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Modeling Early Responses of Loblolly Pine Growth to Thinning in the Western Gulf Coastal Plain Region

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Growth response to thinning has long been a research topic of interest in forest science. This study presents the first 3–4 years of response of loblolly pine (*Pinus taeda* L.) growth to thinning at different intensities. Data were collected from the East Texas Pine Research Project's region-wide loblolly pine thinning study, which covers a wide variety of stand conditions. Four treatments, light, moderate, and heavy thinning, respectively having 370, 555, and 740 residual trees per hectare after thinning, and an unthinned control, were included. Individual tree diameter at breast height (dbh) and total height were recorded annually for the first 3–4 years after thinning. Results indicate significant differences between treatments in dbh growth in each year after thinning, as well as for all years combined. Each thinning treatment had significantly greater dbh growth than the control in the first growing season with this positive response being more evident in the case of the heavier thinning or at the later years post-thinning. Conversely, the thinning effect on tree height growth was initially negligibly negative, then becoming positive after 2–4 years, with the heavier thinning becoming positive sooner. Tree size class, assigned based on prethinning dbh, had a significant effect on both dbh and height growth responses. Compared to the control, small trees had a greater response both in dbh and in height growth than the medium and large trees over the measurement period. At the stand level, the heavier thinning had significantly less stand basal area per hectare, but the difference in stand basal area per hectare between the thinned and the unthinned plots decreased with years post-thinning. Results from this study can improve our understanding in thinning effects and help forest managers make accurate decisions on silvicultural regimes.

Study Implications: Loblolly pine plantations are the most economically important forests in the West Gulf Coastal Plain, and thinning is the most common midrotation silvicultural treatment used in their management. Thinning is an effective practice to improve timber value and reduce rotation lengths, thus increasing the economic return of the stand. Our results suggest that the common thinning regime in the region, having 555 residual trees ha^{-1} after thinning, seems optimal, as it greatly enhances diameter at breast height (dbh) growth yet maintains comparable BA growth to unthinned stands, whereas the other regimes, having 370 and 740 residual trees ha^{-1} after thinning, are suboptimal in terms of balancing dbh and BA growth. Thinning redistributes site resources to growing fewer, higher-value residual trees, making them less stressed from competition and potentially more resilient to changing climatic conditions, pest attacks, and other environmental stresses. Therefore, thinning practices may be modified to address economic, timber production, and environmental goals. Applying the findings to thinning regimes that are not reflected in the data from this study is not recommended. Such applications are extrapolations beyond the range of the data in this study, and predictions of response may not be reliable.

Keywords: loblolly pine, growth and yield, forest management, basal area

Loblolly pine (*Pinus taeda* L.), a shade-intolerant tree species, requires nearly full sunlight to thrive and grow. In order to improve plantation productivity and reduce density-dependent mortality, thinning often is practiced to open the canopy, redistributing light, nutrient, and water availability to residual trees. For this species, numerous studies have shown that thinning substantially improves stem diameter growth but has little impact on tree height (Baldwin et al. 1989, Ginn et al. 1991, Short and Burkhart 1992, Hasenauer et al. 1997, Tasissa and Burkhart 1997, Amateis 2000). These studies have, however, focused more on long-term responses (5 years or greater), with the goal to incorporate thinning responses into growth and yield models. Tree growth response to thinning in the long-term declines, since site resources again become limited (crown closure) (Hasenauer et al. 1997, Tasissa and Burkhart 1997, Russell et al. 2010). Commonly, second thinnings are implemented 5–7 years after the first thinning, so the response in the initial 5 years is most relevant to industrial plantation management. Knowledge of early responses to

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thinning is valuable, yet limited with most studies not beginning tree remeasurements until 3–5 years post-thinning.

Changes in stand environments from thinning are substantial, particularly in the initial 2–3 years post-thinning, and consequently the residual trees are expected to respond quickly and strongly. Studies of the early response of loblolly pine to thinning differ in their results. Some studies show that time elapses before the effects of thinning on diameter growth are evident (Ginn et al. 1991, Amateis 2000), whereas others confirm that improvement in diameter growth is significant immediately after thinning, without a temporary growth decline (Moschler et al. 1989, Tasissa and Burkhart 1997). The significant response in diameter growth immediately after thinning has also been reported in other species (Pukkala et al. 1998, Pape 1999, Peltola et al. 2002). Loblolly pine reacts negatively in height growth immediately after thinning (Peterson et al. 1997, Sharma et al. 2006), although the long-term (i.e., 12 years or more post-thinning) response is positive (Sharma et al. 2006). Overall, our understanding of growth responses of loblolly pine in the first few years after thinning is still far from complete.

It is well known that the immediate thinning response of loblolly pine is a complicated issue, varying with many factors such as site quality, age of the stand at the time of thinning, percentage live crown present, and thinning method, as demonstrated by both modeling (Tasissa and Burkhart 1997, Zhang et al. 1997, Amateis 2000) and empirical data (Baldwin et al. 1989, Harrison et al. 1998). Zhang et al. (1997) investigated the role of tree size in the response of loblolly pine to thinning. They found that smaller loblolly pine trees displayed a greater response in relative height growth on better-quality sites (i.e., higher site index). Effects of tree size in other species have been studied, but findings were sometimes contradictory. Some reported that larger trees have a larger absolute magnitude of response (Pukkala et al. 1998, Mäkinen and Isomäki 2004); others argued that codominant and intermediate trees have the maximum responses (Pukkala et al. 1998) or that the relative thinning response is independent of tree size, especially among trees that are dominant at the time of thinning (Moore et al. 1994, Hynynen 1995, Pape 1999). There is no consensus about the effect of tree size on thinning response. Some studies have reported tree physiological responses following thinning. Significant physiological changes because of thinning were generally observed only in the lower crowns where needle photosynthesis, transpiration, and conductance were greatly improved compared to those of the unthinned counterpart (Ginn et al. 1991, Peterson et al. 1997, Tang et al. 1999). The increase in crown size and the ability (physiologically) of lower crown foliage to take advantage of the increased light following thinning are likely the major factors resulting in the increased growth of 1oblolly pine following thinning (Ginn et al. 1991, Peterson et al. 1997).

Two questions are often asked regarding thinning response: are there any differences among thinning treatments and how do the differences change over years post-thinning? To answer the questions, most studies have analyzed data using either an individual time (year) point analysis (Peterson et al. 1997, Grogan et al. 2018) or a multivariate approach (Canellas et al. 2004). There are serious limitations in both methods, i.e., not a truly repeated-measures analysis for the time point method and inefficient in handling missing values and using the complicated (unstructured) covariance structure for repeated measurements for the multivariate approach.

Loblolly pine plantations form a significant proportion of forest land in the West Gulf Coastal Plain (WGCP) region, the western extreme of loblolly pine range. Most of the above cited loblolly pine thinning studies targeted the southeastern United States, with few or no samples from the WGCP, and therefore their conclusions may not be applicable to the region. Also, the above cited loblolly pine studies have used the method of free thinning from below, which does not reflect the current operational thinning practice in the region that uses a combination of geometric and low thinning/improvement cutting techniques. Thinning responses from low thinning and row thinning may be different. Low thinning will not reduce crowding within the upper canopy substantially, and individual tree growth may not be enhanced (Nyland et al. 2016). Recently, Coble and Grogan (2016) modeled thinning response in basal area and height growth of residual loblolly pine trees in east Texas. They used data collected from operationally thinned plantations, which are not designed thinning studies (i.e., no unthinned control was included).

In order to improve our understanding of loblolly pine response to thinning in the region, the East Texas Pine Plantation Research Program (ETPPRP), a cooperative organization among Stephen F. Austin State University and various industrial forest landowners, initiated a thinning study in 2014 by establishing permanent thinning plots across the region (Coble et al. 2016). Individual tree growth variables were recorded before thinning and annually after thinning. Although long-term thinning responses are important, knowledge of early responses to thinning is also valuable. Given the limited knowledge in tree early response to thinning, the lack of region-specific information, and differences in operational thinning, the ETPPRP members are interested in gaining knowledge of short-term responses to thinning in the region. The objective of this study was to investigate loblolly pine response to thinning during the 4 years after thinning using mixed modeling methods, with specific focus on the effects of thinning treatments and tree size on longitudinal growth of individual trees and stands. The results will provide valuable information for managing loblolly pine plantations in the region.

Methods

Starting in 2014, a thinning study of 16 sites arranged as a randomized complete block design was installed in loblolly pine plantations (Coble et al. 2016). These plantations were distributed across east Texas and western Louisiana, and were selected following guidelines so that various site qualities were sampled. The region, known as the Piney Woods, belongs to the humid subtropical climate zone, characterized by high humidity because of heavy to moderate rainfall (75 mm precipitation in August) and high temperatures (the average maximum temperature in August is 34° C) during the summer. Despite the typical high humidity and precipitation, the region often experiences abnormally dry or moderate drought periods (https://droughtmonitor.unl.edu/CurrentMap/StateDroughtMonitor.aspx?TX). Forested soils in the region belong in the red and yellow soils group characteristic of the southeastern United States, with the surface textures being predominately sandy. Among the 16 sites, 11 (one was dropped because of an incorrect thinning treatment) were established in 2014 and 2015, and another five were established thereafter. Presented here are data on the 10 sites established in 2014/2015, which have either three (four sites) or four (six sites) post-thinning measurements (Figure 1). Initial stand density was uniform across the study at 1,230–1,490 trees per hectare, which is typical for young pine plantations in this region. Stands averaged 12.8 years for age (range: 11–15 years, which is the typical age range for the first thinning in the region) at the time of plot installation and were 20 m for site index (range: 18–24 m; base age 25 years), 18.4 cm for individual tree diameter at breast height (dbh) (range 10.1–32.0 cm), and 13.6 m for height (range: 12.3–17.6 m).

At each plantation, four square (0.202-hectare) plots were established. Plots within a plantation had comparable site index, basal area, and number of trees so that the plot-to-plot variation at the time of establishment was minimized. Plots were randomly assigned to four thinning treatment categories: no thin (control); and thin to 370 (T370, heavily thinned), to 555 (T555, moderately thinned), and to 740 (T740, lightly thinned) residual trees per hectare (trees ha^{-1}). The T555 treatment is a common density target used operationally for first thinnings in the WGCP region (Dean and Baldwin 1983). T370 and T740 correspond to a ±33 percent density target from the T555. Thinning on each site was performed in conjunction with the adjacent stand following current operational practices, using a combination of geometric and low thinning/improvement cutting techniques by removing every fifth row for access, then removing undesirable trees in the remaining rows to meet the thinning target density. Individual tree dbh and height were recorded before thinning and annually after thinning for years 1–4. To examine the effects of thinning on growth per unit area, the stand basal area per hectare (BA ha^{-1}) was calculated as total plot BA multiplied by an expansion factor of 5 (Burkhart et al. 2019). To analyze thinning responses of trees of different sizes, trees were classified into three dbh size classes (small, medium, and large) according to prethinning diameter. The small class consisted of trees with a diameter of 10.0–17.5 cm, medium with a diameter of 17.6–22.6 cm, and large with a diameter of >22.6 cm. A preliminary analysis showed no difference among plots within a plantation for both prethinning dbh ($F = 0.56$, $Pr = .65$) and height ($F = 1.19$, $Pr = .33$). This was expected and provides a basis for comparing the absolute and relative thinning responses with the unthinned control.

Tree growth relation with time (year) was assumed to be linear, which seems reasonable for such a short period, and can be expressed as:

$$y_{ijklm} = \alpha + \beta \times \text{Time} + \varepsilon_{ijklm} \quad (1)$$

where y_{ijklm} was the dbh or height value for the mth time ($m = 0, 1, 2, 3$, where 0, 1, 2, and 3 denote the values at the end of the first, second, third, and fourth year(s) post-thinning, respectively) of the lth tree growing at the ith location which was thinned by the jth intensity and belonging to the kth tree size class, α was the model intercept, β was the slope associated with time, and ε_{ijklm} was random error. Although the intercept has no intrinsic meaning

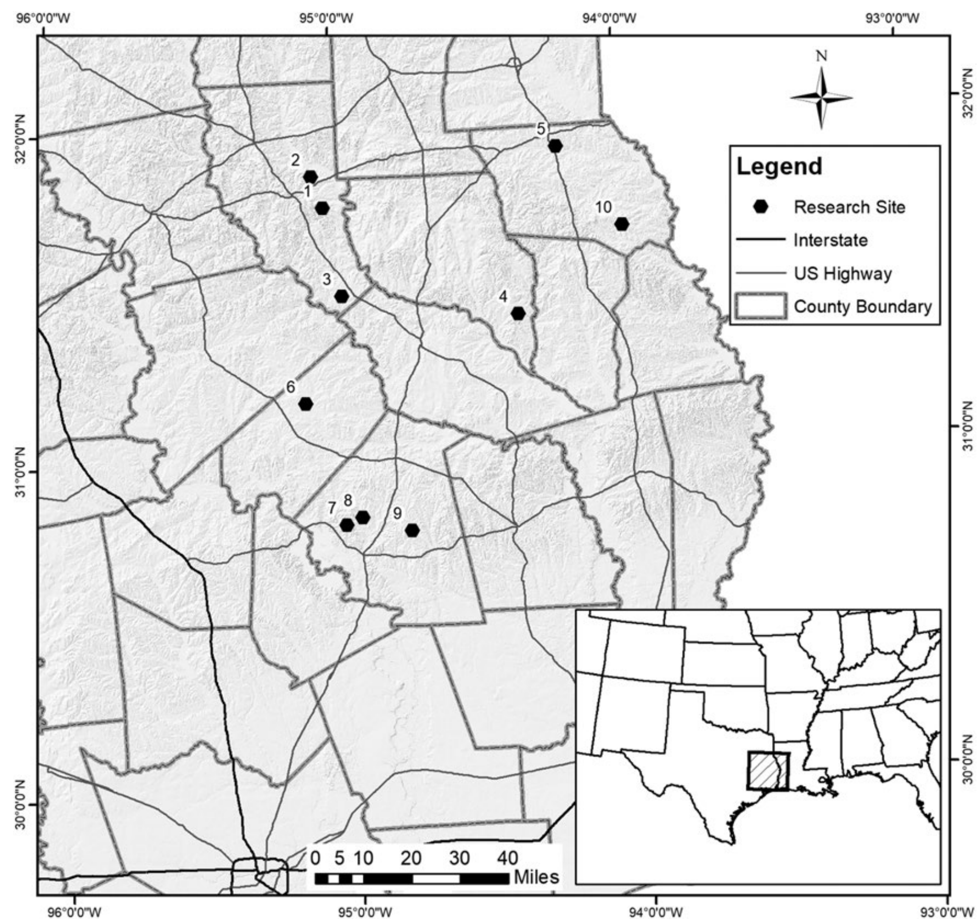

Figure 1. Geographic location of the 10 thinning sites used in the study (locations: 1, Atoy; 2, Bagley; 3, Campbell Group 1; 4, Campbell Group 2; 5, Hilliard; 6; Resource Management Service (RMS) 1; 7, RMS 2; 8, RMS 3; 9, RMS 4; and 10, Walker).

regarding the relation between y_{ijklm} and time, the intercept does represent the initial average tree size (dbh or height) at the end of the first year post-thinning, a result of tree response to thinning as well as the removal of inferior trees. The slope represents the consistent change in y_{ijklm} when time is changed per unit (per year in this study) in the model and is most often of interest to foresters. Effects of fixed, random factors and their interactions were further incorporated:

$$\alpha = \alpha_j T_j + \alpha_k D_k + l\alpha_i \tag{2}$$

$$\beta = \beta_0 + \beta_{0j} T_j + \beta_{0k} D_k + l\beta_i \tag{3}$$

where T_j and D_k represent the fixed effects of the jth thinning treatment and kth tree size, respectively, and $l\alpha_i$ and $l\beta_i$ represent the ith location effect on α and β, respectively, with both being assumed to be random. Preliminary analyses showed that interactions among T_j, D_k, and $l\alpha_i$ or $l\beta_i$ were not significant, and thus, they were not included in the models. Equation 1 was rewritten as:

$$y_{ijklm} = \left(\alpha_j T_j + \alpha_k D_k + l\alpha_i\right) + \left(\beta_0 + \beta_j T_j + \beta_k D_k + l\beta_i\right) \times \text{Time} + \varepsilon_{ijklm} \tag{4}$$

It was assumed that the random effects of $l\alpha_i$ and $l\beta_i \times$ Time are normally distributed with mean 0 and a covariance **G**, which was the direct sum of the (co)variance matrix of the random effects and modeled using an unstructured covariance structure, $\begin{bmatrix} \sigma^2_{l\alpha} & \sigma_{l\alpha \times l\beta \text{ Time}} \\ \sigma_{l\alpha \times l\beta \text{ Time}} & \sigma^2_{l\beta \text{ Time}} \end{bmatrix}$, where $\sigma^2_{l\alpha}$, $\sigma^2_{l\beta \text{ Time}}$, and $\sigma_{l\alpha \times l\beta \text{ Time}}$ were the variances of $l\alpha_i$, $l\beta_i \times$ Time and their covariance, respectively. Significances of $\sigma^2_{l\alpha}$, $\sigma^2_{l\beta \text{ Time}}$, and $\sigma_{l\alpha \times l\beta \text{ Time}}$ were tested based on the Wald test. Three covariance structures, compound symmetric, unstructured, and autoregressive order 1 (AR[1]), were originally included to account for repeated measurements of individual trees, and the AR(1) was selected for use because of the smallest AIC. The ε_{ijklm} was assumed to be independent from other random effects, distributed with $N(0, \mathbf{R})$, where **R** was the (co)variance structure of the residuals of 4-year measurements with mean 0 and multiple covariance structure of AR(1) as: $\sigma^2 \begin{bmatrix} 1 & \rho & \rho^2 & \rho^3 \\ \rho & 1 & \rho & \rho^2 \\ \rho^2 & \rho & 1 & \rho \\ \rho^3 & \rho^2 & \rho & 1 \end{bmatrix}$, where σ^2 was the error variance and ρ was the correlation between observations of two adjacent years. The BA ha^{-1} also was analyzed using a mixed model with a residual covariance structure of AR(1):

$$y_{ijk} = \left(\alpha_j T_j + l\alpha_i\right) + \left(\beta_j T_j + l\beta_i\right) \times \text{Time} + \varepsilon_{ijk} \tag{5}$$

where y_{ijk} was the Ba ha^{-1} value for the kth time ($k = 0, 1, 2, 3$) of the jth intensity at the ith location. The **G** and **R** covariance structures were the same as those of analyzing dbh, although **R** was modeled at the plot level (intensity within a location). Note that in both models (Equations 4 and 5), the fixed factors influence the model intercept, whereas the slopes for time and its interaction with treatment and tree size reflect tree growth over time. The significance level across the manuscript refers to $P < .05$ unless otherwise stated.

All data analyses were performed using the Proc Mixed procedure of the SAS/STAT software (Littell et al. 2006). The Kenward–Roger method for calculating degrees of freedom was applied, and the effects of random location were predicted using the best linear unbiased prediction method (Littell et al. 2006).

The developed models were used to predict average dbh, height, and BA ha^{-1} over time. Both absolute (AD) and relative (RD) differences were calculated to reflect thinning response in growth:

$$\text{AD} = M_j - M_C \tag{6}$$

$$\text{RD} = \frac{M_j - M_C}{M_C} \times 100 \tag{7}$$

where M_j was the estimated least-squares mean for the jth thinning intensity, and M_C was the estimated least-squares mean for the respective control. Both AD and RD have been used in describing thinning responses in forestry (Pape 1999; Mäkinen and Isomäki 2004). A positive value in either absolute or relative terms suggests a positive thinning response.

Results

At the end of the fourth growing season after thinning, the average tree dbh and height across sites and thinning treatments were 24.2 cm and 18.8 m, respectively, and the average BA was 31.2 m^2 ha^{-1}. Average dbh, height, and BA ha^{-1} varied with thinning treatment during the entire measurement interval (Table 1). Clearly, thinned plots had a larger dbh than the control, more so for the heavier thinning. At each year post-thinning, the thinned plots on average were slightly shorter in height than the control, although differences were negligible (Table 1). A lower BA ha^{-1} was observed for the heavier thinning, a result of fewer trees per hectare because of the thinning (Table 1).

For dbh, the model intercept differed significantly among thinning treatments and among tree size classes (Table 2). No statistical difference in intercept was found between the T370 and T555 and also between T740 and the control, but those of T370 and T555 were significantly larger than those of T740 and the control (data not shown). Within a thinning intensity, the larger trees had significantly larger intercepts (Table 3). The slope estimate for the covariate time was significantly larger than zero, suggesting that trees increase in size with each year post-thinning. However, the rates of change differed among the thinning treatments and among tree size classes, as shown by their significant interactions with time (Table 2). The slope differences among the thinning treatments differed significantly, with the heavier thinning having significantly larger values (Table 3), resulting in greater AD and RD in dbh in the case of the heavier thinning and at the later years post-thinning (Figures 2 and 3). For example, for dbh, T370 averaged 22.4 cm and 26.4 cm at the end of the first and fourth growing season, respectively, compared to the respective values of 21.5 and 23.6 cm for the control, a response of 0.9 and 2.8 cm AD and 4.4 percent and 11.9 percent RD, respectively (Figure 2). Within a thinning intensity, larger trees had significantly larger slopes (Table 3), and therefore larger trees had greater dbh increment rates over the years. For example, for T370, the periodic (4 years) annual increment for dbh was 0.81 cm year^{-1} for the small trees, 0.99 cm year^{-1} for

Table 1. Summary statistics (means, SE, and range) for thinning treatments and year(s) post-thinning of the East Texas Pine Plantation Research Project thinning study.

Treatment	Statistics	Year 1 dbh (cm)	Year 1 Height (m)	Year 1 BA (m^2 ha^{-1})	Year 2 dbh (cm)	Year 2 Height (m)	Year 2 BA (m^2 ha^{-1})	Year 3 dbh (cm)	Year 3 Height (m)	Year 3 BA (m^2 ha^{-1})	Year 4[a] dbh (cm)	Year 4[a] Height (m)	Year 4[a] BA (m^2 ha^{-1})
T370	Mean	22.85	16.41	15.35	24.21	17.2	17.27	25.4	18.17	18.97	26.97	19.02	20.92
	SE	0.12	0.06	0.61	0.13	0.06	0.72	0.13	0.06	0.66	0.17	0.08	0.65
	Range	19.9–25.6	14.8–18.9	13.3–19.5	20.9–27.5	15.4–19.3	14.5–22.4	22.7–28.2	16.9–20.4	16.1–23.5	25.1–28.5	17.6–20.9	18.1–22.7
T555	Mean	21.8	16.18	21.02	22.81	16.9	23.1	23.82	17.99	25.05	25.42	18.94	28.02
	SE	0.1	0.05	0.72	0.11	0.05	0.79	0.12	0.05	0.81	0.15	0.07	0.57
	Range	18.9–23.1	14.5–18.6	17.1–24.1	19.4–24.7	15.2–19.1	18.4–27.1	20.9–25.7	16.6–19.8	21.1–28.4	24.6–26.2	16.9–20.7	26.1–29.9
T740	Mean	20.78	16.06	25.57	21.73	16.92	27.89	22.38	17.79	29.65	23.72	18.74	32.89
	SE	0.1	0.05	0.8	0.1	0.05	0.85	0.11	0.05	0.85	0.15	0.07	0.75
	Range	18.4–22.5	14.8–18.4	21.4–29.0	19.1–23.7	15.6–19.3	24.1–31.5	20.0–23.9	16.2–19.8	26.3–33.8	22.7–24.2	17.5–21.1	29.9–35.0
Control	Mean	20.11	16.02	35.42	20.75	16.79	37.48	21.37	17.75	39.14	22.8	18.73	42.94
	SE	0.09	0.04	0.77	0.09	0.04	0.93	0.09	0.04	0.85	0.13	0.05	1.11
	Range	17.4–22.4	14.3–18.4	31.2–38.8	17.6–23.3	14.9–19.8	32.6–40.9	18.6–23.8	15.6–20.4	35.4–43.0	21.4–24.4	17.6–19.4	38.6–45.3

Note: BA, basal area; dbh, diameter at breast height; SE, standard error.
[a]Year 4 only includes data from six sites.

the medium trees, and 1.08 cm $year^{-1}$ for the large trees. Although the AD for each thinning intensity was not affected by tree size, the small trees had a larger RD than the medium and the large trees (Figure 3), suggesting that the small tree had a greater relative response.

For tree height, the effect of the thinning treatment on model intercept was significant (Table 2). The unthinned control had a significantly larger intercept than those of the thinned plots, whereas the latter had comparable intercepts regardless of thinning intensity (Table 3). Consequently, the responses in both absolute and relative terms were numerically negative during the first growing season, and more so for the lighter thinning intensity (Figures 2 and 4). The slope was significantly larger than zero, and thus trees grew taller with each year post-thinning (Table 2). The slopes of the thinned plots were significantly larger than that of the control (Table 3), although the actual differences were small (i.e., <0.07 m $year^{-1}$ for the large trees) and may not have practical significance. Among the three intensities, the moderate thinning, T555, had the largest slope. Thinning effects on height were weak in general, yet some patterns were clear. The heavier thinning had a larger AD and RD regardless of tree size during the measurement period, although the T555 displayed the fastest rate of increase over the period of measurement (Table 3; Figure 2). Consequently, the thinning responses were all negative initially, but quickly became positive in later years, i.e., 2, 3, and 4 years after thinning for T370, T555, and T740, respectively (Figures 2 and 4). Within each thinning intensity, whereas the large and medium trees had comparable intercepts and slopes, they had a significantly larger intercept and slope than the respective values of the small trees (Tables 2 and 3). Similar to the effects on dbh, the AD in height was the same among the tree size classes, but the small trees had greater rates of increase in RD over time than the medium or large trees (Figure 4). By the end of the fourth growing season, the small trees had a larger RD than the medium or large trees, and this was particularly true for the heavily thinned plots (Figure 4).

Significant differences were observed in the BA model intercept among the thinning treatments, with the heavier thinning having a significantly lower BA ha^{-1} (Table 1). The BA ha^{-1} significantly increased with time (Table 2), and the rates of change were smaller, although statistically insignificant, for the heavier thinned plots (Table 4). Thus, the heavier thinned plots had a lower increment per year (i.e., 1.88 and 2.19 m^2 ha^{-1} yr^{-1} for T370 and the control, respectively). Although the AD was consistently negative and comparable over the years post-thinning in general, the T370 showed a clear decline over the period (Figure 5). However, relative BA response increases in the heavier thinning plots faster than in the lighter thinning plots (Figure 5). For example, for T370, the BA ha^{-1} was 15.34 at the end of the first year post-thinning and 20.98 at the fourth year, 43.4 percent and 50.1 percent (6.7 percent increase), respectively, of the control (values of 35.37 and 41.92 BA ha^{-1}, respectively), whereas the corresponding percentages for T740 during the same period increased from 72.3 percent to 76.6 percent (4.3 percent increase), relatively slower. Similar results were obtained by expressing growth as current annual increment (CAI). For example, the CAI for T370 for the second, third, and fourth year was 12.2 percent, 10.9 percent, and 9.8 percent, respectively, compared to 6.1 percent, 5.7 percent, and 5.4 percent for the control (almost doubled).

Information for random factors and the first-order correlation coefficients is provided in Table 2. Compared to the respective error

Table 2. Results of analyses of covariance on growth of diameter at breast height, tree height, and basal area per hectare for the East Texas Pine Plantation Research Project Thinning Study for 3–4 years post-thinning.

Parameter	Source of variation	Diameter at breast height (cm)		Height w (m)		Basal area ($m^2\ ha^{-1}$)	
		F value	Pr > *F*	*F* value	Pr > *F*	*F* value	Pr > *F*
Intercept	Treatment (*T*)	55.08	<.0001	3.96	.021	605.45	<.0001
	Tree size (*D*)	3,750.60	<.0001	660.23	<.000	NA	NA
Slope	Time	757.01	<.0001	677.50	<.000	708.23	<.0001
	T × Time	452.98	<.0001	6.46	.018	0.85	.468
	D × Time	333.78	<.0001	25.74	<.000	NA	NA
		Estimate	Pr > *Z*	Estimate	Pr > *Z*	Estimate	Pr > *Z*
I	$\sigma^2_{1\ \alpha}$	0.52	.019	1.13	.017	3.29	.037
S	$\sigma^2_{1\ \beta\ \mathrm{Time}}$	0.01	.019	0.01	.021	0.00	NA
I × *S*	$\sigma_{1\ \alpha\ \times 1\ \beta\ \mathrm{Time}}$	–0.02	.341	–0.02	.578	0.02	.935
Error	σ^2	5.51	<.0001	1.55	<.0001	2.40	<.0001
Autoregressive order 1	ρ	0.96	<.0001	0.78	<.0001	0.85	<.0001

Note: σ^2_1, $\sigma^2_{1\ \beta\mathrm{Time}}$, and σ^2, variance in intercept because of location, variance in slope because of location, and random error, respectively; $\sigma_{1\alpha\ \times\ 1\beta\ \mathrm{Time}}$, covariance between intercept and slope because of location; ρ, autoregressive order one correlation coefficient; *I*, intercept; NA, not estimable; *S*, slope.

Table 3. Estimates of intercepts and slopes for tree diameter at breast height and height, and their standard errors.

Parameter	Thinning intensity	Tree size	Diameter at breast height (cm)		Height (m)	
			Estimate	Standard error	Estimate	Standard error
Intercept	Control	Large	25.51a	0.25	17.10a	0.35
		Medium	21.43b	0.24	16.42a	0.34
		Small	16.73c	0.24	15.24b	0.34
	T740	Large	25.62a	0.25	16.98a	0.35
		Medium	21.54a	0.24	16.30a	0.34
		Small	16.83b	0.24	15.12b	0.35
	T555	Large	26.25a	0.25	16.99a	0.35
		Medium	22.18b	0.24	16.30a	0.34
		Small	17.48c	0.25	15.13b	0.35
	T370	Large	26.61a	0.26	17.08a	0.35
		Medium	22.53b	0.25	16.40a	0.34
		Small	17.83c	0.25	15.22b	0.35
Slope	Control	Large	0.87a	0.04	0.88a	0.04
		Medium	0.70b	0.04	0.87a	0.04
		Small	0.43c	0.04	0.77b	0.04
	T740	Large	1.07a	0.04	0.92a	0.04
		Medium	0.90b	0.04	0.91a	0.04
		Small	0.63c	0.04	0.81b	0.04
	T555	Large	1.20a	0.04	0.95a	0.04
		Medium	1.03b	0.04	0.94a	0.04
		Small	0.77c	0.04	0.84b	0.04
	T370	Large	1.48a	0.04	0.94a	0.04
		Medium	1.32b	0.04	0.92a	0.04
		Small	1.05c	0.04	0.82b	0.04

Note: Means with the same letter within a cell are not significantly different. Significance among thinning intensities (">" or "<" represents significantly larger or less and "=" represents not significantly different): for diameter at breast height, control = T740 < T555 = T370 for intercept, control < T740 < T555 < T370 for slope; for height, control > T740 = T555 = T370 for intercept and control < T740 = T555 = T370 for slope.

variances, the variation in intercept because of locations across the region was important for height and BA ha^{-1} but small for dbh, whereas the variation in slope across the locations was negligible for all three traits. The covariances also were small in magnitude for all three traits. The AR(1) coefficients were high, ≥0.78, for all models. Table 5 presents the best linear unbiased predictions of the random location effects, which showed the variation from location to location in intercept and slope. The model assumptions (residual normality, independence, and equal variance) were met (data not shown).

Discussion

This study modeled thinning responses over years post-thinning with linear mixed models with a selected residual covariance structure (AR[1]) to account for repeated measurements of the individual trees, which not only tested differences between treatments but also determined whether the growth after thinning diverges from, converges toward, or remains parallel with that of the unthinned treatment. Analyses for dbh and height were based on individual tree data, paired with repeated observations, resulting in large degrees of freedom for the denominator in the suitable *F*-tests for factors such as thinning treatment and tree size class. Consequently, the effects of these factors, and their interactions with time, were statistically significant, even though their *F*-values were small, and from a practical viewpoint, their impacts are negligible (Table 3; Figure 4). This was particular true for tree height responses.

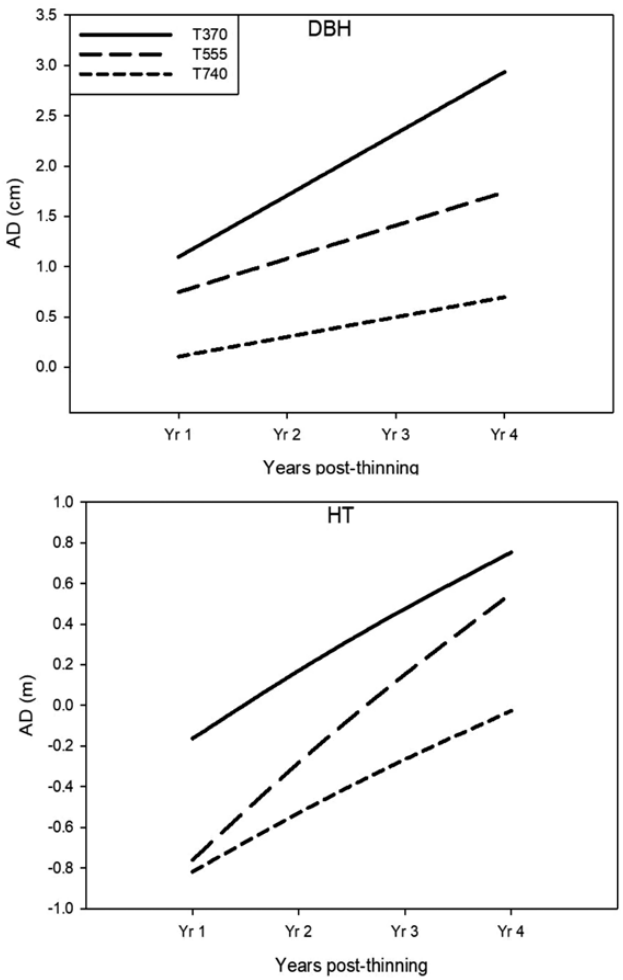

Figure 2. Absolute differences (AD = mean of a thinned treatment minus the respective unthinned control mean) for tree diameter at breast height (dbh) and height (ht) growth for each thinning treatment (T370, T555, and T740) over year(s) post-thinning.

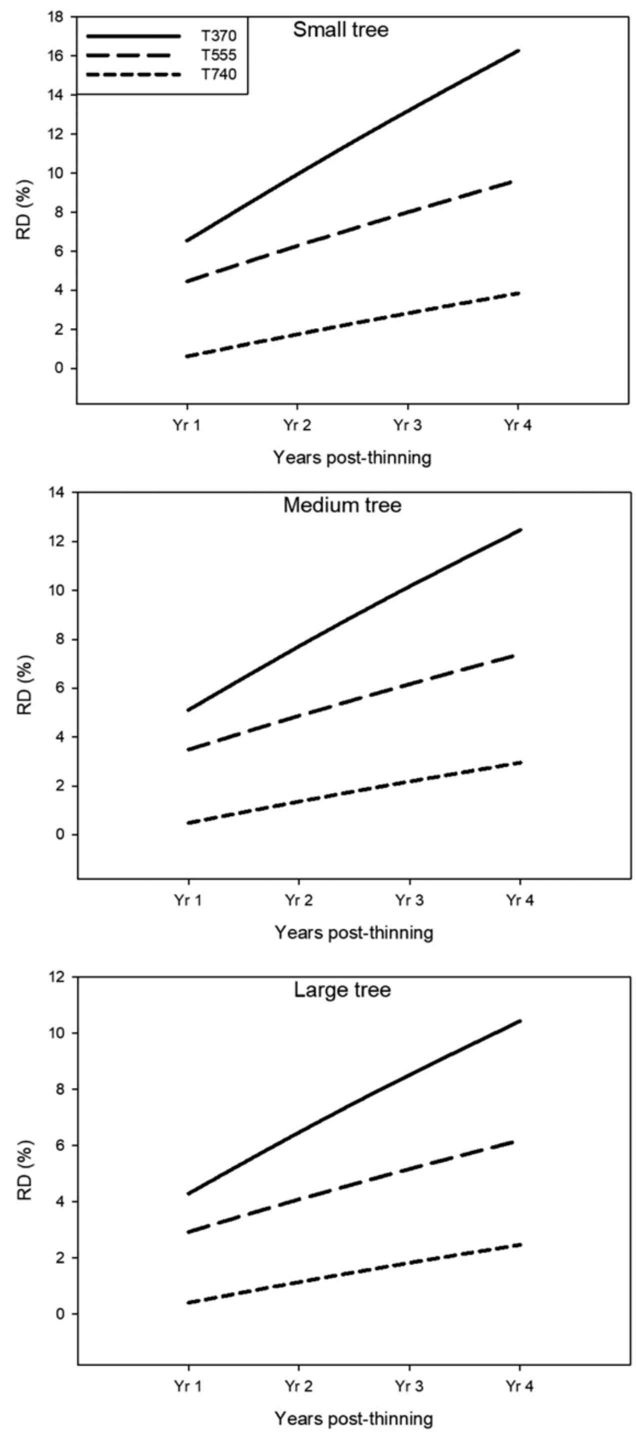

Figure 3. Relative differences (RD, expressed as the absolute difference between a treatment and the respective control means as a percentage of the control mean) in dbh growth for each thinning treatment (T370, T550, and T740) over year(s) post-thinning by tree size in dbh (small: 10.0–17.5 cm; medium: 17.6–22.6 cm; large: >22.6 cm).

The results corroborated that thinning significantly increased individual tree dbh (model intercept) starting at the first growing season after thinning (Tables 2 and 3; Figures 2 and 3). Unfortunately, the model does not allow for separation of how much dbh increase was due to the removal of poorer (i.e., slower-growing) trees in the thinning and how much was due to the response of trees to thinning. A loblolly pine study in Louisiana (Ginn et al. 1991) reported that the first year response in dbh after thinning was not significant. Different thinning methods, timing, intensities, stand condition, site condition, sample sizes, and geographic locations all may contribute to tree response to thinning.

Information on temporal trends in dbh growth response during the first few years immediately after thinning for loblolly pine is scarce. This study found that the thinning response in diameter growth was observed for the thinned plots during the first growing season (Figures 2 and 3; Table 3), the response trends diverged with time after thinning, resulting in a more positive response for the heavier thinning and when more time elapsed since thinning (Figures 2 and 3). Peterson et al. (1997) found that thinned stands had a greater dbh than the unthinned stands during the first 3 years after thinning, but only after four growing seasons did their differences became significant. In the long term, the thinning response in diameter growth will decline, since site resources again will become limited, usually from crown closure. Tasissa and Burkhart (1997) found that thinning significantly increased ring

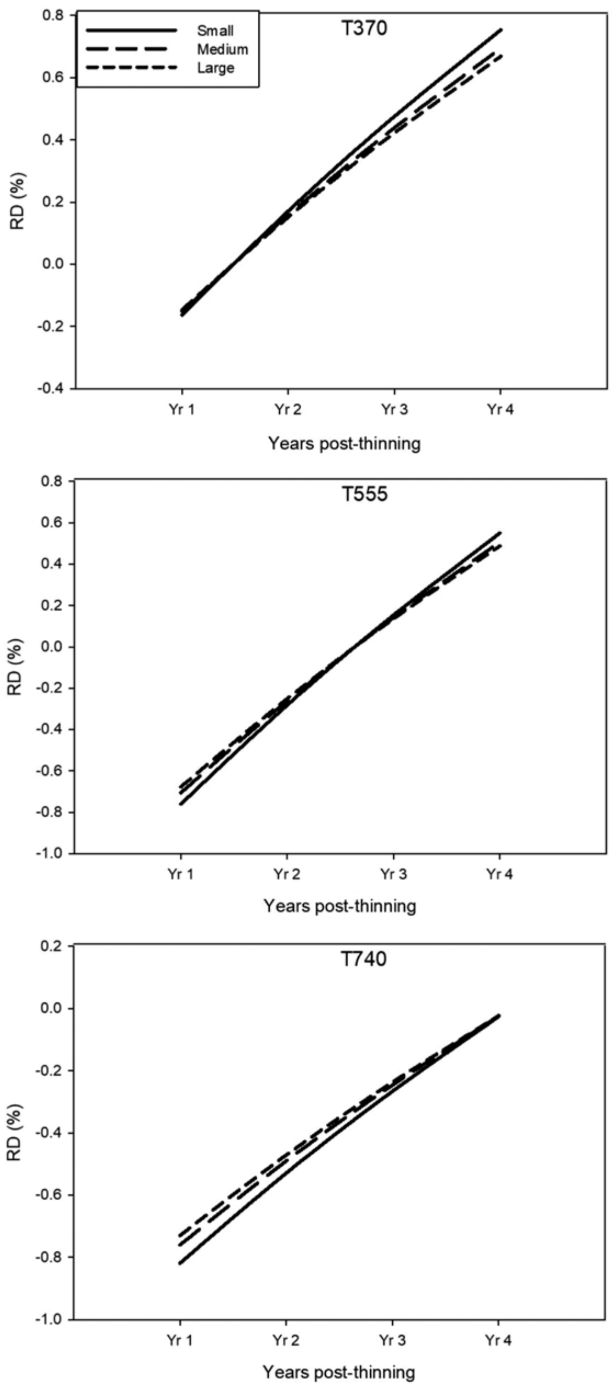

Figure 4. Relative differences (RD, expressed as the absolute difference between a treatment and the respective control means as a percentage of the control mean) in height growth by thinning treatments and tree sizes in dbh (small: 10.0–17.5 cm; medium: 17.6–22.6 cm; large: >22.6 cm).

width, and its effects tended to persist over the 12 years since thinning for loblolly pine. Our results, in both the absolute AD and RD terms, suggest substantial, and immediate, improvement in dbh growth post-thinning, with greater responses from heavier thinning and greater time post-thinning (Figures 2 and 3).

Table 4. Estimates of intercepts and slopes for the basal area per hectare and their standard errors.

Parameter	Thinning intensity	Estimate	Standard error
Intercept	Control	35.37a	0.81
	T740	25.57b	0.81
	T555	21.02c	0.81
	T370	15.35d	0.81
Slope	Control	2.19a	0.16
	T740	2.18a	0.16
	T555	2.05a	0.16
	T370	1.88a	0.16

Note: Means with the same letter within a cell are not significantly different.

Prethin dbh affected dbh growth greatly, but tree responses expressed in AD and RD differently. Since the interaction between thinning treatment and tree size was not significant based on a preliminary analysis, it was not included in the model (Equation 4); therefore, the AD is expected to be the same among the tree sizes. The RD, which further expressed AD as a percentage of the respective control mean, defines the response as the change in growth rate by tree size. In this study, although the AD values were similar among tree sizes, the smaller tree groups had greater RD values over the years post-thinning, and this was especially true for the heavier thinning and when more time had elapsed since thinning (Figure 3). Therefore, relatively, small trees reacted more rapidly and strongly to thinning in dbh growth than medium or large trees, at least for the first 4 years after thinning (Figure 3). In the literature, such information is not available for loblolly pine, but a few studies on other species have been reported, and as expected, results varied with the term of expression. Small trees have shown a larger relative, but less absolute magnitude, response to thinning than the large trees in *Picea abies* (Pukkala et al. 1998, Mäkinen and Isomäki 2004) and also in *Pinus sylvestris* (Peltola et al. 2002). However, in another study of *Pinus sylvestris*, the absolute and relative increase in diameter growth was at its highest among co-dominant and medium-sized trees, whereas the smallest trees were the quickest to respond but demonstrated the lowest total response (Pukkala et al. 1998). Other studies have used other forms to express tree response to thinning, and these studies generally showed that thinning response was independent of tree size (Moore et al. 1994, Hynynen 1995, Pape 1999).

Our analysis showed that the effects of thinning intensity, and its interaction with time, on height growth response to thinning were minimal during the first 4 years after thinning (Figures 2 and 4), which concurs with other loblolly pine thinning studies (Ginn et al. 1991, Liu et al. 1995, Sharma et al. 2006). Although the smaller and lower crown class (intermediate and suppressed) trees were removed in the thinned plots, our models predicted that trees of the thinned plots were shorter, although negligible in magnitude, than those of the control plots by the end of the first season post-thinning, suggesting a negative height growth reaction to thinning during the first year. Ginn et al. (1991) attributed this decrease to a redistribution of photosynthate from height growth to the expansion of the lower crown after thinning. This negative response dissipated over time and became zero or positive with years elapsed post-thinning, and this transition was clearly faster for the heavier thinning (Figures 2 and 4). Overall, the height growth response to thinning begins negative

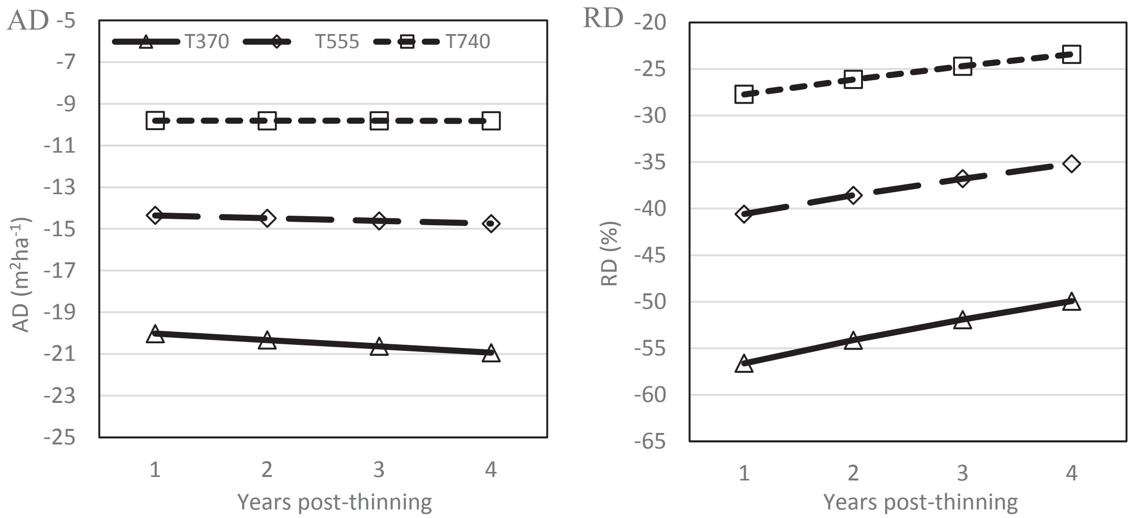

Figure 5. Absolute (AD = treatment mean minus the control mean) and relative (RD = AD/control mean in percent) differences in basal area per hectare by thinning treatments. Note that the estimated control least-squares means were 35.3, 37.6, 39.7, and 41.9 m^2 ha^{-1} at year 1, 2, 3, and 4 post-thinning, respectively.

Table 5. The random location effects on intercepts and slopes for tree diameter at breast height, height, and BA, predicted using the best linear unbiased prediction method.

Location[a]	Intercept			Slope		
	dbh (cm)	Height (m)	BA (m^2 ha^{-1})	dbh (cm)	Height (m)	BA (m^2 ha^{-1})
1	0.5282	−1.2927	1.6395	−0.0323	−0.0373	0.0076
2	1.1819	−0.3846	2.5575	−0.1044	0.1989	0.0119
3	0.2059	−0.1725	−1.9994	0.0992	−0.0830	−0.0093
4	−1.1733	−1.0044	−2.4309	0.0996	−0.0864	−0.0113
5	0.3892	−0.9603	1.1110	0.1954	0.1628	0.0045
6	0.4974	−0.0700	1.5657	−0.1407	−0.0249	0.0075
7	−0.0702	−0.0575	−1.0276	−0.0719	−0.0449	−0.0044
8	−0.1693	1.8042	−0.0771	−0.0796	−0.0879	−0.0002
9	−0.9614	1.8224	−1.2843	0.0167	0.0329	−0.0059
10	−0.4285	0.3153	−0.0545	0.0181	−0.0302	−0.0003

Note: BA, basal area; dbh, diameter at breast height.
[a]1, Atoy; 2, Bagley; 3, Campbell Group 1; 4, Campbell Group 2; 5, Hilliard; 6; Resource Management Service (RMS) 1; 7, RMS 2; 8, RMS 3; 9, RMS 4; 10, Walker.

but approaches or surpasses the unthinned counterparts in two to four seasons after thinning, depending on thinning intensity. It is expected that height growth in the thinned plots likely will maintain a similar growth rate to that of the unthinned plots after crown closure (Brooks and Baily 1992, Liu et al. 1995). Sharma et al. (2006) reported a similar trend in a loblolly pine study in southeastern United States; the average total height of dominant and codominant trees in heavily thinned stands was significantly smaller at the end of three growing seasons post-thinning, and this difference diminished gradually afterwards and exceeded its counterpart in unthinned stands 12 years after thinning to become significant 18 years later. Surprisingly, the moderate thinning (T555) had the fastest rate of increase in AD over the period, regardless of tree size (Table 3). The reason for this is unknown. A significant impact of prethin tree size class on RD (Tables 2 and 4) also was found. The small trees were inferior in RD of height growth to the medium and large trees during the first year post-thinning. However, smaller trees had faster rates of increase as time passed, and by the end of the fourth season, the RD of height became comparable, or superior, to the other size classes (Figure 4). This suggests that in height growth, small trees relatively respond to thinning more quickly, and to a greater degree, at least for the first 4 years after thinning (Figure 4). Zhang et al. (1997) also found that smaller loblolly pine trees displayed more response in relative height growth on better-quality sites.

Thinning greatly reduced BA ha^{-1}, which could be partly explained by the significant lower intercepts for the thinned plots than those for the control plots (Table 4). Most analyses of thinning studies in loblolly pine have assumed that there is no difference in BA ha^{-1} growth rate between thinned and unthinned stands of the same age, site index, and basal area (Cao et al. 1982, Matney and Sullivan 1982). The rates of change of BA ha^{-1} over time of the thinning treatments compared to the unthinned control were generally parallel to each other (Table 2; Figure 5), supporting this assumption. The absolute responses were negative, more so for the heavier thinning over the years post-thinning. The decline over the years was negligible for T740 and T555, but more evident for the T370 (Figure 5), suggesting that T370 may remove too many trees to maintain BA growth comparable to unthinned stands. The RD in BA ha^{-1} increased with elapsed years since thinning, even within such a short period as 4 years. This result was driven by the faster dbh growth in the thinned plots over the unthinned control, suggesting that thinned plot BA ha^{-1} may converge toward that of the control (Figure 5). Such a trend often has been observed in long-term loblolly pine thinning studies (Pienaar 1979, Ginn et al. 1991, Brooks and Baily 1992, Hasenauer et al. 1997, Amateis 2000), particularly when thinning intensity is heavy or at earlier ages. Another reason for this converging pattern is that, with the progress of time, natural mortality on the thinned plots is expected to be considerably lower with consequently a higher BA ha^{-1} growth than with the unthinned plots (Brooks and Baily 1992). The relation between average productivity and stand density in even-aged plantations under natural conditions is negative and is known as the self-thinning rule (Burkhart et al. 2019). Even though thinning reduced BA ha^{-1} substantially relative to the unthinned plots (Table 1), it redistributed future stand growth to larger, better-quality residual trees, potentially increasing sawtimber yields. In the Western Gulf Coastal Plain region, the decision to thin or not is based primarily on product objectives. If pulpwood is the sole objective, the value of thinning(s) is questionable, especially if there are no size restrictions on the product.

Some changes in physiological functioning of trees occur following thinning. Increases in lower crown needle foliage and improved photosynthesis, transpiration, and conductance of needles in the lower crowns have been observed (Ginn et al. 1991, Peterson et al. 1997, Tang et al. 1999). Some theories have been proposed to explain differential responses in dbh and height growth to thinning. After a thinning, a residual tree first must improve its carbohydrate balance through increases in crown diameter and leaf area prior to increasing volume growth. This increased volume growth often is at the expense of height growth, resulting in decreases in height growth during the first 2 years after thinning (Haywood 1994). Harrington and Reukema (1983) argued that thinning response reflects a tradeoff between growing space improvement and thinning shock of a stand after thinning. Our results support both inferences in general, showing a decrease in height growth at all thinning intensities, relative to the control, during the first growing season post-thinning. This shock, however, will be overcome quickly by improved height growth because of an increase in available resources following thinning (Figure 4). No such shock, or negative impact, was found in dbh growth (Figure 3). Thinning timing (prethin relative density, crown ration, etc.) likely plays an important role in whether or not a negative (shock) impact is observed following thinning. Prethinning stand condition and thinning timing are important avenues for additional research into the effects of thinning.

Site quality may affect tree response to thinning (Zhang et al. 1997, Grogan et al. 2018) which can be tested by treating site as a fixed factor in the models. Since our goal is to generalize the findings across the region, not for prediction, a random location effect in the models would better fit this purpose. Nevertheless, the estimated variances (Table 2) and random effects predicted by best linear unbiased prediction method (Table 5) also provided some implications in thinning responses across the region. The small $\sigma^2_{1\ \beta\ \mathrm{Time}}$ suggests that the rate of change with time in thinning responses may be similarly small across the region for dbh, height, and BA ha^{-1}. The intercept varied greatly with location for height and BA ha^{-1} but not for dbh.

Other than intensity of thinning, elapsed time since thinning, and site conditions, factors such as type of thinning, stand age at time of thinning, and site environmental conditions may alter the response (Amateis 2000). For example, for this study, the stand age at time of thinning was relatively young; approximately 12 years. If a thinning is planned at a later stage of stand growth, thinning intensity has to be relatively lighter so that the growth increment can approach the level of prethinning (Nyland et al. 2016). This thinning study was established following operational thinning protocols in the region (i.e., method and stand age at thinning) and sampled diversified environments in the region; therefore, results should provide information for loblolly pine responses to current thinning practiced over a wide range of stand conditions in the region. Note that these thinning trials were established as a randomized complete block design using only one replication at each site; therefore, the study did not capture variation within a site, but accounted for more site to site variation by sampling more sites for a given budget. The assumption of small variation within a site may, in reality, be somewhat violated, resulting in bias of model parameter estimators. Empirical data in New Brunswick Canada showed that among-site variation was much larger than within-site variation for tree growth. Establishing more sites, with fewer replicates per site, was much more effective than vice versa for genetic realized gain tests to compare growth performance among seed lots (Weng 2011). Furthermore, to reduce the effects of within-site variation, the thinning plots within a site in this study were carefully selected to make sure conditions were as similar as possible (Coble 2014).

In summary, current thinning practices in the Western Gulf Coastal Plain region should enhance dbh growth with little impact on height growth during the first 4 years post-thinning. BA ha^{-1} for these stands likely will converge with that of unthinned stands, reinforcing the assertion that thinning redistributes site growth potential to residual trees. In practical terms, current operational thinning practices are successfully redistributing site resources to growing fewer, larger-diameter (higher-value) trees than would be achieved without thinning over the same time period. The actual change varies with thinning intensity, tree size, and years elapsed since thinning. This information should be incorporated into the development of management plans for loblolly pine plantations in the region. Additionally, the information presented may be useful for designing thinning regimes, not only to improve timber production and economic gain, but also lead to improvements in environmental benefits. The WGCP region, in particular, may be impacted greater by a changing climate than other areas of the southern United States because of its location at the western extent of the loblolly pine range. Thinning may be optimized to make stands more resilient to potentially changing climate conditions. Carbon sequestration, another potential environmental benefit of forests, may be considered when planning thinning regimes. Thinning accelerates production of long-lived wood products, such as dimensional lumber (sawtimber), which may improve long-term carbon storage over other management regimes which produce greater percentages of short-lived products, such as paper, or may result in longer time frames before reaching sawtimber size.

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