COMPETING VEGETATION AND THE GROWTH AND YIELD OF MID-ROTATION LOBLOLLY PINE PLANTATIONS

by

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(Under the Direction of Bronson P. Bullock)

ABSTRACT

Competing vegetation limits the production of loblolly pine (*Pinus taeda* L.) plantations in the southeast U.S. The removal of competing vegetation throughout a rotation increases yield at final harvest, and can reinvigorate the growth of pines when site resources are deficient. Competing vegetation control treatments in operational settings are often applied in combination with fertilization or thinning. The effects of competing vegetation on pine growth during stand establishment are well known, but growth following mid-rotation treatment is less understood. Specifically, the growth of competing vegetation in response to treatments targeting pine productivity has not been studied in detail.

Using a long-term study installed across the southeast U.S., the growth of pine plantations and their competing vegetation was assessed. Initially, an assessment of the growth trajectories, an analysis of the growth rates of different stand variables, and the relationship between pine and competing vegetation was conducted. Mid-rotation pine growth was found to be negatively impacted by competing vegetation, and the growth of competing vegetation was found to respond primarily to thinning and chemical herbicide treatment.

Next, an analysis of the spatial distribution of competing vegetation looked at the relationship between spatial autocorrelation in relation to silvicultural treatment. Spatial autocorrelation was significant for both woody and herbaceous vegetation but did not differ among treatments. Models were then fitted for woody vegetation in terms of crown volume, and the percent groundcover of herbaceous vegetation using the same remeasurement data. Local and global parameterizations were considered and included the effect of silvicultural treatments. The local variable equations were able to accurately describe the growth of both vegetation groups when chemical herbicide treatment was accounted for in the model.

Lastly, basal area growth was modeled for thinned stand and unthinned stands to include the effect of competing vegetation and silvicultural treatment. Basal area growth of thinned stands accounting for silvicultural treatment greatly improved the model fit when compared to a previously defined model for similar plantations. Ultimately, competing vegetation was found to be an important component of pine plantation growth and yield but further research is needed to fully develop methods for modeling its impact on plantation development.

INDEX WORDS: forest management; modeling; silviculture

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DEDICATION

To my wife, Hannah.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Competing vegetation (CV) has been recognized as an important component of forest management affecting conifer production (Blazier et al. 2017; Wagner 1994; Wagner et al. 1999). Since the 1950s, advances in management practices have resulted in increased conifer biological productivity, especially when grown as crop-trees in a plantation setting (Borders and Baily 2001). In the U.S. South, the presence of CV and its control are known to affect the growth rates of crop trees at both stand establishment and mid-rotation, typically resulting in a significant growth increase (Glover et al. 1989; Oppenheimer 1989; Clason 1992; Fortson et al. 1996; Miller et al. 2003; Zhao et al. 2009; Albaugh et al. 2012).

Control treatments are commonly applied to limit competition and allocate site resources back to crop tree species (Walstad and Kuch 1987). Treatment intensity depends on management objectives and current site characteristics. Treatments are effective when the cost to reduce competition is offset by the economic gains realized by additional crop-tree volume (Wagner 1999). Crop tree growth and residual CV response vary with treatment intensity and site characteristics; however, efforts to quantify management-specific responses have been limited (Burkhart and Sprinz 1984; Smith and Hafley 1987; Brister 1996). Operationally, control treatments may be applied in conjunction with other silvicultural treatments such as fertilization and thinning (Nyland 2002). Understanding the effect of CV control in combination with other management strategies is important for establishing the role of CV treatments as a management tool among a suit of alternatives.

Growth and yield (GY) of timber volume is an important consideration to forest stakeholders for weighing management alternatives based on current stand conditions (Mason and Dzierzon 2006). Previous efforts have incorporated CV effects as a predictor variable in stand growth and yield models, although the primary focus has centered on hardwood CV as either a percentage of total basal area (Shumacher and Coile 1960; Burkhart and Sprinz 1984; Smith and Hafley 1987; Knowe 1992), or as a portion of per-unit volume area (Shiver and Brister 1996; Martin and Brister 1999). An ongoing study administered by the University of Georgia's Plantation Management Research Cooperative (UGA-PMRC) has been constructed to assess the effects of mid-rotation treatment on crop tree growth and subsequent levels of CV response (UGA-PMRC 2008). Updating current GY models with management-specific CV response will provide land managers with more precise estimates of future stand conditions based upon desired management prescriptions.

1.2 Literature Review

Southern yellow pine (SYP) is one of the most commercially important timber production resources globally (Restrepo et al. 2019). Occupying a broad range across the U.S. from Virginia to East Texas, SYP plantations compromise roughly 20-percent (nearly 50 million acres) of the South's forested land area (South and Harper 2016). SYP is used for a variety of products markets both at home and abroad (Oswalt et al. 2014), and plantation pines require intensive management for their success (Allen et al. 2005). The ability to employ precise management prescriptions will increase the efficiency of SYP utilization into the future.

Impacts of competing vegetation (CV) on forest growth and vigor has been a consistently studied issue on global (Wagner et al. 2006; McCarthy et al. 2011), national (Walsted and Kuch

1987; Dixon 2002), regional (Wagner et al. 1999; Miller et al. 2003) and local scales (Martin and Brister 1999). In natural stands, where crop trees are not the primary focus of stand yield, competing CV is an important component of forest composition (Stage 1973). When efforts are concentrated on crop tree yield production, however, the effects of CV on crop tree growth are viewed as a significant competitor (Burkhart and Sprinz 1984). Forest Vegetation Management (FVM) is a common practice in plantation forestry, where treatments vary with stand management objectives and can range from complete control to one-time applications (Walstad and Kuch 1987). Methods of competition control may include mechanical removal, herbicides, prescribed burning, or any combination of the three (Nyland 2002). Complete control is achieved when treatment is applied consistently throughout the lifetime of a stand and minimizes the amount of vegetation present.

Overstory pine species have been found to respond positively to control treatments (Oppenheimer et al. 1989; Fortson et al. 1996; Albaugh et al. 2012). Plantations are typically more responsive in terms of diameter distribution, and the most extreme control measures have the potential of shifting plantations into larger product classes throughout the lifetime of the stand (Oppenheimer et al. 1989; Albaugh et al. 2012). Responses are generally well-documented for juvenile forests, however, knowledge of response following crown closure is not as well-developed (Oppenheimer 1989; Wagner et al. 1999). Applying concepts from agricultural applications, Wagner et al. (1999) explored the critical period of FVM in which control of CV continues to avoid volumetric losses in crop-tree species. For northern conifer species, there was a limited window of time during which overstory species gain a competitive advantage before being limited again by resurgent CV. Blinn et al. (2011) reported similar results for southern pine plantations. They found competition was effectively removed immediately following mid-rotation treatment but had returned to pre-treatment levels within 4 years following chemical herbicide application.

CV control treatments are often employed in combination, and crop trees have been found to respond positively to the increased management intensity (Albaugh et al. 2012; Subedi et al. 2017; Blazier et al. 2017). Common mid-rotation treatments include thinning, fertilization, or some combination thereof. Total volume was found to be greatest in crop trees experiencing complete CV control when a precommercial thin was present, relative to non-thinned stands (Blazier et al. 2017). CV control with fertilization showed stronger overstory growth responses than either treatment applied individually (Albaugh et al. 2012). Though combined treatments are effective at increasing crop tree growth, CV control alone tends to have the weakest effect on crop tree response (Albaugh et al. 2012, Subedi et al. 2017). If independent CV control treatment only results in marginal gains relative to other treatments, the timing and duration of CV control may need to be reevaluated. Currently, no study assessing the various combinations of all three (thinning, fertilization, and CV control) has been documented.

Modeling forest growth and yield provides stakeholders with a critical view of how current stand conditions might affect future forest conditions (Mason and Dzierzon 2006). Effective model systems rely on explanatory variables which are known to have a significant effect on the response variable. Historically, thinning and fertilization treatments have been used as modeling parameters (Daniels & Burkhart 1975; Hynynen et al. 1998). Given the effect of CV on crop tree growth, methods to include CV as an explanatory variable in model systems have been proposed. CV was initially incorporated as proportion of total stand basal area, with subsequent efforts using a similar basal area proportion index (Shumacher and Coile 1960). Stand-level growth projections have centered around diameter distribution modeling (Burkhart and Sprinz 1984; Smith and Hafley 1987; Knowe 1992) or volume per unit area modeling (Shiver and Brister 1996; Martin and Brister 1999). CV has also been included within individual tree systems (Stage 1973; Salas et al. 2008).

Significant competitive interactions within GY systems imply dependency on the spatial distribution of site resources since individuals manipulate resources that are within their immediate spatial proximity (Mack and Harper 1977; Cannell and others 1984). When individual tree characteristics are either systematically similar or dissimilar to those of neighboring trees, spatial autocorrelation may be present (Reed and Burkhart 1985). The stem characteristics of plantation loblolly pines have been shown to be spatially autocorrelated, indicating that individual growth has a deterministic impact on neighborhood growth (Reed and Burkhart 1985; Bullock and Burkhart 2005). The presence of competing vegetation may also be spatially autocorrelated since its growth is also determined by the same site resource distribution. The spatial dependency of competing vegetation within intensively managed pine plantations has not yet been characterized. Characterizing the spatial autocorrelation of vegetation, in either crop or non-crop species, can increase the precision of stand growth and yield models by adjusting them to account for errors due to spatial variability (Bullock and Burkhart 2005).

Though CV has successfully been included within GY models, there are still limitations. For one, most stand-level models include competition that exists only within the main canopy (Burkhart and Sprinz 1984; Smith and Hafley 1987). This poses a problem when accounting for the magnitude of competition effect, as various forms of competition outside of the canopy are neglected. For example, the works of Smith and Hafley (1984), Burkhart and Sprinz (1984), Martin and Brister (1999), and Harrison and Borders (1996) exclusively use the proportion of hardwood basal area in the main canopy to account for the impacts of competing vegetation on stand growth. Another problem is the lack of observations over time (Burkhart and Sprinz 1984; Smith and Hafley 1987; Shiver and Brister 1996). Treatment intensity has a large impact on CV presence; however, there has been little effort to link specific treatment with magnitude of response (Burkhart and Sprinz 1984; Smith and Hafley 1987; Brister 1996). Current modeling systems may be effective for stand projection, but decision-making tools surrounding CV tend to be “highly localized (Mason and Dzierzon 2006).”

1.3 Rationale and Significance

Competing vegetation is an important consideration for land managers seeking to make informed decisions based on current and future stand conditions. Crop-tree growth responses have been observed for juvenile stands where management strategies to reduce competition have been implemented (Oppenheimer et al. 1989; Albaugh et al. 2012). There are few studies reporting crop-tree response to treatments following crown closure, particularly in the U.S. South. Observing crop-tree response after crown closure will provide land managers with a better understanding of timing and duration of responses when considering management alternatives.

There is a need to utilize additional information associated with CV control in GY model systems. Previous research sought to include CV as a proportion of total stand attributes (Burkhart and Sprinz 1984; Smith and Hafley 1987; Brister 1996). Quantification of crop-tree response to various mid-rotation treatments have been addressed; however, monitoring specific responses to combinations of all thinning, fertilization, and CV control have not yet been observed. Furthermore, inclusion of CV control as a model parameter has not been as prevalent as thinning or fertilization. Temporal response patterns have also not been considered in a GY model environment (Burkhart and Sprinz 1984; Smith and Hafley 1987; Brister 1996), as well as the explicit spatial autocorrelation related to the distribution of competing vegetation at the local level. Updating current GY models with management-specific response curves can give stakeholders more precise estimates on the future condition of forested stands.

The proposed research will use existing UGA-PMRC MRT data to assess the effects of CV, management combinations, and site characteristics on the growth and yield of loblolly pine plantations. Assessment of crop-tree behavior across time will provide information on the potential timing and duration of management applications.

1.4 Objectives and Hypotheses

The goal of the proposed research is to understand the response of both overstory pine and competing vegetation to various combinations of operational management strategies following crown closure and assess the significance of CV control as an explanatory variable in growth and yield models.

Objective 1: Assess the response of loblolly pine plantations to mid-rotation silvicultural treatment following crown closure.

> Null Hypothesis: Loblolly pine will not increase in total volume for any combination of mid-rotation silvicultural treatments.
>
> Alternative Hypothesis: Loblolly pine will increase in total volume following the application of any combination of mid-rotation silvicultural treatment.

Objective 2: Assess the response of competing vegetation to mid-rotation silvicultural treatment following crown closure.

Null Hypothesis: Competing vegetation will not increase in volume for any combination of mid-rotation silvicultural treatments.

Alternative Hypothesis: Competing vegetation will increase in volume for any combination of mid-rotation silvicultural treatments.

Objective 3: Assess the spatial distribution of competing vegetation within stands for significant spatial autocorrelation.

Null Hypothesis: The spatial distribution of competing vegetation is not significantly autocorrelated.

Alternative Hypothesis: The spatial distribution of competing vegetation is significantly spatially autocorrelated.

Objective 4: To model the growth and yield of competing vegetation at mid-rotation in loblolly pine plantations.

Null Hypothesis: Post-treatment competing vegetation growth is stochastic and cannot be explicitly modeled.

Alternative Hypothesis: Post-treatment competing vegetation growth is deterministic and can be explicitly modeled.

Objective 5: Evaluate the significance of CV control as an explanatory variable in growth and yield model systems.

Null Hypothesis: Models including CV control as an explanatory variable will provide no differences in model fit than those without.

Alternative Hypothesis: Including CV control will increase model fit relative to models excluding CV control.

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CHAPTER 2

ASSESSING MID-ROTATION LOBLOLLY PINE (*Pinus taeda*) AND COMPETING VEGETATION RESPONSES TO POST-THIN FERTILIZATION AND HERBICIDE APPLICATION IN THE SOUTHEASTERN UNITED STATES[1]

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Abstract

Mid-rotation silvicultural treatments (MRT) are commonly applied to loblolly pine (*Pinus taeda* L.) plantations in the southeast U.S 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 U.S. was monitored for 8 years following a one-time, post-thin application of either fertilization (224 kg ha^{-1} of N plus 28 kg ha^{-1} P), 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 $m^3ha^{-1}yr^{-1}$) and the Upper Coastal Plain / Piedmont (UCPIE, 0.20-3.72 $m^3ha^{-1}yr^{-1}$). Chemical herbicide application in both the LCP (0.34-4.87 $m^3ha^{-1}yr^{-1}$) and UCPIE (0.89-1.97 $m^3ha^{-1}yr^{-1}$) 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 $m^3ha^{-1}yr^{-1}$ in the LCP and -5.67 $m^3ha^{-1}yr^{-1}$ in the UCPIE. Consequently, we suggest that competing vegetation response should be considered within site-specific management plans aimed at maximizing pine productivity.

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

2.1 Introduction

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 (Vance et al. 2010; D'Amato et al. 2018; Homyack et al. 2022). Mid-rotation silvicultural treatments (MRT) improve productivity in established stands by providing nutrient amendments and reducing competition for site resources (Allen et al. 1990; Allen and Albaugh 2000; 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 m^3 ha^{-1} yr^{-1} to 7.4 m^3 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 m^3 ha^{-1} $year^{-1}$ across the southeast U.S. and is commonly used for plantations at mid-rotation (Hynynen et al. 1998; Amateis et al. 2000; Fox et al. 2007b).

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 (Clutter et al. 1983; Amateis et al. 1989; Haseneuer et al. 1997).

Vegetation control with chemical herbicide applications reduces competition from non-crop 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 m^3 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 reflect industrial application rates have shown 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 (Blinn et al. 2011; Albaugh et al. 2012) 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; Liechty and Fristoe 2013; Gyawali and Burkhart 2015). Post-thin fertilization promotes crown development and increases leaf area index, which is directly related to more vigorous post-treatment growth (Fox et al. 2007a; Albaugh et al. 2019). Post-thin competition control releases site resources from non-crop vegetation. Often, the treatment applications are determined by operational constraints which impact the timing, rate of application, and combination of treatments. Fertilization and/or chemical herbicide application at the time of thinning is common in the U.S. 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 U.S., and the relationship between competing vegetation density and loblolly pine volume growth was assessed. This research aimed to improve our understanding of post-thin 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.

2.2 Materials and Methods

2.2.1 Study Site

The PMRC Mid-Rotation Treatment Study was initialized in 2009 as a regional research field trial, consisting of 24 installations equally distributed between the Lower Coastal Plain (LCP) and combined Upper Coastal Plain & Piedmont (UCPIE) regions of the southeast U.S. (Figure 2.1). Installations were established immediately following thinning on industrial plantations provided by PMRC member companies (Table 2.1). Site selection was based on stem quality and uniformity, and all sites were considered an average operational plantation within either physiographic region. Stands which 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 1627 trees ha^{-1} in the UCPIE and 1040 to 1689 trees ha^{-1} in the LCP. 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 NRCS soil survey data (Soil Survey Staff, NRCS). Initial competing vegetation density varied greatly between installations. Crown volume of midstory woody and shrub species was between 8.95 and 393.35 m^3 ha^{-1} in the UCPIE and between 28.09 and 132.77 m^3 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 comprised of hardwoods and broadleaf shrubs, dominated by sweetgum (*Liquidambar styraciflua L*.), oak (*Quercus spp*.) and American beautyberry (*Callicarpa americana*). Waxy-leafed 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*).

2.2.2 Experimental Design

Each of the 12 installations within a physiographic region represented a unique combination of pre-thin basal area (high, > 27.6 m^2 ha^{-1}; low, ≤ 27.6 $m^2 ha^{-1}$), pre-thin site index (high, > 26 m; low, ≤ 26 m), and post-thin residual basal area (high, 21 m^2/ha; moderate, 16 m^2/ha; low, 11.5 m^2/ha). Four treatment plots were established at each installation immediately following thinning in a randomized pattern unique to each location. The treatments consisted of a thin only (T), T +

fertization (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 following thinning and was applied at a rate of 224 kg ha^{-1} of 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 following 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} of 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.

2.2.3 Measurements

Measurement plots were a 0.2-hectare (0.5-acre) rectangular plot embedded inside a 0.3-hectare (0.75-acre) 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). Ht and Hlc were taken on a subset of trees which represented the diameter distribution at each location, and was used to calculate SI. Plot measurements were collected pre-thin, immediately post-thin, and every two 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 inches 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 inches 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 two 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.

2.2.4 Statistical Analysis

MRT were assessed using a mixed effects model. The treatment plots at each installation represent an unreplicated 2x2 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 modelling 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 BA, Initial SI, and post-thin BA) were excluded from the model to eliminate pseudoreplication. Since treatments were un-replicated at each installation, treatment plots represented a single observation of the unique combination of initial stand conditions. Potential differences due to pre-treatment conditions were accounted for by including a pre-treatment measure of the dependent variable as covariate in the model. The final model was specified as:

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

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 pre-treatment 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 $j = (1, \ldots, 4)$ 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 relative to each measurement period for total outside-bark volume (TVOB), stand BA, stand dominant height (HD), and mortality (TPH). TVOB was calculated using the stem volume equations from Zhao and Kane (2016). Additionally, Equation 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:

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

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 Equation 1 and periodic annual increment.

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), which looked at the relationship between post-treatment volume growth and initial hardwood basal area and determined it was not significant. Unlike Albaugh et al. (2012), here we are 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 periodic annual increment 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).

2.3 Results

2.3.1 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 m^3 ha^{-1} yr^{-1}) post-treatment in the LCP and 6 years (3.72 m3 ha^{-1} yr^{-1}) in the UCPIE (Table 2.2). 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 m^3 ha^{-1} yr^{-1}) and LCP (4.87 m^3 ha^{-1} 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 2.2). Estimated periodic annual increment indicated a decrease in LCP volume growth, with the largest reduction in growth occurring between 6 years (18.95 m^3 ha^{-1} yr^{-1}) and 8 years (10.01 m^3 ha^{-1} yr^{-1}) for the thin-only treatment. Volume growth in the UCPIE was relatively consistent throughout all four measurement periods (Figure 2.2). The only reduction in estimated periodic annual increment for UCPIE was from 6 (23.28 m^3 ha^{-1} yr^{-1}) to 8 years (21.65 m^3 ha^{-1} yr^{-1}) under the combined treatment.

BA growth increased with MRT, although responses were different between physiographic regions (Table 2.2). Fertilization in the LCP resulted in a significant BA growth response sustained up to 6 years post-treatment (0.30 m^2 ha^{-1} yr^{-1}) but was not significant until 4 years post-treatment (0.22 m^2 ha^{-1} yr^{-1}) in the UCPIE. Chemical herbicide application also increased BA growth for up to 4 (0.22 m^2 ha^{-1} yr^{-1}) years in the UCPIE and 8 (0.41 m^2 ha^{-1} 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 2.3), with the most substantial decrease in periodic growth occurring in fertilized stands, ranging from 1.55 m^2 ha^{-1} yr^{-1} to 0.38 m^2 ha^{-1} yr^{-1}. BA growth in the UCPIE remained consistent across all measurement periods (Table 2.2).

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 2.2). 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. HD growth remained consistent throughout the study period, with growth rates being similar across all MRT (Figure 2.5).

Mortality was consistent throughout the post-treatment measurement periods in the LCP (Figure 2.4). The final remeasurement period yielded a large loss in trees per hectare (TPH) in the LCP, with estimated PAI of up to 20 trees ha^{-1} yr^{-1} in the thin-only stands (Table 2.2). Silvicultural treatments in the LCP improved survival conditions for crop trees, with annualized responses (up to 3 trees ha^{-1} yr^{-1}) being greater for treated stands than the thin-only. Survival was greater in the UCPIE, but mortality still occurred throughout the remeasurement period (Figure 2.4). Silvicultural treatment in the UCPIE resulted in greater mortality compared to the thin-only stands, with the greatest difference being an annualized response of -1.27 trees ha^{-1} yr^{-1} following fertilization. However, silvicultural treatment did not result in a significant response in TPH during any remeasurement period (Table 2.2).

MRT increased cumulative final yield for all stand attributes at 8 years post-treatment (Table 2.3). BA in the LCP was 1.44 m^2 ha^{-1} greater in fertilized stands compared to thin-only stands, which resulted in a greater TVOB (22.52 m^3 ha^{-1}). BA and TVOB also increased with chemical herbicide application, by 1.26 m^2 ha^{-1} and 11.07 m^3 ha^{-1}, respectively. The combined treatment had the largest increase in TVOB (32.25 m^3 ha^{-1}) and BA (2.26 m^2 ha^{-1}) but did not have a statistically significant effect on either. 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 were less than in the LCP. Fertilization in the UCPIE resulted in an increase of 17.43 m^3

ha^{-1} in TVOB and 1.35 m^2 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 m^2 ha^{-1}). Only slight differences in HD were also observed in 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.

2.3.2 Competing Vegetation

Herbaceous vegetation responded vigorously to thinning in both regions during the first growth period (Figure 2.6). For all stands in both the LCP and UCPIE, percentage groundcover increased from below 20 percent up to 50 percent 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 percent during the first growing period, and the combined treatment had a response of -7.21 percent. The decreased growth response was not sustained and stands with chemical herbicide application had a higher rate of growth compared to the thin-only treatment starting 4 years following 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 UCPIE was -3.70 percent for the herbicide only treatment, and -5.56 percent 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 2.4).

Crown volume decreased following thinning in both the LCP and UCPIE (Figure 2.7), chemical herbicide application was effective for decreasing woody crown volume growth (Table

2.4). Estimated PAI was negative for all four treatments 2 years post-treatment in the LCP, with the chemical herbicide application (-2.40 m^3 ha^{-1}) and combined treatments (-2.36 m^3 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 m^3 ha^{-1} for the herbicide only treatment and -5.67 m^3 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 m^3 ha^{-1}) and 8 (1.23 m^3 ha^{-1}) post-treatment in the LCP, and at 2 (-0.62 m^3 ha^{-1}) and 4 (-3.08 m^3 ha^{-1}) years post-treatment in the UCPIE.

2.3.3 Pine vs. Competing Vegetation

The relationship between the pre-thin herbaceous groundcover percentage and the periodic pine growth rate was not statistically significant (Figure 2.8). Additionally, no clear trends between pre-thin groundcover and annual pine growth were observed in either region (Figure 2.8). 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 2.9). However, observation of the pre-treatment crown volume suggests that a weak positive correlation may still be present (Figure 2.9).

2.4 Discussion

Post-thin fertilization and chemical herbicide applications effectively increased loblolly pine growth. Volume response to fertilization averaged 3.45 m^3 ha^{-1} yr^{-1} in the LCP and 1.75 m^3 ha^{-1}

yr^{-1} in the UCPIE, which were both less than the previously reported south wide average of 3.8 $m^3\ ha^{-1}\ yr^{-1}$ (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 pre-treatment stocking. The application rate used in this study is common for mid-rotation plantations in the southeast U.S., but differences in site-specific nutrient availability may have limited the capture of nutrient amendments (Fox. et al. 2007a; Albaugh et al. 2019). Pre-thin basal area indicated that stands in both regions were overstocked at all installations in both regions ($\geq$ 30 $m^2\ ha^{-1}$; $\geq$ 130 $ft^2\ ac^{-1}$). Fully stocked stands generally respond well to thinning, and increased thinning intensities have resulted in improved basal area growth (Albaugh et al. 2017). Overstocked stands, however, may not respond to thinning depending on the initial basal area, thinning intensity, and fertilization rate (Wells et al. 1976; Allen and Duzan 1982; Wells and Allen 1985). Response to silvicultural treatment has also been shown to decrease at higher site indices (Zhao et al. 2016). Since many of the stands were of relatively high site index before treatments were applied (>26 m; >85 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. P-deficient sites are common in the LCP (Jokela et al. 1991; Gent et al. 1986) and plantations respond strongly to N and P amendments, especially when P amendments are applied up to 2 years after planting (Martin et al. 1999; Amateis et al. 2000; Fox et al. 2007a). 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 to independent fertilization (Albaugh et al. 2012; Liechty and Fristoe 2013). However, responses to chemical herbicide application are usually sustained for longer periods of time (Oppenheimer et al. 1989; Fortson et al. 1996; Fox et al. 2007a). 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 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 in HD was only observed at a few measurement periods. 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; Haseneuer 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 survival) 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 basal areas, 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 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 U.S. (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 since 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 pre-treatment densities. Liechty and Fristoe (2013) reported a similar pattern in the western Gulf

Coastal Plain, who found no significant increase in woody vegetation following vegetation control. For the treatment plots which 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 (Glover and Zutter 1993; Fortson et al. 1996). The suppression of greater woody crown volume was also positively associated with greater pine volume response, indicating that woody vegetation is a significant limiting factor for loblolly pine production across the southeast U.S.

2.5 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 to how resource allocation impacted 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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2.7 Tables and Figures

Figure 2.1: Approximate locations of MRT 1st-Thin installations distributed within the UCPIE (circles) and LCP (triangles) physiographic regions of the southeast United States.

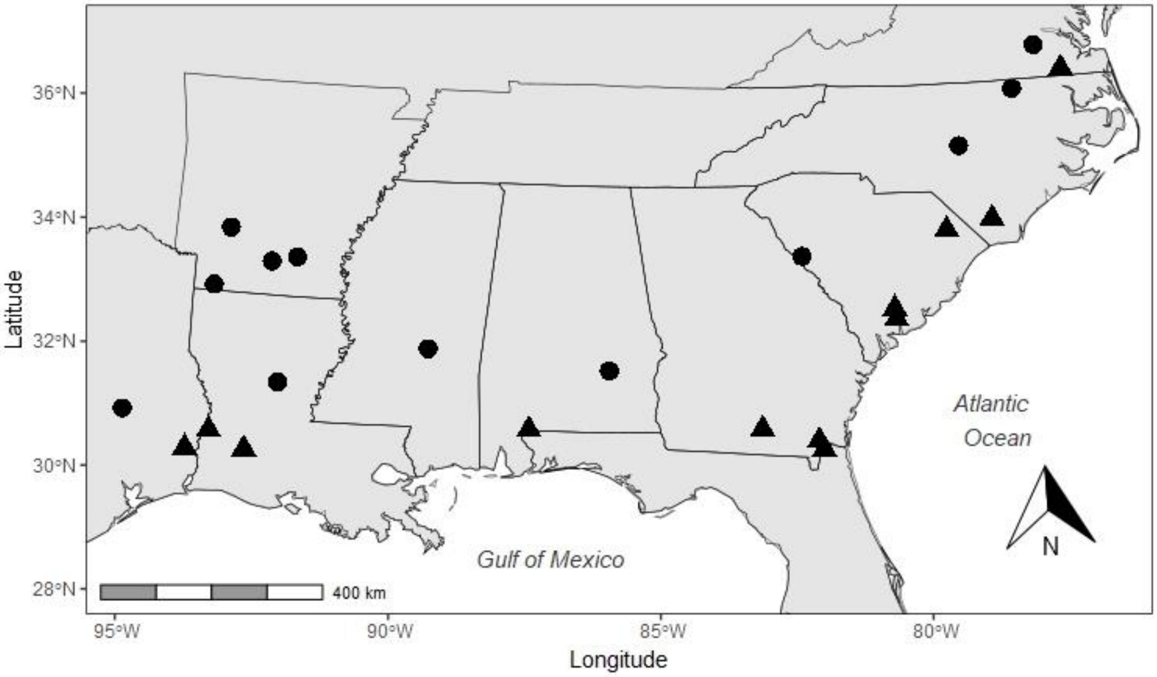


Table 2.1: Summarized stand and site information for the MRT 1st-thin installations located in the UCPIE and LCP regions. Values represent pre-treatment stand conditions as measured before thinning. Locations are approximated to the nearest town.

							Pre-Treatment Stand Values					
							Loblolly pine				Competing Vegetation	
Physiographic Region	Location	Dominant Soil Series (*Order*)	Primary Competing Vegetation	Site Index (base age 25)	Residual Basal Area (m^2/ha)	Year Established (*Age*)	TPH	HD (m)	BA (m^2/ha)	TVOB (m^3/ha)	Crown Volume (m^3/ha)	Groundcover (%)
Upper Coastal Plain & Piedmont	Jena, LA	Rustin/Malbis (*Ultisols*)	American beautyberry (*Callicarpa americana*)	26.5	21	2009 (*16*)	1158	18.71	38.21	313.38	96.44	17.56
	Plum Branch, SC	Herndon (*Ultisols*)	Sweetgum (*Liquidambar styraciflua*)	22.9	16	2011 (*15*)	1491	13.89	34.31	211.26	113.23	25.5
	Antoine, AR	Savannah (*Ultisols*)	American beautyberry (*Callicarpa americana*)	24.1	21	2010 (*16*)	1627	16.86	44.65	332.67	53.74	14.05
	Sanford, NC	White Store (*Alfisols*)	White oak (*Quercus alba*)	24.4	11.5	2011 (*13*)	1585	14.30	37.99	242.11	8.95	20.36
	Dinwiddle, VA	Mattaponi (*Ultisols*)	Southern red oak (*Quercus falcata*)	21.3	21	2011 (*16*)	1560	13.57	35.33	213.44	344.49	10.97
	Groveton, TX	Keltys (*Alfisols*)	Sweetgum (*Liquidambar styraciflua*)	21.0	16	2011 (*16*)	1581	15.85	38.06	268.05	61.97	7.05
	Bradley, AR	Dorcheat (*Alfisols*)	Southern red oak (*Quercus falcata*)	21.3	11.5	2011 (*19*)	1043	14.70	36.55	234.24	55.55	15.05
	Warren, AR	Savannah (*Ultisols*)	American beautyberry (*Callicarpa americana*)	24.1	16	2014 (*17*)	1362	14.09	34.03	211.86	79.12	8.19
	Forest, MS	Kipling (*Alfisols*)	Ash (*Fraxinus spp.*)	26.2	11.5	2013 (*13*)	1586	19.42	43.69	375.00	103.4	31.66
	Troy, AL	Mantachie(*Inceptisols*), Eunola (*Ultisols*)	Sweetgum (*Liquidambar styraciflua*)	24.1	16	2012 (*16*)	1417	16.23	39.07	276.95	163.77	12.09
	Littleton, NC	Cecil (*Ultisols*)	Sweetgum (*Liquidambar styraciflua*)	23.5	21	2013 (*16*)	1397	16.24	42.30	305.11	393.35	16.8
	Hampton, AR	Smithton (*Ultisols*)	Sweetgum (*Liquidambar styraciflua*)	22.6	11.5	2013 (*20*)	955	16.47	43.89	312.46	49.49	4.89
Lower Coastal Plain	Franklin, VA	Rains (*Ultisols*)	Sweetgum (*Liquidambar styraciflua*)	26.8	21	2014 (*18*)	1040	20.75	46.37	418.46	124.79	14.89
	Hilliard, FL	Meggett (*Alfisols*)	Sweetgum (*Liquidambar styraciflua*)	28.0	16	2012 (*12*)	1658	16.61	34.05	248.57	122.6	13.23
	Merryville, LA	Merryville (*Alfisols*), Bearhead (*Ultisols*)	Blackgum (*Nyssa sylvatica*)	25.9	11.5	2013 (*16*)	1412	17.73	36.58	283.57	123.49	3.79
	Lakeland, GA	Rigdon (*Spodosols*)	Southern red oak (*Quercus falcata*)	28.0	11.5	2013 (*13*)	1493	15.07	29.99	198.73	16.48	24.66
	Kinder, LA	Caddo (*Alfisols*), Messer (*Alfisols*)	Yaupon (*Ilex vomiroria*)	25.3	16	2013 (*14*)	1689	14.96	35.80	235.91	73.01	4.49
	Folkston, GA	Pelham (*Ultisols*)	Gallberry (*Ilex glabra*)	26.5	21	2015 (*16*)	1644	17.19	30.73	235.06	65.83	6.49

Jacksonboro, SC	Nemours (*Ultisols*)	Sweetgum (*Liquidambar styraciflua*)	26.2	11.5	2014 (*16*)	1250	19.00	36.63	299.23	132.77	24.02
Cottageville, SC	Hobcaw (*Ultisols*), Yemassee (*Ultisols*)	Sweetgum (*Liquidambar styraciflua*)	26.2	16	2014 (*17*)	1394	19.85	40.74	352.66	70.91	3.7
Lake Waccamaw, NC	Croatan (*Histosols*)	Gallberry (*Ilex glabra*)	25.6	11.5	2015 (*12*)	1334	15.80	35.45	244.67	10.99	1.4
Atmore, AL	Greenville (*Ultisols*)	Yaupon (*Ilex vomiroria*)	24.7	21	2016 (*15*)	1257	16.18	32.28	228.11	53.99	37.5
Buna, TX	Evadale (*Alfisols*)	Yaupon (*Ilex vomiroria*)	25.0	16	2018 (*18*)	1432	18.66	38.57	315.69	85.79	15.36
Marion, SC	Cantey (*Ultisols*)	Sweetgum (*Liquidambar styraciflua*)	25.9	21	2017 (*15*)	1192	17.23	43.10	320.70	28.09	53.13

Table 2.2: Estimated periodic annual increment of loblolly pine stand-level variables for each two-year measurement period following application of MRT. Each stand-level variable was mean adjusted using pre-treatment covariates and the random effects term. Bold *p*-values indicate a significant response at the 0.10 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)*				p < F ($\alpha = .10$)		
			Thin (T)	T + Fert (F)	T + Herb (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*)	**0.06**	0.78	0.75
		4	19.17	23.00 (*3.83*)	21.80 (*2.63*)	23.67 (*4.50*)	**0.01**	**0.09**	0.28
		6	18.95	22.15 (*3.20*)	20.89 (*1.94*)	20.65 (*1.70*)	**0.04**	0.23	**0.10**
		8	10.01	14.02 (*4.01*)	14.88 (*4.87*)	16.67 (*6.66*)	**0.03**	**0.01**	0.33
	BA (m^2 ha^{-1} yr^{-1})	2	1.26	1.53 (*0.27*)	1.29 (*0.03*)	1.47 (*0.21*)	**0.02**	0.82	0.49
		4	1.43	1.68 (*0.25*)	1.71 (*0.28*)	1.77 (*0.34*)	**0.03**	**0.03**	0.20
		6	1.25	1.55 (*0.30*)	1.42 (*0.17*)	1.54 (*0.29*)	**0.02**	0.21	0.27
		8	0.30	0.38 (*0.08*)	0.71 (*0.41*)	0.60 (*0.30*)	0.49	**0.01**	0.30
	HD (m yr^{-1})	2	0.85	0.83 (*-0.02*)	0.82 (*-0.03*)	0.88 (*0.03*)	0.98	0.79	0.75
		4	0.84	0.97 (*0.13*)	0.85 (*0.01*)	0.89 (*0.05*)	0.16	0.86	0.45
		6	0.80	0.72 (*-0.08*)	0.77 (*-0.03*)	0.60 (*-0.20*)	0.58	0.82	0.47
		8	0.63	0.81 (*0.18*)	0.51 (*-0.12*)	0.87 (*-0.24*)	0.13	0.41	0.45
	TPH (trees ha^{-1} yr^{-1})	2	-0.06	-2.36 (*-2.29*)	-2.06 (*-1.99*)	-3.01 (*-2.95*)	**0.06**	0.35	0.43
		4	-2.12	-4.21 (*-2.09*)	-2.26 (*-0.14*)	-3.83 (*-1.71*)	**0.07**	0.97	0.61
		6	-2.46	-0.80 (*1.66)*	-0.99 (*1.46*)	-1.42 (*1.04*)	1.00	0.48	0.71
		8	-19.10	-18.03 (*1.07*)	-10.86 (*1.07*)	-15.89 (*3.21*)	0.82	**0.00**	0.15
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*)	**0.04**	0.46	0.46
		4	18.18	19.30 (*1.12*)	20.46 (*2.28*)	21.69 (*3.78*)	0.30	**0.03**	0.87
		6	19.46	23.18 (*3.72*)	21.43 (*1.97*)	23.28 (*3.82*)	**0.00**	**0.08**	0.23
		8	23.14	23.34 (*0.20*)	22.43 (*-0.71*)	21.65 (*-1.49*)	0.95	0.53	0.65
	BA (m^2 ha^{-1} yr^{-1})	2	1.51	1.62 (*0.11*)	1.51 (*0.00*)	1.62 (*0.11*)	0.23	0.69	0.86
		4	1.55	1.77 (*0.22*)	1.75 (*0.22*)	1.97 (*0.42*)	**0.01**	**0.03**	0.85
		6	1.42	1.54 (*0.12*)	1.57 (*0.15*)	1.65 (*0.23*)	0.16	0.11	0.74
		8	1.57	1.54 (*-0.03*)	1.58 (*0.01*)	1.68 (*0.11*)	0.63	0.83	0.31
	HD (m yr^{-1})	2	0.75	0.87 (*0.12*)	0.93 (*0.18*)	0.90 *(0.15*)	**0.10**	**0.01**	0.13
		4	0.67	0.62 (*-0.05*)	0.70 (*0.03*)	0.65 (*-0.02*)	0.44	0.75	0.96
		6	0.76	0.94 (*0.18*)	0.83 (*0.07*)	0.86 (*0.10*)	**0.03**	0.42	0.21
		8	0.86	0.74 (*-0.12*)	0.68 (*-0.18*)	0.47 (*-0.39*)	0.24	**0.10**	0.54
	TPH (trees ha^{-1} yr^{-1})	2	0.95	-0.19 (*-1.14*)	0.73 (*-0.23*)	0.44 (*-0.52*)	0.39	0.39	0.25
		4	-0.84	-1.87 (*-1.02*)	-1.10 (*-0.25*)	-1.02 (*-0.17*)	0.47	0.40	0.22
		6	-2.22	-1.99 (*0.22*)	-0.90 (*1.31*)	-1.29 (*0.92*)	0.87	0.78	0.73
		8	0.13	-1.14 (*-1.27*)	-0.08 (*-0.21*)	-0.61 (*-0.74*)	0.53	0.57	0.47

Figure 2.2: 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.

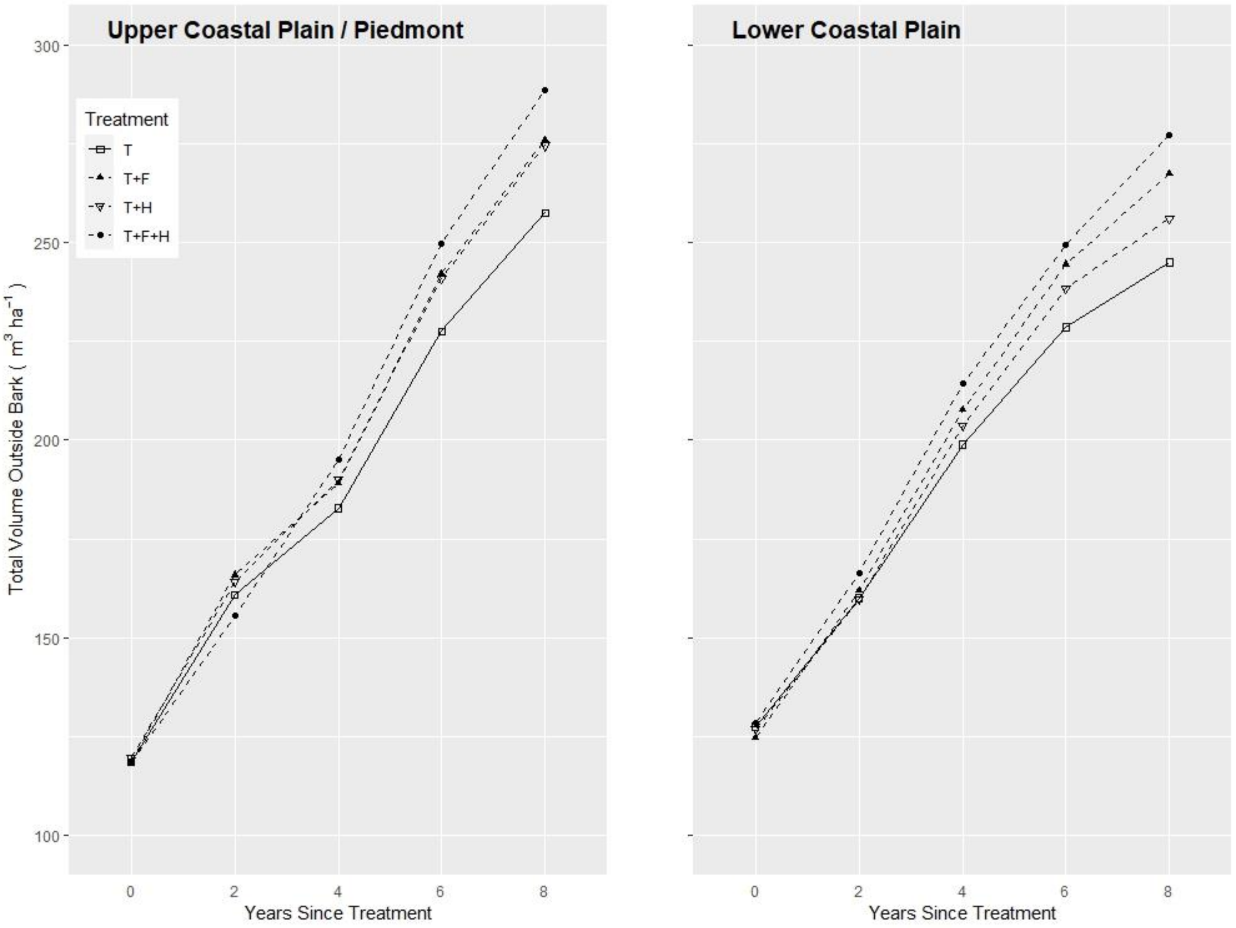


Figure 2.3: Regionally averaged basal area growth trends for loblolly pine in the UCPIE and LCP regions following MRT application. Observed growth trajectories as measured post-treatment are displayed for the thin (T) only, T + fertilization (F), T + herbicide (H), and T + F + H treatments.

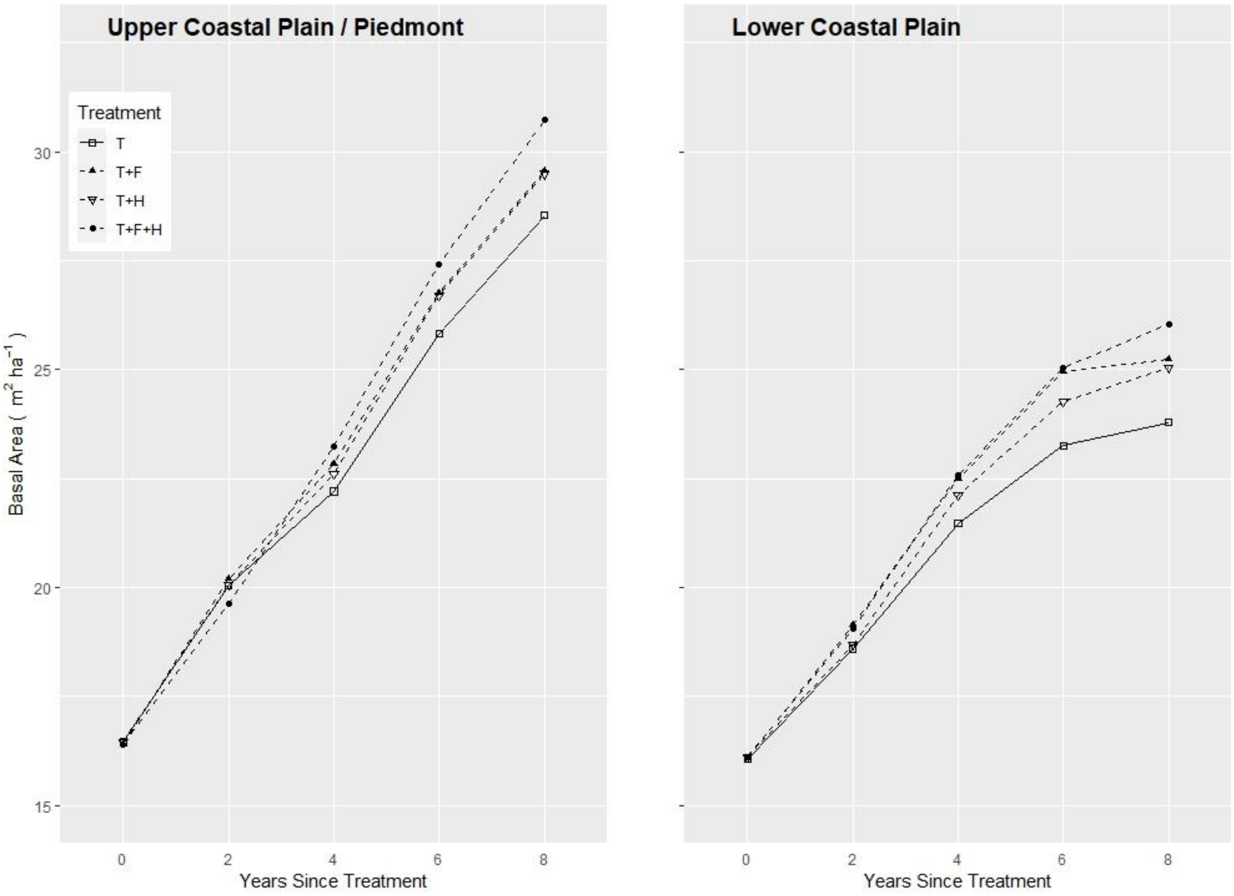


Figure 2.4: Regionally averaged survival trends for loblolly pine in the UCPIE and LCP regions following MRT application. Observed growth trajectories as measured post-treatment are displayed for the thin (T) only, T + fertilization (F), T + herbicide (H), and T + F + H treatments.

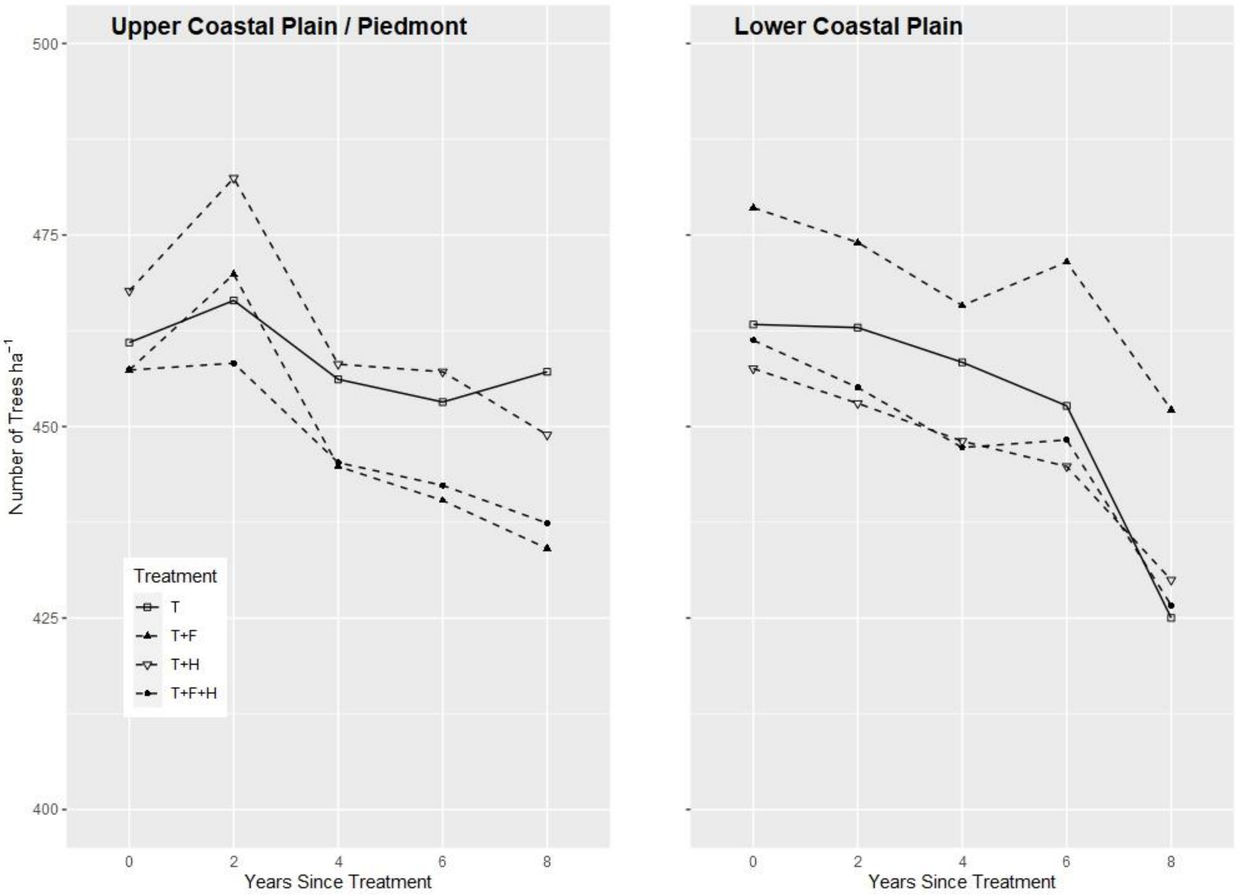


Figure 2.5: Regionally averaged dominant height growth trends for loblolly pine in the UCPIE and LCP regions following MRT application. Observed growth trajectories as measured post-treatment are displayed for the thin (T) only, T + fertilization (F), T + herbicide (H), and T + F + H treatments.

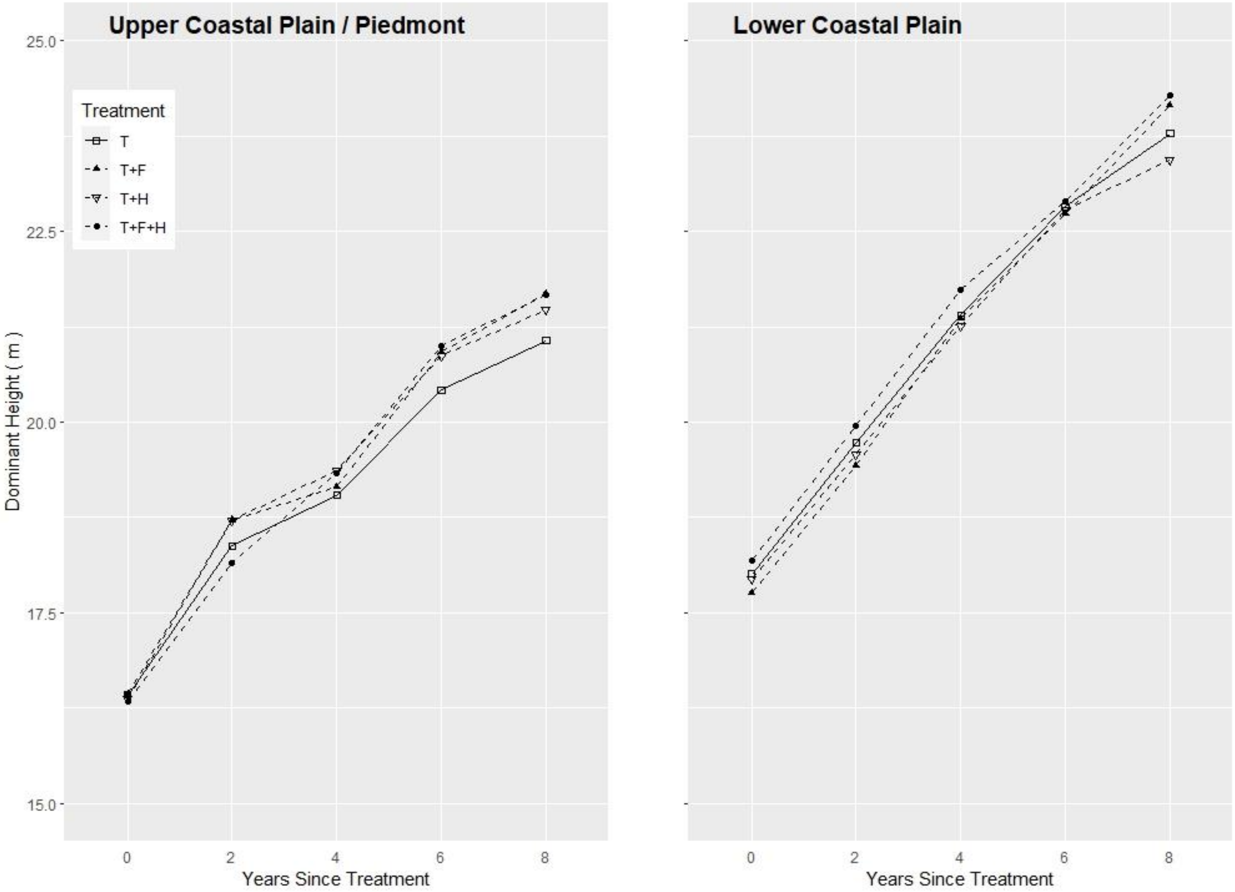


Table 2.3: Cumulative final yield for each stand variable at 8 years post-treatment assessed for all measurement plots within each region. Significant differences are in comparison to the thin-only treatment and assessed using a mixed effects model. Bold values indicate significance at the 0.10 alpha-level.

		Cumulative Final Yield by Treatment (*Response*)				p < F ($\alpha = .10$)		
Physiographic Region	Stand Variable	Thin (T)	T + Fert (F)	T + Herb (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*)	**0.01**	0.17	0.48
	BA (m^2 ha^{-1})	23.79	25.23 (*1.44*)	25.05 (*1.26*)	26.05 (*2.26*)	**0.02**	**0.06**	0.41
	HD (m)	23.78	24.16 (*0.38*)	23.43 (-*0.35*)	24.29 (*0.51*)	0.25	0.62	0.73
	TPH (trees)	425	452 (*27*)	430 (*5*)	427 (*2*)	**0.04**	0.69	**0.09**
Upper Coastal Plain & Piedmont	TVOB (m^3 ha^{-1})	271.53	288.96 (*17.43*)	288.03 (*16.50*)	296.64 (*25.11*)	**0.01**	**0.07**	0.36
	BA (m^2 ha^{-1})	29.63	30.98 (*1.35*)	30.31 (*0.68*)	31.45 (*1.82*)	**0.04**	0.18	0.64
	HD (m)	21.40	21.50 (*0.10*)	21.88 (*0.48*)	21.72 (*0.32*)	0.71	0.59	0.55
	TPH (trees)	494	487 (-*7*)	485 (-*9*)	493 (-*1*)	0.53	0.99	0.76

Figure 2.6: 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.

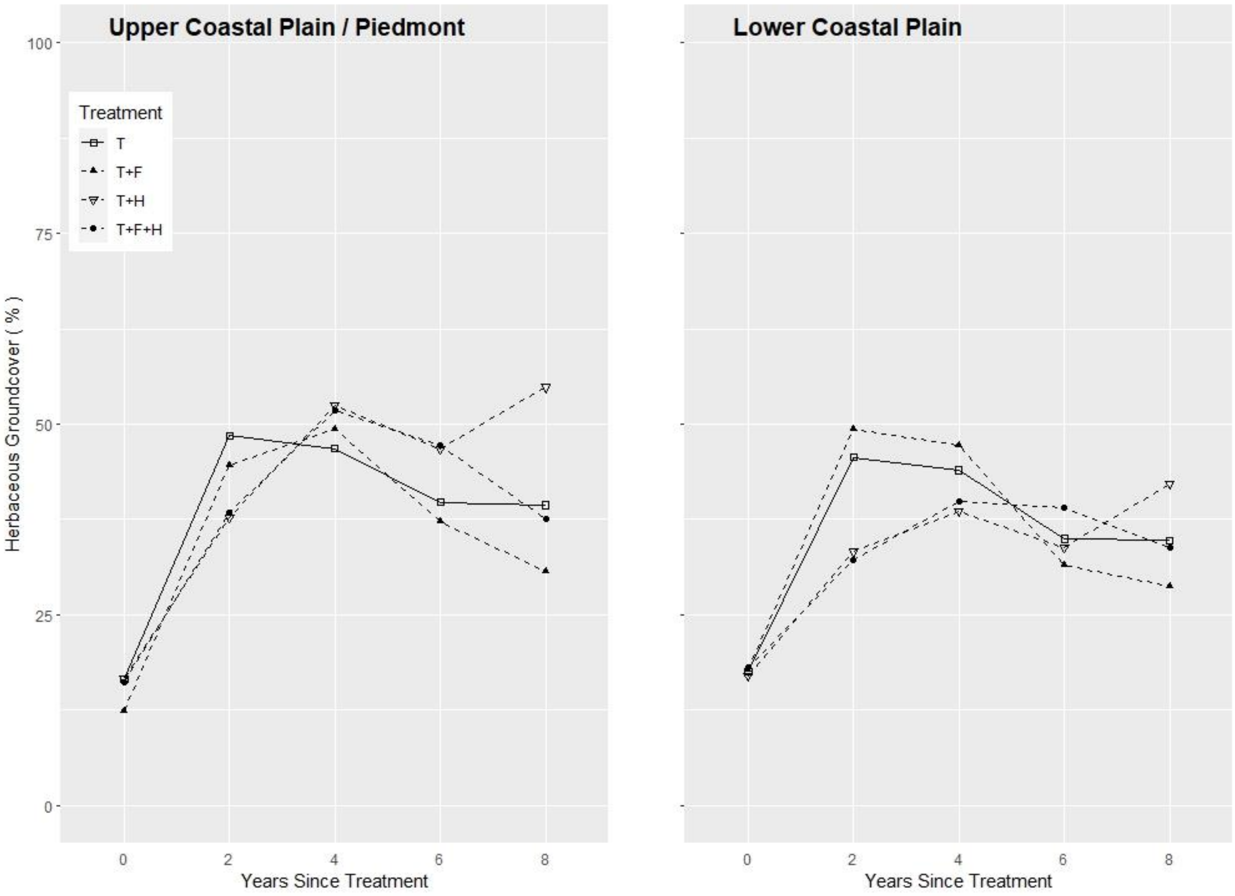


Table 2.4: Estimated periodic annual increment of competing vegetation stand-level variables for each two-year measurement period following application of MRT. Each variable was mean adjusted using pre-treatment covariates and the random effects term. Bold *p*-values indicate a significant response at the 0.10 alpha-level. Treatment responses are relative to the Thin only treatment for each variable.

			Estimated Periodic MAI by Treatment (*Annualized Response*)				$p < F$ ($\alpha = .10$)		
Physiographic Region	Variable	Years Since Treatment	Thin (T)	T + Fert (F)	T + Herb (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*)	0.27	**0.00**	0.46
		4	0.27	0.20 (-*0.07*)	0.16 (-*0.11*)	0.13 (-*0.14*)	0.77	0.72	0.78
		5	0.41	0.27 (-*0.14*)	0.37 (-*0.04*)	0.51 (*0.10*)	0.91	0.85	0.92
		8	-1.17	-0.63 (*0.54*)	0.05 (*1.23*)	-0.15 (*1.02*)	0.16	**0.03**	0.20
	Groundcover (%)	2	14.24	15.85 (*1.61*)	7.68 (-*6.56*)	7.03 (-*7.21*)	0.54	**0.01**	0.54
		4	-0.97	-1.38 (-*0.41*)	3.68 (*4.65*)	5.35 (*6.32*)	0.88	**0.09**	0.59
		6	-3.28	-6.56 (-*3.28*)	-1.11 (*2.17*)	-0.06 (*3.22*)	0.24	0.43	0.28
		8	-0.97	-2.73 (-*1.76*)	2.06 (*3.03*)	-0.95 (*0.02*)	0.67	0.46	0.83
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*)	0.68	0.72	0.11
		4	1.84	2.02 (*0.08*)	-1.24 (-*3.08*)	0.33 (-*1.51*)	0.69	**0.01**	0.56
		6	0.01	-0.42 (-*0.43*)	0.61 (*0.60*)	0.47 (*0.46*)	0.82	0.38	0.86
		8	0.25	-0.57 (-*0.82*)	-0.35 (-*0.60*)	0.16 (-*0.09*)	0.65	0.79	0.68
	Groundcover (%)	2	13.77	15.26 (*1.49*)	10.07 (-*3.7*)	8.21 (-*5.56*)	0.44	**0.08**	0.25
		4	-3.02	-0.80 (*2.22*)	5.94 (*8.96*)	2.89 (*5.91*)	0.26	**0.00**	**0.07**
		6	-4.32	-6.40 (-*2.08*)	-2.24 (*2.08*)	-3.00 (*1.32*)	0.33	0.29	0.69
		8	2.34	-1.12 (-*3.46*)	3.50 (*1.16*)	1.52 (-*0.82*)	0.26	0.68	0.75

Figure 2.7: 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.

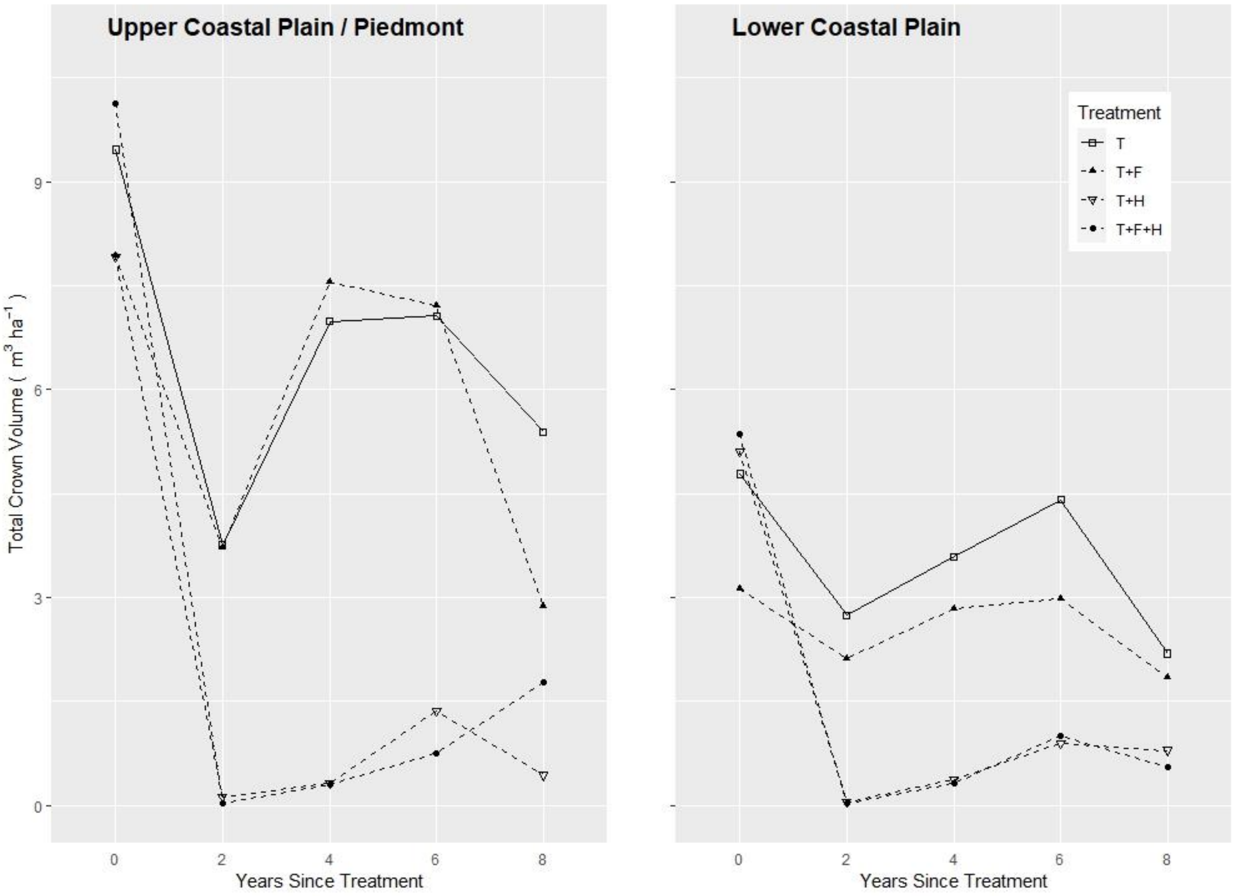


Figure 2.8: Modeled relationship between 6-year post-treatment periodic annual increment of loblolly pine total volume and initial percent groundcover of herbaceous competing vegetation. Predicted trendline and 95% confidence intervals are displayed. Only the thin (T) + herbicide (H), and T + H + fertilization (F) treatments are considered to capture responses to the controlled suppression of competing vegetation.

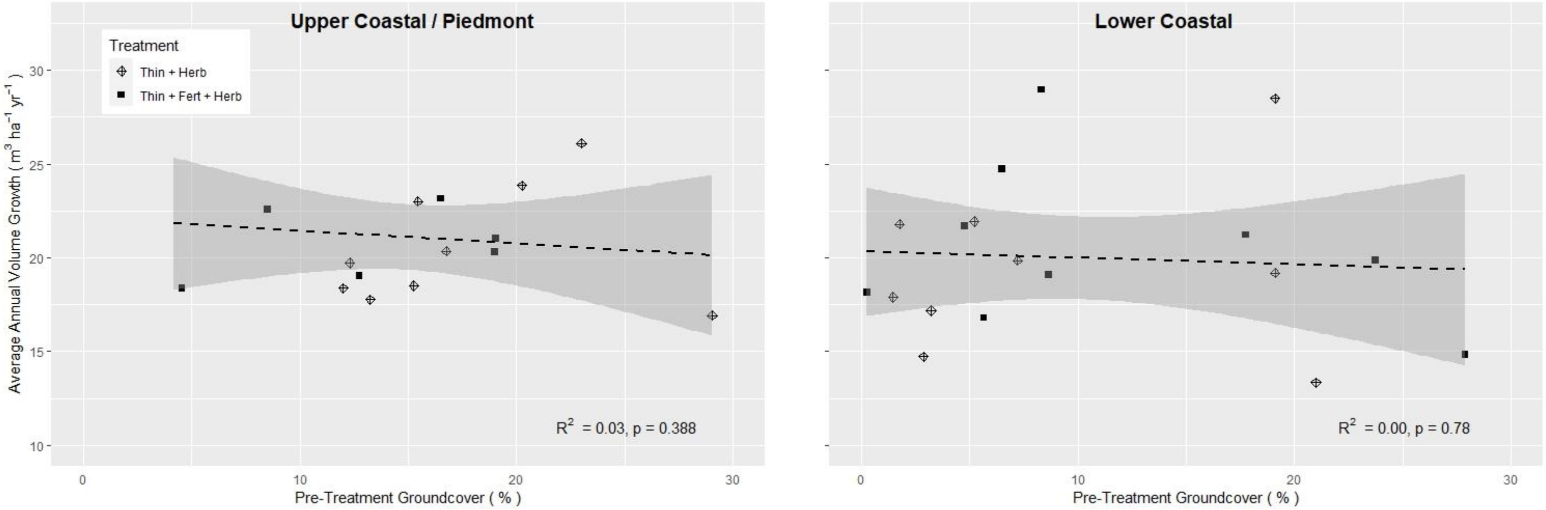
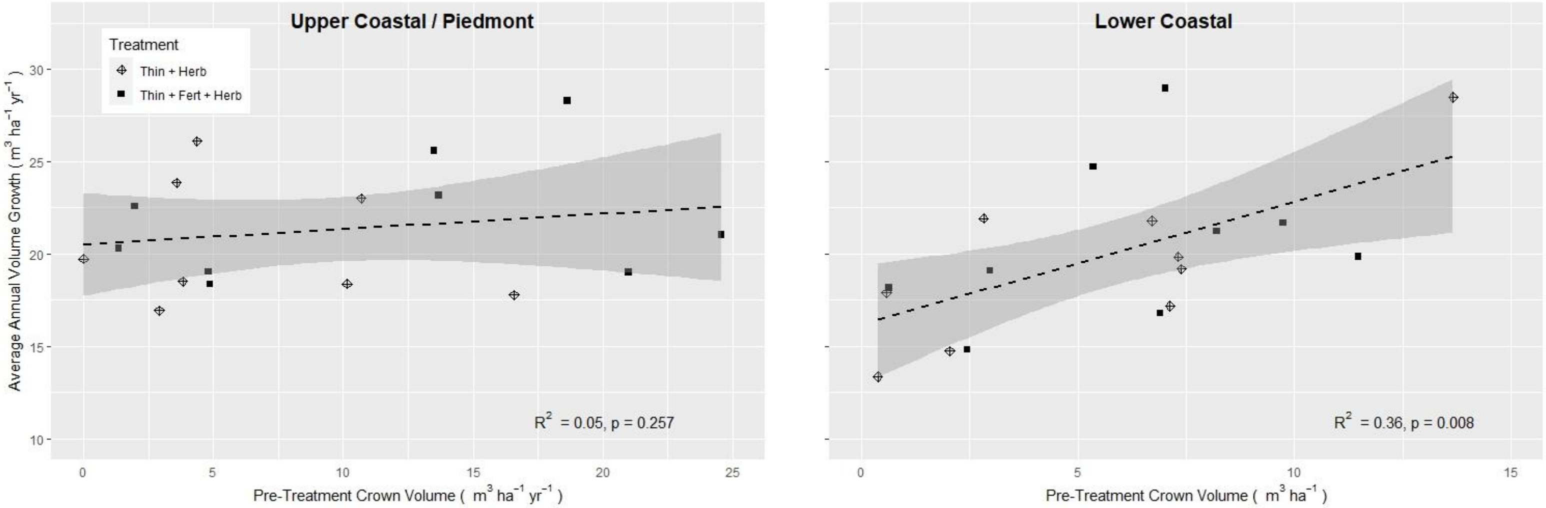


Figure 2.9: Modeled relationship between 6-year post-treatment periodic annual increment of loblolly pine total volume and initial crown volume of woody competing vegetation. Predicted trendline and 95% confidence intervals are displayed. Only the thin (T) + herbicide (H), and T + H + fertilization (F) treatments are considered to capture responses to the controlled suppression of competing vegetation.



CHAPTER 3

CHARACTERIZING SPATIAL DEPENDENCE OF COMPETING VEGETATION IN THINNED LOBLOLLY PINE PLANTATIONS [2]

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[2] Young, J.B., Bullock, B.P., and C.R. Montes. 2023. Accepted by *Proceedings of the 22nd Biennial Southern Silviculture Research Conference*. Reprinted here with permission of the publisher.

Abstract

The spatial structure of vegetation influences the development of forest stands. Individual crop trees, which have either similar or dissimilar traits to their neighbors, are likely to be spatially dependent. In intensively managed plantations, the presence of competing vegetation has been shown to limit crop tree productivity, suggesting that the occurrence of undesired vegetation is also spatially dependent since it is competing for the same site resources. Silvicultural treatments applied throughout rotation systematically alter the spatial structure of forests to favor crop tree production, but any resultant competing vegetation growth is also influenced by changes in resource distribution. However, the spatial dependence of competing vegetation in intensively managed plantations is not well understood. A long-term regional study from the southeast U.S. which monitored the growth of intensively managed loblolly pine, as well as competing vegetation, was used to characterize the spatial dependence of competing vegetation following operational, mid-rotation silvicultural treatments. Competing vegetation was found to be spatially autocorrelated but was not found to differ between silvicultural treatments. Negative spatial autocorrelation, especially for herbaceous vegetation, occurred in response to post-thin stand dynamics. Characterizing the spatial dependence of competing vegetation improves site-specific decisions for loblolly pine plantation management.

3.1 Introduction

Loblolly pine (*Pinus taeda* L.) plantations are the most important commercial pine resource in the southern U.S., covering more than 50 million acres across the region (South and Harper 2016). The productivity of loblolly pine plantations has drastically increased throughout the last century, due to the development of highly effective and site-specific silviculture (Fox and others 2007; Homyack and others 2022). Intensive plantation management often includes a combination of site preparation, fertilization, and the control of competing vegetation (Fox and others 2007). Mid-rotation silviculture treatments are common during intensive management and are typically applied in combination with thinning (Albaugh and others 2017; Liechty and Fristoe 2013). Plantation silviculture is primarily used to maximize the productivity of crop trees within a stand, and to reduce competition for site resources (Fox and others 2007).

Competition is an important factor contributing to the growth and yield of forest stands, and competition between individuals influences the development of stand attributes such as stem size and stand density (Liu and Burkhart 1994a; Miller and others 2003b; Pretzsch 1997). Competition occurs when resources are insufficient to meet the demands of all individuals within a stand. Measures of competition have most often been used to monitor the occurrence of interspecific competition at the stand level, represent some measure of stand density, and have been used to guide the timing and intensity of silvicultural treatments (Liu and Burkhart 1994b; Wagner and others 1996). The presence of competing vegetation can also impact the productivity of crop trees, especially if not controlled during stand establishment (Miller and others 2003a,b). Periodic competition control may be applied throughout the rotation, but the impact of competing vegetation on stand development at mid-rotation is not as well documented (Albaugh and others 2012).

Significant competitive interactions imply dependency on the spatial distribution of site resources since individuals manipulate resources that are within their immediate spatial proximity (Cannell and others 1984; Mack and Harper 1977). When individual tree characteristics are either systematically similar or dissimilar to those of neighboring trees, spatial autocorrelation may be present (Reed and Burkhart 1985). The stem characteristics of plantation loblolly pines have been shown to be spatially autocorrelated, indicating that individual growth has a deterministic impact on neighborhood growth (Bullock and Burkhart 2005; Reed and Burkhart 1985). The presence of competing vegetation may also be spatially autocorrelated since its growth is also determined by the same site resource distribution. The spatial dependency of competing vegetation within intensively managed pine plantations has not yet been characterized. Characterizing the spatial autocorrelation of vegetation, in either crop or non-crop species, can increase the precision of stand growth and yield models by adjusting them to account for errors due to spatial variability (Bullock and Burkhart 2005).

A long-term, regional research field trial administered by the University of Georgia Plantation Management Research Cooperative (PMRC) was used to assess the spatial autocorrelation of competing vegetation at mid-rotation. We hypothesize that competing vegetation in thinned pine plantations will have significant spatial autocorrelation. Additionally, we anticipate the degree of spatial autocorrelation to vary for different mid-rotation silvicultural treatments.

3.2 Methods

3.2.1 Study Design

The Mid-rotation Treatment Study was initiated in 2009 and consists of 24 installations distributed evenly across the Lower Coastal Plain (LCP) and combined Upper Coastal Plain and Piedmont (UCPIE) physiographic regions of the southeast U.S. (Figure 1A). Installation locations were provided by PMRC member companies and site selection was based on an initial assessment of stem quality and heterogeneity. Sites were considered typical operational plantations within either region and were selected to have homogeneous stand characteristics. Each installation consisted of 4 treatment plots, with no replication at an installation. Treatments were Thin only (T), T + Chemical Herbicide (H), T + Fertilization (F), and a fully combined treatment (T+F+H). Treatment plots were thinned to a residual basal area (BA) of either 50, 70 or 90 ft^2 ac^{-1} and was a 5-th row thin with free thinning between rows to achieve the desired BA. Fertilization was applied at a rate of 225 lb ac^{-1} N + 25 lb ac^{-1} P following thinning. The chemical vegetation control was broadcast sprayed following thinning and consisted of 3 oz glyphosate and 3 oz triclopyr (Garlon 3A) mixed with 36 gal of water ac^{-1}. Follow-up applications to remove any remaining woody vegetation was a variable rate of triclopyr (Garlon 4).

Measurement plots were 0.5 acres in size, and a total treatment plot size of 0.75-hectare created a buffer zone to reduce the impact of edge effects from non-treated areas. Within each treatment plot, a competing vegetation survey was established (Figure 1B). The competing vegetation survey was 20, 4-ft radius subplots arranged systematically between thinned rows and leave rows and represented roughly 5 percent of the plot area. At each subplot, measurements of multiple competing vegetation classes were collected (Table 1). Large woody vegetation (> 2 inches) was measured for diameter at breast height (dbh) and height (ht). A stem count and mean ht by species groups was collected for small woody vegetation and shrub species. The groundcover percentage of herbaceous vegetation was ocularly estimated for broadleaf species, Andropogon species, and other grass species and further summed to estimate total herbaceous groundcover. From the competing vegetation measurements, three classes of competing vegetation were considered for this study: overstory hardwood, understory shrubs and hardwoods, and herbaceous vegetation. Preliminary analysis found that overstory hardwoods were present in only a small subset of subplots within either region, and were subsequently excluded from the remaining analysis. Competing vegetation measurements were taken every 2 years post-treatment, beginning in the second growing season after thinning.

3.2.2 Characterizing Spatial Dependence

Spatial dependence is present in forest stands when the characteristics of an individual tree are influenced by its local environment. Spatial autocorrelation in forest systems may either be positive or negative, depending on the proximity to neighboring trees and the underlying resource distribution. Positive spatial dependency indicates that the distribution of site resources has the greatest impact on individual development. For example, nutrient deposits at the toe slope of a hill may lead to a pocket of larger trees that have positively benefitted from favorable nutrient availability. Negative spatial autocorrelation occurs when competition between individuals is the primary influence on stand spatial structure. When individual stems are dissimilar to their neighbors, they are believed to be competing more vigorously for scarce resources. As trees age, a shift from positive to negative spatial correlation is likely (Bullock and Burkhart 2005, Reed and Burkhart 1985).

The spatial autocorrelation among competing vegetation was assessed using Moran's I (MI) statistic (Moran 1950). For a given set of spatial locations $S = \{s_i, \ldots, s_n\}$, MI is a global value representing the overall magnitude of spatial autocorrelation among observations for a desired characteristic of interest, $Z(s_i)$. For the set S, MI can be calculated using the formulation presented by Cliff and Ord 1973,

$$I = \frac{N}{W} \frac{\sum_i^N \sum_j^N w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_i^N (x_i - \bar{x})^2} \tag{1}$$

where N is the total number of spatial observations in the set S, x is the variable of interest for either s_i or s_j, w_{ij} is the weight associated with the relationship between the i^{th} and j^{th} observation when $i \neq j$, and W is the sum of all weights, calculated as

$$W = \sum_i^N \sum_j^N w_{ij} \,. \tag{2}$$

The value of MI ranges between [-1, 1] and represents either perfectly clustered spatial data (1) or perfectly contrasted spatial data (-1). A value of 0 suggests the spatial variation in S is stochastic, indicating that observed values, $Z(s_i)$, are randomly distributed. An important consideration of the MI formulation presented by Cliff and Ord (1973) is the specification of the spatial weights, W. W accounts for a neighborhood structure between the observations in Z, adjusting the value to depend on the strength of their spatial proximity. Here, the individual weights, w_{ij}, make up the entries of W and are the Euclidean distances between each spatial observation (i.e. competing vegetation plot center) s_i and s_j, when $i \neq j$. Significance was determined using an α-level of 0.05.

MI was calculated for two competing vegetation groups, herbaceous and small woody vegetation (i.e., understory shrubs and hardwoods). Herbaceous vegetation was assessed using total groundcover percentage, and woody vegetation using total crown volume. Spatial coordinates were relative to the subplot layout within each treatment plot, and MI was calculated for every post-treatment measurement taken at each treatment and installation. A total of 205 observations in the LCP and 230 observations in the UCPIE were available for this analysis.

3.2.3 Silvicultural Assessment

To assess the impact of mid-rotation silvicultural treatments on the presence of spatial autocorrelation among competing vegetation, a two-way repeated measures ANOVA was fit to the MI values calculated for each physiographic region. The ANOVA model was

$$MI_{ijk} = \mu + I_{Herb} + I_{Fert} + (I_{Herb} * I_{Fert}) + YST_k + \epsilon_{ijk} \tag{3}$$

Where MI_{ijk} is the MI value for each unique combination of measurement year (YST_k), installation and treatment. I_{Herb} and I_{Fert} are indicator values for each operational treatment, which constitutes a 2-way factorial design at each installation.

3.3 Results

MI for herbaceous vegetation in the LCP ranged from -0.145 to 0.203, and approximately 13 percent (27) of the 205 observations in the LCP were significantly spatially autocorrelated. MI in the UCPIE ranged between -0.144 and 0.13, and the proportion of significant observations for the UCPIE was slightly less than the LCP, with 12 percent (27) of 230 observations having significant autocorrelation. MI did not appear to be impacted by the different silvicultural treatments in either the LCP (Figure 2) or the UCPIE (Figure 3). Additionally, MI for any of the treatments did not appear to change with respect to time. The trends observed in Figure 2 and Figure 3 for herbaceous vegetation were confirmed by the ANOVA analysis (Table 2). The LCP results indicated that neither silvicultural treatment nor years since treatment significantly impacted the degree of spatial autocorrelation. In the UCPIE, treatment and years since treatment were also not significantly related to the magnitude of spatial autocorrelation. In both regions, the overall mean value for MI was significant (LCP, $F_{1,156} = 8.33$, $p_{0.05} = 0.004$; UCPIE, $F_{1,176} = 4.61$, $p_{0.05} = 0.033$).

MI trends among woody vegetation reflected those of herbaceous vegetation. Roughly 8 percent of observations were significant for woody vegetation for the LCP (16 of 203) and 9 percent for UCPIE (20 of 225). The range of MI values for woody vegetation were between -0.124 and 0.175 for the LCP, and between -0.116 and 0.156 for the UCPIE. As with herbaceous vegetation, there appeared to be no difference in MI values between silvicultural treatments or changes in values over time for the woody vegetation in either region (Figure 4, Figure 5). The ANOVA results were like those of the observed trends (Table 3) for woody vegetation within both regions. The effects of treatment or time were not significant factors for spatial autocorrelation in either the LCP or UCPIE, respectively. The overall mean trend was still significant among woody vegetation in both the LCP ($F_{1,154} = 17.99$, $p_{0.05} < 0.001$) and UCPIE ($F_{1,167} = 20.365$, $p_{0.05} < 0.001$) and is consistent with the trend of negative spatial autocorrelation found for herbaceous vegetation.

3.4 Discussion

Competing vegetation was found to be spatially autocorrelated in thinned loblolly pine stands. For both the LCP and UCPIE, the number of significant MI values was relatively low but was higher for herbaceous vegetation (12-13 percent) than woody vegetation (8-9 percent). Observing higher degrees of spatial autocorrelation among herbaceous vegetation was not surprising. Herbaceous vegetation is known to be highly sensitive to light availability, and differences in spatial autocorrelation may have occurred in response to increased light availability following thinning (Anderson and others 1969). Herbaceous vegetation growth is also more impacted by seasonal fluctuation, and emergence patterns during the growing season may also contribute to the presence of spatial autocorrelation. Additionally, light availability beneath the main canopy is altered during thinning, and patterns in the canopy may reflect spatial patterns in vegetation growth.

Mid-rotation silvicultural treatments strongly influence stand structure (Bailey and others 1989). Treatments such as row thinning also have an explicit spatial structure, and deterministic changes to stand structure systematically alter the distribution of site resources. It was anticipated these changes to stand structure would lead to a significant effect of mid-rotation silviculture on the spatial distribution of competing vegetation. However, treatments did not significantly impact spatial autocorrelation for either herbaceous or woody vegetation. For herbaceous vegetation, the need for increased light may reduce the influence of mid-rotation treatments on its spatial arrangement. All plots were thinned, which likely increased light availability within all plots along the same spatial pattern (i.e., within thinned rows). Effective broadcast applications of fertilizer and chemical herbicide should be uniformly distributed across space, and the resulting resource distribution should be uniform and promote consistent vegetation growth between treatment plots. Spatial autocorrelation among woody vegetation may be influenced by additional factors. Woody vegetation growth is not as seasonally influenced as herbaceous vegetation, and therefore changes in its spatial distribution over time may not be as easily observable. The thinning treatments in this study also reduced the amount of woody vegetation present within each stand, regardless of whether competition control was applied or not. Following thinning, woody vegetation growth did not ever recover to pre-treatment levels at any location whereas herbaceous vegetation was near pre-treatment levels within 4-years post-treatment at most installations (results not shown).

Even though no difference in spatial autocorrelation was found between treatments, there was an overall trend of significant, negative spatial autocorrelation. Although the proportion of significant MI values were low for both herbaceous and woody vegetation, the average spatial autocorrelation was strongly significant for either population. Negative spatial autocorrelation is generally rare in practice but has been shown to be associated with plant competitive interactions (Griffith 2019, Mead 1968). Negative spatial autocorrelation between individuals implies competition since characteristics of neighbors are dissimilar (Griffith 2019). For the subplot data, negative spatial autocorrelation suggests that surrounding plots have either greater or less competition than neighboring subplots. One potential explanation of the negative spatial autocorrelation among subplots is vegetation response to thinning treatments and light availability. If thin rows are oriented to favor increased light availability following thinning (i.e., North-South vs. East-West), then subplots within thin rows may have higher competing vegetation due to increased light availability relative to neighboring subplots located in shade dominated, non-thinned rows.

Another important consideration is the sampling design used to assess spatial autocorrelation. Competition for site resources occurs between individuals and should be used for modeling competitive interactions when possible (Burton 1993). However, density measures may be appropriate when production is described per unit of land area (Mack and Harper 1977). Here, only aggregate data at the subplot level is available. Although relative subplot locations still provide insight to the spatial distribution of understory vegetation, the spatial variation occurring at either finer or more coarse spatial resolutions is unable to be detected. The results of this analysis indicate that competing vegetation is spatially dependent among subplots, but the degree of spatial autocorrelation between individuals and at the plot level is not determined.

Accounting for spatial autocorrelation among competing vegetation at mid-rotation can be beneficial. By understanding the connection between silvicultural treatments and their effect on stand dynamics, practitioners will be more informed of the impact that spatial relationships have on site-specific stand development. The presence of spatial autocorrelation means that stand structure is not random and neighboring observations are not independent (Bullock and Burkhart 2005). Growth and yield models are often used to make predictions of future stand growth. When incorporated into yield models, spatial autocorrelation can increase the precision of future yield predictions by explaining the variation attributed to spatial relationships (Bullock and Burkhart 2005). Competing vegetation growth is generally variable and difficult to model (Liu and Burkhart 1994). Modeling competition to account for spatial autocorrelation may reduce model variability, resulting in more reliable estimates of understory growth. Updated estimates of competing vegetation are likely to be more suitable for use as a covariate within pine plantation growth and yield models. Improving the estimation of covariates associated with pine productivity will subsequently improve site specific management decisions.

3.5 Conclusions

Data from a long term, regional research field trial in the southeast U.S. was used to characterize the spatial dependence of competing vegetation in thinned loblolly pine stands. Both herbaceous and woody vegetation was found to be negatively spatially autocorrelated. Stands receiving a mid-rotation silvicultural treatment application, namely fertilization, chemical herbicide, and the combination of the two, did not show significant differences in the degree of spatial autocorrelation present. Competition for light is a primary driver of herbaceous vegetation growth, and increased light availability following thinning is likely contributing to the spatial distribution of herbaceous vegetation following thinning. Factors contributing to the spatial distribution of woody vegetation are less clear and may be impacted by silvicultural treatment at the time of application. When present, the effects of spatial autocorrelation can be used to adjust growth and yield models and increase the precision of forest growth estimates. Including spatial variation may also improve models of competing vegetation growth. Future research is needed to explore methods for incorporating spatial autocorrelation and improved estimates of competing vegetation into growth and yield models used for pine plantation management.

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3.7 Tables and Figures

Figure 3.1: (A) Map of mid-rotation treatment study installation locations across the southeast U.S., and (B) an example measurement plot layout for each treatment plot within an installation. Solid lines represent leave rows, dashed lines represent take rows, and circles represent competing vegetation subplot locations. Subplot locations within a measurement plot were standardized at each location but differed between installations. The ratio of subplots located between leave rows and within take rows was the same for every installation. Triangles represent Lower Coastal Plain installations; Circles represent Upper Coastal Plain / Piedmont installations.

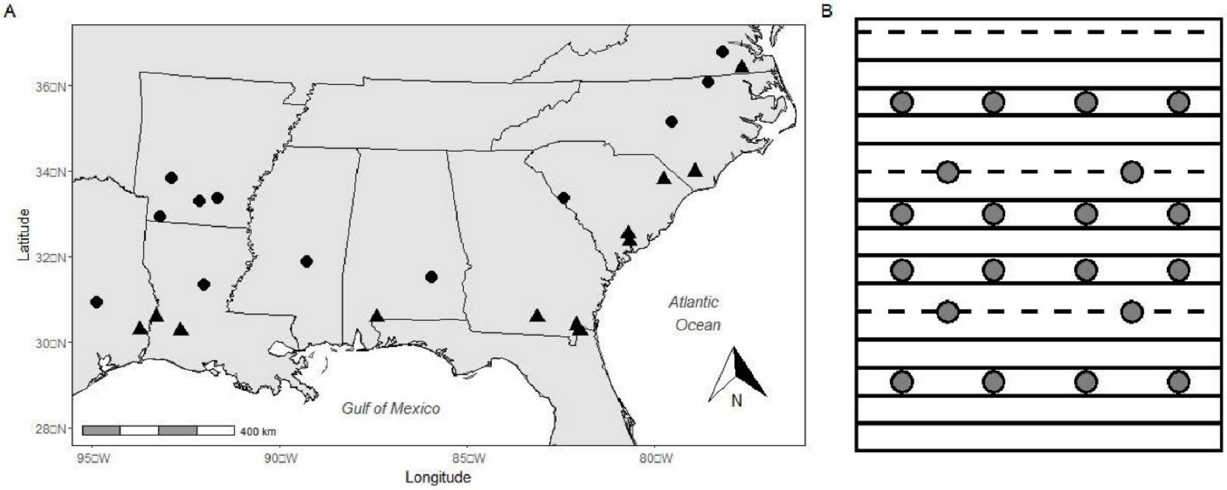

Table 3.1: Summary of average competing vegetation density by treatment in each physiographic region. Herbaceous vegetation was categorized as either Broadleaf, Andropogon, or other Grass during data collection. Values represent the mean across all subplot measurements collected and expanded to a per-acre basis.

		Herbaceous Density		Woody Density	
Region	Treatment	Groundcover (%)	Primary Vegetation	Crown Volume (ft^2 /acre)	Primary Species
Lower Coastal Plain	Thin	17.58	Broadleaf	68.30	*Ilex vomitoria*
	Thin + Herb	17.74	Broadleaf	44.71	*Ilex glabra*
	Thin + Fert	16.93	Broadleaf	73.02	*Ilex glabra*
	Thin + Fert + Herb	18.07	Broadleaf	76.46	*Ilex glabra*
Upper Coastal / Piedmont	Thin	16.55	Broadleaf	135.20	*Liquidambar styraciflua*
	Thin + Herb	12.35	Broadleaf	113.34	*Callicarpa americana*
	Thin + Fert	16.58	Broadleaf	112.97	*Liquidambar styraciflua*
	Thin + Fert + Herb	16.19	Broadleaf	130.55	*Liquidambar styraciflua*

Thin, thinning applied; Herb, chemical herbicide applied; Fert, fertilization applied

Figure 3.2: Distribution of Moran's I for herbaceous vegetation in the Lower Coastal Plain by treatment and measurement year (YST). Moran's I values were calculated for each installation, with a possible range of [-1,1]. The red line at zero indicates complete spatial randomness for a treatment by YST observation.

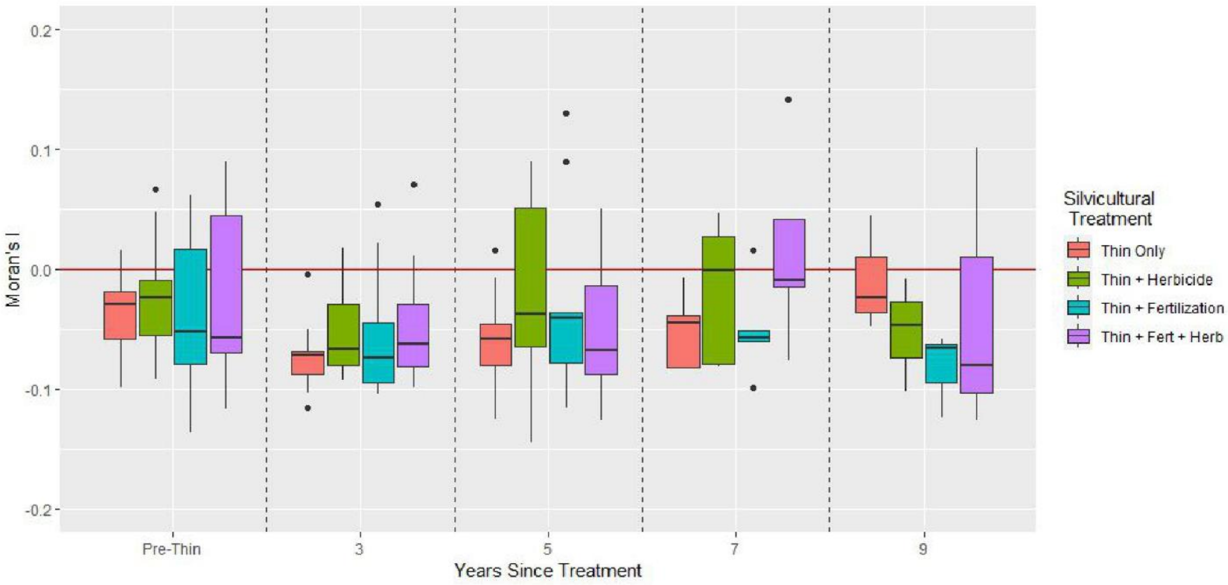

Figure 3.3: Distribution of Moran's I for herbaceous vegetation in the Upper Coastal Plain / Piedmont by treatment and measurement year (YST). Moran's I values were calculated for each installation, with a possible range of [-1,1]. The red line at zero indicates complete spatial randomness for a treatment by YST observation.

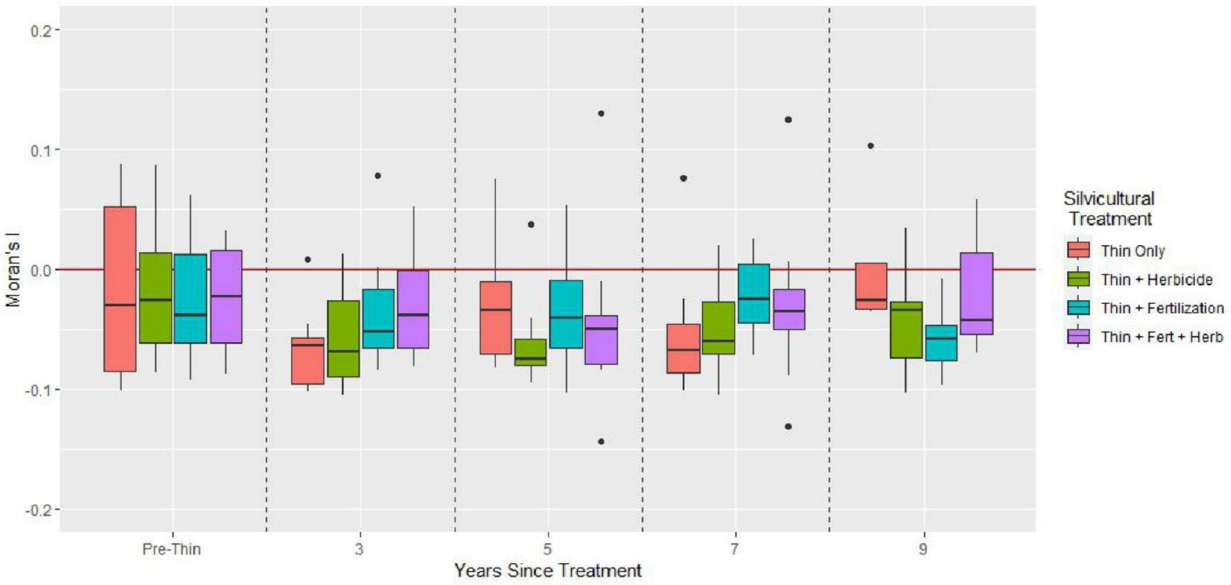

Table 3.2: Two-way repeated measures ANOVA results for herbaceous vegetation Moran's I. Results are presented for analyses conducted in two physiographic regions within the southeast U.S. Significance was considered at the 95-percent confidence level ($p \leq 0.05$).

Region	Factor	Sum of Squares	Degrees of Freedom	*F*-value	P(*p* > *F*)
Lower Coastal Plain	Intercept	0.029	1	8.33	0.004
	Herb	0.005	1	1.39	0.239
	Fert	0.000	1	0.00	0.978
	YST	0.026	4	1.85	0.122
	Herb*Fert	0.000	1	0.03	0.857
	Residual	0.548	156		
Upper Coastal / Piedmont	Intercept	0.012	1	4.61	0.033
	Herb	0.002	1	0.66	0.417
	Fert	0.000	1	0.11	0.736
	YST	0.018	4	1.70	0.152
	Herb*Fert	0.001	1	0.46	0.496
	Residual	0.468	176		

YST, Years Since Treatment; Herb, Herbaceous vegetation control applied; Fert, Fertilization applied

Figure 3.4: Distribution of Moran's I for woody vegetation in the Lower Coastal Plain by treatment and measurement year (YST). Moran's I values were calculated for each installation, with a possible range of [-1,1]. The red line at zero indicates complete spatial randomness for a treatment by YST observation.

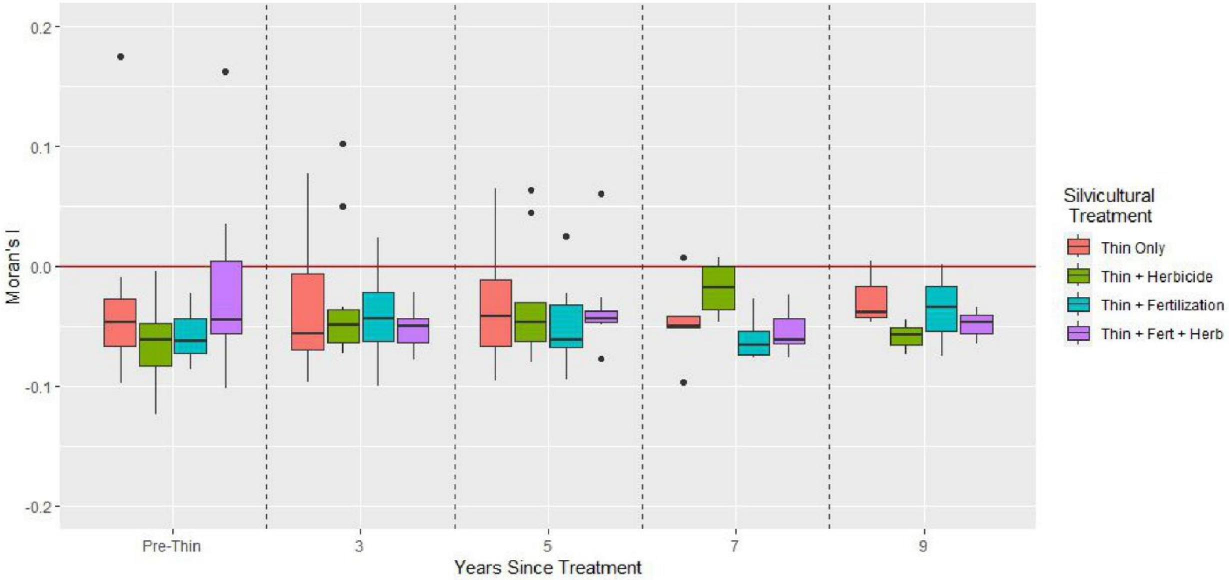

Figure 3.5: Distribution of Moran's I for woody vegetation in the Upper Coastal Plain / Piedmont by treatment and measurement year (YST). Moran's I values were calculated for each installation, with a possible range of [-1,1]. The red line at zero indicates complete spatial randomness for a treatment by YST observation.

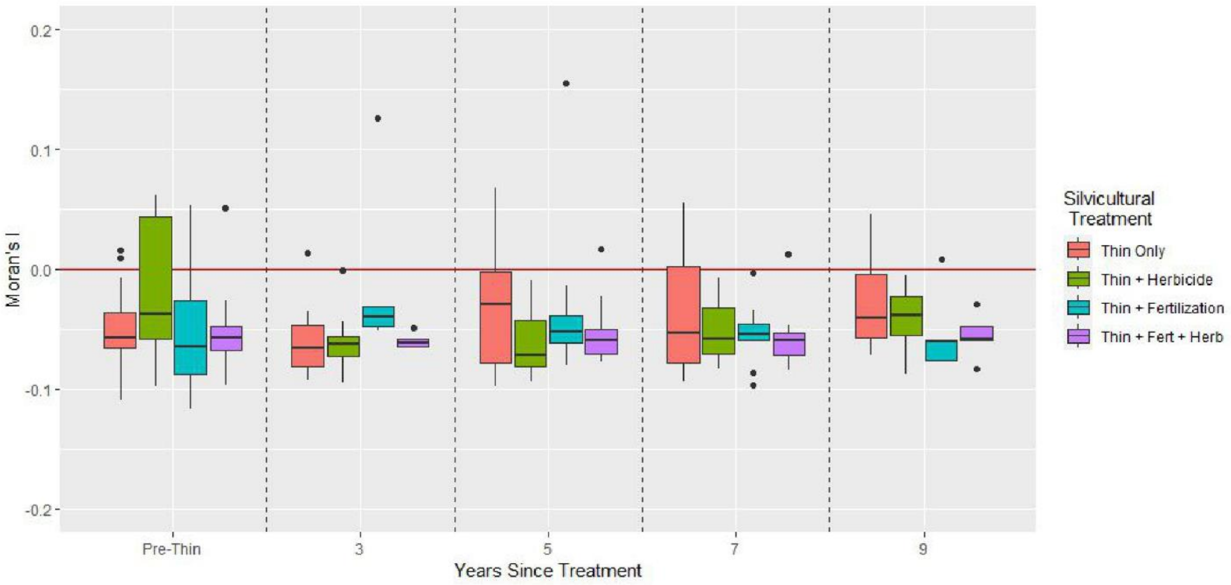

Table 3.3: Two-way repeated measures ANOVA result for woody vegetation Moran's I. Results are presented for analyses conducted in two physiographic regions within the southeast U.S. Significance was considered at the 95-percent confidence level ($p \leq 0.05$).

Region	Factor	Sum of Squares	Degrees of Freedom	F-value	P($p > F$)
Lower Coastal Plain	Intercept	0.036	1	17.99	0.000
	Herb	0.001	1	0.43	0.513
	Fert	0.005	1	2.29	0.132
	YST	0.001	4	0.17	0.952
	Herb*Fert	0.004	1	1.81	0.181
	Residual	0.309	154		
Upper Coastal / Piedmont	Intercept	0.038	1	20.92	0.000
	Herb	0.000	1	0.29	0.590
	Fert	0.000	1	0.05	0.823
	YST	0.002	4	0.21	0.931
	Herb*Fert	0.000	1	0.26	0.613
	Residual	0.307	171		

YST, Years Since Treatment; Herb, Herbaceous vegetation control applied; Fert, Fertilization applied

CHAPTER 4

MODELING WOODY AND HERBACEOUS COMPETING VEGETATION GROWTH IN POST-THIN INTENSIVELY MANAGED LOBLOLLY PINE PLANTATIONS [3]

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Abstract

Competing vegetation impacts the growth and yield of intensively managed pine plantations. Control treatments are often applied throughout a rotation to reduce competition for site resources by non-crop vegetation. Control treatments typically release site resources back to crop trees for a few years following treatment, when competing vegetation may regrow. When competing vegetation continues to grow at a given site following treatment, it is likely to continue limiting the site resources available to crop tree species. Measuring competing vegetation following treatment can provide insight to the limiting relationship between non-crop vegetation and crop tree growth. Explicit growth models of competing vegetation volume across times could be used to improve pine tree growth and yield models. As a biological entity, competing vegetation growth is dynamic and explicit growth models of competing vegetation volume over time are desired. In this research, a long-term study was used to fit competing vegetation growth models for woody and herbaceous vegetation in mid-rotation loblolly pine stands in the southeast U.S. Models were fitted to include the effect of chemical herbicide treatment, which was found to improve estimation relative to base models. A locally defined asymptote allows for site-specific information to be used for predicting stand-level competing vegetation growth, and further improved model fit when compared to a globally parameterized model.

4.1 Introduction

Competing vegetation limits the productivity of intensively managed pine forests in the southeast U.S. (Clason 1978; Tiarks and Haywood 1986; Glover et al. 1989; Miller et al. 1991a; Fortson et al. 1996). Sites across the region are often resource deficient, resulting in forests that produce timber at rates lower than their potential and require intensive management activities to ameliorate site resources (Borders and Bailey 2001; Fox et al. 2007b). The presence of non-crop species impedes pine growth by placing additional stress on the resources available to crop trees (Allen and Albaugh 2000). Vegetation control treatments are commonly used to allocate resources back to crop trees, resulting in increased pine growth (Tiarks and Haywood 1986; Miller et al. 1991a; Fortson et al. 1996). The removal of both woody and herbaceous vegetation at various stages during stand development has a considerable impact on pine growth and yield throughout a rotation (Tiarks and Haywood 1986; Glover et al. 1989; Miller et al. 1991a; Fortson et al. 1996).

Pine growth following early vegetation control has been extensively monitored in the southeast U.S.. Herbaceous vegetation is typically the most significant competitor at stand establishment (Lauer and Glover 1998). Early removal of competing vegetation decreases mortality and ensures the successful establishment of juvenile pines as the dominant species for a given stand (Lauer and Glover 1998, Jokela et al. 2000). Complete removal also increases productivity in juvenile stands, with the benefits of early removal lasting up to 15 years post-treatment (Miller et al. 2003a,b). Because of its impact on survival and productivity, early vegetation control is widely recognized as one of the most important intensive management activities at stand establishment (Fox et al. 2007a). Non-crop woody vegetation is typically considered the primary competitor following stand establishment (Haywood and Tiarks, 1990).

Vegetation control in established stands at mid-rotation compliments the effect of earlier silvicultural treatments, and significantly increases pine productivity in successive years by releasing site resources from competing vegetation (Oppenheimer et al. 1989, Forston et al. 1996, Albaugh et al. 2012). The overall impact of competing vegetation on pine yields can vary depending on the intensity of vegetation control, species composition, and the abundance of competitors (Albaugh et al. 2012). Complete and sustained control applied in a 15-year-old pine stand was shown to increase productivity for up to 8 years following treatment, with total volume increases of up to 50 ft^2 ac^{-1} (Fortson et al. 1996). Pine growth response following operational herbicide applications is less pronounced than stands receiving complete control, but cumulative volume continues to increase up to 8 years following treatment (Oppenheimer et al. 1989, Fortson et al. 1996; Blazier et al. 2017). The effects of operational, mid-rotation vegetation control may also be confounded by additional treatments such as fertilization and thinning (Albaugh et al. 2012, Gyawali and Burkhart 2015, Liechty and Fristoe 2013).

Growth and yield models are used to predict future stand conditions and competition indices have been developed to incorporate competitive interactions within model systems (Burkhart and Sprinz 1984, Burton 1993). Competition indices have been favored as the primary method for including competitive interactions in yield models, as they describe complex system dynamics in a simplified manner (Burton 1993). For stand-level estimates of pine growth, early competition indices focused on adjusting estimates relative to the presence of non-crop, deciduous hardwood competition. Burkhart and Sprinz (1984) fitted a system to predict the growth of naturally regenerated pine on old-field and cutover sites, and incorporated hardwood competition by partitioning total basal area into hardwood and pine components. Smith and Hafley (1986) presented a method for modelling hardwood development as a proportion of total stand basal area. Shiver and Brister (1996) and Martin and Brister (1999) modeled the growth of merchantable volume in pine plantations to account for the proportion of hardwood basal area. Knowe et al. (1992a) included hardwood basal area as a predictor of pine basal area and diameter distribution.

Accounting for hardwood basal area has previously been effective for adjusting stand yields in pine plantations, but changes in silvicultural treatments have altered competing vegetation development in intensively managed pine plantations. Controlling non-crop vegetation during the early stages of stand development is necessary for ensuring high rates of juvenile crop tree survival (Fox et al. 2007a). Competition control treatments, primarily via the use of herbicides, applied at the time of planting and subsequently as needed may result in a sustained reduction in the abundance of non-crop woody vegetation during later stand development stages. Thinning is a common practice at mid-rotation which provides intermittent cash flows and increases the diameter distribution of residual stems to favor higher-valued product classes (Amateis et al. 1989, Hasenauer et al. 1997). Non-crop vegetation may be either removed or mechanically altered during thinning treatments and the residual density of non-crop vegetation can be reduced relative to pre-treatment levels (Young et al. 2023). Mid-rotation competition control through herbicide application may also be applied immediately following thinning to remove any remaining non-crop vegetation.

Modelling the stand dynamics resulting from current intensive silvicultural management requires additional effort, and improvements to the methods used to describe competitive interactions are necessary. Burton (1993) proposed several limitations inherent to static competition indices for individual tree models, some of which extend to stand level models. Static indices represent a single instance of competition and assume a constant level of interaction between crop and non-crop vegetation. Static indices have previously been used to account for competition in plantation pine stands (Burkhart and Sprinz 1984; Shiver and Brister 1996; Knowe et al. 1992) but do not account for changes in competitive interactions over time. Assuming a constant interaction over time may lead to spurious conclusions, as the response of crop and non-crop vegetation can vary greatly between functional groups or individual species (Burton 1993). Additionally, some vegetation groups or species may be abundant but do not impose much limitation on crop-tree growth (Burton 1993). In stands where the abundance of hardwood competition is minimal, competition indices based on the proportion of basal area may not be indicative of local competitive interactions. Secondary functional groups, such as shrubs and herbaceous vegetation species, may assume the role of primary competitor. Models accounting for different vegetation groups or species have been developed (Knowe et al. 1992b) that use additive measures to explain the cumulative impact of multiple vegetation groups on crop tree growth. Burton (1993) warns against making additivity assumptions, since the effects of multiple species on crop growth are dynamic.

Modelling the growth of different competing vegetation functional groups may improve our ability to explain competitive interactions between pine trees and non-crop vegetation in southern pine plantations. Pine tree growth responses to common silvicultural practices throughout a rotation are well documented but competing vegetation dynamics have not been extensively studied. Using remeasurement data to model competing vegetation growth provides an estimation of long-term stand development relative to both pine and competing vegetation. Modeling growth for multiple functional groups allows for complex interactions over time to be assessed in the development of robust, dynamic competition indices. Understanding how vegetation groups grow throughout a rotation, especially in response to intensive silvicultural treatments, is a first step towards improving growth and yield to account for the presence of competing vegetation.

The goal of this study was to fit growth and yield models of woody and herbaceous vegetation at mid-rotation for two physiographic regions in the southeast U.S.. Competing vegetation growth was modeled following thinning and a one-time application of fertilization and chemical herbicide. Mid-rotation treatments often result in growth responses that are less than at early development stages, and there is a need to understand how non-crop vegetation responds to treatment during the later stages of stand development. We hypothesize that vegetation growth will increase following mid-rotation treatment, followed by a steady decline in growth after reaching a maximum yield, due to the increase in light availability and nutrients following treatment and prior to crown closure. We also hypothesize that vegetation growth trajectories will differ significantly by silvicultural activity, namely fertilization and chemical herbicide, since silvicultural activity will target various growth responses between species.

4.2 Methods

4.2.1 Study Design

A long-term study administered by the University of Georgia Plantation Management Research Cooperative (PMRC) was used for this research. The PMRC Mid-rotation Treatment Study consisted of 24 loblolly pine installations distributed between the Lower Coastal Plain (LCP) and the combined Upper Coastal Plain & Piedmont (UCPIE) regions of the southern United States (Figure 4.1). Each installation reflected a unique combination of pre-treatment criteria including pre-treatment basal area, pre-treatment site-index, and post-thin basal area. Four silvicultural treatment plots were established at each location: thinning only, thinning with chemical herbicide, thinning with fertilization, and thinning with chemical herbicide and fertilization. Application rates were intended to reflect common operational practice at the time of study establishment and were applied in the fall immediately following thinning (Table 4.1). For each a treatment plot, a 0.5-acre measurement plot was also established and included both pine and competing vegetation measurements. Competing vegetation measurements were collected using a systematic subsample of 20, 4-ft radius subplots within each measurement plot. Herbaceous vegetation measurements were an ocular estimate of the percent groundcover occupied by herbaceous and broadleaf weed species. Stem count, mean Ht by species, and mean crown width by species were recorded for small arborescent vegetation (< 2 inches dbh). Ht and dbh were recorded for large arborescent vegetation (> 2 inches dbh). Subplots were measured before thinning and in the spring two years following treatment with additional measurements every two years thereafter. For this analysis, all 12 installations in each region had been collected for at least 4 measurement periods resulting in a maximum of 48 plots available in both the LCP and UCPIE regions (Table 4.2; Table 4.3). A detailed description of the MRT site characteristics, experimental design, and measurement plots is found in Young et al. (2023).

4.2.2 Modeling

Estimating Competing Vegetation

To model competing vegetation growth across the southeast U.S., vegetation was categorized as either herbaceous or woody. Herbaceous vegetation growth was assessed using the percent total herbaceous groundcover (HGC), calculated by combining the percent groundcover occupied independently by each herbaceous and deciduous species. Woody vegetation growth was modeled using total crown volume (WCV). WCV was calculated using the formula for cylindrical volume, which assumes that crown shape is generally decurrent for non-crop arborescent species in southern pine plantations. Each of these variables were available using remeasurement data from the MRT study, with measurements for each vegetation group available up to 10 years post-thin. To account for differences in species diversity and site characteristics between regions, each of the vegetation groups were modeled separately for the LCP and UCPIE.

Base Model

A flexible model which could characterize competing vegetation growth in response to operational silvicultural treatment at mid-rotation was desired. Knowe et al. (1997) proposed that a model of herbaceous vegetation growth following a major disturbance should reflect a period of initial growth to an asymptote which occurs within the first 10 years post-disturbance, with a consistent decline thereafter. Growth trajectories for herbaceous and woody vegetation from the MRT study are displayed in Figure 4.2 and Figure 4.3, respectively. Since an initial observation of competing vegetation abundance immediately post-thin was not collected, it was assumed that vegetation was not present following treatment. Herbaceous vegetation growth in both the LCP and UCPIE loosely displayed the pattern described by Knowe et al. (1997), especially in plots which received no chemical herbicide application (Figure 4.2). Woody vegetation growth patterns were more pronounced than herbaceous vegetation and experienced a greater reduction in vegetation abundance following the chemical herbicide application (Figure 4.3). The growth equation proposed by Knowe et al. (1997) was used to model mid-rotation competing vegetation in the southeast U.S. The proposed base model was:

$$C = \alpha YST^{\theta} \exp(\beta YST) + \epsilon \tag{1}$$

where C is the competing vegetation measurement, YST is the number of years since treatment, and $\{\alpha, \theta, \beta\}$ are the asymptote, shape, and slope parameters to be estimated. Equation 1 has a few desirable qualities. The three-parameter form is flexible enough to accommodate variation in the magnitude and duration of growth between regions or treatments. Additionally, the use of more than one parameter facilitates the calculation of explicit anamorphic or polymorphic projection equations which can be used to project competing vegetation growth between any two time points. The base model was fitted as a global model, which is defined by a single estimate of each parameter using the available data.

Response to Silviculture

Because growth trajectories varied following the application of silvicultural treatment, the base model was modified to include silvicultural treatment effects. Effects were modeled using an indicator variable approach to modify growth relative to either the rate, shape, or asymptote parameters. Indicator variables take on the value of either 0 or 1, depending on whether the treatment was applied or not. Modeling treatment effects as indicator variables allows for flexible parameterization in response to treatment combinations and allows the model to differentiate responses as either Type I or Type II (Mason and Milne, 1999; Snowdon 2002). To better understand how silvicultural treatments impact competing vegetation growth in the southeast U.S., several models were proposed which included indicator variables for the post-thin chemical herbicide and fertilization treatments (Table 4.4). Separate parameters were fitted for herbaceous and woody vegetation groups. Fitted models were then compared to determine the best model for characterizing the growth response of each competing vegetation group.

In addition to estimating a set of global parameters for the treatment effects model, the model was also fitted by estimating the asymptote as a local variable. Local variable models estimate a separate parameter for each plot in the available data, resulting in a localized prediction of the independent variable. Fitting one or more parameters as a local variable accounts for variation in stand conditions between plots by incorporating site-specific information into the model, which can increase precision by reducing model error. The starting value for each of the local parameters was the competing vegetation abundance in the first measurement period (2 years post-treatement). By localizing the asymptote in the treatment effects model, predicted growth becomes site-specific relative to the regionally averaged treatment responses.

Model Fitting and Validation

Parameters were estimated with Maximum Likelihood Estimation using the R Statistical Computing Environment (R Core Team). Models were validated using a 5-fold cross validation and compared using model root mean square error (RMSE), Akaike information criteria (AIC), mean difference (MD), and mean absolute difference (MAD).

4.3 Results and Discussion

Fit statistics comparing the proposed treatment effects models fitted to the herbaceous vegetation data from both the LCP and UCPIE are presented in Table 4.5. Model form 8 provided the best overall fit in both regions, which includes a treatment effect modifier for chemical herbicide application on the asymptote and rate parameters. Equation 8 was then used to estimate the local-variable equations, and concurrently improved model fit in both regions relative to the global parameter estimates for the base and treatment effects models (Table 4.6). A comparison of the averaged growth trajectories for each region, and the model residuals associated with the local-variable equation, are illustrated in Figures 4.4 and 4.5, respectively. Parameter estimates for the global, treatment effects, and local-variable models are provided in Table 4.7. The local prediction equation for herbaceous vegetation including the chemical herbicide treatment in the LCP was:

$$CV_{H_{LCP}} = \left(CV_{H_1} * 0.680713^{I_H}\right) YST^{0.699971} e^{-0.26236 * 0.572148^{I_H}} \tag{10}$$

The local prediction equation for herbaceous vegetation in the UCPIE was:

$$CV_{H_{UCP}} = \left(CV_{H_1} * 0.913697^{I_H}\right) YST^{-0.02973} e^{-0.04048 * -1.28312^{I_H}} \tag{11}$$

Chemical herbicide application had a significant impact on post-thin herbaceous vegetation growth. The herbaceous vegetation models for the LCP (Equation 10) and UCPIE (Equation 11) incorporated the treatment effect by modifying both the asymptote and rate parameters, suggesting the growth rate and maximum cover potential of herbaceous vegetation is impacted by mid-rotation treatment. Incorporating the treatment effect modifiers resulted in a greater than 50% decrease in RMSE for the LCP and UCPIE when compared to the base model without treatment effects (Table 4.6). Additionally, the treatment effect modifiers increased R^2 for each region relative to the base models. In the few studies that have measured herbaceous vegetation, percent cover has been shown to recover to pre-treatment levels following control and a similar trend was observed in this study (Blinn et al. 2011, Albaugh et al. 2012). Herbaceous vegetation is greatly influenced by the availability of light, and any additional light introduced post-thin is likely to aid in the resurgence of herbaceous vegetation following treatment (Anderson et al. 1969). The chemical mixture used to treat stands was also targeted towards hardwood and other woody vegetation. These factors help explain the herbaceous response pattern modeled here, which are consistent with previously reported patterns of herbaceous vegetation growth (Anderson et al. 1969, Young et al. 2023). Improvements in model fit for treated stands indicate that accounting for the chemical herbicide effect is an important component of modeling post-thin herbaceous vegetation in treated stands.

Treatment effect models fitted to the woody vegetation data are compared in Table 4.8. Model form 2 resulted in the best model fit in both regions, which includes a treatment effects modifier on the asymptote parameter only. Local-variable equations fitted using Equations 2 reduced model error and improved fit compared to the global base and treatment effects models (Table 4.9). The growth trajectories and model residuals for the local-variable equations are displayed in Figures 4.6 and 4.7, and the parameter estimates for both global models and the local-variable equations are in Table 4.10. The local prediction equation for woody vegetation in the LCP was:

$$CV_{W_{LCP}} = \left(CV_{W_1} * 0.128155^{I_H}\right) A^{2.882365} e^{-0.61648} \tag{12}$$

The local prediction equation for woody vegetation in the UCPIE was:

$$CV_{W_{UCP}} = \left(CV_{W_1} * 0.325099^{I_H}\right) A^{0.712224} e^{-0.003505} \tag{13}$$

Woody vegetation models for each region included a treatment modifier on the asymptote parameter and implies that changes in the maximum amount of woody vegetation abundance are impacted by the post-thin chemical herbicide application. Mid-rotation chemical herbicide reduced woody vegetation crown volume to < 15 ft^2 ac^{-1} in both regions (Figures 4.3) and is reflected in the parameter values for the treatment effect models (Table 4.10). Including the treatment effect parameter reduced the model RMSE in the LCP from 28.58 to 25.12 and from 41.31 to 32.16 in the UCPIE and increased the R^2 value from 0.02 to 0.26 in the LCP, and from 0.06 to 0.42 in the UCPIE (Table 4.9). Including the treatment effect resulted in greater improvement to the woody vegetation models compared to the herbaceous models and demonstrates that chemical release treatments used in this study are an effective strategy for removing woody vegetation. Releasing established pine plantations from woody competition at mid-rotation is an important silvicultural activity for increasing pine productivity and is a necessary component for modeling woody development in treated stands (Oppenheimer et al. 1989, Forston et al. 1996, Leichty and Fristoe 2013).

Local-variable equations improved the model fit and residual distribution in all instances. These equations, which can be robust for modeling site-specific growth curves and responses to silvicultural treatment, may increase the precision of model estimates. For both herbaceous and woody vegetation models, the asymptote parameter was selected as the local variable. For the base model used in this study, the asymptote parameter reflects the maximum cover potential of a site and acts as an indicator of site quality for competing vegetation growth (Knowe et al. 1997). Here, the asymptote is defined as the percent cover in the second growing season following treatment and thus reflects at least some measure of post-thin response of a stand's competing vegetation. This allows for an observed or estimated value of stand volume to be substituted for the parameter value and thus providing a site-specific prediction of vegetation abundance. Site-specific prediction helps managers make informed decisions at a finer spatial resolution and increases the effectiveness of resource amelioration for a given site.

Fitting the herbaceous treatment effect models using a locally defined asymptote reduced RMSE from 17.48 to 7.13 in the LCP and from 22.75 to 7.86 in the UCPIE (Table 4.6). The local-variable method also substantially improved the performance of woody vegetation models (Table 4.9). RMSE was reduced from 28.58 to 18.72 in the LCP and from 41.31 to 22.15 in the UCPIE, and the model R^2 in the LCP increased from 0.26 to 0.58 and from 0.42 to 0.72 in the UCPIE. A major obstacle for modeling competing vegetation growth in mid-rotation stands is the variation in competing vegetation abundance between sites. Fitting growth models on data with relatively large variation may result in models which have little or no practical importance for stand management. Utilizing a method that accounts for the implicit differences in stand conditions, effectively describes local growth trends, and increasing the precision of estimation may provide a practical solution to help improve the site-specific estimation of competing vegetation growth and yield. The improvements in model performance indicate that including a local-parameter is important for capturing site-specific growth trends when highly variable differences in stand growth are observed. The local-variable models were effective for capturing differences in site growth, as well as the site responses to the chemical herbicide application. The local variable equations fitted in this study illustrate the importance of accounting for site-specific variation when modeling growth, and additional consideration should be given to novel methods which incorporate additional site information in the future.

The models presented in this study describe competing vegetation growth relatively well, but some limitations persist. The resulting mean difference values were negative for herbaceous vegetation in the LCP, and for the woody vegetation in both regions (Table 4.6, Table 4.9), which indicates a negative bias in the estimated values. Bias correction may be done analytically, but initial consideration of the underlying data may be pertinent. Extreme variation in the herbaceous and woody vegetation growth is likely to lead to imprecise estimation, and fit statistics calculated uncharacteristic or exaggerated growth trajectories may lead to estimation bias. Given that functional groups were defined based on the study design and using the best available measured variables, it is likely the vegetation groups used may not be well-defined for modeling. Further research assessing functional groups or individual species which are potentially more suitable for modelling stand growth is warranted. For models to be useful in decision making, stand predictions need to be calculated simultaneously with predictions of pine plantation growth. The models presented here are only related to competing vegetation growth. Identifying linkages between different vegetation groups commonly associated with intensively managed forests provides a better understanding of stand dynamics throughout a rotation.

4.4 Conclusions

Herbaceous and woody vegetation growth in post-thin, mid-rotation pine plantations was modeled for two regions in the southeast U.S. Both vegetation groups were significantly impacted by a one-time chemical herbicide application, and the resulting models included a treatment effect modifier to account for response to silvicultural treatment. Treatment effect models with a locally defined variable greatly improved model fit and are a convenient solution to account for inherent differences in stand conditions. Ultimately, competing vegetation growth should be predicted concurrently with pine plantation growth and yield to describe site-specific stand dynamics.

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4.6 Tables and Figures

Figure 4.1. Map of Plantation Management Research Co-operative Mid-Rotation Study (MRT) installations. Installation locations are distributed evenly between the Lower Coastal Plain and combined Upper Coastal Plain / Piedmont physiographic regions.

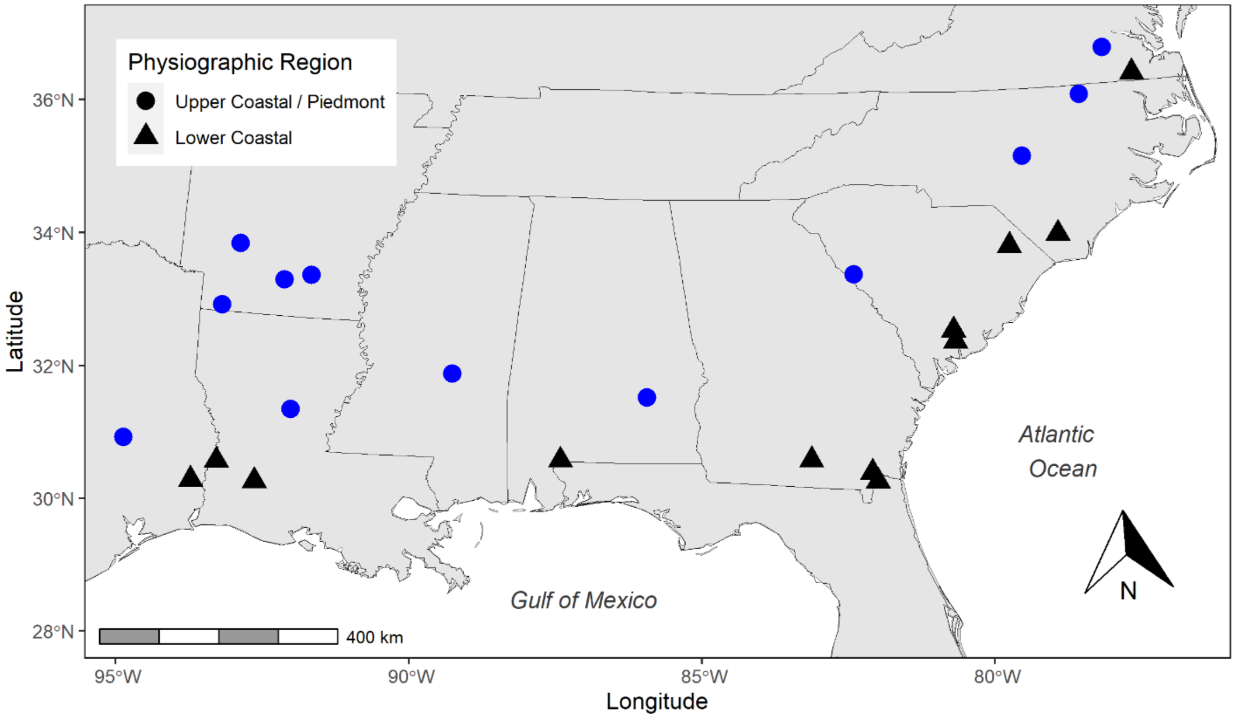

Table 4.1. Silvicultural treatments applied at mid-rotation. Treatment prescriptions were identical for both Lower Coastal Plain and Upper Coastal Plain / Piedmont physiographic regions.

Treatment	Description
Thin Only (T)	5th row thinning, with free thinning between rows to a residual basal area (BA) of either 50, 70 or 90 ft^2 ac^{-1}
T + Fertilization (F)	225 lb ac^{-1} of N plus 25 lb ac^{-1} P with additional nutrients as needed, applied in either fall or spring following thinning.
T + Chemical Herbicide (H)	3 oz glyphosate and 3 oz triclopyr mixed with 36 gal ac^{-1} of water in the fall following thinning. Follow up applications were a variable rate of triclopyr mixed with bark oil as needed.
T + F + H	Joint application of the individual thinning, fertilization, and chemical herbicide treatments.

Table 4.2. Regionally averaged percent groundcover occupied by herbaceous vegetation for the Thin (T), Thin + Fertilization (F), Thin + Chemical Herbicide (H), and T + F + H treatments. Pre-treatment measurements were collected prior to thinning on all plots.

			Silvicultural Treatment (%, *SE*)			
Region	Years Since Treatment	Plots (*n*)	T	T + F	T + H	T + F + H
Lower Coastal Plain	Pre-Treatment	48	17.6 (*4.8*)	17.7 (*4.6*)	16.9 (*5.5*)	18.1 (*5.1*)
	2	48	45.6 (*6.0*)	49.5 (*5.3*)	33.2 (*4.7*)	32.2 (*4.5*)
	4	48	43.9 (*5.2*)	47.2 (*5.4*)	38.6 (*6.1*)	39.9 (*4.9*)
	6	48	34.3 (*4.7*)	30.8 (*4.8*)	34.6 (*4.9*)	39.8 (*4.4*)
	8	40	34.8 (*2.2*)	28.7 (*1.4*)	42.2 (*2.3*)	33.8 (*2.1*)
	10	20	52.8 (*3.2*)	45.9 (*1.7*)	53.4 (*8.5*)	57.1 (*3.7*)
Upper Coastal Plain / Piedmont	Pre-Treatment	48	16.6 (*2.6*)	12.4 (*2.4*)	16.6 (*2.3*)	16.2 (*3.7)*
	2	48	48.5 (*6.4*)	44.6 (*7.7*)	37.7 (*7.3*)	38.3 (*7.5*)
	4	48	46.8 (*5.7*)	49.4 (*7.6*)	52.4 (*6.1*)	51.8 (*7.4*)
	6	48	43.0 (*5.7*)	40.7 (*6.4*)	50.3 (*6.0*)	51.1 (*6.0*)
	8	40	37.4 (*4.9*)	33.1 (*5.8*)	49.8 (*6.7*)	46.8 (*7.5*)
	10	24	50.2 (*9.7*)	46.1 (*10.3*)	54.7 (*10.5*)	46.5 (*9.6*)

Table 4.3. Regionally averaged crown volume of woody and shrub vegetation for the Thin (T), Thin + Fertilization (F), Thin + Chemical Herbicide (H), and T + F + H treatments. Pre-treatment measurements were collected prior to thinning on all plots.

			Silvicultural Treatment (m^3, *SE*)			
Region	Years Since Treatment	Plots (*n*)	T	T+F	T+H	T + F + H
Lower Coastal Plain	Pre-Treatment	48	58.46 (*9.51*)	39.7 (*8.64*)	44.98 (*9.4*)	48.94 (*10.16*)
	2	48	31.22 (*4.65*)	25.3 (*5.93*)	1.41 (*0.48*)	1.92 (*0.8*)
	4	48	45.95 (*9.69*)	53.17 (*9.78*)	5.37 (*1.22*)	4.84 (*1.38*)
	6	48	48.24 (*10.57*)	46.94 (*11.25*)	12.78 (*3.79*)	22.81 (*11.43*)
	8	40	25.41 (*5.33*)	33.53 (*11.17*)	9.06 (*4.11*)	6.61 (*1.39*)
	10	20	27.61 (*12.31*)	44.97 (*5.33*)	33.22 (*8.73*)	50.17 (*9.64*)
Upper Coastal Plain / Piedmont	Pre-Treatment	48	86.98 (*18.3*)	53.99 (*12.05*)	72.99 (*13.27*)	80.33 (*10.04*)
	2	48	38.2 (*5.09*)	37.13 (*9.42*)	5.97 (*2.24*)	2.45 (*0.64*)
	4	48	54.7 (*8.46*)	60.85 (*8.57*)	6.68 (*2.39*)	14.09 (*5.48*)
	6	48	73.83 (*13.06*)	71.29 (*8.64*)	15.64 (*4.81*)	20.11 (*4.72*)
	8	40	86.09 (*16.15*)	73.94 (*14.65*)	20.1 (*4.89*)	138.7 (*102.86*)
	10	24	76.76 (*8.94*)	73.31 (*36.3*)	16.28 (*5.37*)	39.05 (*23.27*)

Figure 4.2. Post-thin herbaceous vegetation growth observed on MRT installations. Trendlines are categorized by region and plots having received a chemical herbicide application following thinning.

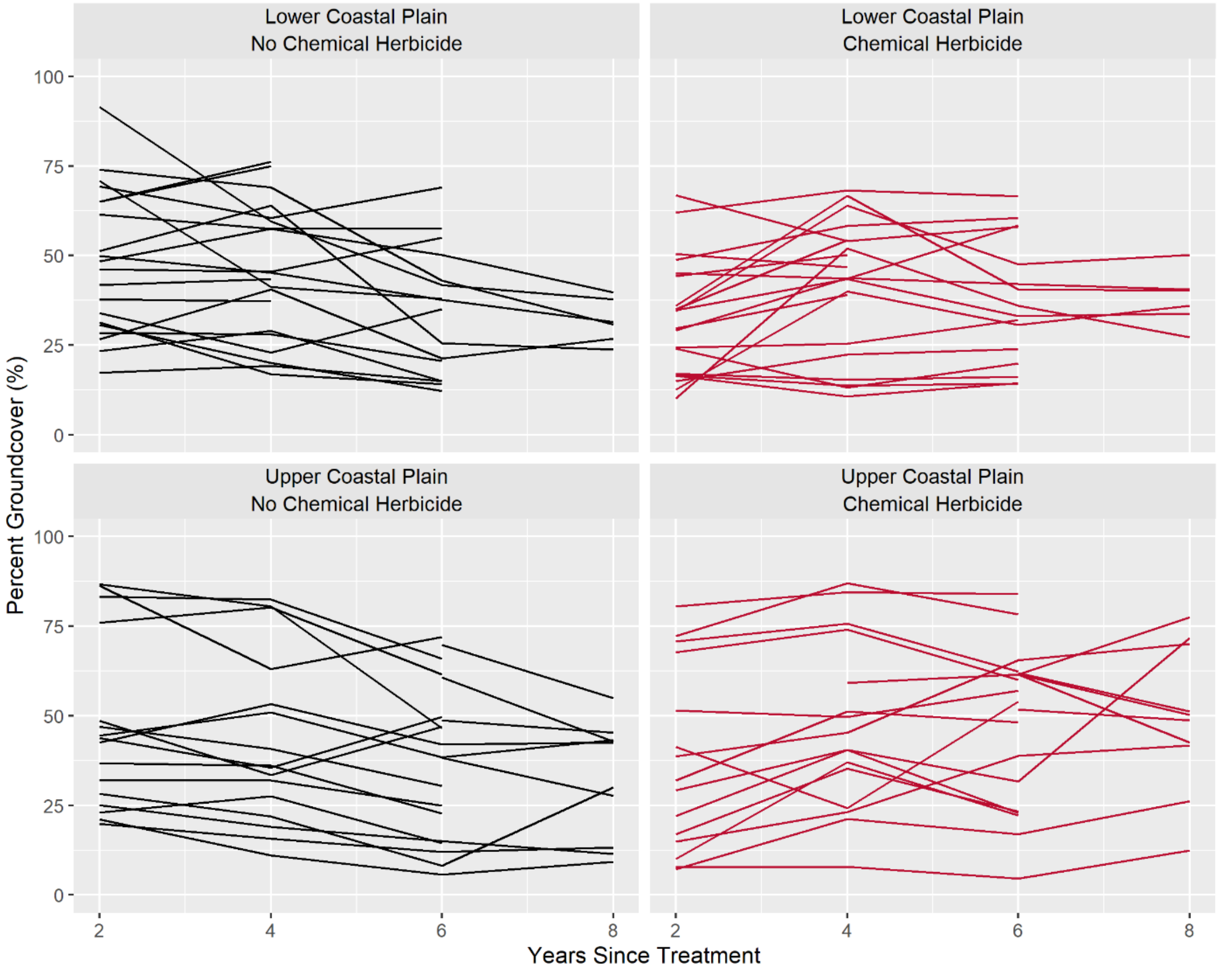

Figure 4.3. Post-thin woody and shrub vegetation growth observed on MRT installations. Trendlines are categorized by region and plots having received a chemical herbicide application following thinning.

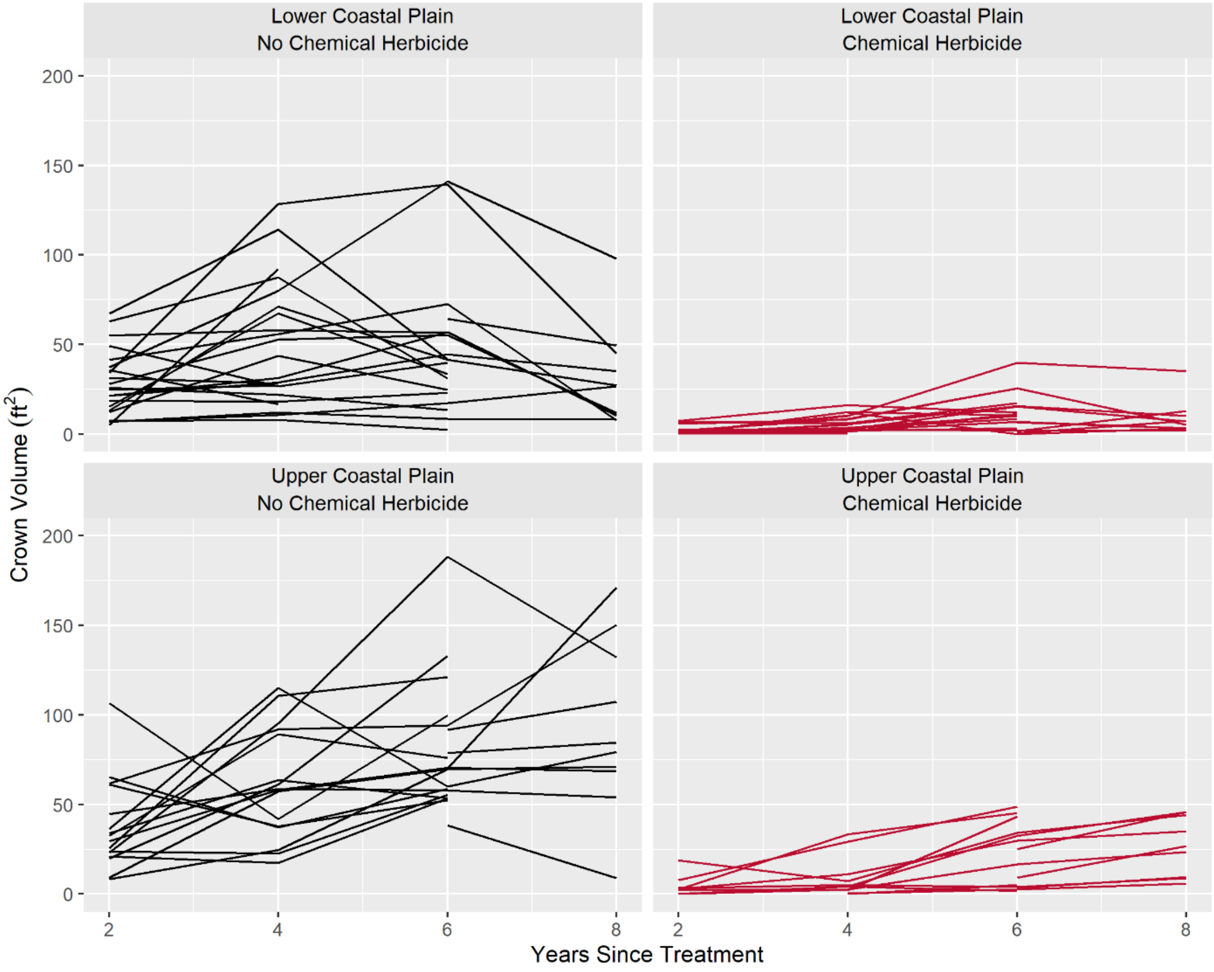

Table 4.4. Proposed growth functions for modelling competing vegetation growth in mid-rotation southern pine plantations. Equation 1 is the original base model from Knowe et al. (!997); all others are modified to include silvicultural treatment effects.

Equation	Model	Parameters
(1)	$C = \alpha YST^{\theta} \exp{(\beta YST)}$	α, θ, β
(2)	$C = \alpha b_1^{I_H} YST^{\theta} \exp{(\beta YST)}$	$\alpha, \theta, \beta, b_1$
(3)	$C = \alpha b_1^{I_H} b_2^{I_F} YST^{\theta} \exp{(\beta YST)}$	$\alpha, \theta, \beta, b_1, b_2$
(4)	$C = \alpha YST^{\theta b_1^{I_H}} \exp{(\beta YST)}$	$\alpha, \theta, \beta, b_1$
(5)	$C = \alpha YST^{\theta b_1^{I_H} b_2^{I_F}} \exp{(\beta YST)}$	$\alpha, \theta, \beta, b_1, b_2$
(6)	$C = \alpha YST^{\theta} \exp{(\beta b_1^{I_H} YST)}$	$\alpha, \theta, \beta, b_1$
(7)	$C = \alpha YST^{\theta} \exp{(\beta b_1^{I_H} b_2^{I_F} YST)}$	$\alpha, \theta, \beta, b_1, b_2$
(8)	$C = \alpha b_1^{I_H} YST^{\theta} \exp{(\beta b_2^{I_H} YST)}$	$\alpha, \theta, \beta, b_1$
(9)	$C = \alpha b_1^{I_H} b_2^{I_F} YST^{\theta} \exp{(\beta b_1^{I_H} b_2^{I_F} YST)}$	$\alpha, \theta, \beta, b_1, b_2$

Notes: YST, Years Since Treatment; H, Chemical herbicide; F, Fertilization

Table 4.5. Model error and fit statistics comparing the proposed growth models including silvicultural treatment, fitted to the herbaceous vegetation (measured as total percent groundcover) data from each physiographic region.

		Fit Statistic			
Region	Equation	$RMSE$	AIC	MAD	MD
Lower Coastal Plain	1	17.48	908.89	3.95	-0.39
	2	17.67	908.21	4.52	-0.43
	3	18.04	909.59	4.43	0.05
	4	17.65	910.28	4.14	-0.34
	5	17.96	911.86	4.16	0.11
	6	17.63	910.51	4.07	-0.33
	7	17.91	912.13	4.15	0.14
	8	17.37	904.85	4.01	-0.44
	9	17.97	908.08	3.83	0.12
Upper Coastal Plain	1	22.72	1008.33	8.99	0.56
	2	23.37	1007.64	9.17	0.24
	3	23.85	1008.45	9.47	0.34
	4	23.12	1005.93	9.05	0.52
	5	23.37	1006.80	9.27	0.17
	6	23.07	1005.63	9.00	0.56
	7	23.49	1007.11	9.47	-0.06
	8	23.15	1006.07	9.12	0.38
	9	23.95	1009.26	9.31	0.22

Notes: RMSE, root mean squared error; AIC, Akaike information criteria; MAD, mean absolute difference; MD, mean difference

Table 4.6. Model error and fit statistics comparing the base, treatment effects (TE), and local-variable TE models fitted to herbaceous vegetation (measured as total percent groundcover) data from each physiographic region.

		Fit Statistic				
Region	Model	R^2	$RMSE$	AIC	MAD	MD
Lower Coastal Plain	Base	0.03	17.48	908.88	3.96	-0.40
	TE	0.03	17.37	904.85	4.01	-0.44
	Local TE	0.81	7.13	805.08	0.95	-0.07
Upper Coastal Plain	Base	-0.02	22.75	1008.30	9.03	0.57
	TE	-0.04	23.15	1006.10	9.13	0.38
	Local TE	0.84	7.86	854.69	1.55	0.19

Notes: RMSE, root mean squared error; AIC, Akaike information criteria; MAD, mean absolute difference; MD, mean difference

Figure 4.4. Predicted average trendlines for the global and local-variable models fitted to the herbaceous vegetation data from the lower coastal plain (a) and the upper coastal plain / piedmont (b). Equations included a treatment effect modifier to account for differences due to chemical herbicide application.

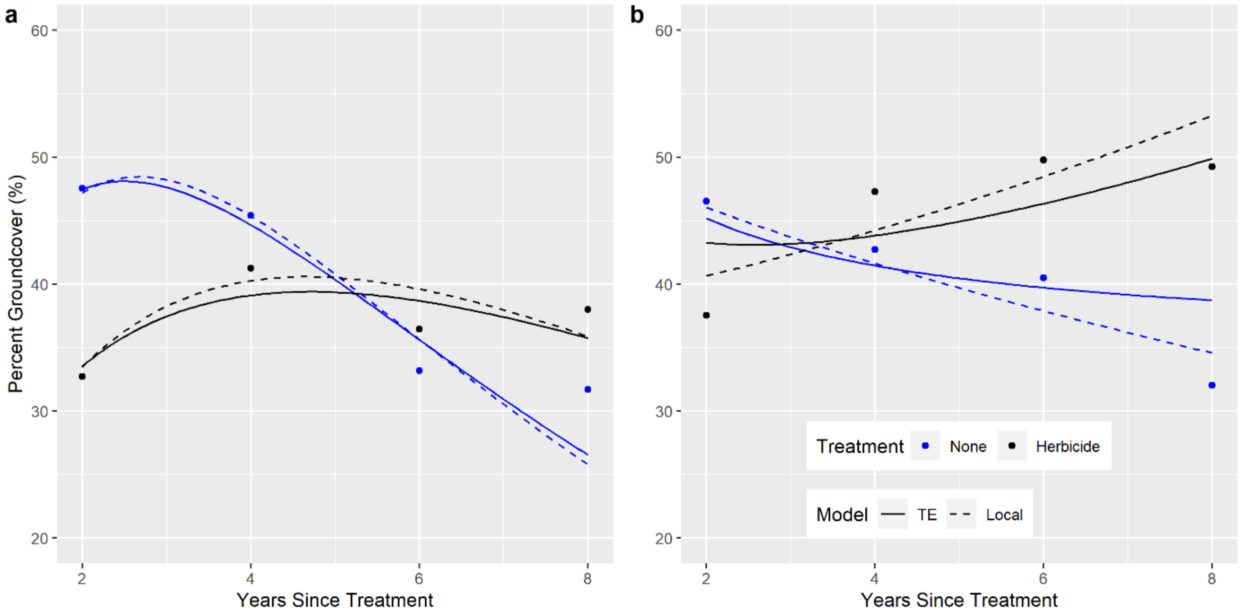

Figure 4.5. Residuals and normal Q-Q plots for the local-variable equations fitted to herbaceous vegetation data in the lower coastal plain (a) and upper coastal plain / piedmont (b).

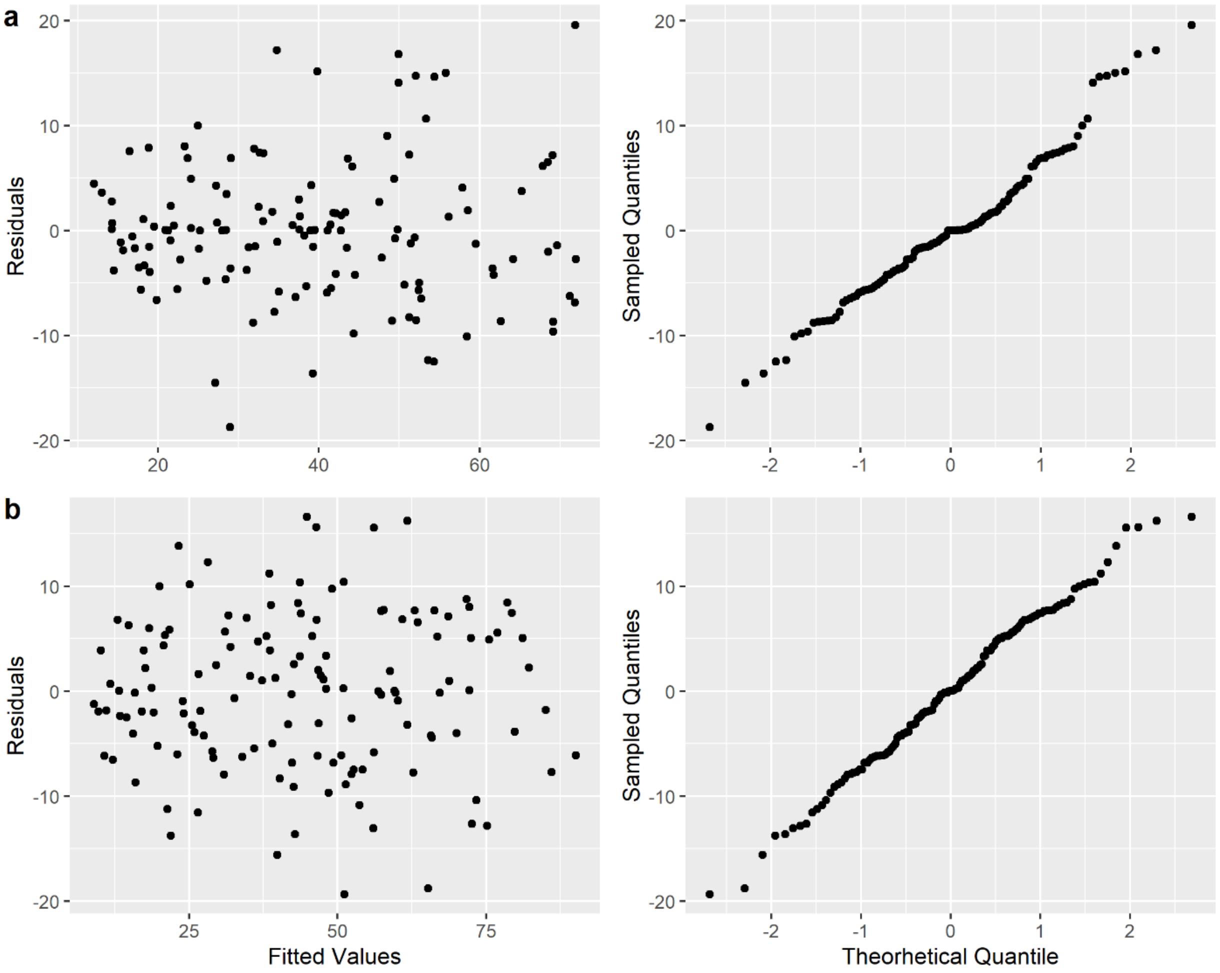

Table 4.7. Estimated parameter values for the base, treatment effects (TE), and local-variable TE models fitted to herbaceous vegetation data from each physiographic region.

		Estimated Parameter				
Region	Model	α	β	θ	b_1	b_2
Lower Coastal Plain	Base	39.07993	-0.16446	0.524269		
	TE	50.46216	-0.22937	0.573856	0.569899	0.531548
	Local TE		-0.26236	0.699971	0.680713	0.572148
Upper Coastal Plain	Base	40.01402	-0.04559	0.21303		
	TE	45.13054	-0.10004	0.276258	0.76712	0.259165
	Local TE		-0.04048	-0.02973	0.913697	-1.28312

Table 4.8. Model error and fit statistics comparing the proposed growth models including silvicultural treatment, fitted to the woody and shrub vegetation (measured as crown volume, ft^3) data from each physiographic region.

		Fit Statistic			
Region	Equation	$RMSE$	AIC	MAD	MD
Lower Coastal Plain	1	29.46	1089.98	4.49	-0.48
	2	25.14	1047.90	5.05	-0.83
	3	25.55	1046.15	4.38	-1.23
	4	25.75	1052.72	6.15	2.67
	5	26.16	1051.33	5.36	2.33
	6	25.76	1052.71	6.14	2.65
	7	26.15	1051.52	5.35	2.29
	8	25.70	1053.83	5.13	1.63
	9	25.86	1055.45	4.14	0.46
Upper Coastal Plain	1	68.70	935.33	14.59	9.77
	2	52.73	883.74	4.73	-1.13
	3	53.66	885.51	4.79	-1.70
	4	53.44	885.11	3.89	1.72
	5	62.78	903.31	20.80	17.67
	6	53.33	885.37	3.94	2.59
	7	84.88	972.14	54.73	54.73
	8	25.36	1051.35	4.88	-0.16
	9	54.49	891.16	4.29	3.15

Notes: RMSE, root mean squared error; AIC, Akaike information criteria; MAD, mean absolute difference; MD, mean difference

Table 4.9. Model error and fit statistics for the base, treatment effects (TE), and local-variable TE models fitted to the woody and shrub vegetation (measured as crown volume, ft^3) data from each physiographic region.

		Fit Statistic				
Region	Model	R^2	$RMSE$	AIC	MAD	MD
Lower Coastal Plain	Base	0.02	28.61	1156.86	2.72	-0.21
	TE	0.26	25.18	1119.29	4.71	-0.27
	Local TE	0.58	18.71	1110.97	3.75	-0.06
Upper Coastal Plain	Base	0.06	41.31	1041.83	5.15	-0.15
	TE	0.42	32.19	986.38	2.86	-0.30
	Local TE	0.72	22.22	979.14	4.95	-0.49

Figure 4.6. Predicted average trendlines for the global and local-variable models fitted to the woody and shrub vegetation data from the lower coastal plain (a) and the upper coastal plain / piedmont (b). Equations included a treatment effect modifier to account for differences due to chemical herbicide application.

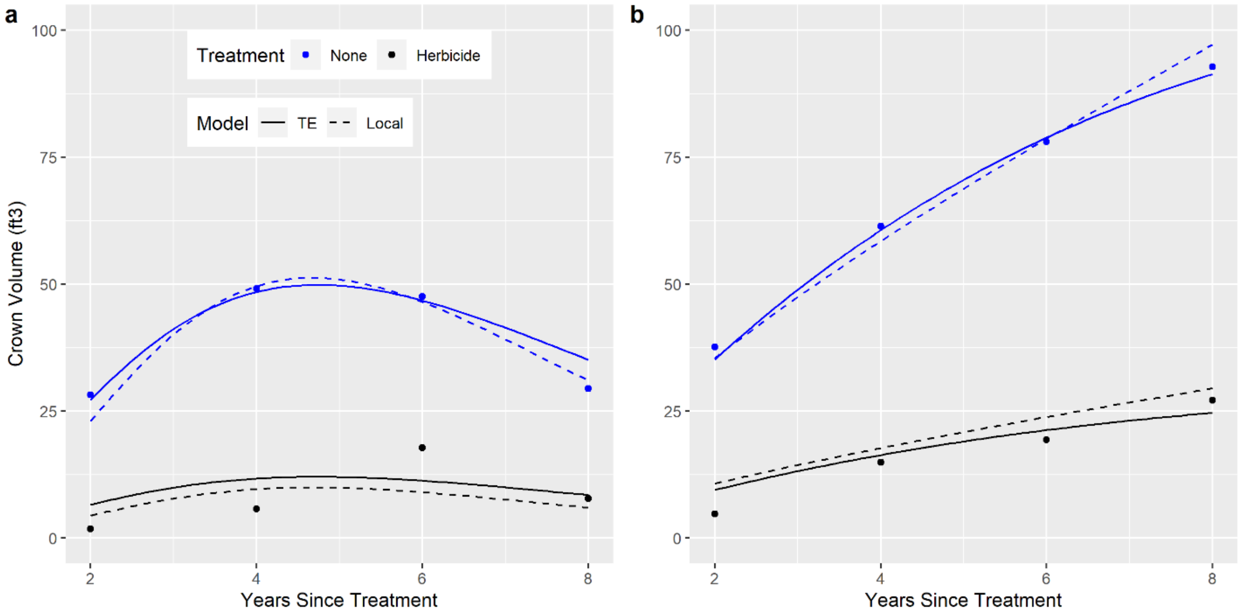

Figure 4.7. Residuals and normal Q-Q plots for the local-variable equations fitted to woody and shrub vegetation data in the lower coastal plain (a) and the upper coastal plain / piedmont (b).

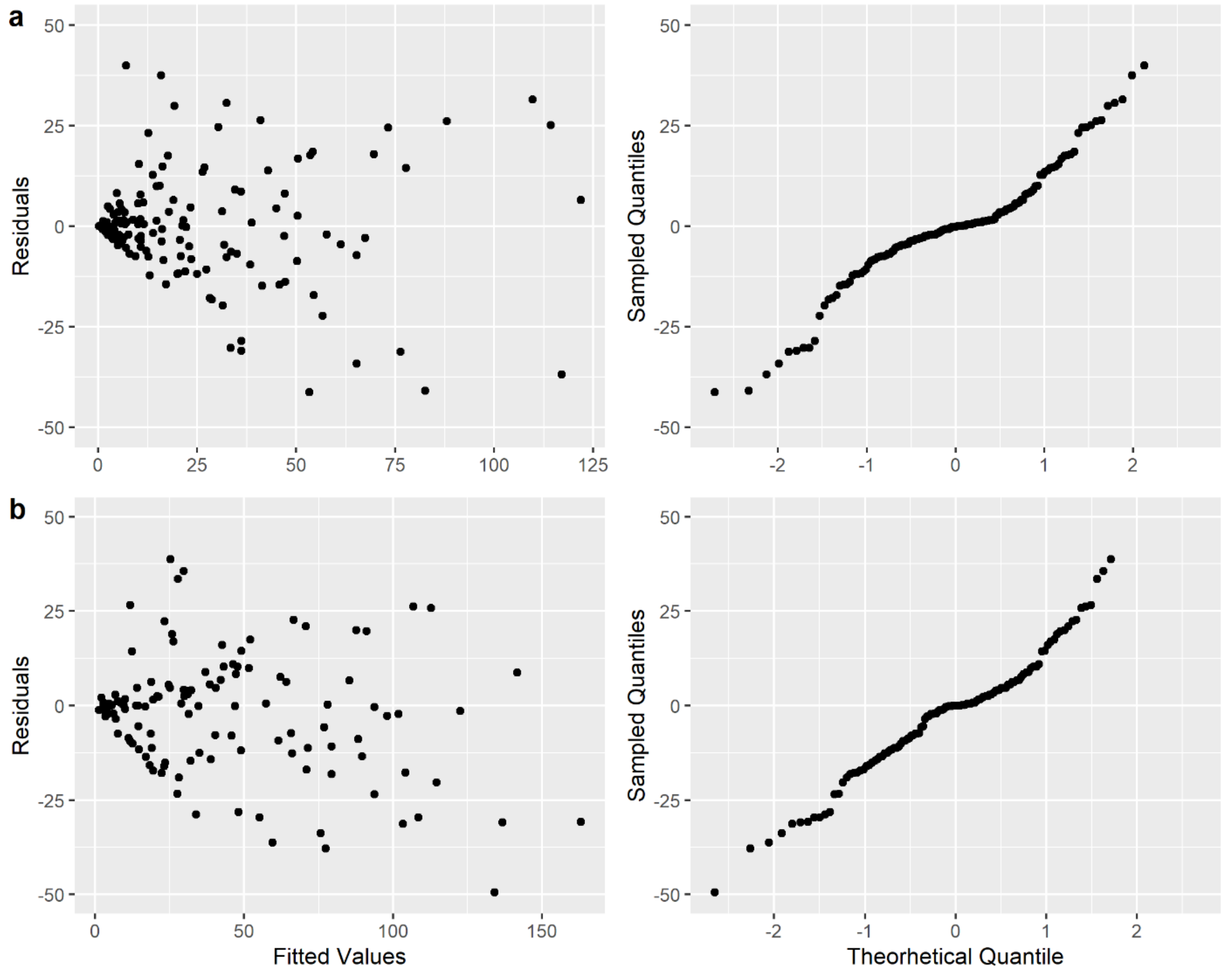

Table 4.10. Estimated parameter values for the base, treatment effects (TE), and local-variable TE models fitted to woody and shrub vegetation data from each physiographic region.

Region	Model	Estimated Parameter			
		α	β	θ	b_1
Lower Coastal Plain	Base	9.543986	-0.33171	1.75344	
	TE	15.29154	-0.44934	2.128832	0.242053
	Local TE		-0.61648	2.882365	0.128155
Upper Coastal Plain	Base	19.27622	-0.00159	0.542201	
	TE	22.24945	-0.0512	0.87483	0.26989
	Local TE		0.003505	0.712224	0.325099

CHAPTER 5

MODELING BASAL AREA GROWTH OF THINNED LOBLOLLY PINE PLANTATIONS TO INCLUDE THE EFFECTS OF SILVICULTURE AND COMPETING VEGETATION [4]

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[4] Young, J.B., Bullock, B.P., and C.R. Montes. To be submitted to *Forest Ecology and Management*.

Abstract

Basal area growth is an important measure of stand density and a primary driver of stand level growth and yield models. Basal area growth throughout a rotation is sensitive to changes in management and the presence of non-crop competing vegetation. Thinning reduces the overall stand basal area but has been shown to increase basal area growth rate. The application of mid-rotation silvicultural treatment also influences stand development in the years following treatment. Growth and yield models are used to describe the growth of stand attributes over time. Basal area models which account for differences in growth following thinning have previously been proposed. Updating models to include silvicultural treatment effects, as well as the effects of competing vegetation, can increase site-specific prediction. A long-term study was used to model thinned basal area including silviculture and competing vegetation effects. Neither treatment modifier improved model fit relative to the base model, although the growth response of thinned stands was significantly different from unthinned stands. Additionally, the unthinned basal area model was refitted, which also resulted in an improved model fit when compared to previously reported parameter values for the southeast U.S. The refitted basal area model in the LCP improved R^2 from 0.74 to 0.95, and the R^2 for the UCPIE model increased from 0.63 to 0.96.

5.1 Introduction

Thinning is an important silvicultural tool used to manage stand density in intensively managemed pine plantations (Amateis 2000). As individual trees grow, their neighbors can limit individual growth especially when site nutrients are limited (Burkart 2013). Stand density heavily influences the diameter growth of individual trees, which is highly correlated with the productivity and quality of forest stands (Jokela et al. 2004). Maintaining high levels of stand density throughout a rotation will ultimately result in self-thinning which may lead to lower value stands at final harvest (Burkhart 2013). Additional problems in overstocked stands include a heightened risk of disease or pest intrusion (Lorio 1980). Thinning can mitigate issues related to high stocking by increasing the growth rate of residual trees and promoting the distribution of trees into larger diameter classes (Amateis 2000; Jokela et al. 2004).

A general assumption regarding thinning is that post-thin volume growth rate should increase, leading to additional volume in higher quality product classes at final harvest (Hasenauer et al. 1997). Previous studies have shown that volume increment is either similar between different levels of stocking in thinned and unthinned stands or decreases in some instances (Hasenauer et al. 1997). Thinning response may also be confounded by additional variables such as differences in the level of stocking prior to thinning, the timing of thinning during a rotation, and the thinning intensity (Pienaar 1979; Pienaar and Shiver 1986; Hasenauer 1997; Amateis 2000). However, when controlled, thinned stand volume increment was still found to remain consistent with unthinned stands (Pienaar 1979; Hasenauer et al. 1997).

Basal area of thinned stands may be a better indicator of post-thin stand growth, since it is measured directly from stem diameter and is highly correlated with tree growth (Hasenauer et al. 1997). It is typically considered one of the most important measures of stand density and is a primary driver of stand growth and yield models (Restrepo et al. 2019). Several loblolly pine basal area models which incorporate thinning response have previously been proposed and successfully fitted (Pienaar 1979, Pienaar et al. 1985; Pienaar and Shiver 1986; Amateis et al. 1989; Hasenauer 1997; Amateis 2000). Unlike post-thin stand volume, where increases in the incremental volume growth have not been consistently identified, previous efforts have concluded that basal area growth does increase following thinning. One of the more prominent approaches used to model basal area response has been the index of suppression, first proposed by Pienaar (1979). This approach models the response of thinned stands relative to an unthinned counterpart of similar stand conditions at the time of thinning. Pienaar et al. (1985), Hasenaur (1997), and Amateis (2000) all modified the index of suppression to model either slash or pine plantations in the southern U.S. Additional approaches have attempted to include an additional term which directly modifies the basal area trajectory based on the thinning intensity (Pienaar and Shiver 1986), but the flexibility of the index of suppression to be easily modified to include additional parameters or site-specific effects is favorable (Amateis 2000).

Mid-rotation fertilization and competition control treatments are often applied individually or in combination to increase stand productivity when site resources are deficient (Albaugh et al. 2012; Liechty and Fristoe 2013; Gyawali and Burkhart 2015). Mid-rotation treatments are intended to re-allocate site nutrients to remaining trees and reduce competition from non-crop species. Most sites across the southeast U.S. are nutrient deficient around the time of crown closure, and fertilization is the most important silvicultural activity for increasing the vigor of plantation pines (Allen et al. 1990; Fox et al. 2007a). Common fertilization application rates of 225 lb ac^{-1} N plus 25 lb ac^{-1} P can increase the growth of plantations of up to roughly 50 ft^{2} ac^{-1} year^{-1} (Fox et al. 2007a). Mid-rotation competition control has also been associated with increased volume, and Forston et al. (1996) found that competing vegetation control increased volume by up to 40 ft^2 ac^{-1} when complete and sustained control was applied. When competing vegetation is present following operational control it will compete for limited site resources and futher inhibit stand growth (Albaugh et al. 2012; Young et al. 2023). Albaugh et al. (2012) found that competing vegetation re-emerged following mid-rotation chemical herbicide applications, which confirmed earlier findings by Blinn et al. (2011) that competing vegetation in treated stands returned to pre-treatment levels 4 years following treatment. Young et al. (2023) found that herbaceous vegetation was the only type to return to pre-treatment levels, and that woody competition was reduced by thin only treatments and further impacted by the addition of chemical herbicides.

Previous models which have incorporated the effect of competing vegetation on pine plantation growth have focused on the percentage of hardwood basal area in the overstory, which can lead to large differences in the growth and yield of a stand over a rotation (Burkhart and Sprinz 1984; Pienaar and Shiver 1986). Burkhart and Sprinz (1984) found that overstory hardwood was a significant predictor of stand development in old-field and cutover sites on the East Coast. Pienaar and Shiver (1986) also found hardwood basal area to be a significant predictor of stand basal area in loblolly pine plantations, and Hasenaur et al. (1997) found it to significantly impact basal area growth in thinned pine plantations. However, current management practices seek to control hardwood presence from establishment onward, and large hardwoods may not be a significant competitor in modern pine plantations (Young et al. 2023). Consequently, the effect of additional competing vegetation groups should be considered to explain the portion of variability due to the presence of non-crop species.

In this study we modeled basal area growth of thinned pine plantations to include the impacts of mid-rotation silvicultural treatment and competing vegetation. Using recent observations from a long-term empirical study, we were specifically interested in answering the following questions: does basal area growth increase following thinning, relative to unthinned stands? Does silvicultural treatment and competing vegetation abundance significantly impact the growth response of thinned pine stands?

5.2 Methods

5.2.1 Study Design

The Mid-rotation treatment study (MRT) is administered by the University of Georgia Plantation Management Research Cooperative (PMRC) and consists of 24, 1st thin installations located in the Lower Coastal Plain (LCP) and combined Upper Coastal Plain / Piedmont (UCPIE) regions of the southeast United States. For a comprehensive description of the study design, including the site descriptions, treatment application rates, and measurement details, see Young et al. (2023). Within each region, 12 plots were categorized by their pre-treatment basal area (high, >120 ft^2 ac^{-1}; low, <=120 ft^2 ac^{-1}) and site index (high, >85 ft ; low, <= 85 ft) which resulted in three stands representing each initial stand condition. Five treatment plots were established at each location, and consisted of a control, a thin-only, thinning with fertilization, thinning with chemical herbicide application, and a thinning with fertilization and herbicide. Thinning was a 5th-row with free thinning between rows to achieve a high (90 ft^2), medium (70 ft^2), or low (150 ft^2) target basal area for each initial stand condition. The fertilization and chemical herbicide treatments were considered common operational application rates at the time of study establishment, and the most intensive treatment was the combination of individual application rates.

Measurements were collected for both loblolly pine trees and competing vegetation species at each treatment plot. Pine measurement plots were 0.5-acres and contained within the 0.75-acre measurement plot to reduce edge effects. Diameter at breast height (dbh) was measured on every pine tree, with total height (ht) and height to live crown (hlc) collected on a subset of pine trees. Large arborescent species measuring greater than 3 inches in diameter were also collected as part of the overstory measurements. Competing vegetation was sampled using a systematic subsample of twenty, 4-foot radius subplots. Diameter at breast height and ht were collected on large aborescent species (> 2 inches), and a stem count, mean ht by species, and mean crown width were collected on small arborescent (< 2 inches) and shrub species. An ocular estimate of the percentage of ground covered by each herbaceous, broadleaf, and weed species was also recorded. Pine trees were measured pre-treatment, post-treatment, and subsequently every two years in the dormant season. Competing vegetation was measured two years following treatment in the growing season and subsequently every two years thereafter. For this report, measurements were available up to 8 years following treatment in both the LCP (Table 5.1) and UCPIE (Table 5.2).

5.2.2 Index of Suppression

Basal area growth of thinned pine plantations was modeled using an index of suppression (Pienaar 1979). The index of suppression (or, competition index) models basal area growth of thinned stands relative to an unthinned counterpart of similar site characteristics and stand management. This approach assumes that residual basal area growth is proportional to the basal area prior to thinning, expressed as

$$CI = \frac{BA_t - BA_u}{BA_t} = 1 - \frac{BA_u}{BA_t} \tag{1}$$

where CI is the index of suppression with range [0,1], BA_u is the basal area of the unthinned counterpart, and BA_t is the basal area of thinned stands. A general assumption of basal area following thinning is that an increase in site resources to the remaining trees results in an increased growth rate compared to unthinned sites with high intraspecific competition, resulting in the basal area of the thinned stand converging with the basal area of the unthinned stand. Since a pattern of convergence following thinning indicates a change in growth rate, the competition index values over time should reflect the new growth rate and modify the unthinned basal area accordingly. Pienaar (1979) proposed using an exponential growth model for describing the competition index change over time (t):

$$CI = \beta_0 e^{-\beta_1 t}\ . \tag{2}$$

Equation 2 was modified to incorporate the effect of competing vegetation, as well as the effect of silvicultural treatments, on stand development (Table 5.3). To account for the effects of competing vegetation, several measures were considered. Crown volume (ft^3) of non-crop woody and shrub species SCV, and the percent ground cover occupied by herbaceous vegetation expressed as a decimal fraction (HGC) were independently included within the model to assess the degree of influence different competing vegetation groups have on the basal area growth response. Additionally, the effects of competing vegetation may be interactive and an index which combined the growth of woody and herbaceous vegetation was proposed

$$CV = \frac{\sqrt{SCV}}{(HGC + 0.01)} \tag{3}$$

Equation 3 assumes that woody competition is the primary competing vegetation at mid-rotation and scales the impact of woody crown volume inversely with the presence of herbaceous vegetation. This relationship assumes that herbaceous vegetation is highly influenced by light availability, and as woody crown volume increases a subsequent decrease in light availability on the forest floor will result in less herbaceous vegetation. When herbaceous vegetation is no longer present, the influence of woody vegetation is at a relative maximum. To account for the effect of competing vegetation on the basal area response, an additional exponential term was included for either the combined variable competition index, or the individual competing vegetation functional groups (Table 5.3). Models fitted using the combined variable was fitted were compared to the models which included the independent measures of competing vegetation to assess the feasibility of using the competing vegetation index.

Silvicultural treatments were included by using a dummy variable approach to adjust the asymptote parameter,

$$CI = \beta_0 b_1^{I_F} b_2^{I_H} e^{\beta_1 t} \tag{4}$$

where the effect of fertilization, I_F, or chemical herbicide, I_H, treatments take the value of either 0 or 1 depending on if they were applied or not. Silvicultural treatment effects have been incorporated into various stand growth and yield models using additive modifiers (Pienaar and Shiver 1986), multiplicative modifiers (Hasenauer et al. 1997), dummy variables (Martin and Milne 1999, Ramirez et al. 2023), and by modeling the change parameters as site specific values (Knowe 1997). Data availability and the response type dictate which method is appropriate for model fitting. Dummy variable approaches are useful for modifying when treatments of varying intensity were not applied and are flexible for describing treatment responses according to the long-terms response type (Mason and Milne 1999; Snowdon 2002). Modification of the asymptote parameter assumes that fertilization and chemical herbicide applications result in a sustained increase in total yield following thinning.

5.2.3 Basal Area Modeling

Application of the competition index to model the basal area response of thinned stands requires a basal area model for unthinned stands to be available. The basal area model of the form originally proposed by Pienaar and Shiver (1986) was used as the base model for unthinned stands:

$$BA = e^{\beta_0 + \beta_1\left(\frac{1}{A}\right)} N^{\beta_2 + \beta_4\left(\frac{1}{A}\right)} H^{\beta_3 + \beta^5\left(\frac{1}{A}\right)} . \qquad (5)$$

Basal area growth using Equation 5 is driven by survival (N) and height (H), and predicted at the stand age (A). This model was selected as it has previously been parameterized using region-wide loblolly pine data from the LCP and UCPIE regions. The model presented in Harrison and Borders (1996) (PMRC96) was simultaneously fitted as part of a whole-stand growth and yield system and included thinned basal area response via the index of suppression. Because parameter values were readily available for the study area and management regime of interest, all models fitted in this analysis were compared to the PMRC96 model. Model comparison was also useful for assessing the growth response of operationally treated stands relative to a regionally averaged growth trend. The compared growth trajectories were obtained by predicting basal area from projected dominant and survival curves fitted as part of the PMRC96 model and using the post-thin observations from the MRT study as the initial starting values.

The projected dominant height curve was:

$$HD_2 = HD_1\left(\frac{1 - e^{=0.014452A_2}}{1 - e^{-0.14452A_1}}\right)^{0.8216}. \tag{6}$$

The projected survival curve was:

$$TPA_2 = 100 + [(TPA_1 - 100)^{-0.745339} + 0.0003425^2 SI_{25}(A_2^{1.97472} - A_1^{1.97472})]^{\frac{1}{0.745339}}. \tag{7}$$

5.2.4 Model Validation and Comparison

Both competition index and the complementing basal area model was fitted using maximum likelihood estimation in the R Statistical Computing Environment (R Core Team). Model error was assessed using the RMSE and R^2 of each model within each region. A 5-fold cross validation was used to calculate the fit statistics for each model, as well as the predicted values obtained from the regional basal area models reported in Harrison and Borders (1996). Fit statistics used to assess model fit including the Akaike Information Criteria (AIC), mean difference (MD), and mean absolute difference (MAD) values.

5.3 Results

Post-treatment basal area growth in both the LCP and UCPIE continued to increase over time throughout the study duration. Some differences in the average growth were observed between treatments in both the LCP (Table 5.1) and the UCPIE (Table 5.2), with the combined treatment yielding the highest basal area in the final measurement period for both regions. The plotted growth trajectories do not clearly show evidence of the thinned stands converging to the unthinned basal area (Figure 5.1). However, the competition index values continued to decrease over time in each region suggesting that basal area growth does converge following treatment for the individual plots. Additionally, there was no clustering or differentiation of the competition index change over time evident in the regional plots when accounting for the silvicultural treatment (Figure 5.2).

The coefficient of determination for models in the LCP ranged from 0.004 to 0.197, and the RMSE ranged from 0.11 and 0.12 for all models (Table 5.4). Mean difference (MD) for LCP models ranged from 0.001 to 0.004, indicating that estimates of the competition index were mostly unbiased. AIC was lowest for the base model (Model 1, -246.84), which did not include effects for silviculture treatment or competing vegetation abundance. The next highest AIC (-244.83) was associated with Model 4, which included silvicultural treatment effects but did not include terms for competing vegetation. Equation 1 resulted in a much closer fit to the MRT data than the previously fitted competition index from the PMRC96 model (Figure 5.3A). Additionally, when the treatment effect model was used to project the competition index the mean trends for the treated stands were followed closely (Figure 5.3B). However, the residual plots for the base model indicated a slight residual trend across the fitted values while including the silvicultural treatment effects resulted in a random distribution (Figure 5.4).

Model fit was better for models fitted using the UCPIE data (Table 5.5). The R^2 ranged from 0.251 to 0.347, with RMSE ranging between 0.09 and 0.10. The MD was arbitrarily close to zero for all models which again indicates that estimates in the UCPIE are unbiased. Model 1 and Model 4 also had the lowest AIC (-328.38 and -326.34, respectively) among UCPIE models. The remaining models, which included terms for the competing vegetation effects, did not improve the model fit in any instance. The projected competition index using the base model fitted in this analysis improved the model fit compared to the PMRC96 model, and including the silvicultural effects resulted in treatment-specific competition index curves (Figure 5.5). The residual values for both UCPIE models were randomly distributed (Figure 5.6). Parameter values for the fitted competition index models with and without silvicultural treatment effects are provided in Table 5.6.

Refitting the basal area model to the MRT data resulted in an improved fit compared to the PMRC96 model. For the LCP data, the R^2 for predicted values using a k-fold cross validation improved from 0.74 to 0.95 using the new model parameters, and the RMSE decreased from 17.75 to 7.95 (Table 5.7). MAD (2.45) and MD (-1.87) were also improved. The MAD (12.65) was equivalent to the absolute value of the MD (-12.65) for the PMRC96 model, meaning the model systematically overpredicted every observation. The fitted trendlines for the LCP data comparing the two models are displayed in Figure 5.7. The PMRC96 trendline shows an obvious positive divergence from the observed basal area trajectories for both the thinned and unthinned stands, which supports the overprediction indicated in the fit statistics. The model comparison was similar for the UCPIE data (Table 5.7). The R2 increased from 0.63 to 0.96, and the RMSE decreased from 30.12 to 9.03 with the new parameterization. MAD decreased from 21.87 to 1.03, and the MD for the new model was 0.76. The MAD and MD were absolute value equivalents for the UCPIE data, meaning the PMRC96 model was also positively biased in this region. The fitted trendlines for the UCPIE basal area models are provided in Figure 5.8, and show the same strong positive bias displayed in the LCP and supports that overprediction in the UCPIE is likely when using the PMRC96 model. Final parameter values for the LCP and UCPIE basal area models are listed in Table 5.8.

5.4 Discussion

The significant index of suppression model supports the assumption that basal area growth following thinning does converge, although the magnitude of the response may not substantiate the claim that thinned and unthinned stands are converging. Response rates that are marginally similar may not provide large enough proportional gains to overcome growth differences due to different starting values. However, a reduction in the rate of change over time suggests that the basal area response is lower than what has been previously reported for loblolly pine plantations in the southeast U.S. This is an important consideration when modeling stands basal area growth, since the original parameter values resulted in a basal area projection which did not fit the observed basal area growth. Differences in the basal area response of thinned stands may impact decisions regarding the intensity and timing of thinning (Pienaar 1979). If thinned stands do not respond strongly, or if resulting stand yields do not produce the desired growth response, then alternative management scenarios may be desired. The regional parameters were also significantly different and warranted that separate models be maintained for predicting basal area growth in each region.

A lower response rate in this study is potentially attributed to a few factors. The MRT study installations were selected to represent typical industry operations at the time of study establishment (Young et al. 2023). The stands all received a single mid-rotation silvicultural treatment of less intensity than what may have been observed on previously measured trials, such as Oppenheimer et al. (1989) and Fortson et al. (1996) which monitored growth in response to complete and sustained competition control at mid-rotation. The initial stand conditions were also varied across a wide range of initial basal area and site index values. Since the control factor in this study was the residual basal area following thinning, as opposed to a measure of thinning intensity (the proportion of BA removed at thinning), the response rates could have been varied across the range of initial BA. Generally, thinning intensity may be a better measure to indicate the potential response of pine trees, since it is relative to the proportion of basal area (citation). Many of the stands were thinned later (past 15 years of age) and at relatively high levels of basal area (> 130 ft^2), which could also contribute to a lack of response. The original models were also fitted using simulated data and validated with few observations (PMRC96). It is likely that the modeled values were not representative of operational forest stands used here. It is also possible that prior expectations of an increase in post-thin, stand-level growth rate were optimistic. Few studies have attempted to replicate or model this phenomenon using empirical evidence for loblolly pine plantations, and the response modeled here demonstrates that post-thin growth may be less than previously defined.

Including silvicultural treatment did not improve the overall model fit, but still may be an appropriate consideration given the management regime and initial stand conditions. Site specific information is often desired as criteria for management decisions, and incorporating silvicultural treatments can help managers account for the potential differences between various treatment regimens (D’Amato et al. 2018; Homyack et al. 2022). Although the MRT applied was generalized to match average operational standards across a wide geographic region, the lack of improvement in model fit does not mean that silvicultural treatment effects are not present. A relatively small data set for the treated stands in each region (4 repeatedly measured stands each) was available for modeling growth. Improvements to the model fit may not have been detected relative to the mean trends. Including the treatment effect modifier as applied in this research does not appear to provide additional benefit when modeling the index of suppression in mid-rotation loblolly pine plantations.

Further limitations to the assessment of silvicultural treatment effects may be related to the approach used to incorporate treatment effects. With the dummy variable approach, base parameters are amended with dummy values to adjust for different treatments. Here, the treatments were only assessed by their relationship with the asymptote parameter in all models. Different silvicultural treatments may impact the basal area response in various ways, and additional hypotheses regarding their impact on model development should be formulated and tested to improve our understanding of how silviculture may influence post-thin basal area growth (Gyawali and Burkhart 2015). Previous assessment of the MRT study found that although response to silvicultural treatment was significant in both the LCP and UCPIE, the general response to operational treatments was weak, and therefore differences in modeled response may be difficult to detect (Young et al. 2023).

The models which included competing vegetation were the worst fitted models in the study. Some limitations of modeling the effect of competing vegetation are like the limitations related to incorporating silvicultural treatment effects. The modification used to capture competing vegetation effects may not be effectively describing the relationship between competition and the competition index, and testing different model forms will likely lead to alternative conclusions regarding competing vegetation and basal area response. Additionally, a weak relationship between the competition index and the variables used to define competing vegetation may restrict the utility of the data in explaining competing vegetation effects.

Aside from the limitations related to model fit, there are additional limitations inherent in the methods used to categorize competing vegetation which may be more pertinent for explaining an insignificant relationship. Competing vegetation effects have not been extensively studied at the stand level, particularly in mid-rotation pine plantations, and thus an understanding of the mechanisms driving the relationship between crop and non-crop vegetation is lacking (Burton 1993; Albaugh et al. 2012; Young et al. 2023). A better understanding of the processes underlying competitive interactions is important for being able to effectively model competition between species or functional groups. The variables used to characterize competing vegetation growth may also be inadequate for describing competitive effects between vegetation groups. The combined variable used in this instance was one iteration of many possibilities and may not be an appropriate predictor variable. Similarly, generalizing the growth of competing vegetation into certain function groups may also inhibit the ability of a model to capture a limiting relationship, especially if the functional groups are ill-defined. Other variables have been defined and assessed for modeling competitive interactions, primarily at the individual tree level, but a strong candidate that is highly correlated with stand variables related to even-aged plantations has yet to be discovered (Daniels 1976; Brand 1986; Lanini and Radoesevich 1986; MacDonald et al. 1990). Testing new definitions of competing vegetation groups, as well as different combinations or measurement variables, may be necessary for improving our understating of the relationship between competing vegetation and overstory growth. Competitive interactions among vegetation are complex, dynamic, and goal dependent. It is pertinent that a well-defined approach to the specific context and a multi-faceted perspective of potential interactions be used in future research of competing vegetation effects on crop tree development.

Refitting the unthinned basal area models to the MRT data demonstrated there were observable differences between the basal area growth of the stands measured in this study, and the stands used to model the PMRC96 growth and yield system. It is reasonable that the new model parameters resulted in an improved fit, especially since the model was fitted using the MRT observations. It was alarming that the projected growth diverged substantially between the two models in both regions and suggests that basal area growth is possibly being influenced by uncontrolled auxiliary factors. These factors, such as site resource availability and local climate, may differentiate the response, as well as management legacy or changes in management regimes between the two studies. At the turn of the 21st century, changes in operational management regimes included updated fertilization schemes as well as different chemical compounds and application rates for chemical herbicides (Fox et al. 2007b). These changes could play a large role in explaining differences in stand growth, especially if suboptimal site conditions are not rectified prior to establishing a new rotation.

If the observed growth for the MRT plots is believed to be representative of the basal area growth across the southeast U.S., further research pertaining to questions of basal area and stand productivity should be addressed. The initial sites were selected from stands across the entire southeast U.S. and were representative of the same physiographic range as the data used to fit the PMRC96 model. Because the data represent the same geographical range, disproportionate growth curves between the two models were not expected. Consideration should be given to this disparity, since modeling growth that does not accurately describe stand conditions for a given site can lead to spurious conclusions.

5.5 Conclusions

Basal area growth of thinned loblolly pine plantations was modeled for two regions in the southeast U.S. Post-thin growth response was modeled using an index of suppression, and the effect of silvicultural treatment and competing vegetation were assessed. The base model with no silvicultural treatment or competing vegetation effects resulted in the best model fit for both the LCP and UCPIE, although models including silvicultural treatment effects performed similarly in both. Competing vegetation was not found to be a significant predictor of basal area response in either region. The relationship between mid-rotation competing vegetation and crop tree growth is complex and the mechanistic properties governing competitive interactions have not been extensively studied across the Southeast. Additional research linking processes which drive competitive interactions and stand productivity are likely needed before an effective growth modifier is available. The rate of change in the competition index over time was lower than previously reported for both regions, which may be attributed to either changes in management regimes over time or a lack of supporting evidence for the hypothesis when previous models were fit using simulated data.

The basal area model proposed by Pienaar and Shiver (1996) was refitted here to account for the growth of plantations receiving operational, mid-rotation silvicultural treatment. The new basal area parameters differed substantially from the previously reported values, which is likely attributed to differences in study scope and scale from when the original models were fitted. The refitted base model, combined with the index of suppression modeled above, improved the model fit in both the LCP and UCPIE. Ultimately, model selection should be specific to the management goals and relevant site characteristics to provide the best information for decision makers regarding key stand metrics.

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5.7 Tables and Figures

Table 5.1: Summary of basal area growth by mid-rotation treatment and time for installations located in the Lower Coastal Plain physiographic region.

Treatment	Years Since Treatment	*n*	Basal Area (ft^2)	*SE*
Control	Pre-thin	12	157.08	*1.95*
Control	0	12	157.08	*1.95*
Control	2	12	168.65	*2.07*
Control	4	12	180.03	*2.11*
Control	6	12	187.33	*2.08*
Control	8	10	179.46	*2.65*
T	Pre-thin	12	160.73	*1.84*
T	0	12	69.96	*1.42*
T	2	12	80.42	*1.52*
T	4	12	92.84	*1.51*
T	6	12	104.29	*1.63*
T	8	10	103.89	*1.76*
T+F	Pre-thin	12	158.31	*1.81*
T+F	0	12	70.01	*1.41*
T+F	2	12	82.90	*1.48*
T+F	4	12	97.63	*1.64*
T+F	6	12	110.63	*1.69*
T+F	8	10	110.26	*2.02*
T+H	Pre-thin	12	160.01	*1.92*
T+H	0	12	70.17	*1.41*
T+H	2	12	80.89	*1.50*
T+H	4	12	95.77	*1.58*
T+H	6	12	107.71	*1.64*
T+H	8	10	110.93	*1.96*
T+F+H	Pre-thin	12	160.27	*1.66*
T+F+H	0	12	70.12	*1.41*
T+F+H	2	12	82.55	*1.46*
T+F+H	4	12	97.90	*1.53*
T+F+H	6	12	111.27	*1.64*
T+F+H	8	10	112.48	*1.80*

Notes: T, Thinning; F, Fertilization; H, Chemical herbicide; SE, standard error

Table 5.2: Summary of basal area growth by mid-rotation treatment and time for installations located in the Upper Coastal Plain / Piedmont physiographic region.

Treatment	Years Since Treatment	*n*	Basal Area (m^2)	SE
None	Pre-thin	12	168.09	*1.55*
None	0	12	168.09	*1.55*
None	2	12	181.91	*1.31*
None	4	12	195.94	*1.08*
None	6	12	205.84	*1.18*
None	8	11	212.95	*1.83*
T	Pre-thin	12	168.17	*1.40*
T	0	12	70.08	*1.43*
T	2	12	82.78	*1.58*
T	4	12	96.25	*1.67*
T	6	12	108.69	*1.72*
T	8	12	120.47	*2.11*
T+F	Pre-thin	12	169.94	*1.34*
T+F	0	12	69.78	*1.41*
T+F	2	12	83.48	*1.68*
T+F	4	12	98.98	*1.80*
T+F	6	12	112.53	*1.94*
T+F	8	12	126.07	*2.57*
T+H	Pre-thin	12	170.90	*1.62*
T+H	0	12	70.08	*1.42*
T+H	2	12	82.98	*1.59*
T+H	4	12	98.18	*1.72*
T+H	6	12	111.93	*1.81*
T+H	8	12	126.50	*2.04*
T+F+H	Pre-thin	12	170.63	*1.36*
T+F+H	0	12	69.88	*1.40*
T+F+H	2	12	83.64	*1.57*
T+F+H	4	12	100.73	*1.77*
T+F+H	6	12	114.95	*1.92*
T+F+H	8	12	131.09	*2.28*

Notes: T, Thinning; F, Fertilization; H, Chemical herbicide; SE, standard error

Table 5.3: Proposed models for fitting the competition index in thinned stands, including the effect of silvicultural treatment and competing vegetation. Equation 1 represents the base model with no additional predictor variables included.

Model	Equation	Parameters
1	$CI = b_0 e^{b_1 YST}$	b_0, b_1
2	$CI = b_0 e^{b_1 YST} e^{b_2 CV}$	b_0, b_1, b_2
3	$CI = b_0 e^{b_1 YST} e^{b_2 SCV} e^{b_3 HGC}$	b_0, b_1, b_2, b_3
4	$CI = b_0 a_1^{I_F} a_2^{I_H} e^{b_1 YST}$	b_0, b_1, a_1, a_2
5	$CI = b_0 a_1^{I_F} a_2^{I_H} e^{b_1 YST} e^{b_2 CV}$	b_0, b_1, b_2, a_1, a_2
6	$CI = b_0 a_1^{I_F} a_2^{I_H} e^{b_1 YST} e^{b_2 SCV} e^{b_3 HGC}$	$b_0, b_1, b_2, b_3, a_1, a_2$

Notes: CI, competition index; YST, years since treatment; CV, competing vegetation index; SCV, woody crown volume; HGC, herbaceous groundcover; F, fertilization; H, chemical herbicide

Figure 5.1: Post-treatment basal area growth of thinned and unthinned stands in the Lower Coastal Plain (A) and the Upper Coastal Plain / Piedmont (B) physiographic regions. Stands were thinned to a residual basal area of either 50, 70, or 90 ft^2 ac^{-1}.

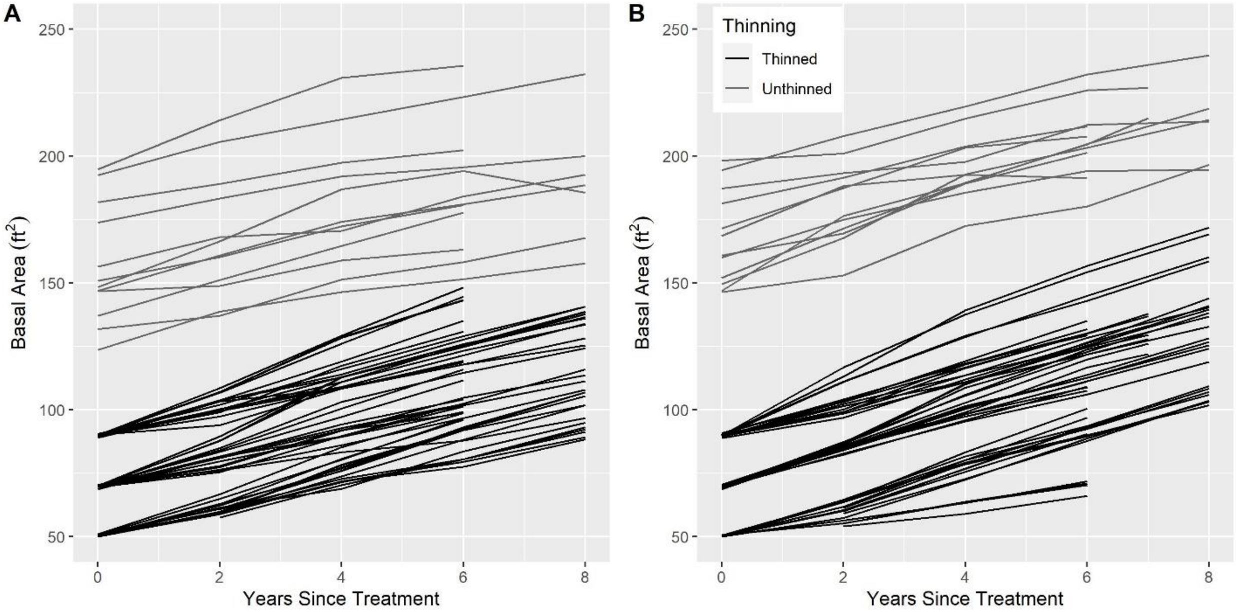

Figure 5.2: Competition index changes over time in the Lower Coastal Plain (A) and Upper Coastal Plain / Piedmont (B) physiographic regions. Following thinning, stands received a one-time application of fertilization (225 lb ac^{-1} of N plus 25 lb ac^{-1} P), chemical herbicide (3 oz glyphosate and 3 oz triclopyr gal^{-1} of water) or a combination thereof.

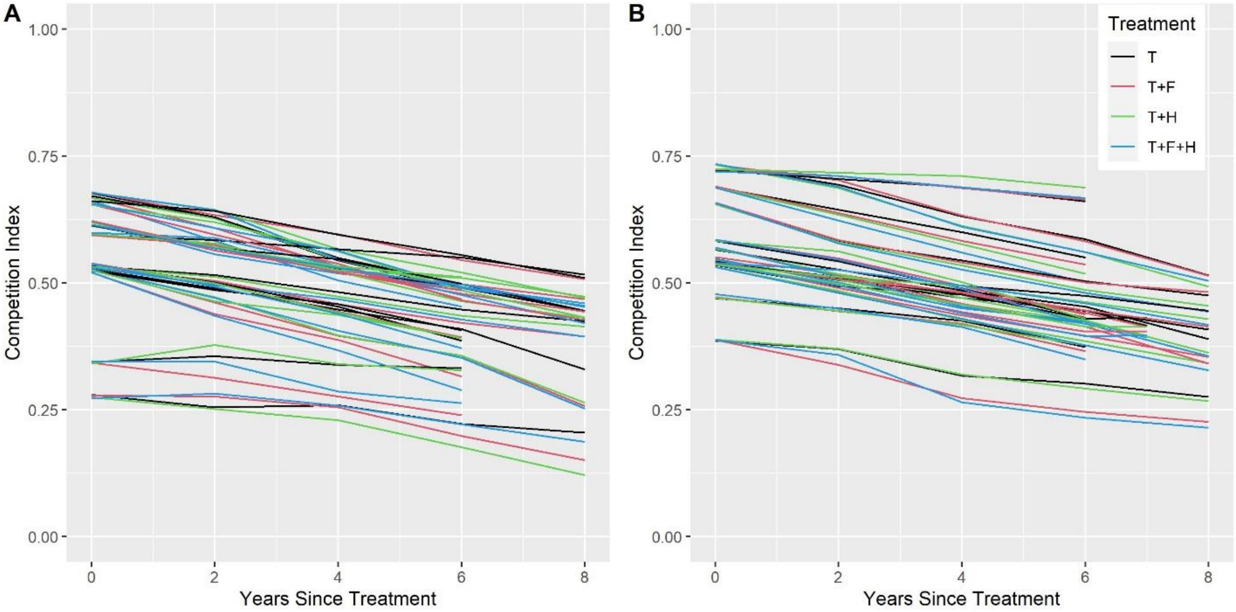

Table 5.4: Fit statistics for the competition index models fitted with data from the Lower Coastal Plain physiographic region. Values were calculated using a 5-fold cross validation, with 20-percent of plots used to validate the model fit.

	Fit Statistic				
Model	R^2	RMSE	AIC	MAD	MD
1	0.197	0.11	-246.84	0.041	0.001
2	0.173	0.11	-193.68	0.041	0.002
3	0.044	0.12	-189.64	0.041	0.002
4	0.177	0.11	-244.83	0.037	0.003
5	0.156	0.11	-191.07	0.037	0.003
6	0.004	0.12	-187.26	0.037	0.004

Notes: RMSE, root mean squared error; AIC, Akaike information criteria; MAD, mean absolute difference; MD mean difference

Figure 5.3: Fitted trendlines for the Lower Coastal Plain competition index model. (A) The base model was compared with the competition index model parameters reported in Harrison and Borders (1996). (B) The dummy variable approach was used to predict competition index values depending on the post-thin silvicultural treatment application.

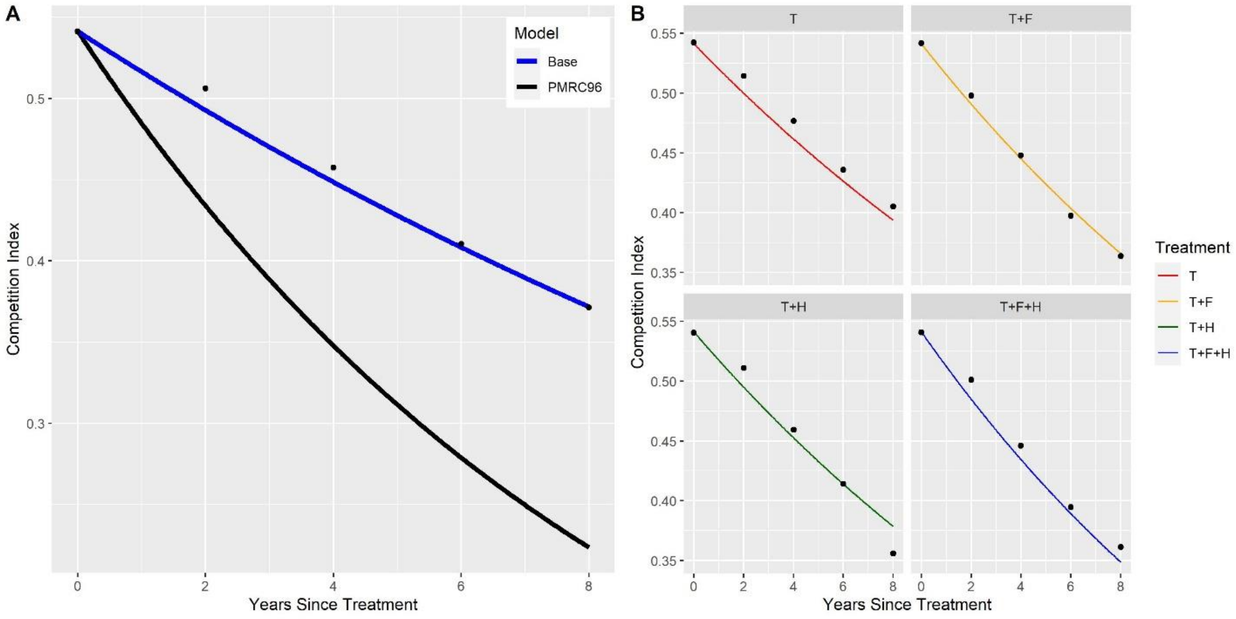

Figure 5.4: Residual plots for the Lower Coastal Plain competition index models fitted without silvicultural treatment effects (A) and with silvicultural treatment effects included (B).

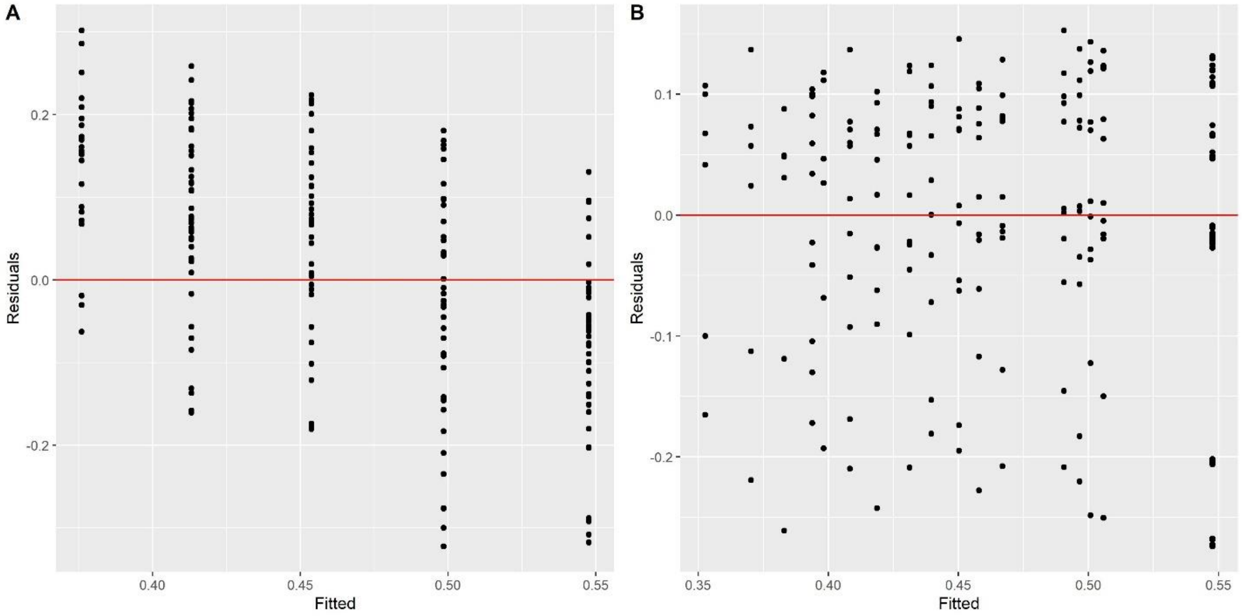

Table 5.5: Fit statistics for the competition index models fitted with data from the Upper Coastal Plain / Piedmont physiographic region. Values were calculated using a 5-fold cross validation, with 20-percent of plots used to validate the model fit.

	Fit Statistic				
Model	R2	RMSE	AIC	MAD	MD
1	0.264	0.10	-328.38	0.044	0.001
2	0.270	0.10	-274.89	0.042	0.004
3	0.347	0.09	-303.65	0.033	0.003
4	0.251	0.10	-326.34	0.046	0.002
5	0.249	0.10	-273.35	0.045	0.005
6	0.337	0.09	-302.80	0.035	0.004

Notes: RMSE, root mean squared error; AIC, Akaike information criteria; MAD, mean absolute difference; MD mean difference

Figure 5.5: Fitted trendlines for the Upper Coastal Plain / Piedmont competition index model. (A) The base model was compared with the competition index model parameters reported in Harrison and Borders (1996). (B) The dummy variable approach was used to predict competition index values depending on the post-thin silvicultural treatment application.

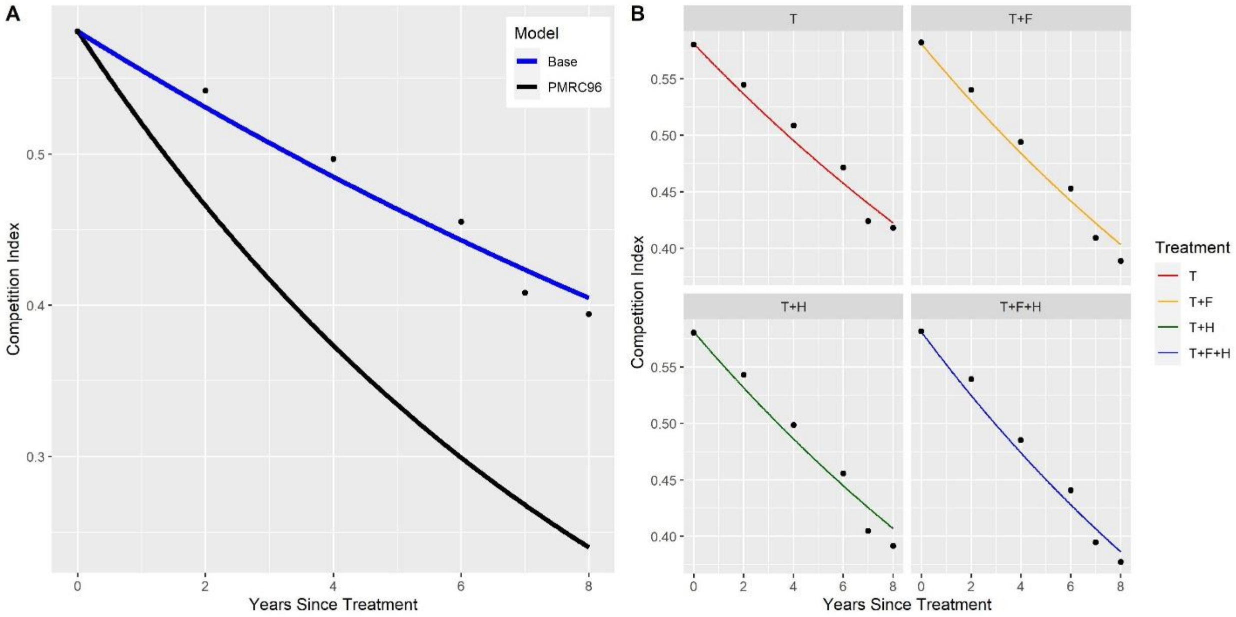

Figure 5.6: Residual plots for the Upper Coastal Plain / Piedmont competition index models fitted without silvicultural treatment effects (A) and with silvicultural treatment effects included (B).

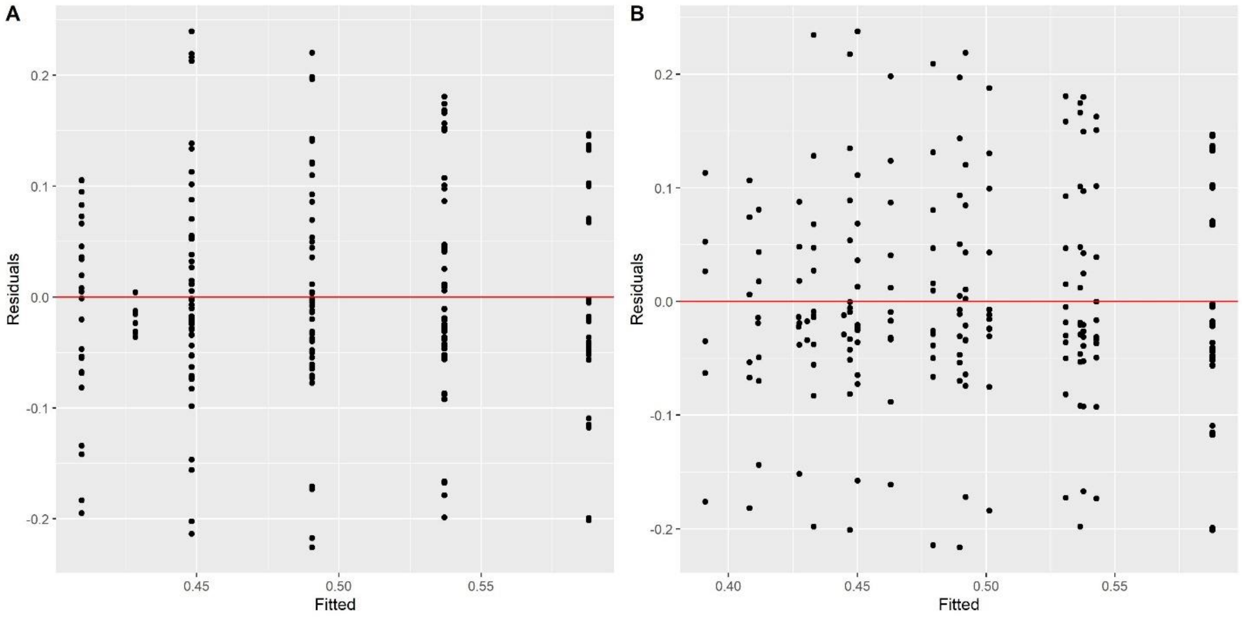

Table 5.6: Parameter estimates for the competition index models fitted with (Model 4) and without (Model 1) without silvicultural treatment effects for the two physiographic regions.

Region	Model	Parameter			
		β_0	β_1	a_1	a_2
Lower Coastal Plain	1	0.547538	-0.04696		
	4	0.547662	-0.03981	1.229328	1.123153
Upper Coastal Plain / Piedmont	1	0.587803	-0.04517		
	4	0.587827	-0.03983	1.144931	1.117487

Table 5.7: Fit statistics comparing the re-fitted basal area model in two physiographic regions with the model reported in Harrison and Borders (1996). Values were calculated using a 5-fold cross validation, with 20-percent of plots used to validate the model fit.

		Fit Statistic				
Region	Model	R^2	RMSE	AIC	MAD	MD
Lower Coastal Plain	Young 2023	0.95	7.95	-323.17	2.45	-1.87
	PMRC96	0.74	17.75	NA	12.65	-12.65
Upper Coastal Plain / Piedmont	Young 2023	0.96	9.03	-333.21	1.03	0.76
	PMRC96	0.63	30.12	NA	21.87	-21.87

Notes: RMSE, root mean squared error; AIC, Akaike information criteria; MAD, mean absolute difference; MD, mean difference

Figure 5.7: Basal area growth model for the Lower Coastal Plain compared to the model reported in Harrison and Borders (1996). Thinned stands were projected by adjusting the growth of unthinned stands with the modeled competition index. Starting values were the global averages across all stands in either category. Silvicultural treatment effect was not included in this example.

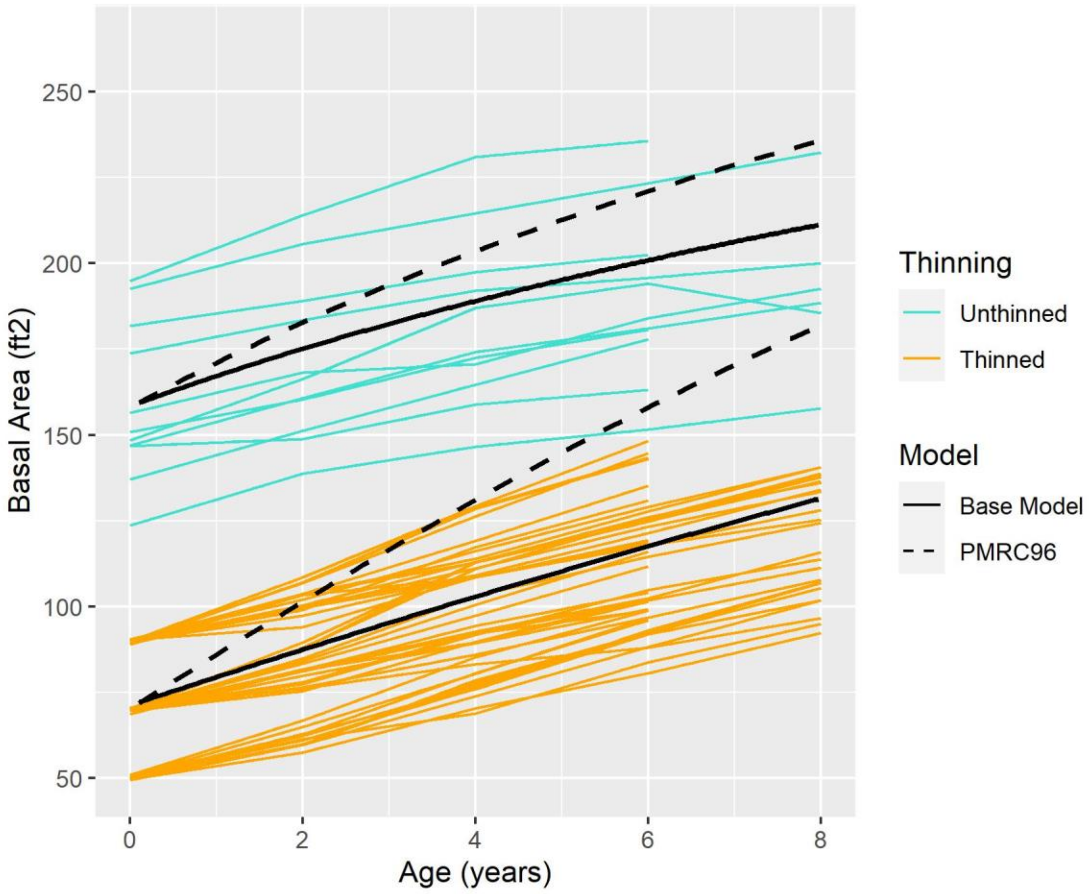

Figure 5.8: Basal area growth model for the Upper Coastal Plain / Piedmont compared to the model reported in Harrison and Borders (1996). Thinned stands were projected by adjusting the growth of unthinned stands with the modeled competition index. Starting values were the global averages across all stands in either category. Silvicultural treatment effect was not included in this example.

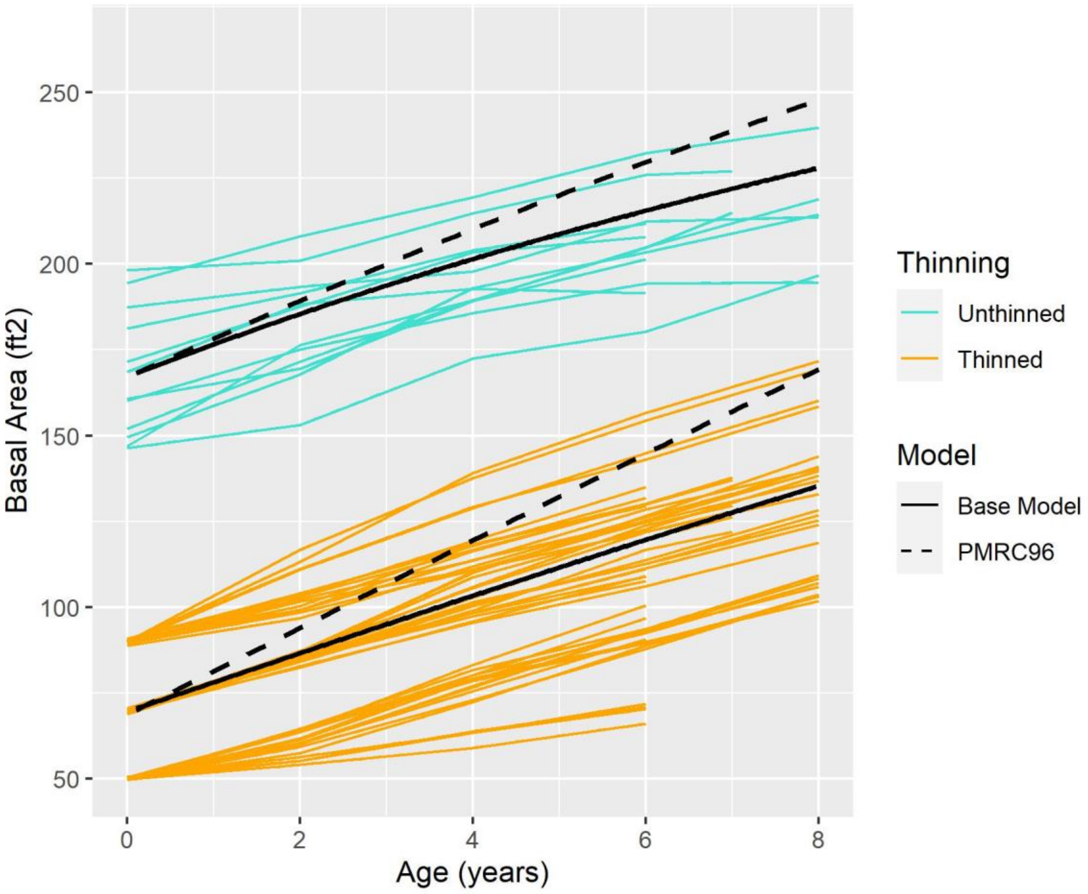

Table 5.8: Parameter estimates for the basal area growth models fitted with data from the Lower Coastal Plain and Upper Coastal Plain / Piedmont physiographic regions.

Region	Parameter					
	β_0	β_1	β_2	β_3	β_4	β_5
Lower Coastal Plain	6.041339	-30.4812	-0.40665	0.376707	2.55771	3.734601
Upper Coastal Plain & Piedmont	4.497098	-48.7435	-0.03462	0.280196	4.4865	4.205274

CHAPTER 6

OVERALL CONCLUSIONS

Understanding how competing vegetation influences the growth and yield of pine plantations in the southeast U.S. is an essential step forward for improving site specific estimates of pine productivity. Although competing vegetation is known to limit the growth of pine plantations throughout a rotation, the dynamics of competing vegetation growth and their impact on stand yield has not been extensively studied. In this research we attempted to answer questions regarding the presence of competing vegetation, specifically for mid-rotation loblolly pine plantations.

To better understand how competing vegetation responds to intensive pine plantation management, an assessment of pine and competing vegetation growth following mid-rotation silvicultural treatments was presented in Chapter 2. Pine volume was found to positively increase with the application of post-thin fertilization and chemical herbicide application in mid-rotation loblolly pine stands in the following order: Thin + Fertilization + Herbicide > Thin + Fertilization > Thin + Herbicide > Thin only. Competing vegetation primarily responded to the chemical herbicide application. Herbaceous vegetation was not a major competitor of site resources, but removal of woody vegetation was associated with increased pine productivity. Vegetation control was an important factor for ensuring that resources were effectively allocated towards post-thin pine productivity. This research supported previous findings (Fortson et al.

1996; Albaugh et al. 2012; Leichty and Fristoe 2013), and provided additional evidence that competing vegetation effects should be considered at mid-rotation.

Chapter 3 explored the possibility of a significant spatial distribution for competing vegetation abundance. For both the Upper Coastal Plain / Piedmont (UCPIE) and Lower Coastal Plain (LCP) physiographic regions, significant spatial autocorrelation was observed. No significant differences in spatial dependence were observed between treatments, indicating that exterior factors influence the spatial distribution of plants. Most notably, competition for light is heavily influences competing vegetation growth. Canopy dynamics following thinning, including increased light availability, likely promote the occurrence of spatial clustering among competing species. Spatial autocorrelation can be used to adjust growth and yield models and increase the precision of forest growth estimates (Reed and Burkhart 1985; Bullock and Burkhart 2005). Future research is needed to explore methods for incorporating spatial autocorrelation and improving estimates of competing vegetation into growth and yield models used for pine plantation management.

Herbaceous and woody vegetation growth in post-thin, mid-rotation pine plantations was modeled for two regions in the southeast U.S in Chapter 4. Previous efforts to incorporate competing vegetation effects into growth and yield models have used competition indices, which are typically limited in their ability to adequately describe competitive interactions (Burton 1993). Both vegetation groups were significantly impacted by a one-time chemical herbicide application, and the resulting models included a treatment effect modifier to account for response to silvicultural treatment. Releasing established pine plantations from woody competition at mid-rotation is an important silvicultural activity for increasing pine productivity and is a necessary component for modeling woody development in treated stands (Oppenheimer et al. 1989, Forton et al. 1996, Leichty and Fristoe 2013). Treatment effect models with a locally defined variable greatly improved model fit and are a convenient solution to account for inherent differences in stand conditions. Ultimately, predicting competing vegetation growth concurrently with pine plantation growth and yield should be desired to describe site-specific stand dynamics.

Chapter 5 assessed a pine basal area growth model which incorporated the effects of silvicultural treatment and competing vegetation. Post-thin growth response was modeled using an index of suppression, and the effect of silvicultural treatment and competing vegetation were assessed. The index of suppression is a flexible method for modeling thinned plantation growth relative to an unthinned counterpart (Pienaar 1979; Hasenauer 1997). The base model with no silvicultural treatment or competing vegetation effects resulted in the best model fit for both the LCP and UCPIE, although models including silvicultural treatment effects performed similarly in both. Competing vegetation was not found to be a significant predictor of basal area response in either region. Additional research linking processes which drive competitive interactions and stand productivity are likely needed before an effective growth modifier is available. The basal area model proposed by Pienaar and Shiver (1996) was also refitted to account for the growth of unthinned plantations. The new basal area parameters differed substantially from the previously reported values. The refitted base model, combined with the index of suppression modeled above, improved the model fit in both the LCP and UCPIE. Ultimately, model selection is contingent upon the goals and individual constraints when trying to provide the best information possible to decision makers.

6.1 Literature Cited

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