

Assessing Mid-rotation Loblolly Pine and Competing Vegetation Responses to Post-thin Fertilization and Herbicide Application in the Southeastern United States

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Abstract

Mid-rotation silvicultural treatments (MRT) are commonly applied to loblolly pine (*Pinus taeda* L.) plantations in the southeastern United States to improve pine productivity. Competing vegetation is often present in operational plantations and limits site resource availability. The benefits of MRT for pine productivity are well known, but competing vegetation growth has not been extensively studied. Pine and competing vegetation growth within two regions of the southeastern United States was monitored for 8 years following a one-time post-thin application of either fertilization (224 kg ha⁻¹ of nitrogen plus 28 kg ha⁻¹ phosphorus), chemical herbicide (0.8 oz glyphosate and 0.8 oz triclopyr L⁻¹ of water) or their combination. Fertilization significantly increased pine volume growth in the Lower Coastal Plain (LCP, 2.67–4.01 m³ ha⁻¹ yr⁻¹) and the Upper Coastal Plain/ Piedmont (UCPIE, 0.20–3.72 m³ ha⁻¹ yr⁻¹). Chemical herbicide application in both the LCP (0.34–4.87 m³ ha⁻¹ yr⁻¹) and UCPIE (0.89–1.97 m³ ha⁻¹ yr⁻¹) also significantly increased pine volume. Chemical herbicide application, individually and combined, did not result in significant decreases in herbaceous vegetation, but reduced woody vegetation by up to -2.40 m³ ha⁻¹ yr⁻¹ in the LCP and -5.67 m³ ha⁻¹ yr⁻¹ in the UCPIE. Consequently, we suggest that competing vegetation response should be considered within site-specific management plans aimed at maximizing pine productivity.

Study Implications: Mid-rotation silvicultural treatments (MRT) improve loblolly pine productivity and are common in the southeast United States. Applications of fertilization and vegetation control following thinning is widespread in operational pine plantations. Competing vegetation is common in operational stands and may inhibit pine growth depending on the abundance and vegetation type. Assessment of both competing vegetation and pine growth following MRT can provide insight on site-specific silvicultural demands. Loblolly pine productivity increased with MRT, and cumulative yield was highest following a combined fertilization and vegetation control. Herbaceous vegetation was not found to be a vigorous competitor for site resources, but the removal of woody vegetation was associated with increased pine growth. Varied responses across the region illustrated the importance of site-specific management for maximizing pine production at mid-rotation.

Keywords: thinning, fertilization, competition control, stand growth, silviculture, forest vegetation management

Loblolly pine (*Pinus taeda* L.) is widely regarded as the most important southern yellow pine species, with the broader loblolly-shortleaf cover type accounting for 71% of the planted forests in the South (Oswalt et al. 2019). Loblolly pine plantations are some of the most intensively managed forests globally. However, pine plantations following the most intensive regimes and on the highest quality sites will often produce timber at rates lower than their potential (Borders and Bailey 2001; Zhao et al. 2016). Efforts to increase productivity have resulted in the development of integrated stand management approaches targeted at maximizing site-specific growth (D'Amato et al. 2018; Homyack et al. 2022; Vance et al. 2010). Mid-rotation silvicultural treatments (MRT) improve productivity in established stands by providing nutrient amendments and reducing competition for site resources (Allen and Albaugh 2000; Allen et al. 1990; Amateis et al. 2000; Fox et al. 2007a).

Inadequate site nutrition is the primary limiting factor at mid-rotation (Allen et al. 1990; Fox et al. 2007b). Established stands typically become deficient in both nitrogen (N) and phosphorus (P) as individual tree demand exceeds site nutrient availability. Combined applications of N and P achieve higher growth rates than independent applications. Loblolly growth responses range from 0.67 m³ ha⁻¹ yr⁻¹ to 7.4 m³ ha⁻¹ yr⁻¹ depending on the site characteristics and application rate. A common operational rate of 224 kg ha⁻¹ N plus 28 kg ha⁻¹ P has been shown to increase yield by an average 3.8 m³ ha⁻¹ year⁻¹ across the southeast United States and is commonly used for plantations at mid-rotation (Amateis et al. 2000; Fox et al. 2007b; Hynynen et al. 1998).

Competition further inhibits productivity by reducing site resources allocated to individual tree growth. Thinning removes a portion of trees to a desired level of stocking and

reallocates site resources to residual trees. Crop trees respond to thinning based on site quality, previous management activity, thinning intensity, and individual tree vigor (Zhang et al. 1989). Although thinning may not guarantee an increase in the residual growth rate, the additional benefits are extensive. Thinning decreases density-related mortality, provides intermittent revenue, and can shift the size-class distribution to favor higher-value product specifications at final harvest (Amateis et al. 1989; Clutter et al. 1983; Hasenauer et al. 1997).

Vegetation control with chemical herbicide applications reduces competition from noncrop vegetation (Allen and Albaugh 2000). Loblolly response to mid-rotation competition control varies with treatment intensity. Fortson et al. (1996) found that complete and sustained control increased volume nearly $37 \text{ m}^3 \text{ ha}^{-1}$ in stands located on Piedmont and Upper Coastal plain mid-slopes and responses were sustained throughout the 8-year study period. However, complete control is often infeasible in practice and operational treatments, which reflects industrial application rates showing mixed results. Growth responses to operational control are typically less than those of complete control (Albaugh et al. 2012), and in some cases, competition control may result in no additional growth (Cain 1985). Additionally, competing vegetation commonly regrows in operational stands (Albaugh et al. 2012; Blinn et al. 2011) and the growth trends of competing vegetation responding to operational MRT have not been extensively studied.

MRT may be combined to optimize site specific growth when multiple limiting factors are present. Combined fertilization and chemical herbicide applications at mid-rotation result in higher growth rates than either treatment applied independently (Albaugh et al. 2012; Gyawali and Burkhart

2015; Liechty and Fristoe 2013). Post-thin fertilization promotes crown development and increases leaf area index, which is directly related to more vigorous post-treatment growth (Albaugh et al. 2019; Fox et al. 2007a). Post-thin competition control releases site resources from noncrop vegetation. Often, the treatment applications are determined by operational constraints that affect the timing, rate of application, and combination of treatments. Fertilization and/or chemical herbicide application at the time of thinning is common in the US South.

The objective of this study was to evaluate loblolly pine and competing vegetation growth responses to a one-time post-thin operational fertilization and chemical herbicide application. Growth trends were compared between two major physiographic regions in the southeast United States, and the relationship between competing vegetation density and loblolly pine volume growth was assessed. This research aimed to improve our understanding of postthin loblolly pine and competing vegetation growth under operational management regimes, and to gain further insight to the relationship between loblolly pine and competing vegetation within intensively managed plantations.

Materials and Methods

Study Site

The PMRC Mid-Rotation Treatment Study was initialized in 2009 as a regional research field trial consisting of twenty-four installations equally distributed between the Lower Coastal Plain (LCP) and combined Upper Coastal Plain & Piedmont (UCPIE) regions of the southeast United States (figure 1). Installations were established immediately following thinning on industrial plantations provided by

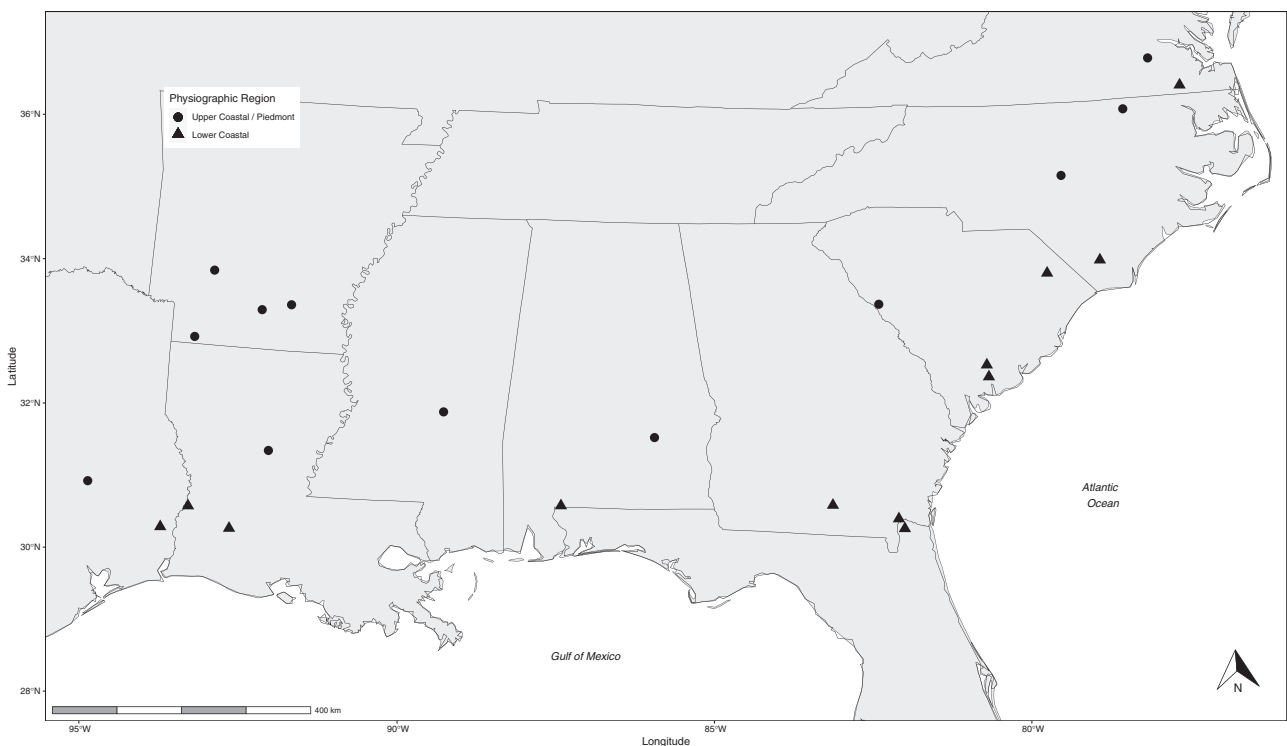


Figure 1. Approximate locations of MRT 1st-thin installations distributed within the UCPIE and LCP physiographic regions of the southeast United States.

Table 1. Summarized stand and site information for the mid-rotation silvicultural treatments 1st-thin installations located in the UCPIE and LCP regions. Values represent pretreatment stand conditions as measured before thinning. Locations are approximated to the nearest town.

Physiographic region	Location	Dominant soil series (order)	Primary competing vegetation	Site index (base age 25)	Residual basal area (m ² ha ⁻¹)	Year established (age)	Pretreatment stand values					
							Loblolly pine			Competing vegetation		
							TPH	HD (m)	BA (m ² ha ⁻¹)	TVOB (m ³ ha ⁻¹)	Crown volume (m ³ ha ⁻¹)	Groundcover (%)
Upper Coastal Plain & Piedmont	Jena, LA	Rustin/Malbis (Ultisols)	American beauty- berry (<i>Callicarpa amer- icana</i>)	26.5	21	2009 (16)	1158	18.71	38.21	313.38	96.44	17.56
	Plum Branch, SC	Herndon (Ultisols)	Sweetgum (<i>Liquidambar styraciflua</i>)	22.9	16	2011 (15)	1491	13.89	34.31	211.26	113.23	25.5
	Antoine, AR	Savannah (Ultisols)	American beauty- berry (<i>Callicarpa amer- icana</i>)	24.1	21	2010 (16)	1627	16.86	44.65	332.67	53.74	14.05
	Sanford, NC	White Store (Alfisols)	White oak (<i>Quercus alba</i>)	24.4	11.5	2011 (13)	1585	14.30	37.99	242.11	8.95	20.36
	Dinwiddle, VA	Mattaponi (Ultisols)	Southern red oak (<i>Quercus falcata</i>)	21.3	21	2011 (16)	1560	13.57	35.33	213.44	344.49	10.97
	Groveton, TX	Keltys (Alfisols)	Sweetgum (<i>Liquidambar styraciflua</i>)	21.0	16	2011 (16)	1581	15.85	38.06	268.05	61.97	7.05
	Bradley, AR	Dorcheat (Alfisols)	Southern red oak (<i>Quercus falcata</i>)	21.3	11.5	2011 (19)	1043	14.70	36.55	234.24	55.55	15.05
	Warren, AR	Savannah (Ultisols)	American beauty- berry (<i>Callicarpa amer- icana</i>)	24.1	16	2014 (17)	1362	14.09	34.03	211.86	79.12	8.19
	Forest, MS	Kipling (Alfisols)	Ash (<i>Fraxinus spp.</i>)	26.2	11.5	2013 (13)	1586	19.42	43.69	375.00	103.4	31.66
	Troy, AL	Mantachie(<i>Incep- tisols</i>), Eunola (Ultisols)	Sweetgum (<i>Liquidambar styraciflua</i>)	24.1	16	2012 (16)	1417	16.23	39.07	276.95	163.77	12.09
	Littleton, NC	Cecil (Ultisols)	Sweetgum (<i>Liquidambar styraciflua</i>)	23.5	21	2013 (16)	1397	16.24	42.30	305.11	393.35	16.8
	Hampton, AR	Smithton (Ultisols)	Sweetgum (<i>Liquidambar styraciflua</i>)	22.6	11.5	2013 (20)	955	16.47	43.89	312.46	49.49	4.89

Table 1. Continued

Physiographic region	Location	Dominant soil series (order)	Primary competing vegetation	Site index (base age 25)	Residual basal area (m ² ha ⁻¹)	Year established (age)	Pretreatment stand values					
							Loblolly pine				Competing vegetation	
							TPH	HD (m)	BA (m ² ha ⁻¹)	TVOB (m ³ ha ⁻¹)	Crown volume (m ³ ha ⁻¹)	Groundcover (%)
Lower Coastal Plain	Franklin, VA	Rains (Ultisols)	Sweetgum (<i>Liquidambar styraciflua</i>)	26.8	21	2014 (18)	1040	20.75	46.37	418.46	124.79	14.89
	Hilliard, FL	Meggett (Alfisols)	Sweetgum (<i>Liquidambar styraciflua</i>)	28.0	16	2012 (12)	1658	16.61	34.05	248.57	122.6	13.23
	Merryville, LA	Merryville (Alfisols), Bearhead (Ultisols)	Blackgum (<i>Nyssa sylvatica</i>)	25.9	11.5	2013 (16)	1412	17.73	36.58	283.57	123.49	3.79
	Lakeland, GA	Rigdon (Spodosols)	Southern red oak (<i>Quercus falcata</i>)	28.0	11.5	2013 (13)	1493	15.07	29.99	198.73	16.48	24.66
	Kinder, LA	Caddo (Alfisols), Messer (Alfisols)	Yaupon (<i>Ilex vomitoria</i>)	25.3	16	2013 (14)	1689	14.96	35.80	235.91	73.01	4.49
	Folkston, GA	Pelham (Ultisols)	Gallberry (<i>Ilex glabra</i>)	26.5	21	2015 (16)	1644	17.19	30.73	235.06	65.83	6.49
	Jacksonboro, SC	Nemours (Ultisols)	Sweetgum (<i>Liquidambar styraciflua</i>)	26.2	11.5	2014 (16)	1250	19.00	36.63	299.23	132.77	24.02
	Cottageville, SC	Hobcaw (Ultisols), Yemassee (Ultisols)	Sweetgum (<i>Liquidambar styraciflua</i>)	26.2	16	2014 (17)	1394	19.85	40.74	352.66	70.91	3.7
	Lake Waccamaw, NC	Croatan (Histosols)	Gallberry (<i>Ilex glabra</i>)	25.6	11.5	2015 (12)	1334	15.80	35.45	244.67	10.99	1.4
	Atmore, AL	Greenville (Ultisols)	Yaupon (<i>Ilex vomitoria</i>)	24.7	21	2016 (15)	1257	16.18	32.28	228.11	53.99	37.5
	Buna, TX	Evadale (Alfisols)	Yaupon (<i>Ilex vomitoria</i>)	25.0	16	2018 (18)	1432	18.66	38.57	315.69	85.79	15.36
	Marion, SC	Cantey (Ultisols)	Sweetgum (<i>Liquidambar styraciflua</i>)	25.9	21	2017 (15)	1192	17.23	43.10	320.70	28.09	53.13

PMRC member companies (Table 1). Site selection was based on stem quality and uniformity, and all sites were considered an average operational plantation within either physiographic region. Stands that had excessive damage or stem defects were excluded from consideration as well as stands that had received silvicultural amendments within the 5 years preceding establishment. Pines were either 1st or 2nd generation improved seedlings and stands had no more than 15% stem defects at any location prior to establishment. Initial pine stocking ranged from 955 to 1,627 trees ha⁻¹ in the UCPIE and 1,040 to 1,689 trees ha⁻¹ in the LCP. The UCPIE stands were between 13 and 20 years old at the time of installation and were between 12 and 18 years old in the LCP. Soil orders of both LCP and UCPIE installations were primarily Alfisols and Ultisols, represented across a wide array of soil series. Additional soil orders were Spodosols, Histosols, and Inceptisols. Soils information was referenced using Natural Resources Conservation Service (NRCS) soil survey data (Soil Survey Staff, Natural Resources Conservation Service). Initial competing vegetation density varied greatly between installations. Crown volume of midstory woody and shrub species was between 8.95 and 393.35 m³ ha⁻¹ in the UCPIE and between 28.09 and 132.77 m³ ha⁻¹ in the LCP. Percentage groundcover in herbaceous vegetation ranged from 4.89% to 31.66% in the UCPIE and 1.4% to 53.13% in the LCP. Competing vegetation in the UCPIE was composed of hardwoods and broadleaf shrubs dominated by sweetgum (*Liquidambar styraciflua* L.), oak (*Quercus* spp.), and American beautyberry (*Callicarpa americana*). Waxy-leaved competitors were more present in the LCP, where the primary competition consisted of sweetgum and various holly species (*Ilex* spp.), including yaupon (*Ilex vomitoria*) and gallberry (*Ilex coriacea* and *Ilex glabra*).

Experimental Design

Each of the twelve installations within a physiographic region represented a unique combination of pre-thin basal area (high, >27.6 m² ha⁻¹; low, ≤27.6 m² ha⁻¹), pre-thin site index (high, >26 m; low, ≤26 m), and post-thin residual basal area (high, 21 m² ha⁻¹; moderate, 16 m² ha⁻¹; low, 11.5 m² ha⁻¹). Four treatment plots were established at each installation immediately after thinning in a randomized pattern unique to each location. The treatments consisted of a thin only (T), T + fertilization (F), T + chemical herbicide (H), and T + F + H, which were applied to the entire treatment plot area to ensure a treated buffer zone surrounding each measurement plot. Thinning was a 5th row thin, with free thinning between rows to achieve the desired residual basal area. Fertilization occurred in either the fall or spring after thinning and was applied at a rate of 224 kg ha⁻¹ N plus 28 kg ha⁻¹ P with additional nutrients as needed based on foliar testing at each installation. The chemical herbicide was applied by backpack sprayer in the fall after thinning, as a combination of glyphosate and triclopyr (Garlon 3A) at a rate of 0.8 oz glyphosate and 0.8 oz triclopyr L⁻¹ water (3 oz glyphosate and 3 oz triclopyr gal⁻¹), and 360 L water ha⁻¹ (36 gal ac⁻¹). Follow up applications were a variable rate of triclopyr (Garlon 4) mixed with bark oil to eliminate any remaining woody vegetation. The combined treatment was a joint application of the individual fertilizer and chemical herbicide treatments.

Measurements

Measurement plots were a 0.2 ha (0.5 ac) rectangular plot embedded inside a 0.3 ha (0.75 ac) treatment plot. The measurement plot size was selected to ensure that at least 50 pine trees were measured per plot at the most intensively thinned locations. Pine trees were measured for diameter at breast height (DBH), total height (Ht), and height to live crown (Hlc). The Ht and Hlc were taken on a subset of trees that represented the diameter distribution at each location and was used to calculate site index (SI). Plot measurements were collected pre-thin, immediately post-thin, and every 2 years following treatment in the dormant season. Twenty 1.22 m (4 ft) radius competing vegetation subplots were systematically located throughout each measurement plot and represented 5% of the plot area. Large arborescent vegetation (>2 in. DBH) was measured for DBH and Ht. A stem count, mean Ht by species group, and crown width by species was collected for small arborescent vegetation (< 2 in. DBH) and shrub species. Ocular estimates of the percent groundcover occupied by herbaceous species, as well as the amount occupied by broadleaf weed species, were also recorded. Subplot measurements were collected prior to treatment and subsequently every 2 years post-treatment starting in the second growing season. Three classes of competing vegetation were derived from the subplot measurements: overstory hardwoods, understory shrubs, and woody stems, and herbaceous vegetation. Preliminary analysis found that overstory hardwood density was either absent or occurred in extremely low frequencies and was subsequently excluded from the analysis.

Statistical Analysis

MRT were assessed using a mixed effects model. The treatment plots at each installation represent an unreplicated 2 × 2 factorial design of post-thin fertilization and chemical herbicide with repeated measures. Installations were established in subsequent years beginning in 2009, resulting in an unbalanced design at each measurement period. Mixed-effect models are robust for modeling unbalanced longitudinal designs (Vonesh and Carter 1992; Ware 1985). Additionally, specifying the installations as a random variable characterizes the random error associated with inherent local variability. The three higher-order categorical variables representing the initial stand conditions (Initial basal area, Initial SI, and post-thin basal area) were excluded from the model to eliminate pseudoreplication. Because treatments were unreplicated at each installation, treatment plots represented a single observation of the unique combination of initial stand conditions. Potential differences due to pretreatment conditions were accounted for by including a pretreatment measure of the dependent variable as covariate in the model. The final model was specified as:

$$Y_{ijk} = \mu_{ijk} + \alpha_{0jk} + \beta_i P_i + \gamma_j TRT_j + \tau_{ij} P_i TRT_j + u_k P_i + \epsilon_{ijk} \quad (1)$$

where Y_{ijk} represents a stand variable of interest, μ_{ijk} is the average growth at each treatment plot for each measurement period, α_{0jk} represents a pretreatment estimate of Y_{0jk} , β_i is the coefficient associated with the i^{th} period of growth (P), γ_j is the coefficient for the j^{th} treatment (TRT) and where TRT is a categorical dummy variable with $j = (1, \dots, 4)$ representing the T, T + F, T + H, and T + F + H treatments, τ_{ij} describes the two-way interaction between P and TRT, $u_k P_i$ is the random-effect term accounting for random error of the

k^{th} installation and i^{th} P, and ϵ_{ijk} is the fixed error. Significance was determined at an α level of 0.10, which was selected to account for potential complications due to a low-power statistical test arising from an unreplicated design spanning a large geographic region (Gaino 2006).

Pine responses were assessed using periodic annual increment (PAI) relative to each measurement period for total outside-bark volume (TVOB), stand basal area (BA), stand dominant height (HD), and mortality (trees per hectare [TPH]). The TVOB was calculated using stem volume equations from Zhao and Kane (2016). Additionally, (1) was used to model the effects of MRT on the cumulative final yield of each stand variable at 8 years post-treatment. Understory growth was assessed in terms of crown volume (m^3), which was calculated as

$$V_{UC} = \pi (H_{UC}) \left(\frac{W_{UC}}{2} \right)^2, \quad (2)$$

where V_{UC} is the total understory crown volume, W_{UC} is the understory crown width, and H_{UC} is the understory crown height. We assumed understory crowns were cylindrical to account for the decurrent stem form generally expressed by deciduous species. Herbaceous vegetation growth was evaluated in terms of total percent groundcover by combining the ocular groundcover estimates for both herbaceous weeds and broadleaf species. Competing vegetation growth was also assessed using (1) and PAI.

The relationship between overstory pine growth and competing vegetation density was assessed using linear regression. It was hypothesized that higher levels of competing vegetation removed should result in a larger pine growth response in similarly treated stands. A similar hypothesis was tested by Albaugh et al. (2012), who considered the relationship between post-treatment volume growth and initial hardwood basal area and determined it was not significant. Unlike Albaugh et al. (2012), we were testing pine growth against different vegetation groups (woody and herbaceous) and following a controlled thinning and chemical herbicide application. Pre-treatment understory crown volume and herbaceous groundcover percentage were modeled independently against the 6-year TVOB PAI for the T + H and T + F + H treatment plots. All statistical analysis was completed using the R Statistical Computing Environment (R Core Team 2022), and mixed-effect models were fitted using the lme4 package (Bates et al. 2015).

Results

Pine Growth

Pine volume growth responded positively to MRT in both the UCPIE and LCP. Fertilization increased TVOB growth relative to the thin-only treatment up to 8 years ($4.01 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) post-treatment in the LCP and 6 years ($3.72 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) in the UCPIE (Table 2). Volume growth also responded to chemical herbicide application, with significant gains observed 4 years following treatment and lasting up to 6 and 8 years post-treatment in the UCPIE ($1.97 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) and LCP ($4.87 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$), respectively. The combined treatment was only significant in the LCP 6 years post-treatment. Volume growth in the LCP slowed throughout the study period (figure 2). Estimated periodic annual increment indicated a decrease in LCP volume growth, with the largest reduction in growth occurring between 6 years ($18.95 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) and 8 years

($10.01 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) for the thin-only treatment. Volume growth in the UCPIE was relatively consistent throughout all four measurement periods (figure 2). The only reduction in estimated periodic annual increment for UCPIE was from 6 ($23.28 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) to 8 years ($21.65 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$) under the combined treatment.

The BA growth increased with MRT, although responses were different between physiographic regions (Table 2). Fertilization in the LCP resulted in a significant BA growth response sustained up to 6 years post-treatment ($0.30 \text{ m}^2 \text{ ha}^{-1} \text{ yr}^{-1}$) but was not significant until 4 years post-treatment ($0.22 \text{ m}^2 \text{ ha}^{-1} \text{ yr}^{-1}$) in the UCPIE. Chemical herbicide application also increased BA growth for up to 4 ($0.22 \text{ m}^2 \text{ ha}^{-1} \text{ yr}^{-1}$) years in the UCPIE and 8 ($0.41 \text{ m}^2 \text{ ha}^{-1} \text{ yr}^{-1}$) years in the LCP. In both regions, the combined treatment was not statistically significant at any period following treatment. Although stands responded positively to MRT, BA growth decreased throughout the study period in the LCP (figure 3), with the most substantial decrease in periodic growth occurring in fertilized stands, ranging from $1.55 \text{ m}^2 \text{ ha}^{-1} \text{ yr}^{-1}$ to $0.38 \text{ m}^2 \text{ ha}^{-1} \text{ yr}^{-1}$. The BA growth in the UCPIE remained consistent across all measurement periods (Table 2).

The HD responded to MRT only in the UCPIE. The effect of fertilization was significant at 2 (0.12 m yr^{-1}) and 6 years (0.18 m yr^{-1}) post-treatment (Table 2). Response to chemical herbicide was significant 2 (0.18 m yr^{-1}) and 8 years (-0.18 m yr^{-1}) years post-treatment. The combined treatment effect did not result in any additional growth within either region. The HD growth remained consistent throughout the study period, with growth rates being similar across all MRT (figure 4).

Mortality was consistent throughout the post-treatment measurement periods in the LCP (figure 5). The final remeasurement period yielded a large loss in TPH in the LCP, with estimated PAI of up to 20 trees $\text{ha}^{-1} \text{ yr}^{-1}$ in the thin-only stands (Table 2). Silvicultural treatments in the LCP improved survival conditions for crop trees, with annualized responses (up to 3 trees $\text{ha}^{-1} \text{ yr}^{-1}$) being greater for treated stands than thin-only stands. Survival was greater in the UCPIE, but mortality still occurred throughout the remeasurement period (figure 5). Silvicultural treatment in the UCPIE resulted in greater mortality than the thin-only stands, with the greatest difference being an annualized response of -1.27 trees $\text{ha}^{-1} \text{ yr}^{-1}$ following fertilization. However, silvicultural treatment did not result in a significant response in TPH during any remeasurement period (Table 2).

MRT increased cumulative final yield for all stand attributes at 8 years post-treatment (Table 3). BA in the LCP was $1.44 \text{ m}^2 \text{ ha}^{-1}$ greater in fertilized stands than in thin-only stands, which resulted in a greater TVOB ($22.52 \text{ m}^3 \text{ ha}^{-1}$). The BA and TVOB also increased with chemical herbicide application by $1.26 \text{ m}^2 \text{ ha}^{-1}$ and $11.07 \text{ m}^3 \text{ ha}^{-1}$, respectively. The combined treatment had the largest increase in TVOB ($32.25 \text{ m}^3 \text{ ha}^{-1}$) and BA ($2.26 \text{ m}^2 \text{ ha}^{-1}$) but did not have a statistically significant effect on either. The MRT resulted in marginal differences in HD of up to 0.51 m . The final TPH also varied between treatments, ranging from 425 TPH for the thin-only stands to 452 TPH for fertilized stands. Results were similar in the UCPIE, but response to MRT was less than in the LCP. Fertilization in the UCPIE resulted in an increase of $17.43 \text{ m}^3 \text{ ha}^{-1}$ in TVOB and $1.35 \text{ m}^2 \text{ ha}^{-1}$ in BA relative to the thin-only treatment. Only TVOB was found to have a significant response to chemical herbicide application ($16.50 \text{ m}^2 \text{ ha}^{-1}$). Only slight differences in HD were also observed in

Table 2. Estimated periodic annual increment of loblolly pine stand-level variables for each 2-year measurement period following application of mid-rotation silvicultural treatments. Each stand-level variable was mean adjusted using pretreatment covariates and the random effects term. Bold *p*-values indicate a significant response at the .10 alpha-level. Treatment responses are relative to the thin-only treatment for each variable.

Physiographic region	Variable	Years since treatment	Estimated periodic annual increment by treatment (annualized response)				<i>p</i> < F (α = .10)		
			Thin (T)	T + Fert (F)	T + Herbicide (H)	T + F + H	T + F	T + H	T + F + H
Lower Coastal Plain	TVOB (m ³ ha ⁻¹ yr ⁻¹)	2	16.02	18.69 (2.67)	16.36 (0.34)	18.77 (2.75)	.06	.78	.75
		4	19.17	23.00 (3.83)	21.80 (2.63)	23.67 (4.50)	.01	.09	.28
		6	18.95	22.15 (3.20)	20.89 (1.94)	20.65 (1.70)	.04	.23	.10
		8	10.01	14.02 (4.01)	14.88 (4.87)	16.67 (6.66)	.03	.01	.33
	BA (m ² ha ⁻¹ yr ⁻¹)	2	1.26	1.53 (0.27)	1.29 (0.03)	1.47 (0.21)	.02	.82	.49
		4	1.43	1.68 (0.25)	1.71 (0.28)	1.77 (0.34)	.03	.03	.20
		6	1.25	1.55 (0.30)	1.42 (0.17)	1.54 (0.29)	.02	.21	.27
		8	0.30	0.38 (0.08)	0.71 (0.41)	0.60 (0.30)	.49	.01	.30
	HD (m yr ⁻¹)	2	0.85	0.83 (-0.02)	0.82 (-0.03)	0.88 (0.03)	.98	.79	.75
		4	0.84	0.97 (0.13)	0.85 (0.01)	0.89 (0.05)	.16	.86	.45
		6	0.80	0.72 (-0.08)	0.77 (-0.03)	0.60 (-0.20)	.58	.82	.47
		8	0.63	0.81 (0.18)	0.51 (-0.12)	0.87 (-0.24)	.13	.41	.45
	TPH (trees ha ⁻¹ yr ⁻¹)	2	-0.06	-2.36 (-2.29)	-2.06 (-1.99)	-3.01 (-2.95)	.06	.35	.43
		4	-2.12	-4.21 (-2.09)	-2.26 (-0.14)	-3.83 (-1.71)	.07	.97	.61
		6	-2.46	-0.80 (1.66)	-0.99 (1.46)	-1.42 (1.04)	1.00	.48	.71
		8	-19.10	-18.03 (1.07)	-10.86 (1.07)	-15.89 (3.21)	.82	.00	.15
Upper Coastal Plain & Piedmont	TVOB (m ³ ha ⁻¹ yr ⁻¹)	2	16.43	18.39 (1.96)	17.23 (0.89)	18.13 (1.70)	.04	.46	.46
		4	18.18	19.30 (1.12)	20.46 (2.28)	21.69 (3.78)	.30	.03	.87
		6	19.46	23.18 (3.72)	21.43 (1.97)	23.28 (3.82)	.00	.08	.23
		8	23.14	23.34 (0.20)	22.43 (-0.71)	21.65 (-1.49)	.95	.53	.65
	BA (m ² ha ⁻¹ yr ⁻¹)	2	1.51	1.62 (0.11)	1.51 (0.00)	1.62 (0.11)	.23	.69	.86
		4	1.55	1.77 (0.22)	1.75 (0.22)	1.97 (0.42)	.01	.03	.85
		6	1.42	1.54 (0.12)	1.57 (0.15)	1.65 (0.23)	.16	.11	.74
		8	1.57	1.54 (-0.03)	1.58 (0.01)	1.68 (0.11)	.63	.83	.31
	HD (m yr ⁻¹)	2	0.75	0.87 (0.12)	0.93 (0.18)	0.90 (0.15)	.10	.01	.13
		4	0.67	0.62 (-0.05)	0.70 (0.03)	0.65 (-0.02)	.44	.75	.96
		6	0.76	0.94 (0.18)	0.83 (0.07)	0.86 (0.10)	.03	.42	.21
		8	0.86	0.74 (-0.12)	0.68 (-0.18)	0.47 (-0.39)	.24	.10	.54
	TPH (trees ha ⁻¹ yr ⁻¹)	2	0.95	-0.19 (-1.14)	0.73 (-0.23)	0.44 (-0.52)	.39	.39	.25
		4	-0.84	-1.87 (-1.02)	-1.10 (-0.25)	-1.02 (-0.17)	.47	.40	.22
		6	-2.22	-1.99 (0.22)	-0.90 (1.31)	-1.29 (0.92)	.87	.78	.73
		8	0.13	-1.14 (-1.27)	-0.08 (-0.21)	-0.61 (-0.74)	.53	.57	.47

BA, ; HD, dominant height; TPH, trees per hectare; TVOB, total outside-bark volume.

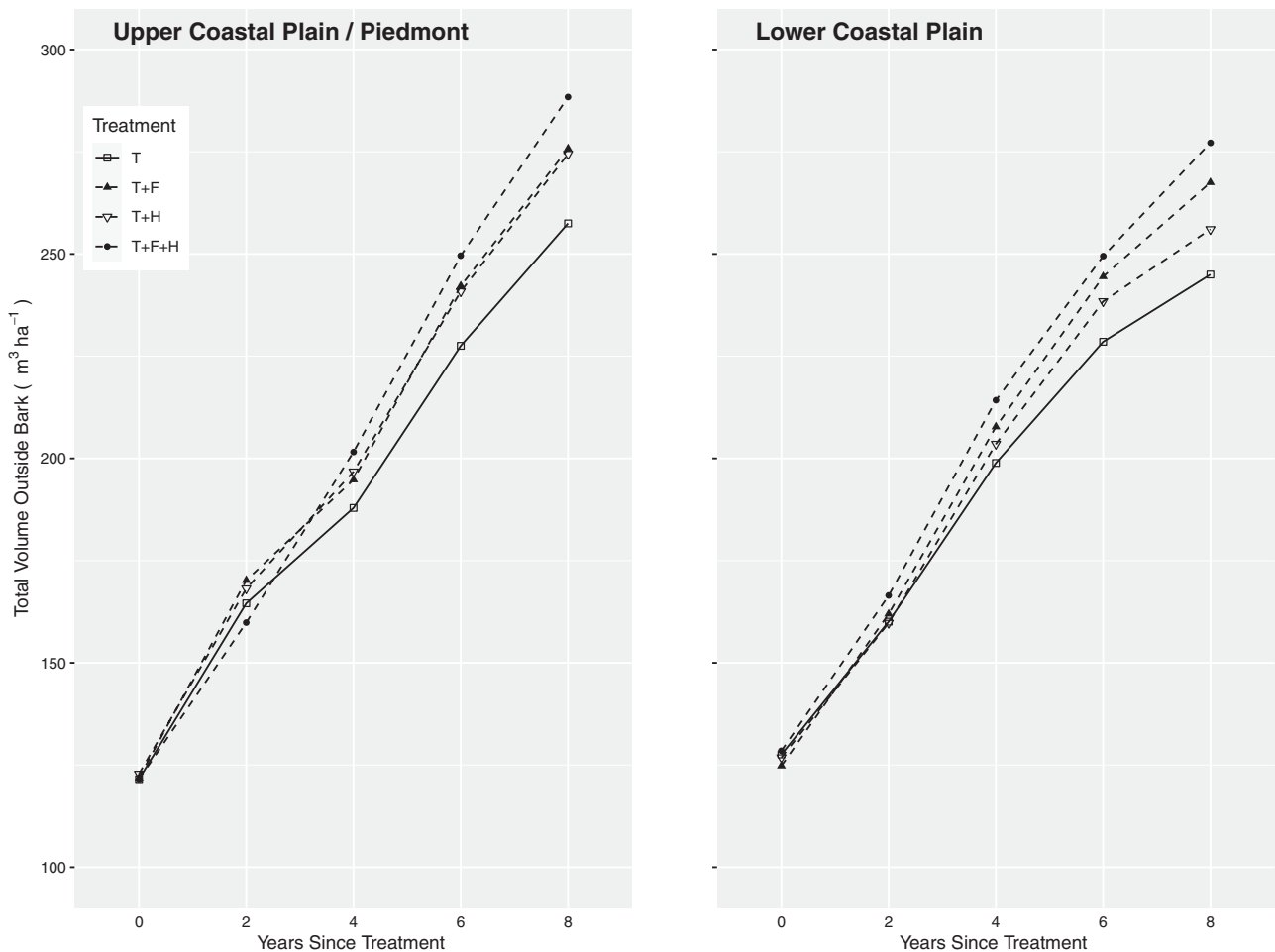


Figure 2. Regionally averaged total volume growth trends for loblolly pine in the UCPIE and LCP regions following MRT application. Observed growth trajectories as measured post-treatment are displayed for the thin (T) only, T + fertilization (F), T + herbicide (H), and T + F + H treatments.

the UCPIE (up to 0.48 m). Treated stands in the UCPIE had lower TPH than the thin-only stand, but MRT did not have a significant effect on mortality in the region.

Competing Vegetation

Herbaceous vegetation responded vigorously to thinning in both regions during the first growth period (figure 6). For all stands in both the LCP and UCPIE, percentage groundcover increased from below 20% up to 50% by the second remeasurement period. Chemical herbicide application initially slowed the growth of herbaceous vegetation in both regions. The herbicide-only treatment in the LCP had an annualized response of -6.56% during the first growing period, and the combined treatment had a response of -7.21%. The decreased growth response was not sustained and stands with chemical herbicide application had a higher rate of growth than the thin-only treatment starting 4 years after treatment and continuing throughout the subsequent measurement periods. Herbaceous growth in the UCPIE reflected that of the LCP but did not have as strong a growth response. The annualized response of percent groundcover in the LCP was -3.70% for the herbicide only treatment, and -5.56% for the combined treatment during the first growing period. In subsequent growth periods, the rate of growth was higher than that of the thin-only treatment for stands receiving the chemical herbicide application (Table 4).

Crown volume decreased following thinning in both the LCP and UCPIE (figure 7); chemical herbicide application was effective for decreasing woody crown volume growth (Table 3). Estimated PAI was negative for all four treatments 2 years post-treatment in the LCP, with the chemical herbicide application ($-2.30 \text{ m}^3 \text{ ha}^{-1}$) and combined treatments ($-2.36 \text{ m}^3 \text{ ha}^{-1}$) resulting in the largest decrease in crown volume. Chemical herbicide applications in the UCPIE also resulted in large decreases, with an estimated PAI of $-3.97 \text{ m}^3 \text{ ha}^{-1}$ for the herbicide-only treatment and $-5.67 \text{ m}^3 \text{ ha}^{-1}$ for the combined treatment. Following treatment, woody crown volume response also decreased. Although woody crown volume was reduced following thinning for all MRT, only the chemical herbicide application was found to significantly reduce woody crown volume growth. Chemical herbicide application was significant at 2 ($-1.50 \text{ m}^3 \text{ ha}^{-1}$) and 8 ($1.23 \text{ m}^3 \text{ ha}^{-1}$) years post-treatment in the LCP, and at 2 ($-0.62 \text{ m}^3 \text{ ha}^{-1}$) and 4 ($-3.08 \text{ m}^3 \text{ ha}^{-1}$) years post-treatment in the UCPIE.

Pine versus Competing Vegetation

The relationship between the pre-thin herbaceous groundcover percentage and the periodic pine growth rate was not statistically significant (Table 4). Additionally, no clear trends between pre-thin groundcover and annual pine growth were observed in either region (figure 8).

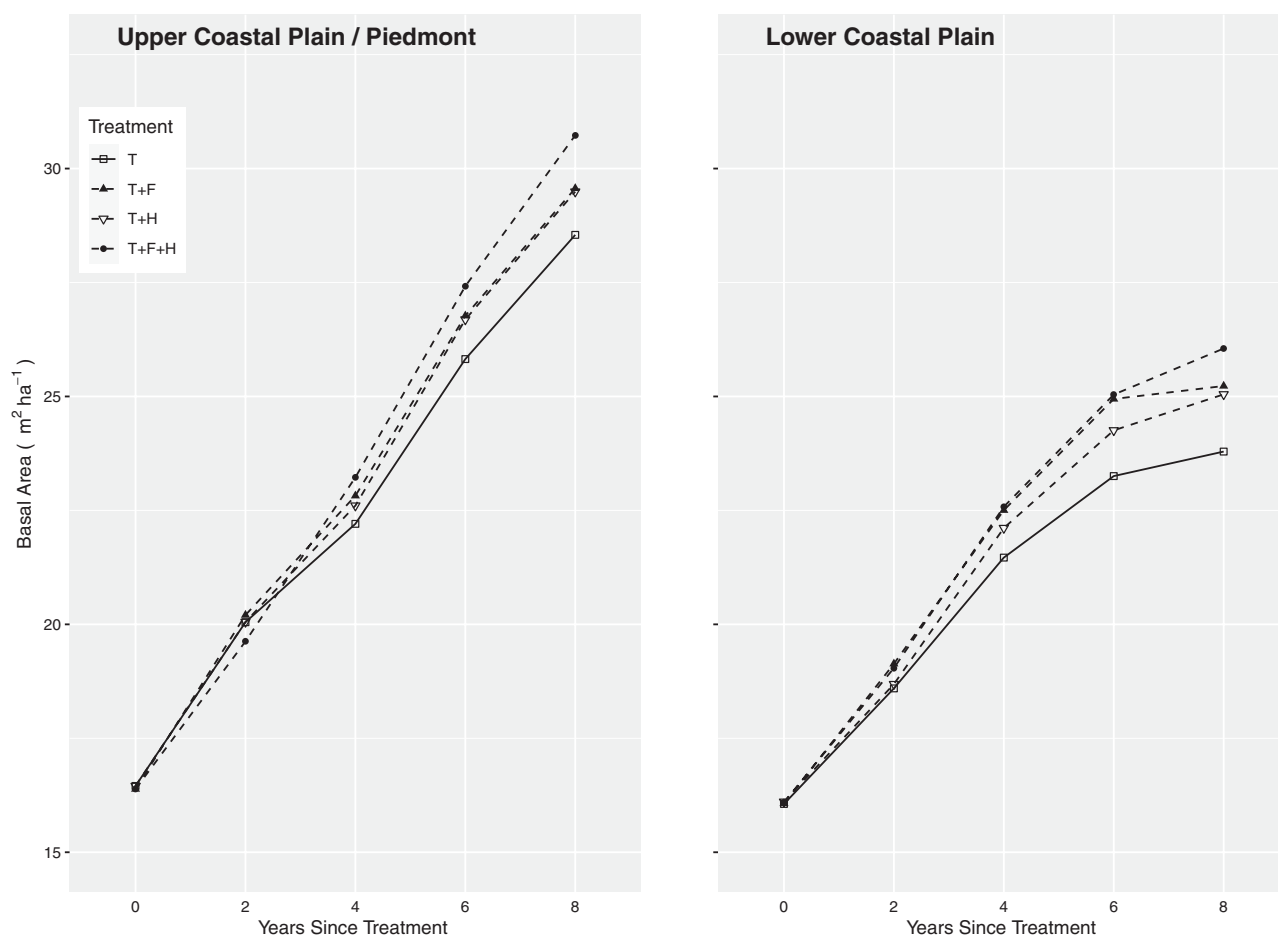


Figure 3. Regionally averaged basal area growth trends for loblolly pine in the UCPIE and LCP regions following MRT application. Observed growth trajectories as measured post-treatment are displayed for the thin (T) only, T + fertilization (F), T + herbicide (H), and T + F + H treatments.

Initial woody crown volume was found to have a significant positive correlation with mean annual TVOB growth in the LCP, but the same relationship was not significant in the UCPIE (Table 4). However, observation of the pre-treatment crown volume suggests that a weak positive correlation may still be present (figure 9).

Discussion

Post-thin fertilization and chemical herbicide applications effectively increased loblolly pine growth. Volume response to fertilization averaged $3.45 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in the LCP and $1.75 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ in the UCPIE, which were both less than the previously reported South-wide average of $3.8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (Albaugh et al. 2012; Fox et al. 2007b; Rojas 2005). Factors contributing to a below-average response may include the specific application rate, site quality, and pretreatment stocking. The application rate used in this study is common for mid-rotation plantations in the southeast United States, but differences in site-specific nutrient availability may have limited the capture of nutrient amendments (Albaugh et al. 2019; Fox et al. 2007a). Pre-thin basal area indicated that stands in both regions were overstocked at all installations in both regions ($\geq 30 \text{ m}^2 \text{ ha}^{-1}$; $\geq 130 \text{ ft}^2 \text{ ac}^{-1}$). Fully stocked stands generally respond well to thinning, and increased thinning intensities have resulted in improved BA growth (Albaugh et al. 2017). Overstocked stands, however, may not respond to thinning

depending on the initial BA, thinning intensity, and fertilization rate (Allen and Duzan 1982; Wells and Allen 1985; Wells et al. 1976). Response to silvicultural treatment has also been shown to decrease at higher site indices (Zhao et al. 2016). Because many of the stands were of relatively high SI before treatments were applied ($>26 \text{ m}$; $>85 \text{ ft}$), there may have been a higher likelihood of observing a below-average response among the installations. A more pronounced response to fertilization in the LCP is typical. Phosphorus-deficient sites are common in the LCP (Gent et al. 1986; Jokela et al. 1991) and plantations respond strongly to N and P amendments, especially when P amendments are applied up to 2 years after planting (Amateis et al. 2000; Fox et al. 2007a; Martin et al. 1999). The difference in volume response between the two regions illustrates the importance of site-specific treatments tailored to local nutrient availability.

Volume growth also responded positively to chemical herbicide application, and the resulting growth was less than that of fertilization. This result matches previous work which has found that, typically, pines are less responsive to independent chemical herbicide application than independent fertilization (Albaugh et al. 2012; Liechty and Fristoe 2013). However, responses to chemical herbicide application are usually sustained for longer periods of time (Fortson et al. 1996; Fox et al. 2007a; Oppenheimer et al. 1989). We found the response time to be similar for both fertilization and chemical herbicide application, which was up to 6 years in the UCPIE and 8

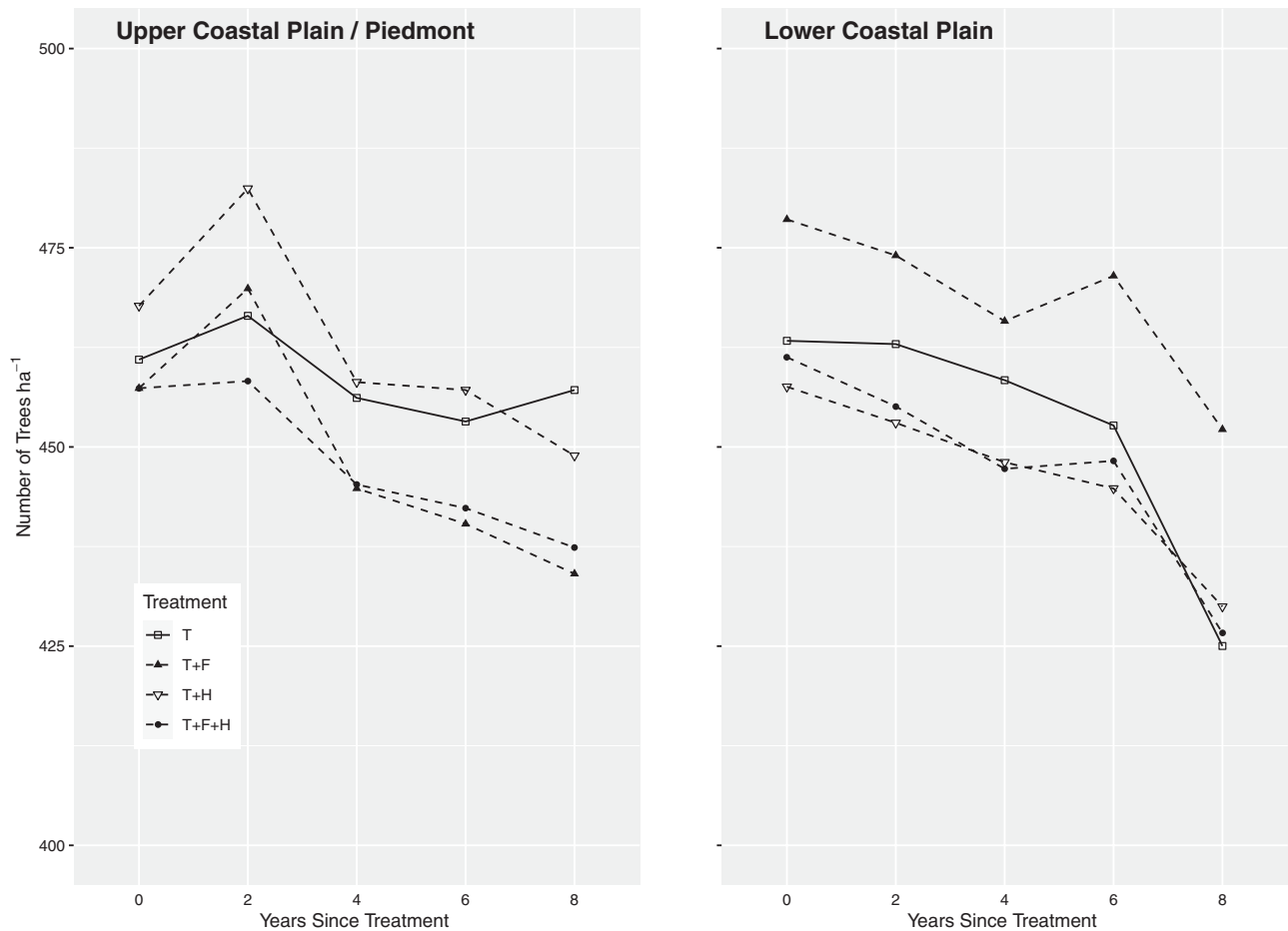


Figure 4. Regionally averaged dominant height growth trends for loblolly pine in the UCPIE and LCP regions following MRT application. Observed growth trajectories as measured post-treatment are displayed for the thin (T) only, T + fertilization (F), T + herbicide (H), and T + F + H treatments.

years in the LCP. The response duration to N and P was similar to previously reported timelines for the southeast (Amateis et al. 2000; Fox et al. 2007a). Given there were no remeasurements after the 8th year following treatment, the effects of a post-thin chemical herbicide application in this study may continue to influence stand growth. Fortson et al. (1996) found the effects of complete and sustained vegetation control to last for up to 15 years. The duration and magnitude of post-treatment growth following vegetation control may also depend on the nutrient availability at different stages of stand development (Amishev and Fox 2006; Fox et al. 2007a).

Increases in BA and HD growth were concurrent with volume responses to MRT, when treatment effects were significant. This implies that growth responses captured by either one or both stand attributes effectively translates to significant increases in TVOB. Generally, HD was generally increased with fertilization and BA with chemical herbicide application. This is typical for the different MRT, as fertilization increases the vigor of individual trees and vegetation control manipulates stand density (Amishev and Fox 2006). When large gains in site productivity are observed, average HD and the expressed site index may also increase (Zhao et al. 2016). In this study, a significant growth response HD was only observed at a few measurement periods. The BA growth was significantly increased over at least one measurement period for each MRT, suggesting that volume gains were directly related to the manipulation of stand density via

thinning and competition control. Mid-rotation treatments often target stand density responses, with the intention of increasing the residual size distribution and stem quality of remaining trees (Amateis et al. 1989; Hasenauer et al. 1997). Mortality was not a major limiting factor in this study but was found to be influenced by MRT in both regions. In the LCP, mortality rates were initially lower (higher mortality) in the treated stands. In the UCPIE, lower mortality rates in treated stands were generally sustained throughout the study. A contributing factor may have been the treatment of overstocked stands, which can result in increased mortality when stand density is not adequately accounted for at the time of treatment (Allen and Duzan 1982). Fertilization of overstocked stands can result in increased mortality under high BA, and the resulting leaf area index may be inadequate for nutrient uptake and delay or negate growth responses. Issues due to the timing and intensity of thinning are important considerations when applying MRT, and the potential drawbacks should be assessed prior to treatment.

Increased growth responses throughout the study period resulted in significant differences in the cumulative final yield between the treated stands. The independent applications of fertilization and chemical herbicide application both increased yield over the thin-only treatment, and the combined treatment resulted in the highest volume and BA yield in both regions. Interestingly, the combined treatment was not significant for increasing growth or final yield. However, a

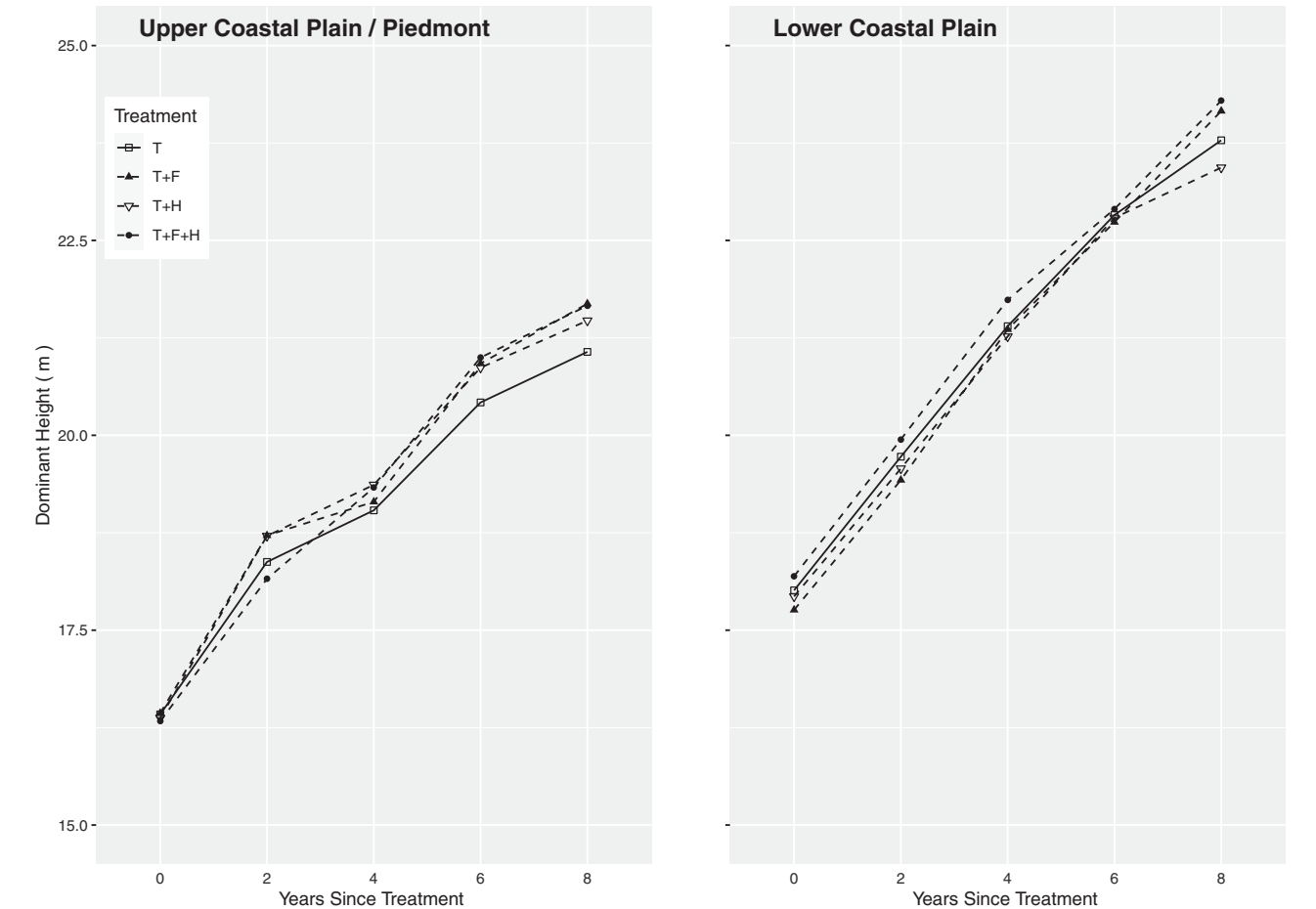


Figure 5. Regionally averaged mortality trends for loblolly pine in the UCPIE and LCP regions following MRT application. Observed growth trajectories as measured post-treatment are displayed for the thin (T) only, T + fertilization (F), T + herbicide (H), and T + F + H treatments.

Table 3. Cumulative final yield for each stand variable at 8 years post-treatment assessed for all measurement plots within each region. Significant differences are in comparison to the thin-only treatment and assessed using a mixed effects model. Bold values indicate significance at the .10 alpha-level.

Physiographic region	Stand variable	Cumulative final yield by treatment (response)				<i>p</i> < F (α = .10)		
		Thin (T)	T + Fert (F)	T + Herbicide (H)	T + F + H	T + F	T + H	T + F + H
Lower Coastal Plain	TVOB (m ³ ha ⁻¹)	244.96	267.48 (22.52)	256.03 (11.07)	277.21 (32.25)	.01	.17	.48
	BA (m ² ha ⁻¹)	23.79	25.23 (1.44)	25.05 (1.26)	26.05 (2.26)	.02	.06	.41
	HD (m)	23.78	24.16 (0.38)	23.43 (-0.35)	24.29 (0.51)	.25	.62	.73
	TPH (trees)	425	452 (27)	430 (5)	427 (2)	.04	.69	.09
	TVOB (m ³ ha ⁻¹)	271.53	288.96 (17.43)	288.03 (16.50)	296.64 (25.11)	.01	.07	.36
Upper Coastal Plain & Piedmont	BA (m ² ha ⁻¹)	29.63	30.98 (1.35)	30.31 (0.68)	31.45 (1.82)	.04	.18	.64
	HD (m)	21.40	21.50 (0.10)	21.88 (0.48)	21.72 (0.32)	.71	.59	.55
	TPH (trees)	494	487 (-7)	485 (-9)	493 (-1)	.53	.99	.76

BA, ; HD, dominant height; TPH, trees per hectare; TVOB, total outside-bark volume.

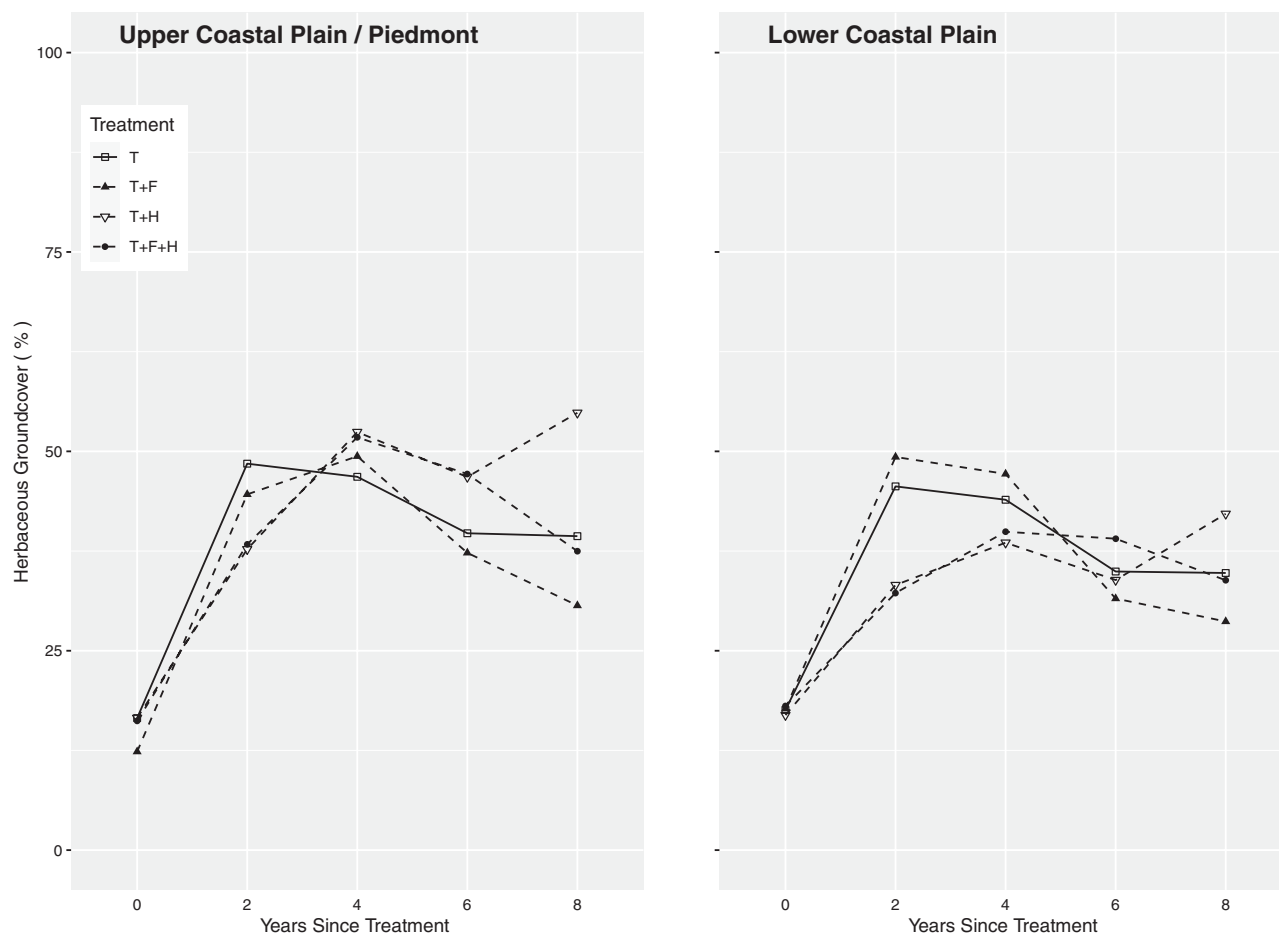


Figure 6. Regionally averaged net change in percent groundcover for herbaceous competing vegetation in the UCPIE and LCP regions following MRT application. Observed changes as measured post-treatment are displayed for the thin (T) only, T + fertilization (F), T + herbicide (H), and T + F + H treatments.

lack of statistical significance does not mean a lack of practical significance. The lack of significance in the model indicates that treatment effects of fertilization and chemical herbicide are additive, meaning that combining the two treatments still captures both treatment responses. Realizing the benefits of each individual treatment is important when assessing the potential economic gains of MRT and can still lead to greater valuation of stands at harvest. An additive response to fertilization and chemical herbicide is characteristic of the regional pine responses to MRT in the southeast United States (Albaugh et al. 2012; Allen and Albaugh 2000). Differences in yield between the treatments continually diverged throughout the study period, and the volume and BA growth trends illustrate that cumulative volume among treated stands may continue diverging beyond the measurement periods assessed in this study.

Competing vegetation growth varied in response to MRT. Herbaceous vegetation abundance increased during the measurement period immediately following thinning. Previous research has shown that light availability is inversely related to canopy density and promotes herbaceous growth (Anderson et al. 1969). It is likely that greater light availability following thinning favored herbaceous growth at mid-rotation. In the subsequent measurement periods, herbaceous growth was asymptotic. A maximum response of

herbaceous vegetation to additional light interception has also been identified and explains the response observed in this study (Anderson et al. 1969). Although herbaceous vegetation was persistent on most sites, it is not typically regarded as a strong competitor for site resources at mid-rotation as stands have typically reached crown closure and shade intolerant vegetation is generally present in low levels prior to treatment (Fortson et al. 1996). Additionally, the specific herbicide mixtures used in this study target woody and broadleaf species and are unlikely to result in substantial differences between MRT. Coinciding increases in herbaceous vegetation and pine volume suggest that herbaceous vegetation is potentially an insignificant limiting factor regarding pine productivity.

Woody crown volume significantly decreased immediately following thinning in all stands. Chemical herbicide application was effective for nearly eliminating and subsequently maintaining low crown volume in both regions. Fertilization did not appear to significantly influence woody vegetation development in either region. Woody vegetation regrowth was observed following the initial elimination but was not accelerated and never recovered to pretreatment densities. Liechty and Fristoe (2013) reported a similar pattern in the western Gulf Coastal Plain and found no significant increase in woody vegetation following vegetation

Table 4. Estimated periodic annual increment (PAI) of competing vegetation stand-level variables for each two-year measurement period following application of MRT. Each variable was mean adjusted using pretreatment covariates and the random effects term. Bold *p*-values indicate a significant response at the .10 alpha-level. Treatment responses are relative to the thin-only treatment for each variable.

Physiographic region	Variable	Years since treatment	Estimated periodic annual increment (PAI) by treatment (annualized response)				<i>p</i> < <i>F</i> (α = .10)		
			Thin (T)	T + Fert (F)	T + Herbicide (H)	T + F + H	T + F	T + H	T + F + H
Lower Coastal Plain	Crown Volume (m ³ ha ⁻¹ yr ⁻¹)	2	-0.90	-0.61 (0.29)	-2.40 (-1.50)	-2.36 (-1.46)	.27	.00	.46
		4	0.27	0.20 (-0.07)	0.16 (-0.11)	0.13 (-0.14)	.77	.72	.78
		5	0.41	0.27 (-0.14)	0.37 (-0.04)	0.51 (0.10)	.91	.85	.92
		8	-1.17	-0.63 (0.54)	0.05 (1.23)	-0.15 (1.02)	.16	.03	.20
	Groundcover (%)	2	14.24	15.85 (1.61)	7.68 (-6.56)	7.03 (-7.21)	.54	.01	.54
		4	-0.97	-1.38 (-0.41)	3.68 (4.65)	5.35 (6.32)	.88	.09	.59
		6	-3.28	-6.56 (-3.28)	-1.11 (2.17)	-0.06 (3.22)	.24	.43	.28
		8	-0.97	-2.73 (-1.76)	2.06 (3.03)	-0.95 (0.02)	.67	.46	.83
Upper Coastal Plain & Piedmont	Crown Volume (m ³ ha ⁻¹ yr ⁻¹)	2	-3.35	-3.16 (0.19)	-3.97 (-0.62)	-5.67 (-2.32)	.68	.72	.11
		4	1.84	2.02 (0.08)	-1.24 (-3.08)	0.33 (-1.51)	.69	.01	.56
		6	0.01	-0.42 (-0.43)	0.61 (0.60)	0.47 (0.46)	.82	.38	.86
		8	0.25	-0.57 (-0.82)	-0.35 (-0.60)	0.16 (-0.09)	.65	.79	.68
	Groundcover (%)	2	13.77	15.26 (1.49)	10.07 (-3.7)	8.21 (-5.56)	.44	.08	.25
		4	-3.02	-0.80 (2.22)	5.94 (8.96)	2.89 (5.91)	.26	.00	.07
		6	-4.32	-6.40 (-2.08)	-2.24 (2.08)	-3.00 (1.32)	.33	.29	.69
		8	2.34	-1.12 (-3.46)	3.50 (1.16)	1.52 (-0.82)	.26	.68	.75

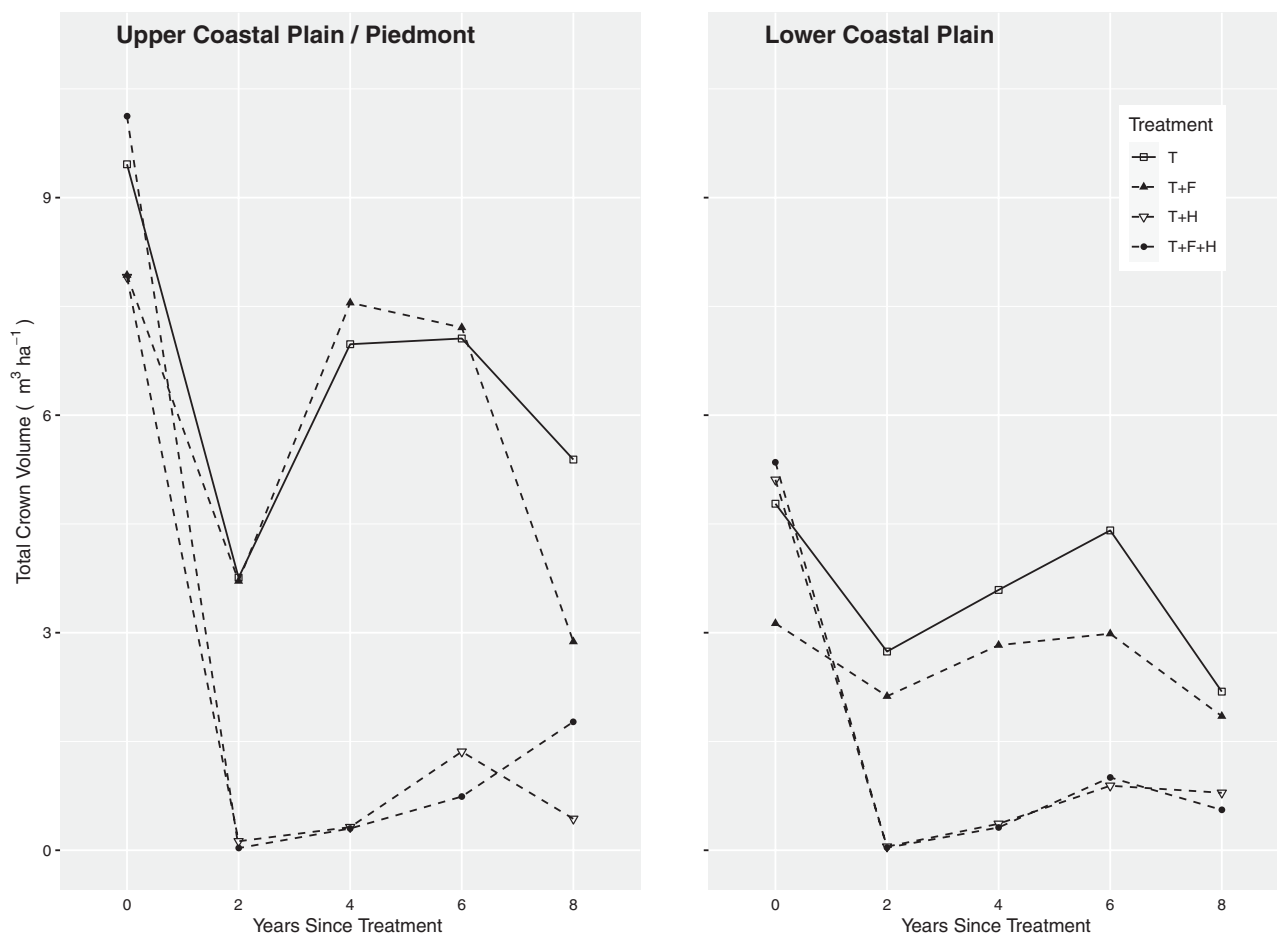


Figure 7. Regionally averaged net crown volume growth for woody competing vegetation in the UCPIE and LCP regions following MRT application. Observed growth trajectories as measured post-treatment are displayed for the thin (T) only, T + fertilization (F), T + herbicide (H), and T + F + H treatments.

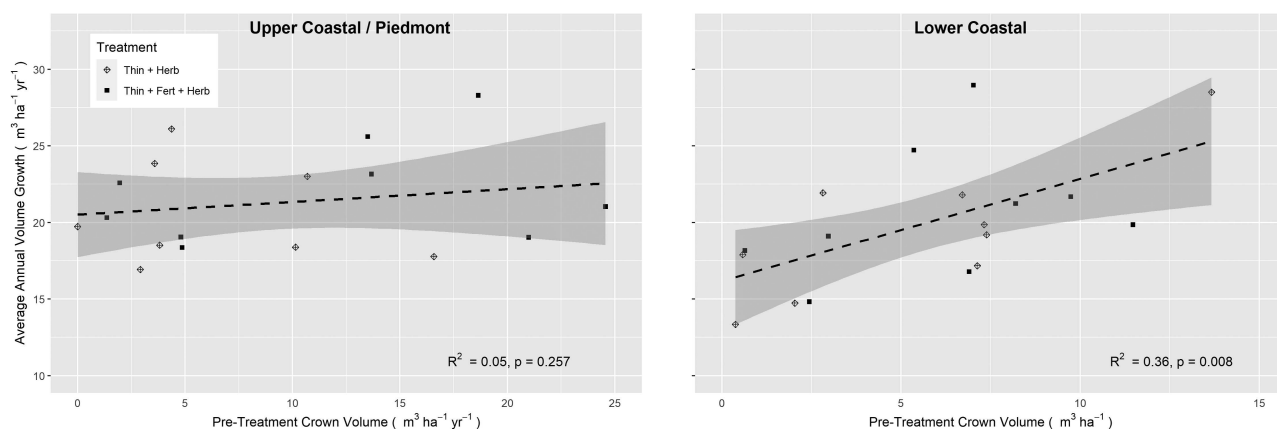


Figure 8. Modeled relationship between 6-year post-treatment periodic annual increment of loblolly pine total volume and initial percent groundcover of herbaceous competing vegetation. Predicted trendline and 95% confidence intervals are displayed. Only the thin (T) + herbicide (H), and T + H + fertilization (F) treatments are considered to capture responses to the controlled suppression of competing vegetation.

control. For the treatment plots that did not include competition control, a substantial reduction in woody vegetation was also observed, although the residual volume was higher than that of released stands. A post-thin reduction in woody vegetation without the aid of herbicides has important implications. If vegetation control is either costly or infeasible, operational thinning regimes may still be able

to capture a portion of the response attributable to a one-time vegetation control. Removal of even small amounts of woody competitors have resulted in significant increases in final yield (Fortson et al. 1996; Glover and Zutter 1993). The suppression of greater woody crown volume was also positively associated with greater pine volume response, indicating that woody vegetation is a significant limiting

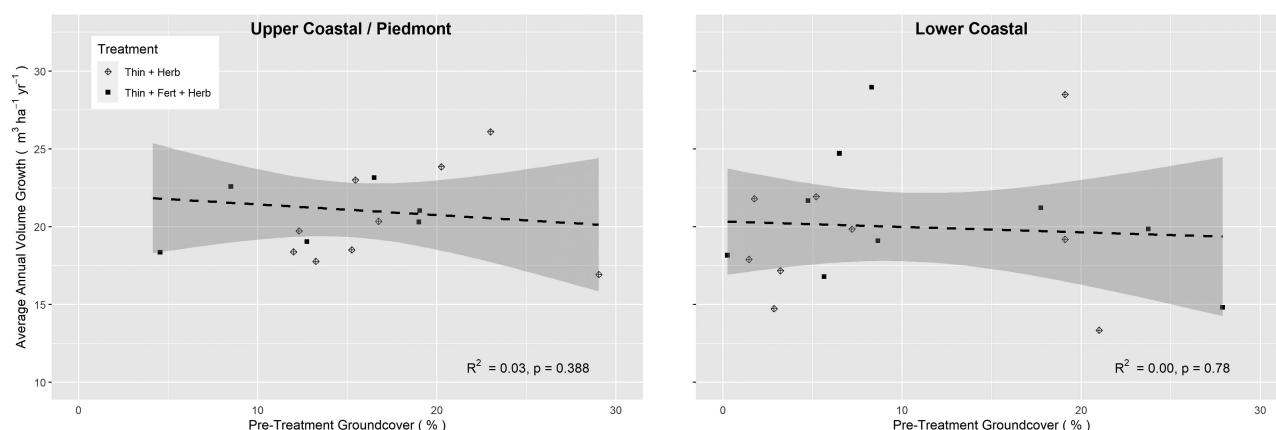


Figure 9. Modeled relationship between 6-year post-treatment periodic annual increment of loblolly pine total volume and initial crown volume of woody competing vegetation. Predicted trendline and 95% confidence intervals are displayed. Only the thin (T) + herbicide (H), and T + H + fertilization (F) treatments are considered to capture responses to the controlled suppression of competing vegetation.

factor for loblolly pine production across the southeast United States.

Conclusions

Post-thin fertilization and chemical herbicide application increased productivity in mid-rotation loblolly pine stands. The magnitude and duration of responses varied between vegetation types and for each silvicultural treatment. Growth responses differed between the LCP and UCPIE and demonstrated that site specific silvicultural prescriptions are desirable for maximizing operational treatment responses. MRT generally increased pine productivity in the following order: thin + fertilization + herbicide > thin + fertilization > thin + herbicide > thin only. Assessing competing vegetation growth following treatment provided additional insight into how resource allocation affected pine productivity. Herbaceous vegetation was not a major competitor of site resources and responded vigorously to increased light availability following thinning. The presence of woody vegetation was a limiting factor, and the removal thereof was associated with increased pine productivity. Vegetation control was an important factor for ensuring that resources were effectively allocated towards post-thin pine productivity. All treatments resulted in additional volume in both the UCPIE and LCP, which further confirmed that post-thin MRT is an important consideration for forest managers looking to increase loblolly pine productivity. The post-thin growth of competing vegetation, especially woody vegetation, should be considered when making site-specific management decisions.

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Conflict of Interest

The authors have no conflicts of interest to declare.

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