woody plus herbaceous vegetation control.

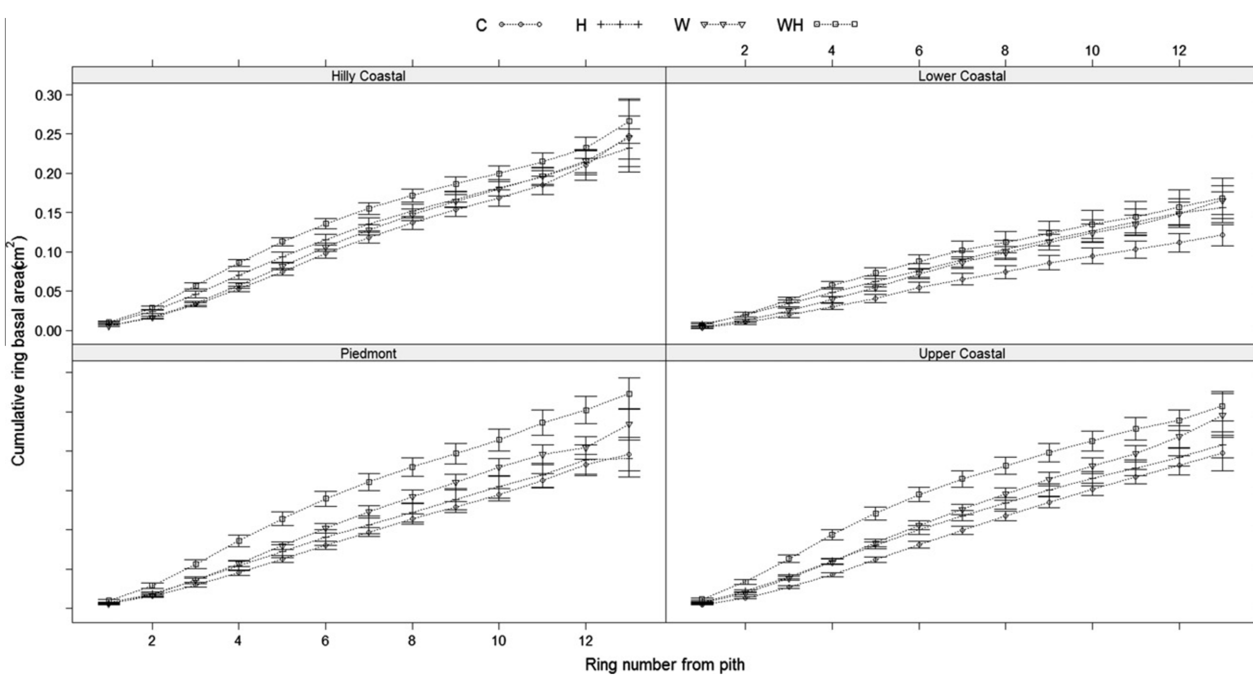

Fig. 4. Observed mean cumulative ring basal area from pith-to-bark for each treatment by region. C – No weed or competition control; H – herbaceous vegetation control; W – woody vegetation control and WH – woody plus herbaceous vegetation control.

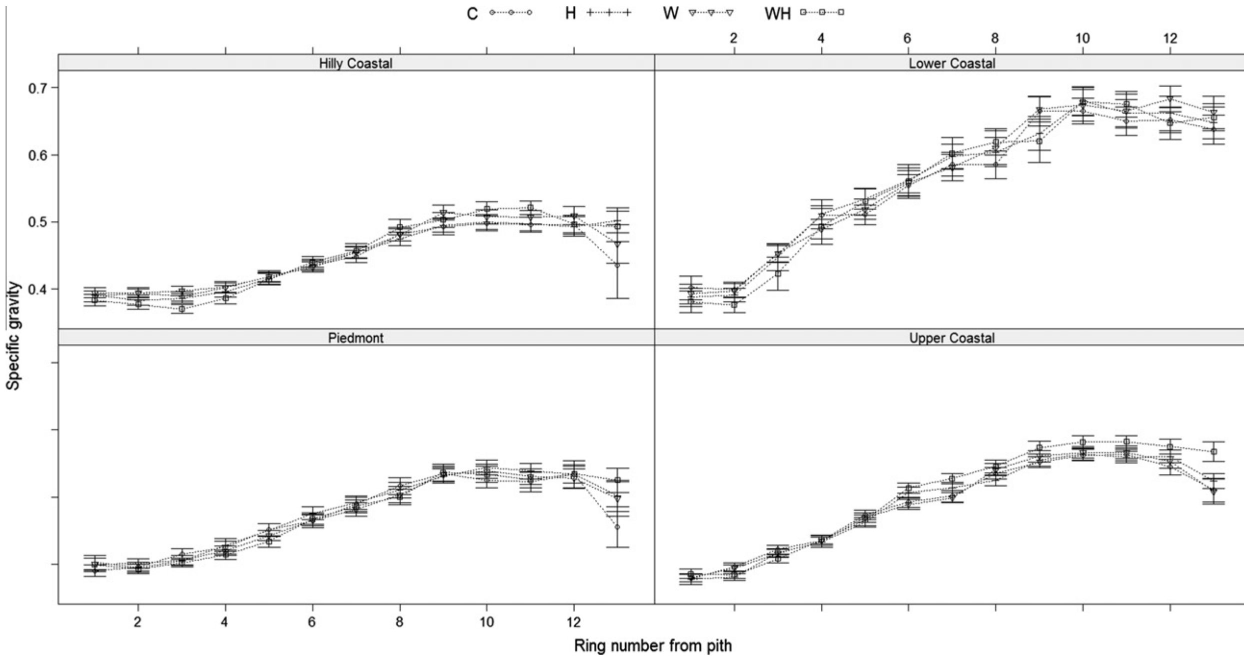

Fig. 5. Observed mean ring specific gravity from pith-to-bark for each treatment by region. C – No weed or competition control; H – herbaceous vegetation control; W – woody vegetation control and WH – woody plus herbaceous vegetation control.

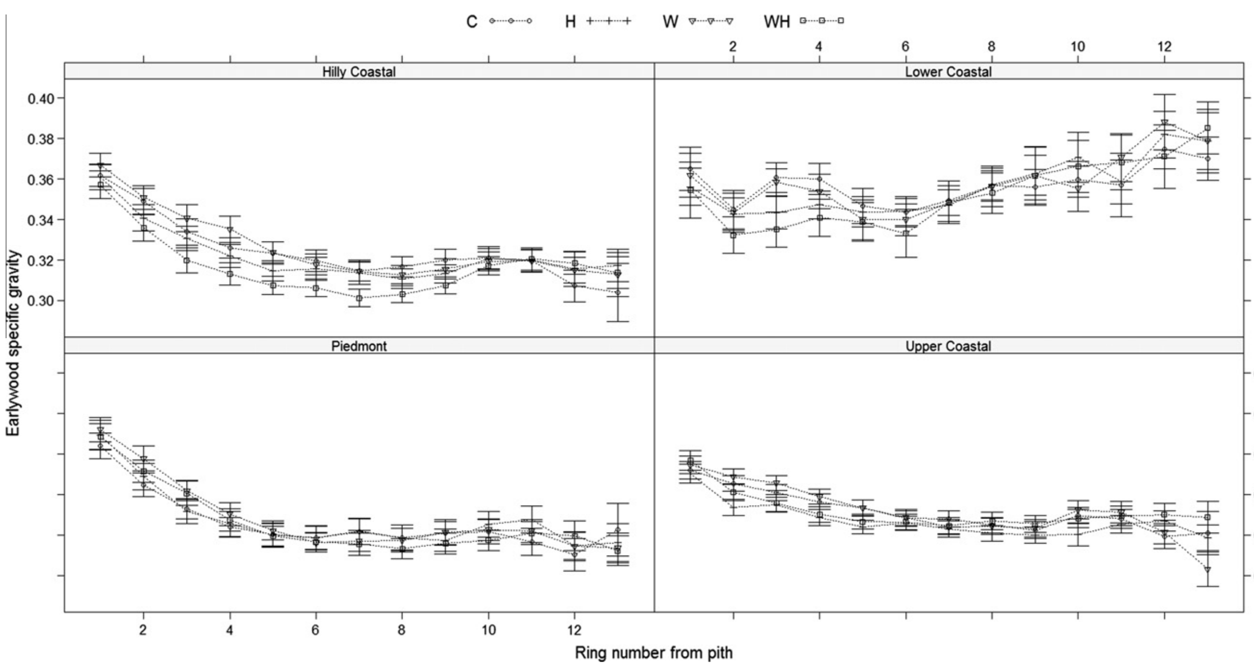

Fig. 6. Observed mean earlywood specific gravity from pith-to-bark for each treatment by region. C – No weed or competition control; H – herbaceous vegetation control; W – woody vegetation control and WH – woody plus herbaceous vegetation control.

the past for loblolly pine (eg. Clark et al., 2006b; Jordan et al., 2008) with a rapid initial increase in the first few rings (from age 1 to 10) and then reaching an upper asymptote as the trees get older.

4. Discussion

Gains in growth and yield of loblolly pine following early-age competition control (herbaceous and woody) have been reported previously (Borders et al., 2004; Allen et al., 2005; Jokela et al., 2010); however, the effect of competition control on wood properties has rarely been examined. In this study, we utilized the samples collected from the COMP study which had been established with the objective of understanding the long-term changes in stand dynamics and improvements in growth following different methods of competition control. Based on data collected from the COMP study after 15 years of growth, Miller et al. (2003b) reported volume increases ranging from 23% to 231% for woody and herbaceous weed control compared to untreated plots. Based on our data on ring basal area and cumulative basal area from breast height increment cores improvements in growth at an early-age were observed for trees that received any of the weed control treatments (Figs. 3 and 4).

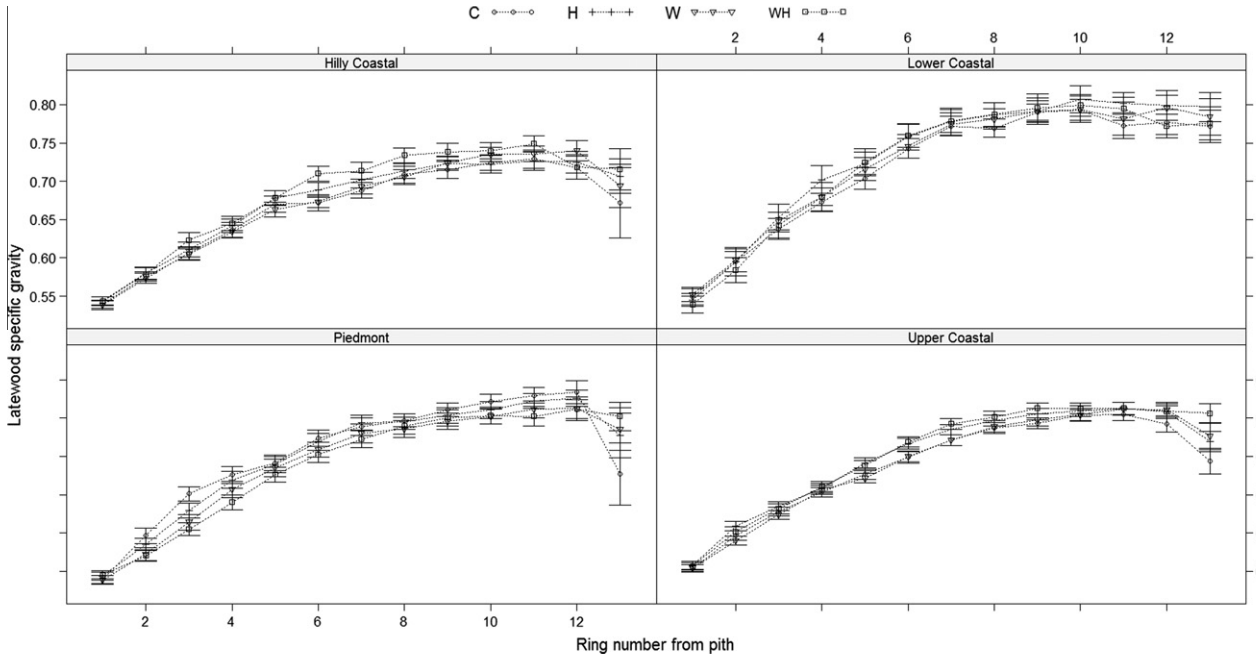

Fig. 7. Observed mean latewood specific gravity from pith-to-bark for each treatment by region. C – No weed or competition control; H – herbaceous vegetation control; W – woody vegetation control and WH – woody plus herbaceous vegetation control.

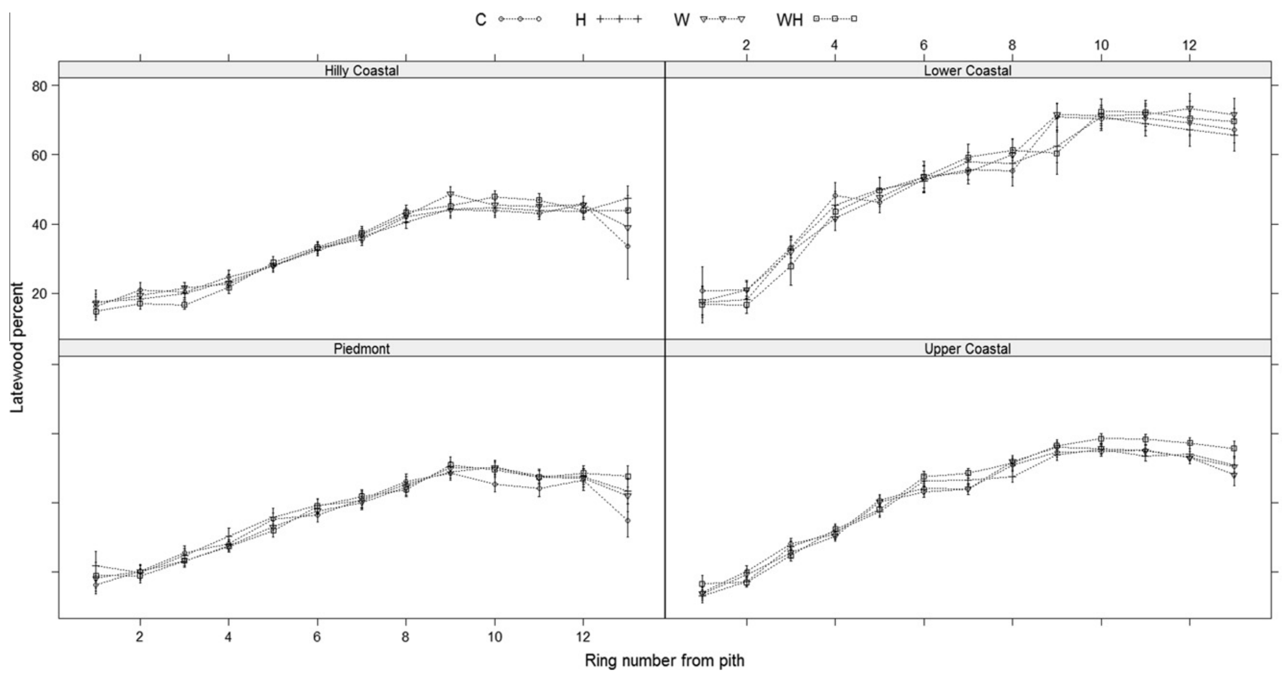

Fig. 8. Observed mean latewood percent from pith-to-bark for each treatment by region. C – No weed or competition control; H – herbaceous vegetation control; W – woody vegetation control and WH – woody plus herbaceous vegetation control.

Individual ring SG and LWP did not show a discernible change among treatments. However, after weighting these properties to take into consideration the differences in growth observed for the weed control treatments it was shown that basal area weighted whole disk SG and LWP decreased for the WH treatment compared to treatment C. Differences in the proportion of juvenile wood produced by trees in the first 4–6 years of growth within each treatment probably explain the difference observed in SG among treatments. Trees grown in the absence of any herbaceous or woody competition during their early period of growth have a higher proportion of low SG juvenile wood and a lower whole disk SG. Even though we observed an overall decrease in whole disk SG and LWSG following competition control at early ages, these trends are site specific as indicated by the results from stand level treatment comparisons.

The length of the juvenile period (ring number) did not change considerably among treatments, though regional differences were observed (Clark et al., 2006b; Jordan et al., 2008) based on the estimated juvenile period using both the threshold and derivative methods. However, an increase in the diameter of the juvenile core was observed for trees which received the WH treatment compared to treatment C. Based on the threshold method the average diameter of the juvenile core for trees which received treatment WH increased by 36%, 21%, 10% and 21%, respectively for the lower, upper and Hilly Coastal Plain and Piedmont compared to that of trees that received treatment C, with an overall increase of 20% for the treated plot. These values are in agreement with Clark et al. (2006a). Based on the estimates from the derivative method, an increase of 33%, 50%, 17% and 40% was observed for the juvenile core for trees which received treatment WH compared to treatment C, for the lower, upper and Hilly Coastal Plain and Piedmont respectively. Similarly, the juvenile/transition wood zone of trees which received the WH treatment increased by 18%, 23%, 17% and 30%, for the lower, upper and Hilly Coastal Plain and Piedmont respectively, compared to trees grown without competition control. The increase in ring basal area growth of trees in the first 4–6 years (Figs. 3 and 4) following competition control explains this phenomenon. In general, the larger juvenile core of trees which received any type of vegetation competition control is probably due to the additional growth attained through improved resource availability (nutrients and moisture), especially prior to canopy closure in these stands. Improved resource availability following woody and herbaceous competition control might have significantly increased total biomass production and stem volume growth by improving leaf area index and growth efficiency (production per unit of light interception) during early growing periods of these stands (Albaugh et al., 2004, 1998; Martin and Jokela, 2004; Allen et al., 2005). Evidence from past studies indicates that increased availability of resources accelerates growth prior to self-thinning (Morris and Myerscough, 1991), but growth rate declines as stands get older (Martin and Jokela, 2004).

In summary, weed control increased the proportion of juvenile wood formed within a tree. The maximum change was observed for the total weed control treatment and it produced a significant increase in the diameter of juvenile wood. While ring-by-ring wood properties (EWSG, LWSG, LWP) didn't change significantly among treatments, a significant reduction in basal area weighted whole disk SG and LWP was observed for woody plus herbaceous competition control compared to treatment C. Juvenile wood is reported to have lower stiffness and strength and thus it can be expected that wood obtained from plantations subject to intensive management practices, such as competition control in this study, might have inferior strength properties. The growth gain following such intensive management practices reduces the rotation length of plantations by achieving the target diameter and height in a shorter period of time and led to an increase in the proportion of juvenile wood within a stem. This suggests that caution must be exercised if such wood was going to be used for structural purposes since a major proportion of wood in the stem is of low stiffness (Watt et al., 2009). Even though a reduction in whole disk SG and LWP was observed in some sites, gains in growth following competition control are large. If such extensive competition control was to become common practice in the future it is recommended that growth gains be carefully considered in light of the losses in wood quality before fully adopting such practices.

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