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Research Article

Silviculture

Crown Lifting of Low-Density Loblolly Pine (*Pinus taeda*) Plantations on Nonindustrial Private Forest Lands

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Abstract

Pruning or the physical removal of lower branches, in combination with wider tree spacing, offers an alternative management scheme for small nonindustrial private forest landowners in areas lacking markets for small diameter wood. A 5-year-old loblolly pine (*Pinus taeda)* plantation was thinned to 495 trees/ha (200 trees/ac). Four crown-lifting treatments of 35%, 40%, 45%, and 50% live crown ratio (LCR) were then implemented. An additional unmanaged plot was established in an unthinned, unpruned area. Two replications were established for all pruning treatments. The target LCR was maintained throughout the study with the additional crown-lifting activities in 2003, 2004, and 2008. At age 8, the average diameter of the unmanaged plot was 13.5 cm (5.3 in), and the diameter of the 50% LCR treatment, which had the greatest diameter growth of all the treatments, was 20.8 cm (8.2 in). The highest mortality rate (22%) was observed in the unmanaged plot, but it was not significantly greater than the other treatments. Low density plantings maintained with pruning could allow small nonindustrial private landowners to obtain a high value sawtimber product while eliminating the need for thinning practices commonly used in traditional pine plantation management.

Study Implications: Pruning in combination with wider tree spacing offers an alternative management scheme for nonindustrial private forest landowners in areas lacking small diameter wood markets. This study compared the performance of thinned and pruned treatments with four live crown ratios (LCR) with unmanaged stands. At age 21, total tree height and survival were not affected by the treatments. The unmanaged plot had a significantly lower average diameter than all of the treatment plots. There was no significant difference in tree diameters between the pruned treatments. Therefore, the 50% LCR was most efficient since more pruning did not confer added growth gains.

Keywords: nonindustrial private forests (NIPF), private forest landowners, pruning, stem quality, thinning

As of 2013, there were over 10.4 million nonindustrial private forest (NIPF) landowners in the United States (Hatcher et al. 2013), with the majority of ownership managing holdings between 0.4 and 19.8 ha (1–49 ac) in size (Butler et al. 2021). As of 2018, about 88.8 % of the forest land in the state of Mississippi was managed by private forest landowners (USDA Forest Service Southern Research Station 2020), with 6,207,878 ha (15,340,000 ac) of that private forest distributed among 370,000 NIPF landowners (USDA Forest Service 2018). This division of acreage has led to greater land fragmentation and reduced parcel size across the state. In general, NIPF landowners manage less intensively than other types of private landowners (Arano and Munn 2006), and NIPF landowners with small landholdings often face challenges implementing midrotation silvicultural practices such as fertilization, competition control, thinning, and pruning (Hatcher et al. 2013; Measells et al. 2005). A lack of midrotation management can lead to greater mortality rates and reduced stand productivity compared with intensively managed timber stands (Weng et al. 2020; Zhao et al. 2011).

Thinning, the practice of reducing stand density, is regularly performed to improve residual tree growth, reduce density-dependent mortality, increase value of final harvest products, capture an early return on investment, and promote structural and spatial uniformity (Helms 1998; Newton 2009). Pine plantations in the southeastern United States often implement one or more successive thinning entries. Thinning provides additional growing space for the residual crop trees, which improves diameter growth and, in some cases, height growth (Ashton and Kelty 2018; Zhang et al. 1997). In light-limited systems, residual trees often reoccupy physical space by expanding their crown diameters. However, the rate of expansion is dependent on stand age, thinning intensity, and site quality (Peterson et al. 1997). The timing of thinning has a large impact on both return on investment as well as stand response postthinning. Thinning should be implemented prior to the onset of density-dependent mortality to minimize cost and maximize growth gain (Ashton and Kelty 2018).

Thinning is often categorized by the return on investment. Precommercial thinning is often conducted in high-density

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stands where intense competition limits diameter and sometimes height growth in unthinned stands. Extremely overstocked stands that do not undergo a precommercial thinning have been shown to experience both height and diameter growth stagnation (Grano 1969). As diameter growth is inversely proportional to stand density (Baldwin et al. 2000; Lohrey 1977), a potential alternative to thinning could be planting at relatively low densities (Dean and Baldwin 1996). Reduced planting densities can extend the interval between or eliminate the need for thinning entries but may result in lower wood quality (Clark et al. 1994). Increased physical space between trees results in larger branches and knots (Clark et al. 1994), and rapid growth results in lower modulus of rupture, modulus of elasticity, and corewood stiffness (Amateis and Burkhart 2013; Biblis et al. 1995; Clark et al. 2008; Roth et al. 2007).

Crown lifting, or pruning, is defined as the removal of living or dead branches and multiple leaders from standing trees (Helms 1998). Pruning is commonly used in urban forestry to improve tree aesthetics and maintain tree health, whereas in industrial forestry, it is used to increase the amount of wood free of knots (Helms 1998). The effects of trees pruned per acre, crown lifting height, age of pruning, and pruning frequency have been investigated in loblolly pine plantations in Virginia (Amateis and Burkhart 2011). Regarding the timing and frequency of pruning, it was reported that a 50.0% canopy reduction at age 3 negatively affected total height growth, but only for one year posttreatment. Additionally, pruning at ages six and nine in other treatments showed similar short-term growth reductions. Repeated pruning, however, at ages three, six, and nine reduced cumulative diameter at breast height (DBH) growth by 14.0% at age 11 compared to the control treatment (Amateis and Burkhart 2011). Crown canopy reductions of 50.0% after years three and six resulted in greater or equivalent diameter growth compared with the control treatment (Amateis and Burkhart 2011). However, no statistically significant differences were noted for total height growth and total diameter growth by year with regards to other crown lifting heights tested.

Pruning improves log quality in nearly all cases, regardless of pruning intensity (Amateis and Burkhart 2011; Ares and Brauer 2005; Clark et al. 2004; Larson et al. 2001), especially since pruning allows trees to begin to produce clear wood much faster than self-pruning. Although important, knot size and distribution are not solely responsible for quality of dimensional wood products. Pruning can temporarily increase the percentage of summerwood and transition from corewood characteristics to those of outerwood, with these changes lasting up to a few years, depending on pruning intensity (Larson et al. 2001). Ring specific gravity is also affected by pruning, with one study finding that all pruning treatments, whether they had taken place at different ages or multiple times, yielded significantly higher ring specific gravity (Burkhart and Amateis 2020), which improves wood quality.

Pruning in conjunction with thinning has been shown to decrease the number of knots, especially in butt logs, and increase the yield of more valuable lumber products (Burton and Shoulders 1974; Clark et al. 2004; Huang and Kronrad 2004). The combined effects of crown lifting and intensive thinning were studied extensively at the USDA Crossett Experimental Forest in south Arkansas (Clark et al. 2004). This study was established in 1954 with the goal to produce loblolly pine sawtimber within a 30-year rotation. Intensive management included precommercial thinning, pruning, and mowing to control understory vegetation. Results indicated DBH values of the intensively managed trees were 37.0% greater than the control plots. Most importantly, pruning to keep 50% LCR by age 15 resulted in a greater proportion of No. 1 and better grade lumber in butt logs (Clark et al. 2004). Pruning above 4.9 m (16 ft), or the second log, however, did not yield higher quality lumber when compared with lumber from unpruned second logs in the control treatment. Reduced planting density or thinning combined with pruning could translate to greater sawtimber stumpage values for landowners.

The primary objective of this study was to gain insight into whether pruning intensity and low stand density affect rapid sawtimber production. Developing this knowledge will help NIPF landowners and foresters determine whether initial planting and pruning can be used to bypass the need for thinning in pine plantations. The findings of this study have relevance for forest management throughout the southeastern United States and other timber producing locations, where declining demand for small-diameter wood and land fragmentation are expected to challenge traditional production models.

Methods

Study Site

The study site is located at the Truck Crops Experiment Station in Copiah County, MS, USA (Figure 1). Soils were identified as a Providence silt loam, with an estimated site index of 26.5 m (87 ft) for loblolly pine at base age 50 (Soil Survey Staff 2022). The plantation was established in 1998 using 1.5 generation improved loblolly pine seedlings acquired from the Mississippi Forestry Commission. The seedlings were machine planted on 1.2 × 2.7 m (4 × 9 ft) spacing for an average initial density of 2,990 trees/ha (1,210 trees/ac). A survival check in 2003 found that 2,664 trees/ha (1,078 trees/ac) had survived, with an average of 7.1 cm (2.8 in) in DBH. Following this check, the best 494 trees/ha (200 trees/ac) were marked as crop trees, with a desired spacing of 4.5 m (14.8 ft) between trees. All trees not marked as crop trees were precommercially thinned by hand with chainsaws in April of 2003. The average DBH, height, and LCR of the remaining trees was 9.7 cm (3.8 in), 6.0 meters (19.8 ft), and 84%, respectively. Herbaceous competition beneath the remaining crop trees was controlled with mowing between planted rows and glyphosate application within the rows.

Study Design

The study site was split into eight 0.125 ac (0.05 ha) blocks with two replicates of four live crown ratios (LCR): 50%, 45%, 40%, and 35%. Initial LCR were approximately 85%–95% in May of 2003 prior to the first crown lifting. Branches were removed outside the bark ridge using loppers, hand pruners, and pruning saws (Figure 2). Trees were pruned to a target height, which was calculated using the LCR treatment percentage and the total tree height in Equation 1:

$$\textit{Pruning Height} = \textit{Total Height} \times \left(1 - \frac{\textit{Desired LCR}}{100}\right) \quad (1)$$

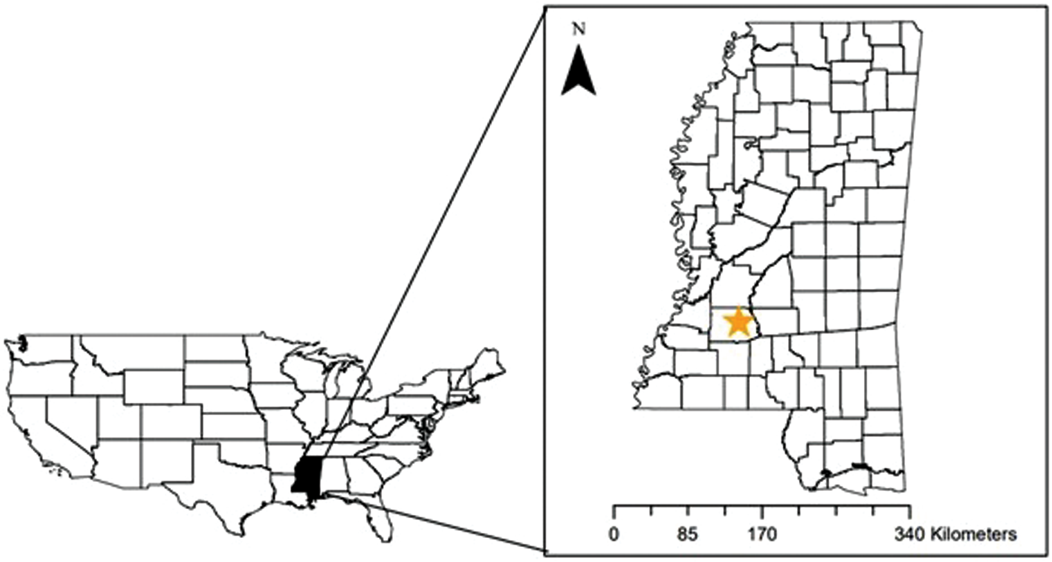

Figure 1 Study site location at the Truck Crops Experiment Station near Crystal Springs, Mississippi USA.

Figure 2 Images from the study including (a) a 35% live-crown ratio LCR treatment plot in 2003 prior to treatment implementation, (b) the same plot immediately following thinning and pruning in 2003, (c) a 35% LCR treatment plot (foreground) and unmanaged plot (background) as observed in 2004, and (d) a 35% LCR treatment at age 18 observed in 2016.

Whereas target heights were calculated for each tree, actual LCR of individuals varied slightly. However, the averages for the four treatments were very close to the target LCR values. Initial height, DBH, and live crown measurements were taken after pruning. Subsequent pruning treatments to maintain target LCR occurred in February 2004, January 2005, January 2006, and March 2008. A 0.004 ha (0.01 ac) unmanaged plot was established at age eight in an area of the stand not thinned or pruned. Although it is not a true control plot, it could be considered an alternative scenario for plantations on small private lands where traditional silvicultural options are impractical. It is referred to as the unmanaged plot for ease. DBH, height, and LCR measurements for all plots were taken again from 2004 to 2008, and from 2014 to 2019. Crown-lifting treatments were repeated throughout the study to maintain desired live crown ratios.

Analyses

Analysis was completed using the statistical software R Version 4.0.3 (R Core Team 2020), as well as the *nlme* package (Pinheiro et al. 2021), *emmeans* package (Lenth 2021), *ggplot2* (Wickham 2016), and *multcomp* package (Hothorn et al. 2008). Due to a lack of data in the unmanaged plot for ages five, six, and seven, 1,000 replications of DBH and total height values for all trees across treatments at age five were estimated from a normal distribution. The mean and standard deviations were set to the average and standard deviation values of the DBH and total height of the nonmissing dataset. These values were used as the age five baseline starting point for all trees within this project. A mixed effects model was developed using the log transformed measurements of DBH and total height. Natural log of DBH and natural log of total height were the dependent variables for their respective regression equations, with age acting as a fixed effect predictor and a random effect for each tree. Using the resulting equation, natural log of DBH and natural log of total height values were modeled for each tree in the unmanaged treatment for ages six and seven. These estimated values for the unmanaged treatment for years six and seven were then incorporated into the full dataset for all subsequent modeling. Mean DBH and total height for ages five to nine and 14–21 were determined for each treatment for comparison and were reported with standard errors. No data were collected in years 10–13. DBH was modeled using a mixed effects model, with the natural log of DBH (cm) acting as the dependent variable, a combination of age and treatment as the independent variables, and the plot as the random effect. Total height was modeled using a linearized mixed-effects model, with the natural log of total height (m) used as the dependent variable, age and treatment functioning as predictor variables, and plot acting as a random effect. Treatment comparisons were conducted with the cld function within the *emmeans* package. This compared each treatment against the unmanaged plot, and against all other treatments using Tukey's pairwise comparison. Mortality significance was tested using a chi-square test. Back-transformed means and standard errors are reported throughout. All statistical differences were analyzed at the $\alpha = 0.05$ level of significance.

Results

The average diameter of the unmanaged plot was significantly less than all other treatments at age eight ($P < 0.05$). Additionally, the 50% LCR treatment was significantly greater in DBH than the other treatments from ages seven to nine. The average DBH for the unmanaged plot was 12.6 cm (± 0.6 cm, 5.0 ± 0.2 in.) at age eight. The 35%, 40%, 45%, and 50% treatments averaged greater diameters by 3.2 cm (± 0.2 cm, 1.2 in ± 0.1 in) to 6.0 cm (± 0.3 cm, 2.3 ± 0.1 in) than the unmanaged plot (Table 1). By age 21, the unmanaged plot had a significantly lower mean DBH than all other treatments of 19.8 cm (± 1.4 cm, 7.8 ± 0.6 in) whereas the 50% LCR treatment had a greater DBH of 38.3 cm (± 0.7 cm, 15.1 ± 0.3 in) on average (Table 1). The 50% LCR treatment maintained a greater average diameter than all other pruning treatments. Initially, the 45% and 40% treatments were comparable, but the diameter of the 45% treatment became the slowest-growing by age 13 (Figure 3). The 35% and 40% treatments were similar in terms of average diameter, with the 40% LCR treatment barely greater than that of the 35% LCR treatment. However, by age 14, there were no statistical difference among any of the LCR treatments.

Unlike DBH, height did not vary significantly between treatments. Additionally, average height in the pruned treatments did not exceed the unmanaged plot (Figure 4). The unmanaged plot had greater average height values than all other treatments until age 20. At age eight, the unmanaged plot had a mean height of 9.9 m (± 0.3 m, 32.5 ± 1.0 ft), whereas the 35%, 40%, 45%, and 50% treatments had mean heights of 9.0 m (± 0.1 m, 29.5 ± 0.3 ft), 8.4 m (± 0.1 m, 27.6 ± 0.3 ft), 8.7 m (± 0.1 m, 28.5 ± 0.3 ft), and 9.1 m (± 0.1 m, 29.9 ± 0.3 ft), respectively. By age 21, average heights ranged from 19.8 m (± 0.2 m, 65.0 ± 0.7 ft) to 20.8 m (± 0.2 m, 68.2 ± 0.7 ft) for all treatments (Table 1).

Survival did not differ statistically between treatments ($P > 0.05$) at age 21 (Table 1). Survival ranged from 77.8% (± 0.0%) in the unmanaged treatment to 91.8% (± 5.9%) in the 50% LCR treatment. Survival was more variable for the 45% and 50% LCR treatments than all other treatments.

Discussion

Pruning has been found to either slightly decrease or have little impact on diameter growth (Amateis and Burkhart 2011; General et al. 2013; Young and Kramer 1947). Reduction in diameter growth on lower positions of the boles of trees appears to be a result of increased distance from the crown postpruning (Ashton and Kelty 2018; Young and Kramer 1947). Amateis and Burkhart (2011) noted heavy or repeated crown-lifting treatments negatively affected diameter growth. However, Amateis and Burkhart also noted the decrease in diameter growth appeared to diminish over time, typically becoming normal after around three years for the trees that experienced a single crown-lifting treatment, whereas the trees that experienced multiple pruning treatments seemed to suffer sustained decreases in diameter growth. Additionally, they found that light pruning

Table 1. Mean (± standard error) for diameter at breast height (DBH), height, and survival by treatment at age 21. Averages with the same letter do not differ at α = 0.05.

Treatment	Mean DBH (cm)	Mean height (m)	Survival (%)
Unmanaged	19.8 ± 1.4[b]	20.5 ± 0.3[a]	77.8 ± 0.0[a]
35% LCR	36.5 ± 0.7[a]	20.8 ± 0.2[a]	91.3 ± 0.4[a]
40% LCR	36.2 ± 0.7[a]	20.1 ± 0.2[a]	91.4 ± 0.9[a]
45% LCR	34.5 ± 0.7[a]	19.8 ± 02[a]	87.5 ± 3.7[a]
50% LCR	38.3 ± 0.7[a]	20.8 ± 0.2[a]	91.8 ± 5.9[a]

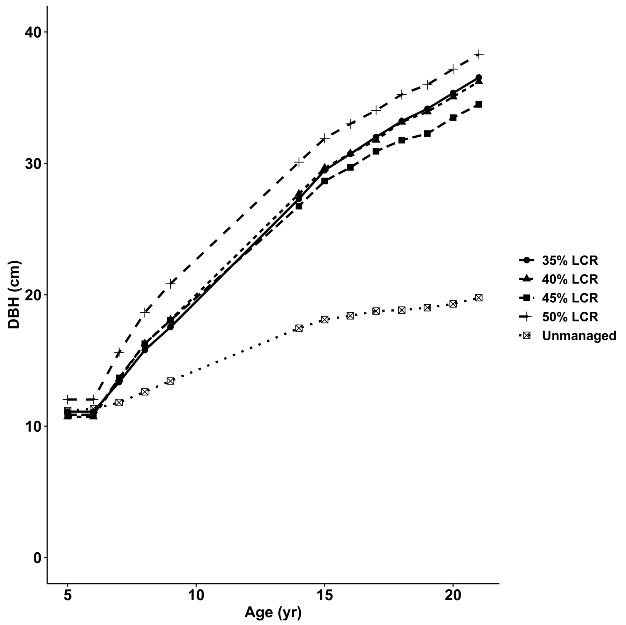

Figure 3 Mean DBH by treatment throughout the study years (2003–2019) broken down by live-crown ratio (LCR) treatments with the unmanaged plot (Unmanaged) for comparison.

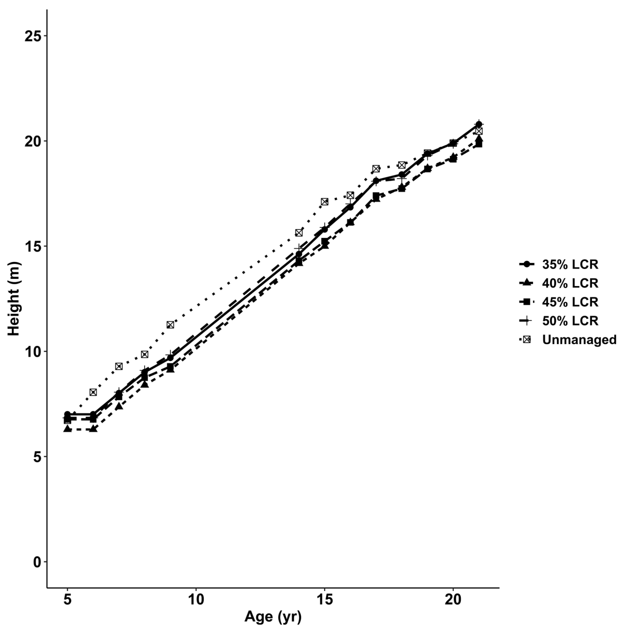

Figure 4 Mean height by treatment throughout the study years (2003–2019) broken down by live-crown ratio (LCR) treatments with the unmanaged plot (Unmanaged) for comparison.

treatments did not affect growth negatively, and the pruning of some trees within a stand did not appear to diminish stand-level growth. In this study, there was no noticed decline in diameter growth related to pruning, despite the trees in this study being pruned multiple times.

The diameter of all pruning treatments was significantly greater than the unmanaged plot. However, this difference was likely due to the thinning that took place in the pruned treatments, especially since pruning can decrease the ability of a tree to intercept light, thus reducing growth potential (Young and Kramer 1947). Releasing a tree from competition allows growth acceleration as a result of resource availability for the residual trees as well as eventual foliage increases (Ashton and Kelty 2018; Haywood 2005; Peterson et al. 1997). In general, diameter growth can be greatly affected by stand density, and intensive thinning can greatly increase the final diameter of crop trees compared to an unthinned stand. Low densities can promote larger tree diameters, which encourages more rapid sawtimber production (Russell et al. 2009; Zhao et al. 2012). Increasing thinning intensity has also been shown to create a higher and narrower diameter distribution (Baldwin et al. 2000), which could support the use of a more aggressive thinning treatment at an early age for small landholdings or stand establishment at a lower relative density.

There was no significant difference in height growth among treatments. Stand density has been shown to have a wide variety of impacts on height of dominant and co-dominant trees. Thinning has been shown to positively affect height growth in some cases, especially if the site was of better quality (Zhang et al. 1997). In this study, however, this impact was minimal, and, if noticeable, was much less than the impact on diameter growth. Antôn-Fernández et al. (2011) noted dominant height was dependent upon planting density, with differences expressing themselves as early as age six. This difference was still significant at age 25 but increases of dominant height diminished as spacing increased past 9 m^2/tree (Antón-Fernández et al. 2011). However, despite the link found between height and density in the Antôn-Fernández et al. (2011) study, differences were slight, and depending on the definition of dominant height used, there were no significant differences. This supports the similarities in average heights across all treatments observed in our study. Pruning, like thinning, has been shown to have no impact or discernable trend in relation to total height and height growth (Ares and Brauer 2005; Young and Kramer 1947). Height, being mostly dependent on site conditions, will likely not see any impacts as a result of pruning unless taken to an extreme that causes the affected individuals to suffer permanent stunting of growth. In this case, since the trees chosen for the study were the most dominant, pruning would have to eliminate most of the productive crown to cause any sort of photosynthetic limitation that could stunt growth.

Mortality occurred in all of the treatments. Although the unmanaged plot had the highest mortality, it was a single plot with a small number of trees, so this mortality was not considered significantly different than any of the other treatments. There was some Ips (*Ips* spp.) beetle and fusiform rust (*Cronartium quercuum* f. sp. *fusiforme*) damage within the study plots, as well as hurricane damage. It was unclear whether these factors were the cause of the mortality experienced within the stand, but they could have helped to further weaken trees already experiencing stress. The 35% LCR treatment did not have the highest mortality rate among the pruned treatments. Even if differences in mortality had been significant, it could not be attributed to a more aggressive crown-lifting treatment. Thinning and pruning have not been shown to be linked to any increase in mortality.

Conclusion

The combination of low stand density and pruning could be used by NIPF landowners to reduce the need for thinning treatments. Planting at a lower density would reduce planting costs and eliminate the need for precommercial thinning. Additionally, by the end of the rotation, landowners could have an attractive stand with potentially high-value sawtimber. This might entice contractors to bid on small parcels of land. It is important to note the treatments examined in this study would require significant labor or costs for the landowner to maintain. The significant difference between all pruned and thinned treatments and the unmanaged plot further supports the need for lower density management to achieve rapid diameter growth. Since there was no significant difference between the diameter growth of the various live crown ratios, the lowest pruning intensity (50% LCR) could be used to save time and money while still achieving desired results. Pruning could also be done less frequently than in this study, since repeated crown-lifting treatments could negatively affect long-term growth. The exact age may vary, but pruning should occur once trees are tall enough that pruning up to 5.3 m (17.3 ft) does not reduce the LCR to less than 35%. This low-density crown-lifting management option is more viable for landowners with small parcels of land where hand pruning will not be overly time consuming. Moreover, landowners interested in this option must be willing and able to devote time, labor, or money to prune their stands.

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Conflict of Interest

None declared.

Literature Cited

Amateis, R.L., and H.E. Burkhart. 2011. Growth of young loblolly pine trees following pruning. *Forest Ecology and Management* 262(12):2338–2343.

Amateis, R.L., and H.E. Burkhart. 2013. Relating quantity, quality, and value of lumber to planting density for loblolly pine plantations. *Southern Journal of Applied Forestry* 37(2):97–101.

Antón-Fernández, C., H.E. Burkhart, M. Strub, and R.L. Amateis. 2011. Effects of initial spacing on height development of loblolly pine. *Forest Science* 57(3):201–211.

Arano, K.G., and I.A. Munn. 2006. Evaluating forest management intensity: a comparison among major forest landowner types. *Forest Policy and Economics* 9(3):237–248.

Ares, A., and D. Brauer. 2005. Aboveground biomass partitioning in loblolly pine silvopastoral stands: Spatial configuration and pruning effects. *Forest Ecology and Management* 219(2–3):176–184.

Ashton, M.S., and M.J. Kelty. 2018. *The Practice of Silviculture: Applied Forest Ecology*. West Sussex: John Wiley and Sons Ltd, 461–505.

Baldwin, V.C., K.D. Peterson, A. Clark, R.B. Ferguson, M.R. Strub, and D.R. Bower. 2000. The effects of spacing and thinning on stand and tree characteristics of 38-year-old loblolly pine. *Forest Ecology and Management* 137(1–3):91–102.

Biblis, E.J., H. Carino, R. Brinker, and C.W. McKee. 1995. Effect of stand density on flexural properties of lumber from two 35-year-old loblolly pine plantations. *Wood Fiber Science* 27(1):25–33.

Burkhart, H.E., and R.L. Amateis. 2020. Effects of early pruning on ring specific gravity in young loblolly pine trees. *Wood Fiber Science* 52(2):139–151.

Burton, J.D., and E. Shoulders. 1974. Fast-grown, dense loblolly pine sawlogs: a reality. *Journal of Forestry* 72(10):637–641.

Butler, B.J., J.H. Hewes, B.J. Dickinson, K. Andrejczyk, S.M. Butler, and M. Markowski-Lindsay. 2021. *Family forest ownerships of the United States, 2018: results from the USDA Forest Service National Woodland Owner Survey*. USDA Forest Service Gen. Tech. Rep. NRS-199, Northern Research Station, Madison, WI, 52.

Clark, A., L. Jordan, L. Schimleck, and R.F. Daniels. 2008. Effect of initial planting spacing on wood properties of unthinned loblolly pine at age 21. *Forest Products Journal* 58(10):78–83.

Clark, A., J.R. Saucier, V.C. Baldwin, and D.R. Bower. 1994. Effect of initial spacing and thinning on lumber grade, yield, and strength of loblolly pine. *Forest Products Journal* 44(11–12):14–20.

Clark, A., M. Strub, L.R. Anderson, H.G. Lloyd, R.F. Daniels, and J.H. Scarborough. 2004. *Impact of early pruning and thinning on lumber grade yield from loblolly pine*. USDA Forest Service Gen. Tech. Rep. SRS–71, Southern Research Station, Asheville, NC, 199–204.

Dean, T.J., and V.C. Baldwin. 1996. Growth in loblolly pine plantations as a function of stand density and canopy properties. *Forest Ecology and Management* 82(1–3):49–58.

General, D.R., C.L. VanderSchaaf, and B. Zeide. 2013. The longest active thinned and pruned loblolly pine permanent plots: the last measurement. In Proceedings of the 15th Biennial Southern Silvicultural Research Conference, edited by Guldin, J.M.., USDA Forest Service Gen. Tech. Rep. SRS-GTR-175, Southern Research Station, Asheville, NC. 479–486.

Grano, C.X. 1969. Precommercial thinning of loblolly pine. *Journal of Forestry* 67(11):825–827.

Hatcher, J.E., T.J. Straka, and J.L. Greene. 2013. The size of forest holding/parcelization problem in forestry: A literature review. *Resources*. 2(2):39–57.

Haywood, J. 2005. Influence of precommercial thinning and fertilization on total stem volume and lower stem form of loblolly pine. *Southern Journal of Applied Forestry* 29(4):215–220.

Helms, J.A. 1998. *The Dictionary of Forestry*. Bethesda: Society of American Foresters, 1998.

Hothorn, T., F. Bretz, and P. Westfall. 2008. Simultaneous inference in general parametric models. *Biometrical Journal: Journal of Mathematical Methods in Biosciences* 50(3):346–363.

Huang, C.H., and G.D. Kronrad. 2004. Economic analysis of pruning and low-density management compared to traditional management of loblolly pine plantations in East Texas. *Southern Journal of Applied Forestry* 28(1):12–20.

Larson, P.R., D.E. Kretschmann, A. Clark, and J.G. Isebrands. 2001. *Formation and properties of juvenile wood in southern pines: A synopsis*. USDA Forest Service Gen. Tech. Rep. FPL-GTR-129, Forest Products Laboratory, Madison, WI, 42.

Lenth, R.V. 2021. emmeans: estimated marginal means, aka least-squares means. R Package Version 1.3.1. Date accessed 3 November 2022.

Lohrey, R.E. 1977. Growth responses of loblolly pine to precommercial thinning. *Southern Journal of Applied Forestry* 1(3):19–22.

Measells, M.K., S. Grado, and H.G. Hughes. 2005. The status of Mississippi forest landowners. In Proc. of the 2004 Southern Forest Economic Workers Annual Meeting, edited by Alavalapati, J.R.R., and D.R. Carter, 157–166. St. Augustine, FL.

Newton, P.F. 2009. Development of an integrated decision-support model for density management within jack pine stand-types. *Ecological Modelling* 220(23):3301–3324.

Peterson, J.A., J.R. Seiler, J. Nowak, S.E. Ginn, and R.E. Kreh. 1997. Growth and physiological responses of young loblolly pine stands to thinning. *Forest Science* 43(4):529–534.

Pinheiro, J., D. Bates, S. DebRoy, D. Sarkar, and R Core Team. 2021. nlme: linear and nonlinear mixed effects models. R package version 3.1-152. Date accessed 1 November 2022.

R Core Team. 2020. R: A language and environment for statistical computing. Date accessed 3 November 2022.

Roth, B.E., X. Li, D.A. Huber, and G.F. Peter. 2007. Effects of management intensity, genetics and planting density on wood stiffness in a plantation of juvenile loblolly pine in the southeastern USA. *Forest Ecology and Management* 246(2–3):155–162.

Russell, M.B., H.E. Burkhart, and R.L. Amateis. 2009. Biomass partitioning in a miniature-scale loblolly pine spacing trial. *Canadian Journal of Forest Research* 39(2):320–329.

Soil Survey Staff. 2022. *Web Soil Survey*. Washington, D.C: USDA, Natural Resources Conservation Service. Available online. Date accessed 29 August 2022.

USDA Forest Service. 2018. State and Private Forestry Fact Sheet: Mississippi 2018. https://www.stateforesters.org/wp-content/uploads/2018/07/Mississippi-2018.pdf. Date accessed 14 December 2021.

USDA Forest Service Southern Research Station. 2020. *Forests of Mississippi, 2018*. USDA Forest Service Resource Update FS-258, Southern Research Station, Asheville, NC, 2.

Weng, Y.H., J. Grogan, and D.W. Coble. 2020. Modeling early responses of loblolly pine growth to thinning in the western gulf coastal plain region. *Forest Science* 66(5):623–633.

Wickham, H. 2016. *ggplot2: Elegant Graphics for Data Analysis*. Date accessed 1 November 2022.

Young, H.E., and P.J. Kramer. 1947. The effect of pruning on the height and diameter growth of loblolly pine. *Journal of Forestry* 50(6):474–479.

Zhang, S., H.E. Burkhart, and R.L. Amateis. 1997. The influence of thinning on tree height and diameter relationships in loblolly pine plantations. *Southern Journal of Applied Forestry* 21(4):199–205.

Zhao, D., M. Kane, and B.E. Borders. 2011. Growth responses to planting density and management intensity in loblolly pine plantations in the southeastern USA Lower Coastal Plain. *Annals of Forest Science* 68(3):625–635.

Zhao, D., M. Kane, B. Borders, S. Subedi, and M. Akers. 2012. Effects of cultural intensity and planting density on stand-level aboveground biomass production and allocation for 12-year-old loblolly pine plantations in the upper coastal plain and piedmont of the southeastern United States. *Canadian Journal of Forest Research* 42(1):111–122.