CHARACTERIZING SPATIAL DEPENDENCIES OF COMPETING VEGETATION IN THINNED LOBLOLLY PINE PLANTATIONS

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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 because 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 Southeastern United States which monitored the growth of intensively managed loblolly pine (*Pinus taeda*), 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 postthin stand dynamics. Characterizing the spatial dependence of competing vegetation improves site-specific decisions for loblolly pine plantation management.

INTRODUCTION

Loblolly pine (*Pinus taeda*) plantations are the most important commercial pine resource in the Southern United States, covering nearly 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 2003a, 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

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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 because 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 because 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 noncrop 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's Plantation Management Research Cooperative (PMRC) was used to assess the spatial autocorrelation of competing vegetation at mid-rotation. We hypothesized that competing vegetation in thinned pine plantations would have significant spatial autocorrelation. Additionally, we anticipated the degree of spatial autocorrelation to vary for different mid-rotation silvicultural treatments.

MATERIALS AND METHODS

Study Design

The mid-rotation treatment study was initiated in 2009 and consisted of 24 installations distributed evenly across the Lower Coastal Plain (LCP) and combined Upper Coastal Plain and Piedmont (UCPIE) physiographic regions of the Southeastern United States (fig. 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 four treatment plots, with no replication at an installation. Treatments were thin only (T), T + chemical herbicide (H), T + fertilization (F), and a combined treatment of all three (T+F+H). Treatment plots were thinned to a residual basal area (BA) of 50, 70, or 90 square feet per acre and were a fifth-row thin with free thinning between rows to achieve the desired BA. Fertilization was applied at a rate of 225 pounds nitrogen per acre plus 25 pounds phosphorus per acre following thinning. The chemical vegetation control was broadcast sprayed following thinning and consisted of 3 ounces glyphosate and 3 ounces triclopyr (Garlon® 3A, Corteva Agriscience, Riverside, CA) mixed with 36 gallons of water per acre. Follow-up applications were applied to remove any remaining woody vegetation with a variable rate of triclopyr (Garlon® 4, Corteva Agriscience, Riverside, CA).

Measurement plots were 0.5 acres in size, and a total treatment plot size of 0.75 acres created a buffer zone to reduce the impact of edge effects from nontreated areas. Within each treatment plot, a competing vegetation survey was established (fig. 1b). The competing vegetation survey was twenty 4-foot-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

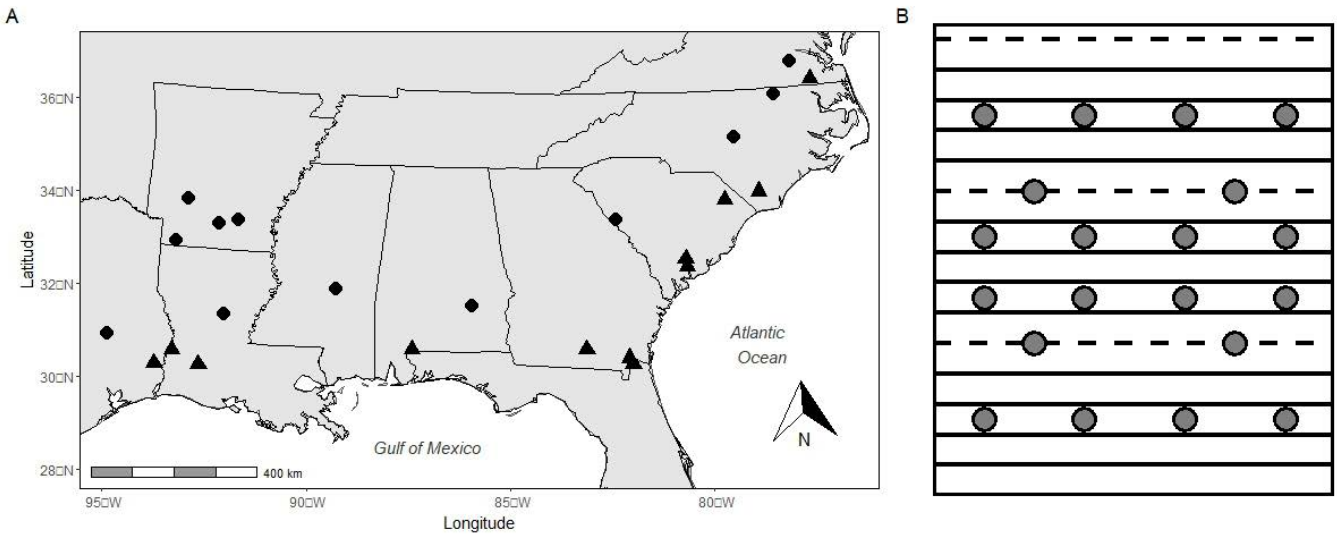

Figure 1—(A) Map of mid-rotation treatment study installation locations across the Southeastern United States. Triangles represent Lower Coastal Plain installations; circles represent Upper Coastal Plain/Piedmont installations. (B) An example measurement plot layout for each treatment plot within an 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.

height (d.b.h.) and height. A stem count and mean height 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* spp., and 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 posttreatment, beginning in the second growing season after thinning.

Table 1—Summary of average competing vegetation density by treatment in each physiographic region

		Herbaceous density		Woody density	
Region	**Treatment**	**Groundcover**	**Primary vegetation**	**Crown volume**	**Primary species**
		percent		*cubic feet*	
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*

Herbaceous vegetation was categorized as either broadleaf, *Andropogon* spp., or grass during data collection
Values represent the mean across all subplot measurements collected and expanded to a per-acre basis.
Thin = thinning applied; Herb = chemical herbicide applied; Fert = fertilization applied.

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).

Spatial autocorrelation among competing vegetation was assessed using Moran's I (MI) statistic (Moran 1950). For a given set of spatial locations $S = \{s_i, ..., s_n\}$, 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 was calculated using the formula presented by Cliff and Ord (1973),

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

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 relationship between the i^{th} and j^{th} observation when $i \neq j$

W is the sum of all weights

W was calculated as

$$W = \sum_i^N \sum_j^N w_{ij} . \quad (2)$$

The value of MI ranges between -1 and 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 posttreatment 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.

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 analysis of variance (ANOVA) was fit to the MI values calculated for each physiographic region. The ANOVA model was

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

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 two-way factorial design at each installation.

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 0.130, 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 (fig. 2) or the UCPIE (fig. 3). Additionally, MI for any of the treatments did not appear to change with respect to time. The trends observed in figure 1 for herbaceous vegetation were confirmed by the ANOVA (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, $F_{1,156} = 8.33$, $P = 0.004$; UCPIE, $F_{1,176} = 4.61$, $P = 0.033$).

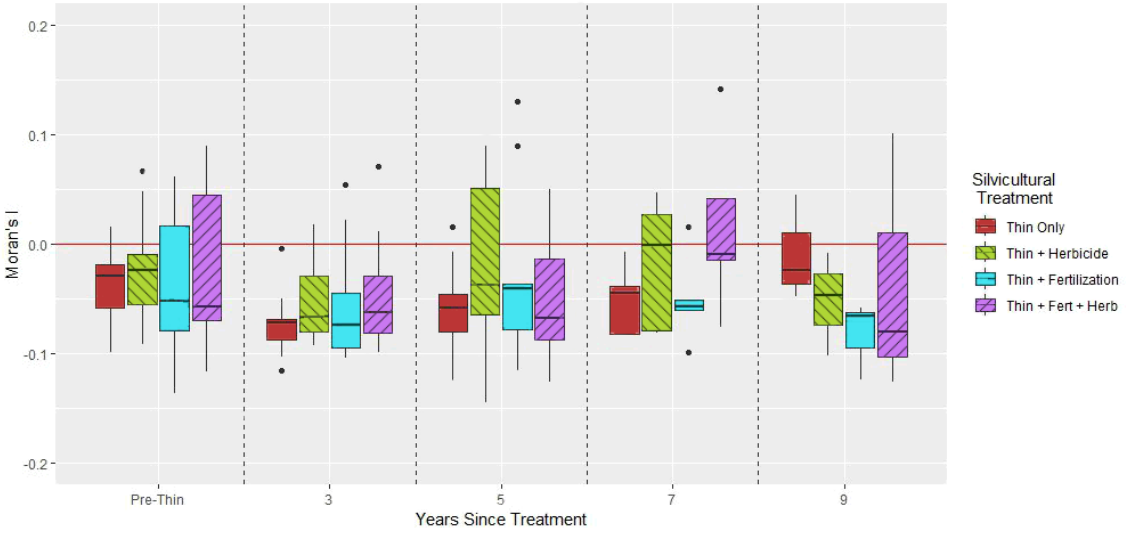

Figure 2—Distribution of Moran's I for herbaceous vegetation in the Lower Coastal Plain by treatment and measurement year (years since treatment). Moran's I values were calculated for each installation, with a possible range of -1 to 1. The red line at zero indicates complete spatial randomness for a treatment by years since treatment observation.

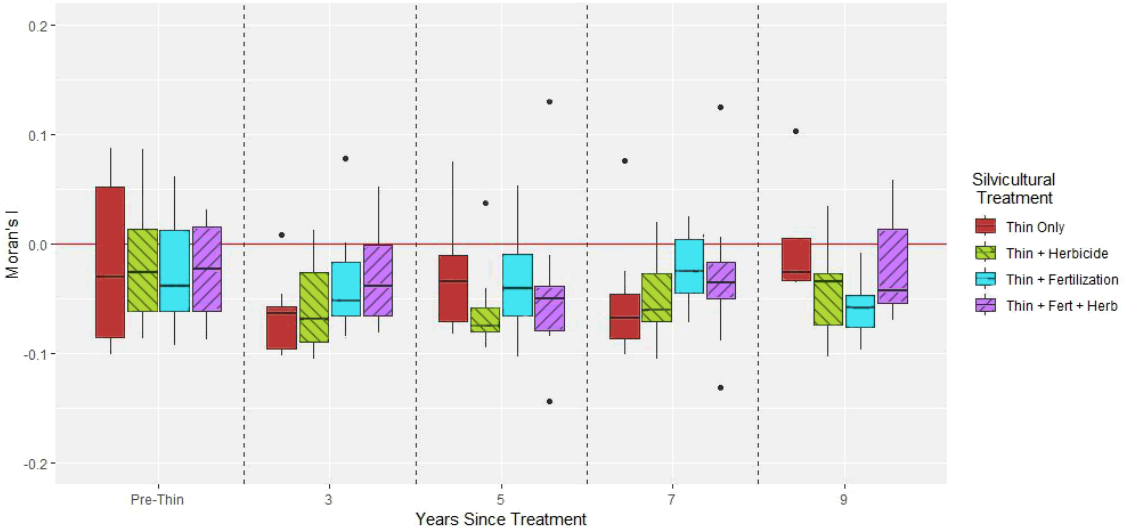

Figure 3—Distribution of Moran's I for herbaceous vegetation in the Upper Coastal Plain/Piedmont by treatment and measurement year (years since treatment). Moran's I values were calculated for each installation, with a possible range of -1 to 1. The red line at zero indicates complete spatial randomness for a treatment by years since treatment observation.

Table 2—Two-way, repeated measures analysis of variance results for Moran's I based on herbaceous vegetation

Region	Factor	Sum of squares	Degrees of freedom	F	*P*
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		

Significance was considered at the 95-percent confidence level (P <0.05).
YST = years since treatment; Herb = herbaceous vegetation control applied; Fert = fertilization applied.

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 (figs. 4 and 5). The ANOVA results were similar to 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 <0.001) and UCPIE ($F_{1,167}$ = 20.365, P <0.001) and is consistent with the trend of negative spatial autocorrelation found for herbaceous vegetation.

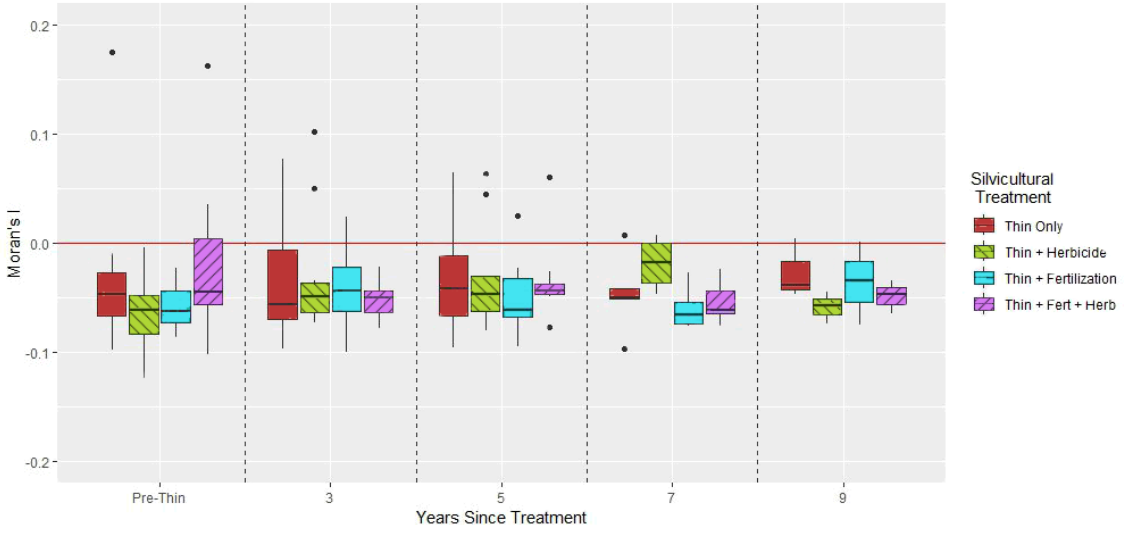

Figure 4—Distribution of Moran's I for woody vegetation in the Lower Coastal Plain by treatment and measurement year (years since treatment). Moran's I values were calculated for each installation, with a possible range of -1 to 1. The red line at zero indicates complete spatial randomness for a treatment by years since treatment observation.

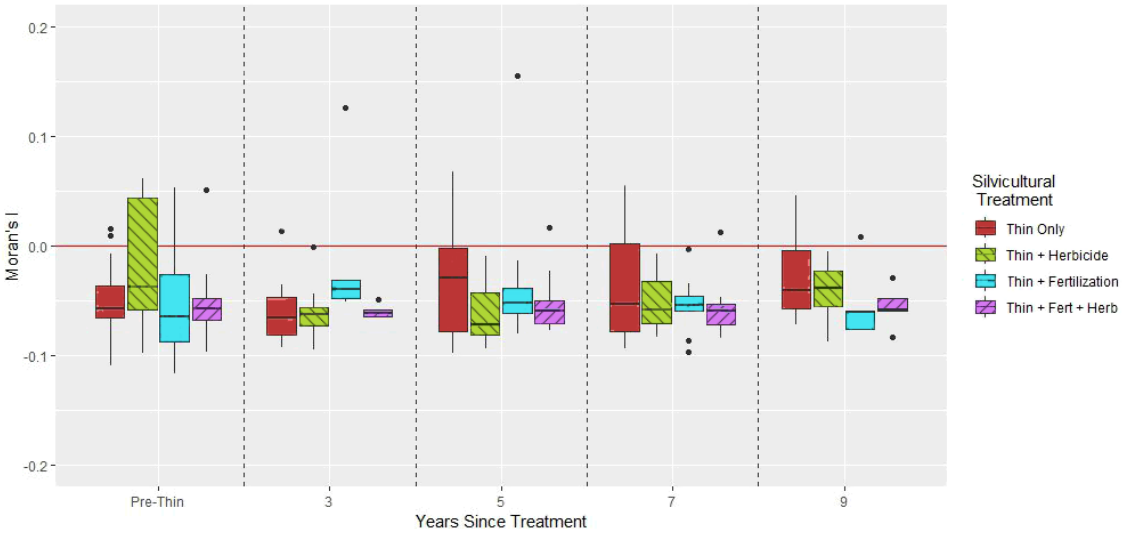

Figure 5—Distribution of Moran's I for woody vegetation in the Upper Coastal Plain/Piedmont by treatment and measurement year (years since treatment). Moran's I values were calculated for each installation, with a possible range of -1 to 1. The red line at zero indicates complete spatial randomness for a treatment by years since treatment observation.

Table 3—Two-way, repeated measures analysis of variance result for Moran's I based on woody vegetation

Region	Factor	Sum of squares	Degrees of freedom	F	*P*
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		

Significance was considered at the 95-percent confidence level ($P < 0.05$).
YST = years since treatment; Herb = herbaceous vegetation control applied; Fert = fertilization applied.

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. Following thinning, woody vegetation growth did not recover to pretreatment levels at any location, whereas herbaceous vegetation was near pretreatment levels within 4 years posttreatment 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 because 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, nonthinned 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 into the spatial distribution of understory vegetation, the spatial variation occurring at either finer or more coarse spatial resolutions was not 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 was 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 1994a). 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.

CONCLUSIONS

Data from a long-term, regional research field trial in the Southeastern United States 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.

LITERATURE CITED

Albaugh, T.J.; Fox, T.R.; Rubilar, R.A. [and others]. 2017. Post-thinning density and fertilization affect *Pinus taeda* stand and individual tree growth. Forest Ecology and Management. 396: 207–216. https://doi.org/10.1016/j.foreco.2017.04.030.

Albaugh, T.J.; Stape, J.L.; Fox, T.R. [and others]. 2012. Midrotation vegetation control and fertilization response in *Pinus taeda* and *Pinus elliottii* across the southeastern United States. Southern Journal of Applied Forestry. 36(1): 44–53. https://doi.org/10.5849/sjaf.10-042.

Anderson, R.C.; Loucks, O.L.; Swain, A.M. 1969. Herbaceous response to canopy cover, light intensity, and throughfall precipitation in coniferous forests. Ecology. 50(2): 255–263. https://doi.org/10.2307/1934853.

Bailey, R.L.; Burgan, T.M.; Jokela, E.J. 1989. Fertilized midrotation-aged slash pine plantations – stand structure and yield prediction models. Southern Journal of Applied Forestry. 13(2): 76–80. https://doi.org/10.1093/sjaf/13.2.76.

Bullock, B.P.; Burkhart, H.E. 2005. An evaluation of spatial dependency in juvenile loblolly pine stands using stem diameter. Forest Science. 51(2): 102–108. https://doi.org/10.1093/forestscience/51.2.102.

Burton, P.J. 1993. Some limitations inherent to static indices of plant competition. Canadian Journal of Forest Research. 23: 2141–2152. https://doi.org/10.1139/x93-267.

Cannell, M.G.R; Rothery, P.; Ford, E.D. 1984. Competition within stands of *Picea sitchensis* and *Pinus contorta*. Annals of Botany. 53: 349–362. https://doi.org/10.1093/oxfordjournals.aob.a086699.

Cliff, A.D.; Ord, J.K. 1973. Spatial autocorrelation. London: Pion. 178 p.

Fox, T.R.; Jokela, E.J.; Allen, H.L. 2007. The development of pine plantation silviculture in the southern United States. Journal of Forestry. 105(7): 337–347. https://doi.org/10.1093/jof/105.7.337.

Griffith, D.A. 2019. Negative spatial autocorrelation: one of the most neglected concepts in spatial statistics. Stats. 2: 388–415. https://doi.org/10.3390/stats2030027.

Homyack, J.; Sucre, E.; Maglaska, L.; Fox, T. 2022. Research and innovation in the private forestry sector: past successes and future opportunities. Journal of Forestry. 120(1): 106–120. https://doi.org/10.1093/jofore/fvab039.

Liechty, H.O.; Fristoe, C. 2013. Response of midrotation pine stands to fertilizer and herbicide application in the western Gulf Coastal Plain. Southern Journal of Applied Forestry. 37(2): 69–74. https://doi.org/10.5849/sjaf.11-044.

Liu, J.; Burkhart, H.E. 1994a. Modelling inter- and intra-specific competition in loblolly pine (*Pinus taeda* L.) plantations on cutover, site-prepared lands. Annals of Botany. 73(4): 429–435. https://doi.org/10.1006/anbo.1994.1053.

Liu, J.; Burkhart, H.E. 1994b. Spatial characteristics of diameter and total height in juvenile loblolly pine (*Pinus taeda* L.) plantations. Forest Science. 40(4): 774–786. https://doi.org/10.1093/forestscience/40.4.774.

Mack, R.N.; Harper, J.L. 1977. Interference in dune annuals: spatial pattern and neighbourhood effects. Journal of Ecology. 65(2): 345–363.

Mead, R. 1968. Measurement of competition between individual plants in a population. Journal of Ecology. 56(1): 35–45.

Miller, J.H.; Zutter, B.R.; Zedaker, S.M. [and others]. 2003a. Growth and yield relative to competition for loblolly pine plantations to midrotation—a southeastern United States regional study. Southern Journal of Applied Forestry. 27(4): 237–252. https://doi.org/10.1093/sjaf/27.4.237.

Miller, J.H.; Zutter, B.R.; Zedaker, S.M. [and others]. 2003b. Stand dynamics and plant associates of loblolly pine plantations to midrotation after early intensive vegetation management—a southeastern United States regional study. Southern Journal of Applied Forestry. 27(4): 221–236. https://doi.org/10.1093/sjaf/27.4.221.

Moran, P.A.P. 1950. A test for the serial independence of residuals. Biometrika. 37(1/2): 178–181. https://doi.org/10.1093/biomet/37.1-2.178.

Pretzsch, H. 1997. Analysis and modeling of spatial stand structures. Methodological considerations based on mixed beech-larch stands in Lower Saxony. Forest Ecology and Management. 97: 237–253. https://doi.org/10.1016/S0378-1127(97)00069-8.

Reed, D.D.; Burkhart, H.E. 1985. Spatial autocorrelation of individual tree characteristics in loblolly pine stands. Forest Science. 31(3): 575–587. https://doi.org/10.1093/forestscience/31.3.575.

South, D.B.; Harper, R.A. 2016. A decline in timberland continues for several southern yellow pines. Journal of Forestry. 114(2): 116–124. https://doi.org/10.5849/jof.15-006.

Wagner, R.G.; Noland, T.L.; Mohammed, G.H. 1996. Timing and duration of herbaceous vegetation control around four northern conifer species. New Zealand Journal of Forestry Science. 26(1/2): 39–52.