

ABSTRACT

HAUSLE, JACQUELINE MARIE TWIFORD. Evaluating the Effect of Planting Rate in *Pinus palustris* Plantations: Tradeoffs between Timber Quality and Understory Conditions. (Under the direction of Dr. Jodi Forrester).

Longleaf pine (*Pinus palustris*) has been a species of growing interest to conservationists across the Southeastern United States for the last few decades. One tool used to promote establishment of longleaf pine is the use of government cost-share programs. These programs place restrictions on maximum planting rate of longleaf pine plantations to promote wildlife habitat, as greater tree planting density may reduce canopy openness and herbaceous plant cover that are critical components of habitat for priority species, including gopher tortoise (*Gopherus polyphemus*) and Bachman's sparrow (*Peucaea aestivalis*). However, there is expressed concern among some forest managers that more open grown trees in the plantations will be of inferior timber quality with more and larger horizontal branches and associated knots. Branches and knots are detrimental to timber quality, but difficult to quantify. This project is in two parts, the first evaluated the effectiveness of using acoustic velocity to quantify branchiness, and the second examined the dynamics among planting rate, understory vegetation structure and composition, longleaf pine stem form (branch density and straightness), and longleaf pine survival. We found that acoustic velocity is negatively related to the number of living branches larger than 2.54cm in diameter ($r=-0.27$, $p<.0001$), but that this relationship is not strong enough to be used to quantify branchiness. In evaluating the effect of planting rate, we documented a strong relationship between planting rate and longleaf pine density at time of sampling ($r=0.69$, $p=0.0001$) and strong relationships between stand density and habitat and timber quality metrics. Higher stand density resulted in lower average tree diameters but greater stand basal area than lower stand density. Higher planting rates led to lower branch density and lower straightness grades than

lower planting rates. Canopy openness, bare ground cover, and herbaceous cover all decreased with higher stand density. Based on our results, we suggest that lower maximum planting rates are appropriate when wildlife habitat is a program objective, and leading to fewer tradeoffs than those that occur from higher maximum planting rates that have only mixed benefits on timber quality.

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Evaluating the Effect of Planting Rate in *Pinus palustris* Plantations:
Tradeoffs between Timber Quality and Understory Conditions.

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Forestry and Environmental Resources

Raleigh, North Carolina
2023

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DEDICATION

This thesis work is dedicated to everyone who refused to let me quit, but in particular my mom,
who has more confidence in me than I have had in anything in my life.

BIOGRAPHY

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ACKNOWLEDGMENTS

This work would not have been possible without too many people name here, and I want to thank everyone who assisted along the way.

In particular, I would like to thank:

Jodi Forrester, whose mentorship has been the backbone of this project. You have greatly impacted how I view science, education, and the world. Thank you for your patience and guidance along the way, and for having gotten me into forestry in FOR172, which now seems like forever ago.

Chris Moorman, whose perspective and holistic way of thinking about wildlife and conservation has been invaluable, you have been amazing to learn from and work with.

Melissa Martin, who was fundamental in project design, identifying and contacting landowners.

This project would not have been possible without you.

Everyone who braved the Southern heat over the two field seasons, including Rachel Jessup, Corrine Morales, Mya Wilson, Jared Lamb, Kelsey Bakken, and Casey Wofford.

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CHAPTER 1:

Introduction

The southeastern United States was once occupied by an estimated 37 million hectares of longleaf pine ecosystems prior to European colonization (McIntyre et al. 2017). Today, less than 3 million hectares remain (McIntyre et al. 2017). There are over 900 plant species and 300 wildlife species associated with longleaf pine communities, 29 of which are federally listed as threatened or endangered (McIntyre et al. 2017). Over the last 3 decades, there has been an increased interest in restoring longleaf pine ecosystems across the region, for wildlife, timber and non-timber product production, aesthetics, and other ecosystem services (Noss et al. 1995; Van Lear et al. 2005).

A central approach to longleaf pine community restoration is use of incentive programs to help fund the establishment of longleaf pine plantations. Two such incentives programs, both offered through the Natural Resources Conservation Service (NRCS), are the Longleaf Pine Initiative (LLPI) and the Working Lands for Wildlife Gopher Tortoise Partnership (WLFW). These programs have different goals and management recommendations, including different allowable maximum planting rates. WLFW limits planting rate to 1483 trees per hectare (TPH) or 600 trees per acre (TPA), and LLPI allows planting at up to 2223 TPH or 900 TPA. Maximum planting rate is lower in the WLFW program because the program's primary goal is to establish, enhance, and maintain habitat for the gopher tortoise. It is believed that planting at lower rates promotes gopher tortoise habitat by allowing more light to reach the understory, promoting a herbaceous layer. Planting at higher rates is believed to encourage better timber by increasing straightness and reducing branchiness of trees, and providing a buffer in the case of low seedling survival. Although the underlying reasons for the difference planting rates are accepted

paradigm, few studies have quantified the relationships among planting rate, conditions important for wildlife, and timber quality.

The primary goal of this project was to quantify relationships between planting rate and timber quality and between planting rate and understory structure and composition, and to identify how planting rate influences tradeoffs between timber and habitat quality. We measured longleaf pine survivorship, light dynamics, understory vegetation structure and composition, and timber quality in 73 stands across North Carolina, South Carolina, Georgia, Alabama, and Florida. In 2019, we sampled plantations in North Carolina and developed a sampling protocol to later implement throughout a wider geographic range. During the 2019 field season, we evaluated the effectiveness of acoustic velocity as a surrogate measure for branchiness. The technique was not effective, so acoustic velocity was not incorporated into the bulk of the project.

CHAPTER 2:

Effects of Planting Rate on *Pinus palustris* Plantations:

Evaluating Timber and Habitat Quality

Abstract

Longleaf pine (*Pinus palustris*), a historically important and abundant tree species in the southeastern United States, is often planted to restore the ecologically and culturally important longleaf pine ecosystem that once covered vast acreages in the southeastern United States. Government cost-share programs that support establishment of these plantations place restrictions on planting rates to promote wildlife habitat, as greater tree planting density may reduce canopy openness and herbaceous plant cover that are critical components of habitat for priority species, including gopher tortoise (*Gopherus polyphemus*) and Bachman's sparrow (*Peucaea aestivalis*). However, there is expressed concern among some forest managers that more open grown trees in the plantations will be of inferior timber quality with more and larger horizontal branches and associated knots. We examined the dynamics among understory vegetation structure and composition, longleaf pine stem form (branch density and straightness), and longleaf pine survival by sampling 73 plantations of various ages (5-25 years) and planting rates (653-2445 trees per hectare (TPH) / 264-990 trees per acre (TPA)) throughout the southeastern United States. We documented a strong relationship between planting rate and longleaf pine density at time of sampling ($r=0.69$, $p=0.0001$) and strong relationships between stand density and habitat and timber quality metrics. Higher stand density resulted in lower average tree diameters but greater stand basal area than lower stand density. Higher planting

rates led to lower branch density and lower straightness grades than lower planting rates. Canopy openness, bare ground cover, and herbaceous cover all decreased with higher stand density.

Based on our results, we suggest that lower maximum planting rates are appropriate when wildlife habitat is a program objective, and leading to fewer tradeoffs than those that occur from higher maximum planting rates that have only mixed benefits on timber quality.

Introduction

Longleaf pine (*Pinus palustris*) ecosystems once covered over 37 million hectares in the southeastern United States (Frost 1993) and are central to the designation of the North American Coastal Plain as the world's 36th biodiversity hotspot (Noss et al. 2015). Due to declines in fire occurrence because of fire suppression and lack of human ignition, intensive logging, and conversion to other land uses (e.g., agriculture, forest plantations), longleaf pine forests declined to only 3-5% of the pre-colonial range (Frost 1993, Guldin et al. 2016). Many plant and animal species associated with longleaf pine communities are now declining or rare (VanLear et al. 2005, Mitchell et al. 2006).

Longleaf pine conservation efforts are often focused on using plantation forestry to restore the longleaf pine ecosystem, but densely stocked plantations may fail to provide many ecosystem services (Oswalt 2012). Conservation partners, including non-industrial private landowners, non-governmental organizations, and government agencies, typically manage longleaf pine forests for diverse objectives, including producing forest products, providing wildlife habitat, yielding aesthetics, offering recreational opportunity, and conserving biodiversity. However, plantations may not adequately mimic the characteristics of the historical longleaf pine ecosystem, including the provision of habitat for important flora and fauna (Greene et al. 2019). Densely stocked pine plantations transition quickly to the stem exclusion stage of stand development, at which point crown closure casts heavy shade on the understory. This rapid canopy closure results in an understory with low herbaceous cover and biomass, which results in lower habitat quality for many species of wildlife (Thomas, 2013).

Longleaf pine also is recognized for its value as timber or other related forest products, but timber quality can be affected by planting density. Longleaf pine is resistant to fusiform rust

(*Cronartium fusiforme*) and the southern pine bark beetle (*Dendroctonus frontalis*), and has been proven to be less vulnerable to wind damage than other pines (Van Lear et al., 2005; Oswald et al., 2012; Samuelson et al., 2014). Common silvicultural recommendations are to plant 1236-1853 trees per hectare (TPH) and manage for early thinnings to promote pole or sawtimber quality stems (Dickens et al 2012). Recommendations for planting in old fields suggest using 1483 -2223 TPH to foster an earlier first thinning and to produce fuels to support prescribed burning earlier in the rotation (Albritton 2012). Proponents of higher planting rates indicate it will maximize options for managing for multiple forest products. High stocking rates promote rapid canopy closure, which leads to self-pruning and higher quality wood products from crop trees (Harrington 2011, Albritton 2012). Early recommendations for planting rates in longleaf pine plantations were as high as 3459 TPH and may reflect rates proposed to provide protection from high seedling mortality associated with low quality bareroot stock (Wahlenberg, 1946). Despite the important implications of branching and knots on lumber strength, little information is available on the relationship between planting density and tree form for plantation grown longleaf pine (Smith 2006).

Initial planting rate affects light dynamics and thus vegetation composition and structure in young plantations. In fact, previous studies documented an inverse relationship between planting density and biodiversity, and between planting density and herbaceous cover (Carnus 2006, Newmaster 2006, Brockerhoff 2003). Lower planting rates, in the range of 618 to 1236 TPH, have been recommended when managing for wildlife to prolong the onset of crown closure and maintain conditions for open forest species (e.g., gopher tortoise (*Gopherus polyphemus*), Bachman's sparrow (*Peucaea aestivalis*)). Wider spacing reduces the costs associated with establishment because it requires fewer seedlings and less site preparation, unless survival is low

and replanting is necessary. The need for pre-commercial thinning is often reduced, though management of competing vegetation may be necessary.

More than half (58%) of forested land within the southeastern US is owned by private non-corporate landowners (Oswalt 2017). Government incentive programs encourage private landowners to restore longleaf pine communities by providing financial and technical assistance. Two primary incentives programs are the Longleaf Pine Initiative (LLPI) and the Working Lands for Wildlife Gopher Tortoise Partnership (WLFW) administered by the Natural Resource Conservation Service (NRCS). The LLPI provides resources in nine states to support establishment of longleaf pine forest and implement conservation practices to maintain ecosystem function. The WLFW program is concentrated on the southern portion of the longleaf pine range, specifically targeting longleaf pine community restoration to provide habitat for gopher tortoise. Moreover, the NRCS has different recommendations for wildlife-focused plantations (1122-1495 TPH or 400-600 TPA) and timber-focused plantations (1483 -2223 TPH or 600-800 TPA). Gopher tortoise habitat is characterized by sparse woody understory cover, abundant herbaceous cover, open canopy, and bare sandy soil (Wilson, 1997). This vegetation condition may support other longleaf pine associate species, including the Bachman's sparrow (Choi et. al, 2021, Fish et. al, 2020). These attributes of gopher tortoise habitat are not associated with densely stocked plantations, and active management is required to maintain openness in the canopy and herbaceous groundcover. Thinning can be used to slow canopy closure, but prescribed fire or other vegetation control is necessary to limit woody plant cover and favor forbs and grasses (Thomas 2013).

Research on longleaf pine planting regimes is limited (Harrington 2011) and only more recently explored for relationships with wildlife habitat quality (Wheeler et al. 2019). Smith

(2006) suggested the decision to use a planting rate less than 1235 seedlings per ha is straightforward if the landowner is primarily interested in maximizing the stand's net present value. However, it is not clear if there is an optimal range of planting densities where both wildlife and timber are enhanced. We quantified the relationships among planting density, timber quality, and vegetation composition and structure in longleaf pine plantations across the southeastern US. We evaluated privately owned and publicly managed properties with a range of site histories and management objectives. We were interested primarily in evaluating how planting rate affects longleaf pine survival, habitat quality metrics such as canopy openness and understory composition and structure, and treeform metrics that affect economic return such as branchiness and straightness. We sought to examine if longleaf pine quality is positively correlated with planting rates and if important herbaceous groundcover is negatively correlated with planting rates as has been widely speculated. We designed our study to encompass a broad range of planting densities, and a mix of ages and ownerships, so that we could document survivorship and growth patterns of seedlings across a large portion of the longleaf pine range. By including a wide range of planting rates, we were able to evaluate the direction and shape of relationships to determine if there is an optimal rate or range where both timber and wildlife objectives are enhanced.

Methods

Study Area

We sampled longleaf pine plantations in 2019 and 2021, with sampling locations ranging from North Carolina westward to Alabama and south to Florida (latitude range from 30.84° N to 34.74 ° N; longitude range from -87.09° W to -79.97° W) (Fig.2.1). The geographic range included the Piedmont and Coastal Plain physiographic regions, and incorporated a wide variation in soil type and moisture levels. The most common soil series were Waukegan, Onteora, Talbott, and Lackawanna. Prior land use varied among sites, with some plantings occurring on previously forested sites and others on old-field or pasture sites.

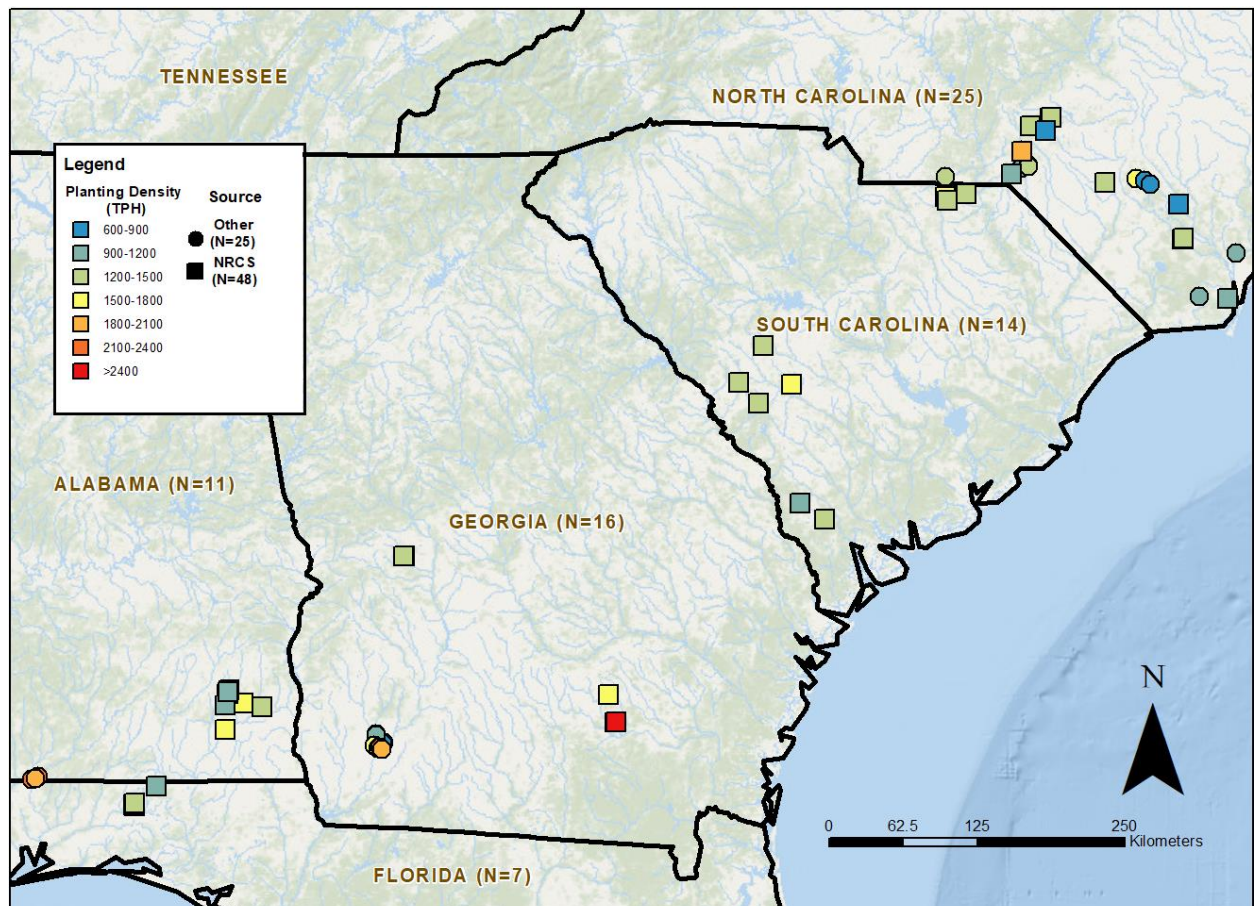


Figure 2.1 Locations of longleaf pine plantations included in the study; symbology reflects ownership (shape) and planting rate (color). State labels indicate sample size.

Study Design

Initial selection criteria in 2019 included plantations that: (1) had not been thinned or raked, (2) were at least 2 ha, and (3) were between 5-20 years since planting. In 2021, we increased the minimum age to 8 years to avoid younger plantations that had limited canopy formation. A random subset of projects fitting these criteria was identified in the NRCS database, and landowners were contacted to request participation in the project. We selected sites to have a wide geographic range, but to maximize sampling efficiency sites were clustered by county, based on which counties had the most NRCS cooperators. We prioritized sampling on properties of NRCS cooperators, but we sampled plantations on other properties to supplement the NRCS sites.

In 2019, we measured 27 plantations; 14 were on properties managed by the North Carolina Wildlife Resource Commission (referred to as NCWRC gamelands), 13 were privately owned plantations from the NRCS database, and 2 were privately owned plantations not from the NRCS database. In 2021, we measured 46 plantations; 33 were privately owned NRCS program properties, 10 were affiliated with a privately-owned research forest, and 3 were affiliated with a US Forest Service property. We measured sites from June to October in 2019 (North Carolina and South Carolina) and 2021 (South Carolina, Georgia, Alabama, Florida).

Data Collection

For every longleaf pine in a plot, we recorded basic timber measurements, and for a subset of the five longleaf pine closest to plot center, we recorded more detailed quality metrics. Timber measurements were diameter at breast height (DBH), total height, height to live crown, forks/ramicorn branches (noted on a presence absence basis), status (living, dead, grass, or bottlebrush), and crown class (the crown's position relative to the canopy). Grass and bottlebrush

refer to early stages of longleaf pine development, grass being the earliest stage before any vertical growth, and bottlebrush being the second stage, prior to branch development. For a subset of 5 trees, we additionally measured branch density and straightness. Branch density was measured by recording all branches within a meter surrounding breast height by size class (<2.54cm, 2.54cm-7.62 cm, >7.62cm) and categorized as being living or dead; later we used these data to calculate weighted branch density, which was the sum of branches weighted by the midpoint of their size class. The straightness of the main stem was graded using a visual stem assessment scale adapted from Prince et al. (2017) (Appendix Table 1). Stems were graded based on the length and number of straight stretches of main bole within the first 5m; a 1 (the lowest grade) indicated no stretches of straight stem within the first 5m. A score of 7 (the highest grade) indicated a straight stretch of 5m along the bole. We estimated initial planting rate by measuring the average distances between trees within planted rows; however, for stands with less of an apparent pattern in the placement of planted trees, we used the reported target planting rate from landowner documents.

We measured understory vegetation using a modified version of the Wiens pole or point-contact method (Wiens 1969, Wiens and Rotenberry 1981, Moorman and Guynn 2001). A graduated pole was held vertically and placed at points along transects across the plot, and any intersection of vegetation with the pole was recorded by cover class and height. The pole used was 2m long, and graduated at 0.1m intervals for the first 0.5m, and at 0.5m intervals for the upper 1.5m of the pole. Transects originated at plot center and extended for 5m in each cardinal direction, with an additional point at plot center, for a total of 21 points. We recorded contacts with the pole into the following cover classes – wiregrass (*Aristida stricta*), broomsedge (*Andropogon virginicus*), other grass, legume (in 2021 only), other forb, longleaf pine, other

pine, and other woody. We measured ground cover under the pole as litter, bare ground, or a vegetation cover class when applicable. Simplified contact cover classes were created to summarize total grass cover (combined broomsedge, wiregrass, and other grass), total forb cover (forbs and legumes in 2021), and total herbaceous cover (total grass and forb cover).

We measured canopy cover using a spherical densiometer with readings recorded at the ends of each vegetation transect and plot center (for a total of 5 readings per plot) in 2019. In 2021, we collected hemispherical photos using a Nikon D700 with a fisheye lens mounted and leveled pointing directly up from 1m above the ground at plot center, and later analyzed using Gap Light Analyzer (Frazer, 1999). The two methods were calibrated using the method described in Beele et al. (2021).

A number of site characteristics were compiled from either the NRCS database or communication with the landowners. We obtained site history information from landowners, and when that was not possible, by using satellite imagery. The percent sand, silt, clay, organic content, bulk density, soil type, and site index for each site were extracted from Web Soil Survey using plot geographic coordinates (Soil Survey Staff, 2021).

Statistical Analyses

All plot level tree measurements were averaged for each stand, including basal area, current stand density, total height, live crown ratio, quadratic mean diameter, straightness, branch density, and canopy cover. Longleaf pine survival was calculated by dividing the density at the time of measurement by the initial planting density by plot and averaged for each stand. We evaluated treeform characteristics in plantations with trees meeting a minimum criterion of 4.9 m (based on 16 foot log) to exclude stands with trees still in the bottlebrush and grass stages. This reduced the timber quality analysis to 60 stands.

We summarized Wiens pole data in multiple ways: (1) horizontal percent cover for each cover class, defined as the percentage of the 21 transect points containing that cover class, at any height along the pole, (2) vertical vegetation density, defined as the average number of vegetation contacts along the pole across all transect points, (3) average vegetation height, defined as the average of the max contact height along the pole across the 21 transect points, and (4) vegetation heterogeneity index (VHI), defined as the variation in vertical density within a plot, as described in Wiens (1969). Plot-level values for each Wiens pole metric were averaged for each stand.

Given the potential correlation among the soil variables, we used a collinearity test to identify potential covariates to be used in analyses relating planting rates and quality trends. As expected, soil texture components (the percentage of sand, silt, and clay in the soil) were highly correlated ($r_{\text{sand,silt}}=0.84$, $r_{\text{sand,clay}}=0.87$, $r_{\text{clay,silt}}=0.48$). To eliminate this multicollinearity, we elected to retain only the percentage of sand in the model selection, as percentage of sand had the widest and most variable spread of data.

To evaluate the relationships between planting rate and timber and habitat quality characteristics, we first evaluated simple correlations between planting rate and density and each characteristic (PROC CORR, SAS). We then used best fit regression modeling selection procedures to evaluate if the relationship with stand density remained important when other covariates were included. Models were selected using a backwards general linear model selection process where models were ranked based on the Akaike information criterion (AIC), with goodness of fit determined by comparing AIC to the full model AIC (PROC GLMSELECT). Input parameters included percent sand, site index, bulk density, organic content, longitude, stand density (planting rate when modeling survival and stand density),

height, plantation age, and interaction terms between planting rate and plantation age. Bulk density and percentage of organic content in soil were never selected, and therefore removed from further consideration. We used a T-test to evaluate the effect of density on the presence of wiregrass, broomsedge, and legumes (continuous variables were converted to presence/absence due to low occurrence) (PROC TTEST). We also used a T-test to compare differences in response variables between previously agricultural and forested sites. We performed all analyses using SAS software, version 9.4 (SAS 2013).

To summarize the relative value for timber and wildlife objectives, we calculated the overall benefit score using methods from Bradford and D'Amato (2011). Each individual characteristic was relativized on a scale of 0-1, and detrimental characteristics (weighted branch density, large branches, and woody cover) were inverted to scale so that lower woody cover values represented higher benefit values. Average timber benefit was based on straightness, weighted branch density, number of large (>3 inch) branches, and live crown ratio. Average wildlife benefit was based on canopy openness, percent bare ground cover, percent herbaceous cover, and percent woody cover. The overall benefit was calculated by averaging individual benefits including both management objectives. To evaluate tradeoffs between planting rates associated with each management goal (timber and wildlife), the root mean squared error (RMSE) of individual benefits compared to the overall benefit was calculated. A high RMSE indicates greater differences (trade-offs) among individual benefits.

Results

Sample Summary

Longleaf plantations ranged from 5 to 25 years of age and 654 to 2445 TPH planting rate (Fig. 2.2, Table 2.1). Stand density (in 2019 or 2021) ranged from 81 to 2319 TPH. Average survival was 60%, ranging from 17% to 100%. Survivorship did not differ based on previous land use (mean and SD for agriculture versus continuously forested = $53\% \pm 18\%$ versus $61\% \pm 22\%$; $p=0.4$). Canopy openness averaged $43\% \pm 14\%$, ranging from 6% to 66%. We observed a wide range in understory vegetation conditions across the plantations, with herbaceous cover averaging $54\% \pm 25\%$, and woody cover averaging $34\% \pm 21\%$. Bare ground cover averaged $25\% \pm 18\%$, ranging from 0 to 68%.

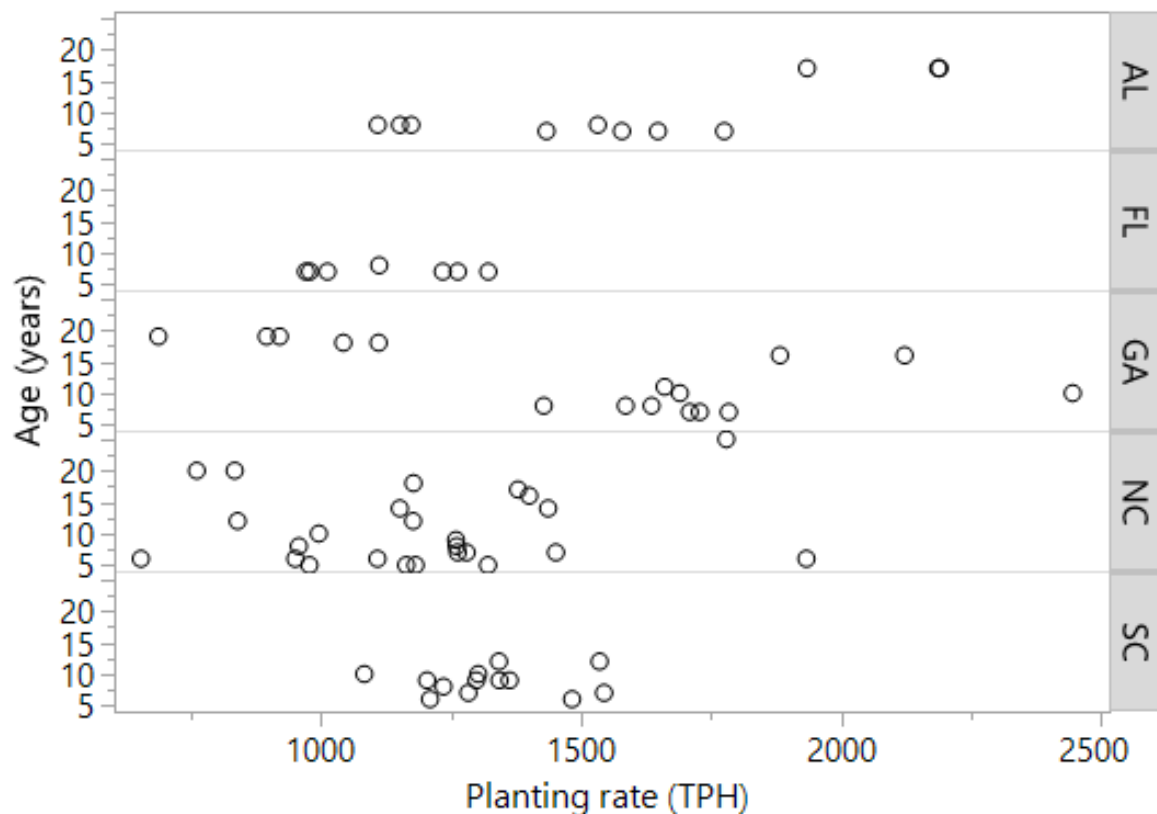


Figure 2.2 Age of longleaf pine plantations established across a range of planting rates (trees per hectare) displayed by state.

Table 2.1 Summary statistics for variables characterizing the structure and composition of longleaf pine plantations across the southeastern US (n=73). Description of how each variable was defined is explained in the methods section.

Variable	Mean	Standard Deviation	Minimum	Maximum
Stand Summary				
Age	10	4.7	5	25
Planting Density (TPH)	1,344	364	654	2,445
Basal Area (m ² /ha)	8.5	6.0	0.1	27.0
Density (TPH)	860	361	199	2,319
Average Height (m)	7.3	3.1	2.2	15.8
QMD (cm)	4.5	1.7	0.7	9.1
Survival (%)	60	22	17	100+
Soils				
Sand (%)	86.3	10.9	42.6	97
SI	68	7	53	80
Quality				
Straightness	5	1	1	7
Branch Density	3.96	1.84	0	9.15
Live Crown Ratio	0.73	0.12	0.37	1
Habitat				
Canopy Openness (%)	50	22	6	98
Broomsedge Cover (%)	12	15	0	58
Wiregrass Cover (%)	3	7	0	31
Legume Cover (%)	0	1	0	2
Herbaceous Cover (%)	53	25	0	99
Shrub Cover (%)	27	17	0	59
Mean Understory Height (m)	0.62	0.27	0	1.50
Bare Ground Cover (%)	24	18	0	68

Effects of Planting Rate

Planting rate was related to stand density, and to timber and habitat quality metrics. Independently, planting rate was strongly correlated with stand density ($r=0.69$, $p<0.0001$). Understory woody cover increased with greater planting rates and weighted branch, canopy openness, and understory vegetation heterogeneity decreased with greater planting rates (Table 2.2). As stand density increased, basal area and woody understory cover increased and weighted branch density, stem straightness, canopy openness, and understory vegetation heterogeneity decreased (Table 2.2).

Best fit modeling procedures indicated that planting rate was a strong predictor in the presence of biotic and abiotic covariates (Table 2.3). Survivorship was best explained as a function of age at time of sampling, planting rate, percent sand in soil, and geographic range. Survival was positively related to planting rate in older stands, and was not affected by planting rate in younger stands. (Fig. 2.3, Table 2.4). Survivorship demonstrated a positive relationship with the percentage of sand in the soil composition. Longitude described a significant portion (34%) of the variation in survivorship, indicating that survivorship was lower in the two eastern most states relative to the three more western oriented states (FL, GA, AL). Because planting rate was strongly related to the density at the time of sampling, we substituted stand density for planting rate in all subsequent analyses to minimize the influence of early mortality that occurred at several sites.

Stand density was an important predictor for several of the timber and habitat quality variables, though it often interacted with other covariates (Table 2.2). The effect of stand density generally differed with the age of the plantation (TPH*Age in Table 2.3). Weighted branch density and QMD were lowest in the older stands established with higher planting densities (Fig.

2.5, Table 2.1). Similarly, the cover of herbaceous vegetation and bare ground decreased with age for higher density stands (Fig. 2.6, Table 2.2). Indicators of site quality explained additional variation in basal area (increased with site index), canopy openness (decreased with site index), and herbaceous cover (decreased with increased percentage of sand in soil). Our covariates added little to explain the variation in straightness grade beyond density, though the increased percentage of sand in soil led to a slightly higher grade. Straightness was weakly negatively related to stand density (Fig. 2.5, Table 2.2, $R^2=0.14$). Diameter decreased with stand density in older stands, but had no effect on diameter in younger stands (Fig. 2.4, Table 2.3, $R^2=0.32$). Basal area increased with stand density and age (Fig. 2.3, Table 2.3, $R^2=0.34$). A number of these relationships, including between stand density and bare ground, canopy openness, and herbaceous cover, showed variation across the geographic range. Relationships with longitude and soil quality overshadowed the weak relationship between stand density and the habitat quality variables, including woody cover, total grass cover, total forb cover, heterogeneity, total forb cover, and understory heterogeneity.

Table 2.2 Correlation coefficients and associated p-values for relationships between planting rate and density, and habitat and timber quality metrics. Associated p-values are below the coefficients in italics.

	Stand Density (TPH)	p	Planting rate (TPH)	p
Stand Density (TPH)	.		0.69	<i><0.0001</i>
Planting rate (TPH)	0.69	<i><0.0001</i>	.	
Diameter (cm)	-0.21	<i>0.07</i>	-0.2	<i>0.1</i>
Basal Area (m ² /ha)	0.38	<i><0.001</i>	0.19	<i>0.11</i>
Straightness Grade	-0.29	<i>0.02</i>	-0.17	<i>0.16</i>
Weighted Branch Density	-0.51	<i><0.0001</i>	-0.31	<i>0.01</i>
Canopy Openness (%)	-0.28	<i>0.01</i>	-0.32	<i>0.01</i>
Bare Ground (%)	-0.14	<i>0.24</i>	-0.31	<i>0.01</i>
Herbaceous Understory Cover (%)	0.15	<i>0.22</i>	0.01	<i>0.94</i>
Forb Cover (%)	0.22	<i>0.06</i>	0.05	<i>0.68</i>
Grass Cover (%)	0.03	<i>0.77</i>	-0.05	<i>0.69</i>
Vegetation Heterogeneity Index	-0.24	<i>0.04</i>	-0.23	<i>0.05</i>

Table 2.3 Best fit models were chosen using a backwards selection procedure, based on the Akaike's information criteria (AIC). Parameters included in the full and/or final models are shaded and symbols are used to indicate the direction of the effect. K indicates the number of parameters and Δ AIC indicates the change from the full to the selected model. TPH represents planting rate in models for survival and density; TPH represents density at time of sampling for all other models. Age is included as a continuous variable, but displayed as a categorical in associated figures to highlight relationships with planting rate and density.

Model	TPH*						K	Δ AIC	R ²
	TPH	Age	Age	SI	%Sand	Longitude			
Full							6		
Survival	-	-	+		+	-	5	-1.83	0.50
Density		-	+		+	-	4	-3.18	0.73
QMD		+	-				2	4.65	0.32
BA	+	+					2	-2.78	0.34
Straightness	-				+		2	-3.07	0.14
Branch									
Density			-			+	2	-4.41	0.31
Bare Ground			-			-	2	-5.73	0.24
Canopy									
Openness	-	-		-		-	4	-3.62	0.30
Herbaceous									
Cover			-		-	-	3	-3.49	0.26

Table 2.4 Selected best fit models for survival and density. Models were selected via backwards selection based on AIC. Model goodness of fit statistics are displayed in Table 2.2.

Response	Parameter	Estimate	Standard Error	Pr > t
Survival	Intercept	-3.25	0.60	<0.0001
	Planting Rate	-2.65E-4	1.41E-4	0.06
	Age	-0.03	1.4E-4	0.02
	Planting Rate (TPH)*Age	2.02E-5	1.0E-5	0.05
	% Sand	0.003	0.002	0.15
	Longitude	-0.5	0.007	<.0001
Density	Intercept	-5007.1	780.69	<.0001
	Planting Rate*Age	0.045	0.005	<.0001
	Age	-63.09	8.80	<.0001
	% Sand	4.57	2.34	0.051
	Longitude	-66.35	8.74	<.0001

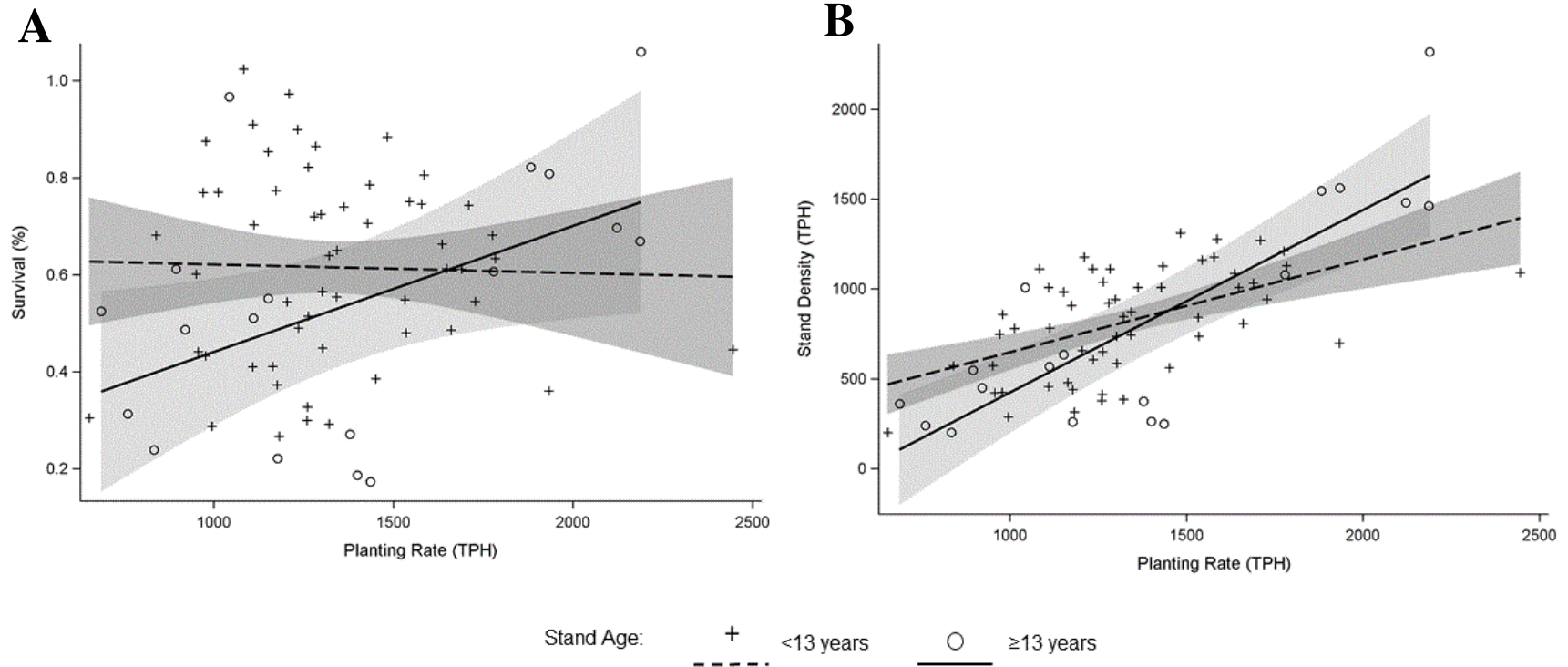


Figure 2.3 Planted longleaf survival (A) and density (B plotted against planting rate. Sites were divided into two age classes, which is reflected by symbology (Table 2.3).

Table 2.5 Selected best fit models for branch density, straightness, quadratic mean diameter (QDM), and basal area. Diameter and basal area were modeled using only stands reaching a minimum average height requirement of 1.35m; straightness and branch density were modeled only using stands reaching a minimum average height requirement of 4.88m. Models were selected via backwards selection based on AIC. Model goodness of fit statistics are displayed in Table 2.2.

Response	Parameter	Estimate	Standard Error	Pr > t
Branch Density	Intercept	23.41	5.54	<.0001
	Density (TPH)*Age	-8.24E-5	2.89E-5	.006
	Longitude	0.23	0.07	0.0014
Straightness Grade	Intercept	4.05	1.02	2.00E-04
	Density (TPH)	-8.00E-04	3.00E-04	0.01
	% Sand	2.10E-02	0.01	0.07
QMD (cm)	Intercept	-6.62	1.04	<0.0001
	Age	0.60	0.11	<0.0001
	Density (TPH)*Age	-1.78E-4	7.77E-05	0.02
Basal Area (m²/ha)	Intercept	-2.13	1.85	0.25
	Density (TPH)	5.85E-3	7.79E-05	1.00E-04
	Age	0.56	0.12	<0.0001

Table 2.6 Selected best fit models canopy openness, bare ground cover, and herbaceous cover. Model goodness of fit statistics are displayed in Table 2.2. Models were selected via backwards selection based on AIC.

Response	Parameter	Estimate	Standard Error	Pr > t
Canopy Openness (%)	Intercept	-28.76	47.25	0.54
	Density (TPH)	-1.65E-02	4.63E-03	0.00
	Age	-0.98	0.30	0.00
	SI	-0.53	0.24	0.03
	Longitude	-1.59	0.64	0.02
Bare Ground (%)	Intercept	-1.41	0.55	0.01
	Density (TPH)*Age	-1.42E-05	3.16E-06	<.0001
	Longitude	-2.15E-02	6.89E-03	0.001
Herbaceous Cover (%)	Intercept	-1.98	0.87	0.03
	Density (TPH)*Age	-9.21E-06	4.48E-06	0.04
	% Sand	-5.50E-03	2.47E-03	0.03
	Longitude	-3.75E-02	9.92E-03	0.003

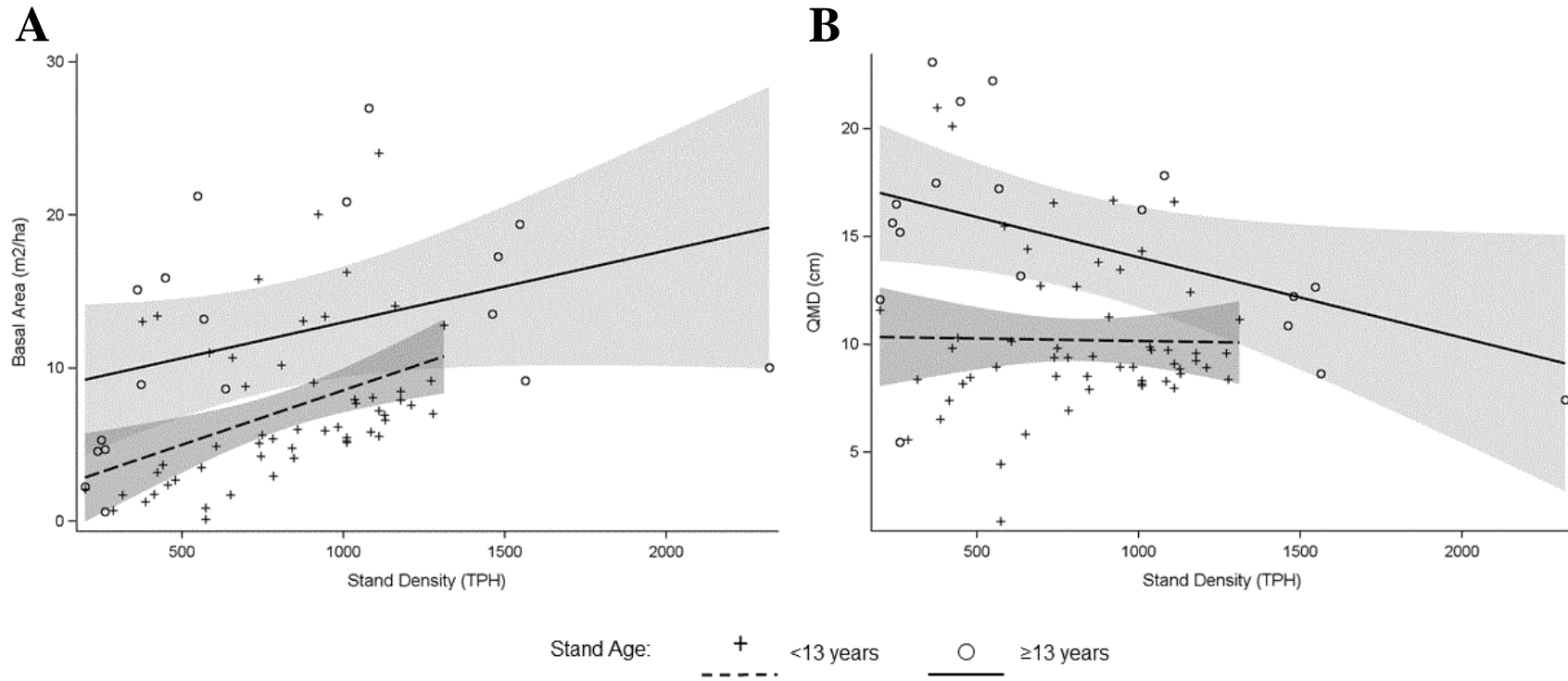


Figure 2.4 Planted longleaf basal area (A) and quadratic mean diameter (B) plotted against planting rate. Sites were divided into two age classes, which is reflected by symbology. Only plots with an average height greater than 1.35m were included (N=70).

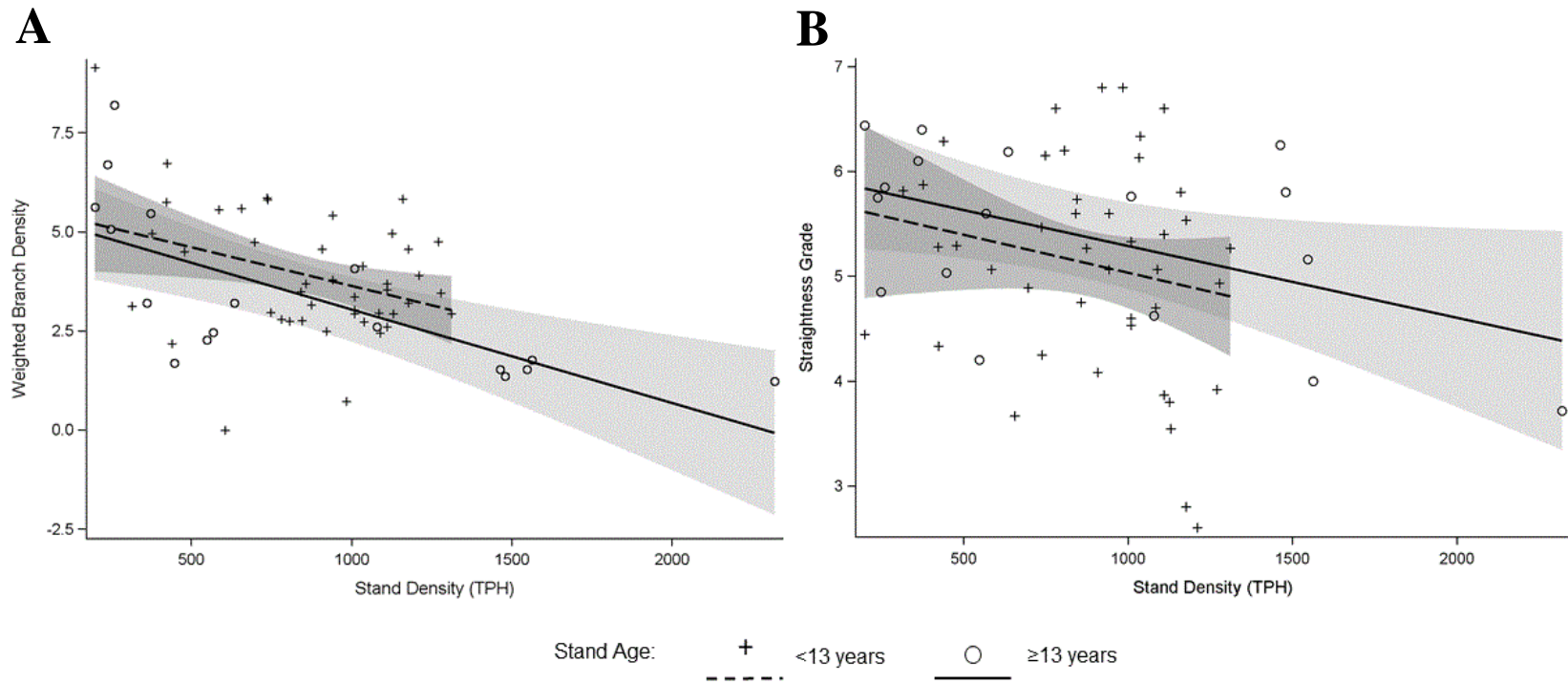


Figure 2.5 Weighted branch density (A) and straightness (B) of planted longleaf pine plotted against density in stands with an average height greater than 4.88 m (1 log, N=65). Sites were divided into two age classes, which is reflected by symbology.

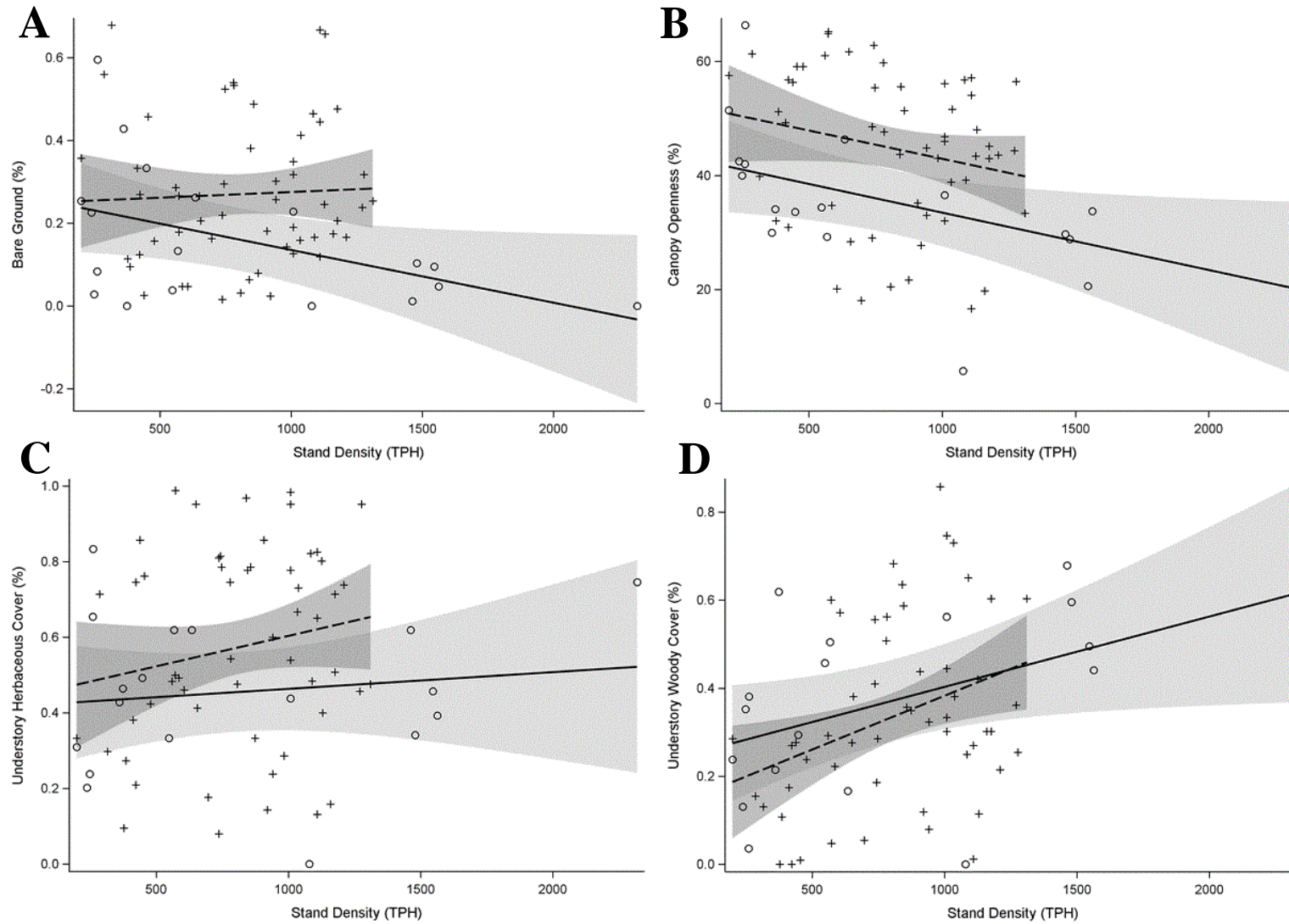


Figure 2.6 Bare ground cover (A), canopy openness (B). Herbaceous cover (C), and shrub cover (D) of all stands plotted against density. Sites were divided into two age classes, which is reflected by symbology.

Benefits and Tradeoffs

The average timber benefits varied minimally based on age or initial planting rate (Fig. 2.7). The average wildlife benefits declined with plantation age across planting rates, but with greater magnitude in plantations established with higher planting rates (Fig. 2.7). The overall benefit (average of all timber and wildlife benefits) decreased with age in both planting rate recommendation ranges but more so for the higher planting rates (Fig. 2.8). The relationship between tradeoffs and stand age differed greatly between the two sets of planting rates, with tradeoffs decreasing with age for plantations established at lower wildlife oriented planting density while tradeoffs increased with age for plantations established with higher timber oriented planting rates.

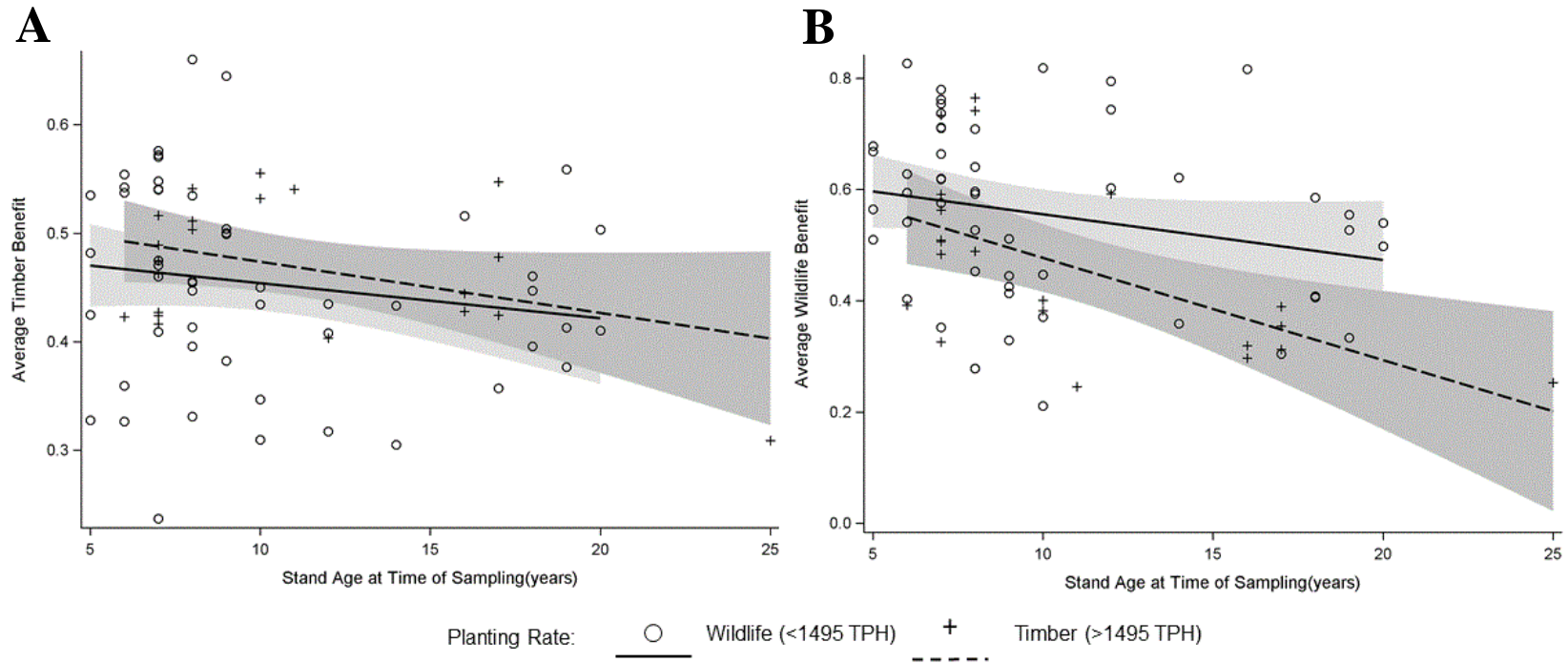


Figure 2.7 Average timber (A) and wildlife (B) benefit by stand age; plots are grouped by whether they fall into the recommended planting rate range for timber or wildlife (greater or less than 1495 TPH).

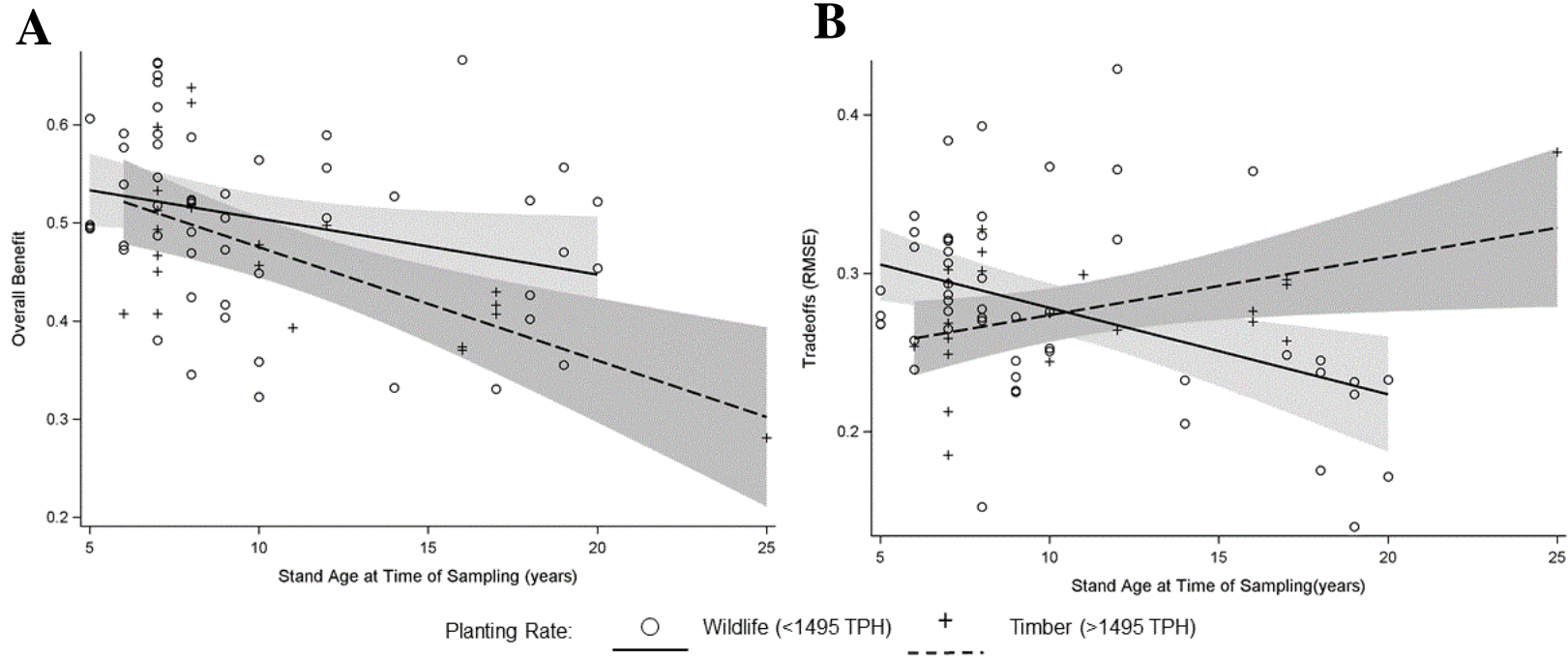


Figure 2.8 Overall (combined timber and wildlife) benefit (A) and tradeoffs (B) between individual benefits (calculated as RMSE) by stand age; plots are grouped by whether they fall into the recommended planting rate range for timber or wildlife (greater or less than 1495 TPH).

Discussion

We demonstrated that planting rate and stand density influenced timber quality and wildlife habitat quality in longleaf pine plantations. Within our inventory, 53 stands were established within the planting range recommended for providing wildlife habitat (988-1483 TPH / 400-605 TPA), and 20 were within the higher range recommended for timber (1483 -2223 TPH / 600-900 TPA). In many cases, planting rate exerted a stronger influence on stand characteristics in older stands. Plantations with lower initial planting rate had larger average tree diameters, lower basal area, and stems with more branches than stands of similar ages with higher initial planting rates. Plantations with lower initial planting rate had more open canopies, more bare ground cover, less woody cover, and more herbaceous cover than stands of similar ages with higher initial planting rates. These findings support the paradigm that lower planting rates promote higher quality wildlife habitat by increasing desirable vegetation characteristics, but effects of planting rates on timber quality were mixed; at higher planting rates, branch density declined but stem straightness also declined. Stands planted below 1495 TPH had a constant relationship between average timber benefit and stand age, and average wildlife benefits declined less rapidly as stands aged than in higher density plantations. Tradeoffs increased with age in higher (>1495 TPH) stocked stands, as wildlife benefits declined more rapidly than timber benefits in these stands than in lower density stands.

Longleaf pine diameters decreased with higher planting rates, indicating that individual trees grow more quickly in widely spaced stands relative to tighter spacings (Kush et al. 2006). As higher value forest products have larger diameters, lower planting rates could reduce the time until plantations are merchantable. Multiple growth and yield models predict that longleaf pine stands planted at 625-1111 TPH will outperform stands planted at 1600-2066 TPH in terms of

sawtimber produced (Hepp 1996; ForesTech 2005; South, 2006), although timber quality is often not included in these models.

We hypothesized that higher planting rates would lead to more positive timber quality benefits, including lower branch density and higher straightness grades. Our results only partially supported this hypothesis as both stem straightness and branch density declined with increased planting rate. X Paul (1938) similarly reported that higher stocked longleaf stands had fewer knots in the first log when compared to lower stocked stands. However, the lower straightness grade resulting from higher planting density in our study contradicts previous studies. Malinauskas (2003) reported that increased planting rate increased stem straightness in 20- and 25-year-old Scots pine (*Pinus sylvestris*), and that a 500 TPH stand would have only 13% grade A butt logs, and a 8000 TPH stand would have 82% grade A butt logs. Stahl (1990) documented less extreme, but similar patterns in slightly more mature (27–29-year-old) Scots pine, finding on average 5% more stems with minimal crookedness in 6410 TPH stands than 2500 TPH stands. It is possible we did not document this relationship because the maximum planting rate in our study (2445 TPH) was lower than in Malinauskas (2003) and Stahl (1990), which were 8000 TPH and 6410 TPH, respectively. The relatively young age of plantations (average of 10 years) of longleaf pines in our study also may have masked some of the relationships.

Planting density influenced understory vegetation, and in turn likely influenced habitat quality for gopher tortoise and other longleaf pine community wildlife associates. Open canopy longleaf pine plantations with extensive herbaceous and bare ground cover and limited woody understory cover offer high quality habitat for the gopher tortoise. Canopies were more closed and herbaceous cover lower in stands with higher planting rates. Dense canopy casts heavy shade and may limit the development of the herbaceous layer. Woody vegetation cover increased with

stand density, which was surprising given decreased light penetration through denser canopy should have restricted woody understory similar to herbaceous cover (Kush and Meldahl 2006). The target ranges for gopher tortoise habitat are 24-53% canopy openness, 9-41% bare ground cover, <24% woody understory cover, and 33-67% herbaceous cover (Wilson et al. 1997). Only 7% of stands met all of these characteristics, 37% met 3 standards, 34% met 2 standards, 23% met 1 standard, and 5% met no standards.

Relationships among planting density, tree form, and vegetation structure and composition likely are confounded by numerous site characteristics. Site history has a strong influence on seedling survivorship and the quality of understory plants originating from the seed bank. Agricultural usage of the land alters the soil profile and removes the former seed bank, requiring more effort and cost in the establishment of an herbaceous understory in the conversion process. In comparison, following clearcut harvests, legacy forbs and grasses establish readily from the seed bank, especially after prescribed fire (Guldin et al, 2016). Finally, site quality is a major determinant of the rate of stand development, as stand growth increases with the quality and quantity of soil nutrients and water. Thus, although the choice of initial planting density is critical in plantation management, stand growth can appear independent of initial stocking due to the carrying capacity or quality of the site.

Though we focused on how planting rate influenced longleaf pine stands, we also observed effects of other abiotic factors on timber quality and vegetation characteristics. Basal area increased and canopy openness decreased as site index increased. Longleaf pine, like other trees species, grows more quickly on more productive sites, resulting in earlier canopy closure and faster basal area accumulation. The percentage of sand in soil also had a positive effect on

seedling survival, which could be due to less competition from other tree species on sandy soils where longleaf pine is most competitive (Gilliam 1993).

We observed geographic patterns (correlations with longitude) in branch density, herbaceous cover, bare ground cover, and canopy openness. All these relationships likely represent differences in plantation ownership across the range of our study sites. A greater number of plantations managed to promote wildlife use were measured in North Carolina (NCWRC gamelands, $n=12$ sites). Survivorship (mean \pm SD; $40 \pm 15\%$) was lower for sites in North Carolina than in stands measured in the other states to the south and west ($71 \pm 15\%$; $t=-8.5$, $p<0.0001$), which could be partially due to regional differences in management, longleaf pine seed source, or local weather.

Canopy closure drives changes in understory dynamics. Planting at lower rates can slow the rate of canopy closure, but not stop it. Previous studies have found that mid-rotation management options, like prescribed fire can delay canopy closure, and increase habitat quality in older plantations (Noss, 1989). We did not have detailed site history information containing fire regime history, and were not able to include any prescribed fire in our analyses: doing so would likely better isolate the effect of planting rate, and would be useful to include in future studies.

We demonstrated that plantations established at lower planting rates were more beneficial for wildlife later in stand development than plantations with higher planting rates. Tradeoffs between timber and wildlife objectives decreased with age in low density stands, and increased with age in high density stands. Planting at higher rates reduced habitat quality, by decreasing the availability of light, herbaceous plant cover, and bare ground cover, and increasing woody understory cover. Although higher planting rates may buffer the effects of post-planting seedling

mortality, the higher rate appears to have mixed effects on tree form and inhibits diameter growth, therefore increasing the time needed to harvest larger diameter (and more valuable) forest products. We suggest this validates the restricted planting rates used in programs targeting conservation of wildlife habitat, but does not support that higher planting density (1483 TPH / 600 TPA) definitively improves timber quality.

Although the lower planting rates improved understory conditions for longleaf pine wildlife associates, stand structure eventually becomes unfavorable for these species regardless of planting density. Early and frequent thinnings and frequent use of prescribed fire are critical to maintain an open canopy, high herbaceous and bare ground cover, and low woody cover.

CHAPTER 3:

Determining the Effectiveness of Using Acoustic Velocity as an Indirect Measurement of Branchiness in Standing Longleaf Pine

Abstract

Knots and branches influence wood stiffness and density, and have a detrimental effect on stem quality. The number, size, and geometry of knots dictate the level of this effect, but quantifying branchiness is difficult, as visual estimates are prone to subjectivity, and mechanical measurements are impractical. Acoustic Velocity (AV) is a relatively recent assessment technique that measures the time a stress wave travels through wood. This measurement is correlated with wood stiffness and is affected by internal characteristics like knots. This project aimed to test if Acoustic Velocity can be used as an indirect measure of branchiness, by measuring Acoustic Velocity, height, diameter, and counting branches classified by size on 255 standing 8 year old longleaf pine (*Pinus palustris*). AV was highly correlated with height ($r=0.76$, $p<0.0001$) and slenderness ($r=0.52$, $p<0.0001$). However, there was no relationship between AV and total branch count, and only moderate correlation with living branches in the larger (diameter >2.54 cm) size classes ($r=-0.27$, $p<0.0001$). Height, slenderness, and the count of living branches greater than 2.54 cm in diameter were included in the selected model for AV. Including dead branches or branches smaller than 2.54 cm in diameter reduced the predictive power of the model. As the best model only explained 11% of the variation in acoustic velocity, and branches only accounted for 5% of the total variation, we determined that this technique would not be a good surrogate measurement for quantifying branchiness.

Introduction

The wood quality and size of a log are critical determinants of its value, with size being an easily obtainable metric and quality being less straight-forward. The number, size, and geometry of knots and branches influence the stiffness, density, and overall quality of the stem for lumber and can be included in grading systems used to determine tree value (Anon, 1994, Cown et al. 1995). Although the internal knottiness of the stem can be estimated from the outwardly visible branchiness (Kellomaki, 1984), quantifying the effect of branchiness on timber quality is time-consuming as there are numerous factors at play such as the absolute number of branches, size and angle of individual branches, and the number of branches at any particular node. Current methods of evaluating branchiness involve either visual estimates that may be prone to subjectivity (Falk, 1990) or mechanical measurements that are time-consuming and impractical from a forest inventory standpoint (Wessels, 2011). Such methods are expected to result in quality scores with low certainty.

A relatively recent innovation in wood quality assessment technology includes tools that measure acoustic velocity (AV), or the speed that a stress wave travels through wood (Wang et al. 2000). The AV can be measured by inserting two probes into a stem and timing the speed at which an induced stress wave travels between the two. AV has been used successfully in several studies as an indirect measure of wood stiffness, with which it is highly correlated (Lindstrom et al. 2002, Shmulsky et al. 2006, Mora et al. 2009). Internal characteristics of the wood also affect the speed of the wave, for example, the stress wave follows any distorted grain around knots and branches, lowering the speed of the wave (Gehards, 1982). In theory, the more knots within a stretch of stem, the longer a wave will take to transverse it. AV measurements in felled logs have been successfully correlated with the grades of resulting sawn lumber that include visual

inspection for knots (Wang et al. 2004). However, we are unaware of any studies evaluating how AV relates to the branchiness of standing trees.

The purpose of this study was to evaluate the use of acoustic velocity as a predictor of branchiness in standing trees. Acoustic velocity in 255 standing longleaf pine was measured along with a number of quality variables such as branch density and branch size. The relationships between AV and quality metrics were evaluated and regression models developed to determine the contribution of the characteristics of standing trees to the prediction of branchiness. If there is a relationship between AV and the time-consuming measures of branchiness, AV could potentially be used as a low-cost and rapid-assessment indicator of branchiness and its impact on timber value.

Methods

Site Description

Measurements were collected at a North Carolina Forest Service longleaf pine progeny trial in Wake County, NC (35.787 ° N, -78.911 ° W). The site was an old field in the Piedmont region of North Carolina with a Creedmoor-Green Level Complex soil. The area was burned and planted in 2011 (1347 TPH, with a 2.44 m by 3.66 m spacing) with multiple offspring from different genetic lines of longleaf pine. Following planting, volunteer loblolly pines (*Pinus taeda*) and hardwoods were mechanically removed, and between rows were mowed and sprayed with herbicide. The site was burned again four years post-planting.

Measurements

The following attributes were measured on 255 standing trees: height, diameter at breast height (DBH), live-crown ratio, AV, and branchiness. We measured 36 of 120 rows, for 30% of the total stand. Height was measured to the nearest 0.1m with a laser rangefinder. DBH was measured to the nearest millimeter with a diameter tape. The AV was measured using a FAKOPP TreeSonic Device, designed by Weyerhaeuser Co. (Seattle, WA) (Huang 2005). Two probes were inserted into the stem at heights of 1.9 m and 0.9 m (1 meter total length between the probes surrounding breast height) and then the top probe struck with a small hammer. The TreeSonic measures the time in microseconds it takes the stress wave from the hammer strike to reach the lower probe, called the time-of-flight (TOF). Three values were recorded for each tree. Within the same meter surrounding breast height, living and dead branches were counted, and recorded in size classes (<2.54 cm/1 in, 2.54-7.62 cm/1-3 in, >7.62 cm/3 in). Stem slenderness has been known to affect AV, and was calculated as the ratio of height and diameter, similar to Watt (2017).

Analysis

We measured the AV for standing trees using the TOF method, while AV of logs is measured using the resonance acoustic method. Standing tree TOF AV and log resonance AV values have been observed to be highly correlated, particularly in smaller trees (Wang et al. 2007). Stress waves in small trees propagate more like one-dimensional longitudinal waves than waves in larger trees, which behave more like dilatational waves. One-dimensional longitudinal waves provide a more accurate assessment of internal characteristics (Wang et al. 2013). Wang et al. (2007) developed a method of converting standing tree TOF measurements (which produce a dilatational wave) to log resonance measurements (which produce a one-dimensional longitudinal wave); their combined model, calculated using 6 softwood species was:

$$AV_{adjusted} = 5.5092 \left(\frac{DBH}{S} \right)^{.0295} AV_{TOF}^{.7677}$$

Where $AV_{adjusted}$ is the estimated value of a one-dimensional longitudinal wave, S is the length of stem within which the wave travels, and AV_{TOF} is the measured dilatational wave speed.

Pearson correlation coefficients were calculated between $AV_{adjusted}$ and height, DBH, slenderness, branches by size class, living branches by size class, all living branches, and all branches to investigate for simple linear relationships. To identify combinations of tree size and branchiness measurements that best explained the variability in $AV_{adjusted}$ a backward selection procedure for multiple linear regression was used. We evaluated the most influential predictor variables for $AV_{adjusted}$ based on the models' Akaike Information Criterion. Multiple model selection procedures were performed, maintaining height, slenderness, and live crown ratio for all models, but changing the classification level of branches. Branch densities were included as a combined count across sizes and statuses, a combined count across sizes classified by status, a

combined count across statuses classified by size, and classified by status and size. The model selection procedure was conducted with SAS v 9.4 (PROC GLIMMIX; SAS version 9.4, SAS Institute, Cary, North Carolina, USA.).

Results and Discussion

The longleaf pine we measured were even-aged but varied in size and form (Table 3.1). Mean DBH was $14.0 \text{ cm} \pm 2.9 \text{ cm (SD)}$, and mean height was $7.3 \text{ m} \pm 1.4 \text{ (SD)}$. Total branch count ranged from 1 to 18, with a mean of $8.5 \pm 3.3 \text{ (SD)}$. Of all branches measured, 36% were living, and 95% of living branches were greater than 2.54 cm in diameter. 87% of dead branches were greater than 2.54 cm in diameter. Mean number of whorls was $1.5 \pm 1.3 \text{ (SD)}$ and mean live crown ratio was $0.79 \pm 0.09 \text{ (SD)}$.

AV_{adjusted} was positively correlated with tree height (Fig. 3.1, $r = 0.23$) and negatively related to the density of live branches (Fig. 3.1, $r = -0.25$), particularly those in the middle and largest size class measured (Fig. 3.1, $r = -0.21$ and -0.18 respectively). The smallest size class of living branches and all size classes of dead branches showed no association with AV_{adjusted} .

The best model for predicting AV_{Adjusted} explained 11% of the variation, and incorporated height, slenderness, and the combined count of branches greater than 2.54 cm in diameter. Using the total branch count and/or including small branches (<2.54 cm in diameter) or dead branches reduced the effectiveness of the model (Table 3.2). Models indicated that AV_{Adjusted} increased with height and slenderness, and decreased with the number of living branches (Table 3.3, Fig. 3.2). Height and slenderness have been reported to affect AV_{Adjusted} by several authors, and this relationship is attributed to height and slenderness both being positively related to stiffness (Roth et al. 2007, Lasserre et al. 2007, Antony et al. 2012). The count of branches greater than 2.54 cm in diameter only accounted for 5% of the total variation in AV_{Adjusted} when accounting for the effect of height and slenderness.

The mean AV_{Adjusted} was 1786 m/s, which is within the range of values measured for other softwood species, from 1327 to 4761 (Wang et al 2007; Table 3.4). Our results were on the

low end of the range previously observed in other species, likely due to the difference in sampled ages. The sampled stand was much younger and would be characterized by mostly juvenile wood, which is associated with lower AV values corresponding to poorer wood quality compared to mature wood (Zobel and Sprague 1998). Krajnc (2019) reported that crown position relative to canopy impacted the direction of the relationship between AV and crown length. As we sampled an even aged plantation with fairly uniform canopy, we did not see this interaction with crown position, though our finding that slenderness had a positive effect on $AV_{Adjusted}$ was consistent with their finding that slenderness increased $AV_{Adjusted}$ in co-dominant trees (Krajnc, 2019).

Due to the relatively weak relationship between $AV_{Adjusted}$ and our measures of branchiness, it is unlikely that this method could be used to evaluate branchiness on young trees. It is unfortunate and unexpected that $AV_{Adjusted}$ is not a reliable way to evaluate branchiness. Although the predictive power of this model was poor, the weak negative relationship we observed between $AV_{Adjusted}$ and branches implies that branches do slightly negatively impact acoustic velocity.

Future studies could factor stiffness to potentially better model branchiness using AV. Stiffness has been shown to be strongly related to $AV_{Adjusted}$, and to be highly heritable (Lindstrom et al. 2002, Shmulsky et al. 2006, Mora et al. 2009, Isik 2011). Future studies could reevaluate the relationship between branches and $AV_{Adjusted}$ using a sample from a single progeny line, to reduce genetic variation in stiffness, or measure stiffness in the field to account for this variation, but having to measure stiffness in the field would mitigate the efficiency of using AV to evaluate branchiness. The relationship between branches and $AV_{Adjusted}$ is

interesting, but based on our results we do not believe that AV_{Adjusted} can be used as a surrogate measurement for branches on standing trees.

Table 3.1 Descriptive statistics of standing longleaf pine (n=254) DBH, height, AV_{adjusted}, branches by size class, total branches, and total living branches for a longleaf pine progeny trial in Wake County, NC measured at age eight years.

	Mean	Std. Dev	Min	Max
AV_{adjusted} (m/s)	2084.77	190.84	1616.49	2843.71
Height (m)	7.26	1.38	2.96	10.76
Diameter (cm)	13.96	2.90	4.10	20.10
Slenderness	4.40	0.67	1.84	7.55
Live Crown Ratio	0.79	0.09	0.30	0.98
Whorls (count)	1.49	1.34	0	8
All Branches	8.45	3.33	1	18
Living Branches	2.76	2.41	0	12
Dead Branches	5.68	3.65	0	18
Living Branches >2.54cm	2.62	2.36	0	12

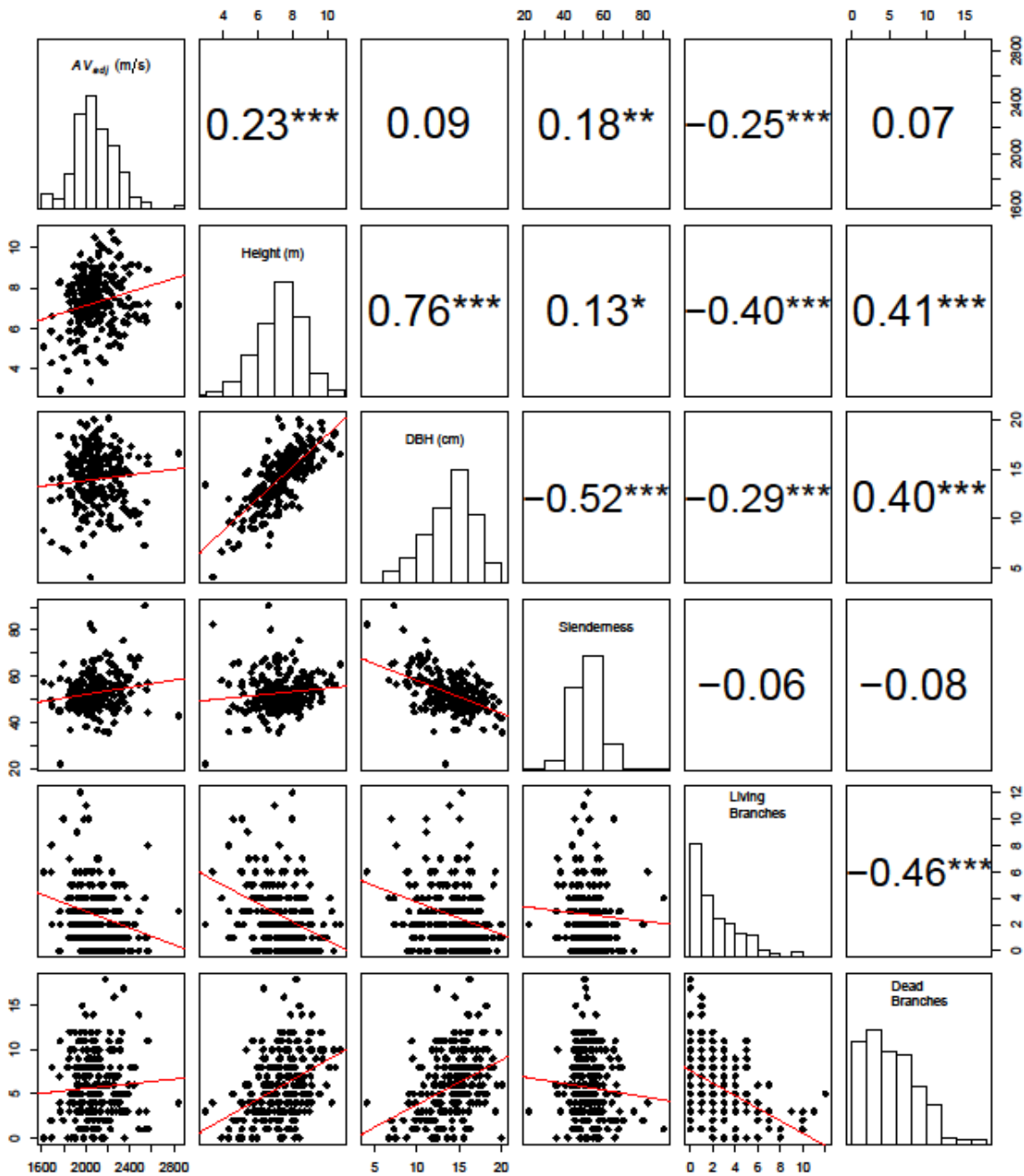


Figure 3.1 Scatterplot matrix showing correlation between $AV_{adjusted}$ and multiple variables relating to tree size and branch density. Scatterplots in the lower side of the matrix show the spread of the two variables, histograms show the distribution of individual variables, and the numbers in the upper half of the matrix are Pearson correlation coefficients; asterisks following correlation coefficients represent significance (**= $\alpha < .001$, *= $\alpha < .01$, = $\alpha < .05$)

Table 3.2 Full and reduced (Red.) linear regression models to estimate $AV_{Adjusted}$ with adjusted R^2 and ΔAIC . Some variables were repeated in all models, with difference levels of classifying branches (by size, and by status) differentiating each model selection process. Small branches are <2.54cm in diameter. Medium Branches are 2.54<7.62cm in diameter. Large Branches are >7.62cm in diameter. The final model is the selected model described in Table 3.3.

Variables	Model 1		Model 2		Model 3		Model 4		Best Model	
	Full	Red.	Full	Red.	Full	Red.	Full	Red.	Full	Red.
Height	X	X	X	X	X	X	X	X	X	X
Slenderness	X	X	X	X	X	X	X	X	X	X
Live Crown	X		X		X		X		X	
All branches	X	X								
All Dead branches			X							
All Living Branches			X	X						
All Small Branches					X					
All Medium Branches					X					
All Large Branches					X	X				
Small Living Branches							X			
Medium Living Branches							X	X		
Large Living Branches							X	X		
Small Dead Branches							X			
Medium Dead Branches							X			
Large Dead Branches							X			
Living Medium and Large Branches									X	X
Dead Medium and Large Branches									X	
Model output										
Adj R^2		0.077		0.092		0.079		0.094		0.097
ΔAIC		4.11		2.57		2.53		6.43		1.58

Table 3.2 Selected AV_{Adjusted} prediction model parameter estimates. Total model $R^2=0.11$.

Parameter	Estimate	Standard Error	t Value	Pr > t
Intercept	1820.48	101.46	17.9	<.0001
Height	18.37	8.97	2.05	0.04
Slenderness	39.33	17.31	2.3	0.02
Branches >2.54cm	-16.11	5.23	-3.1	0.002

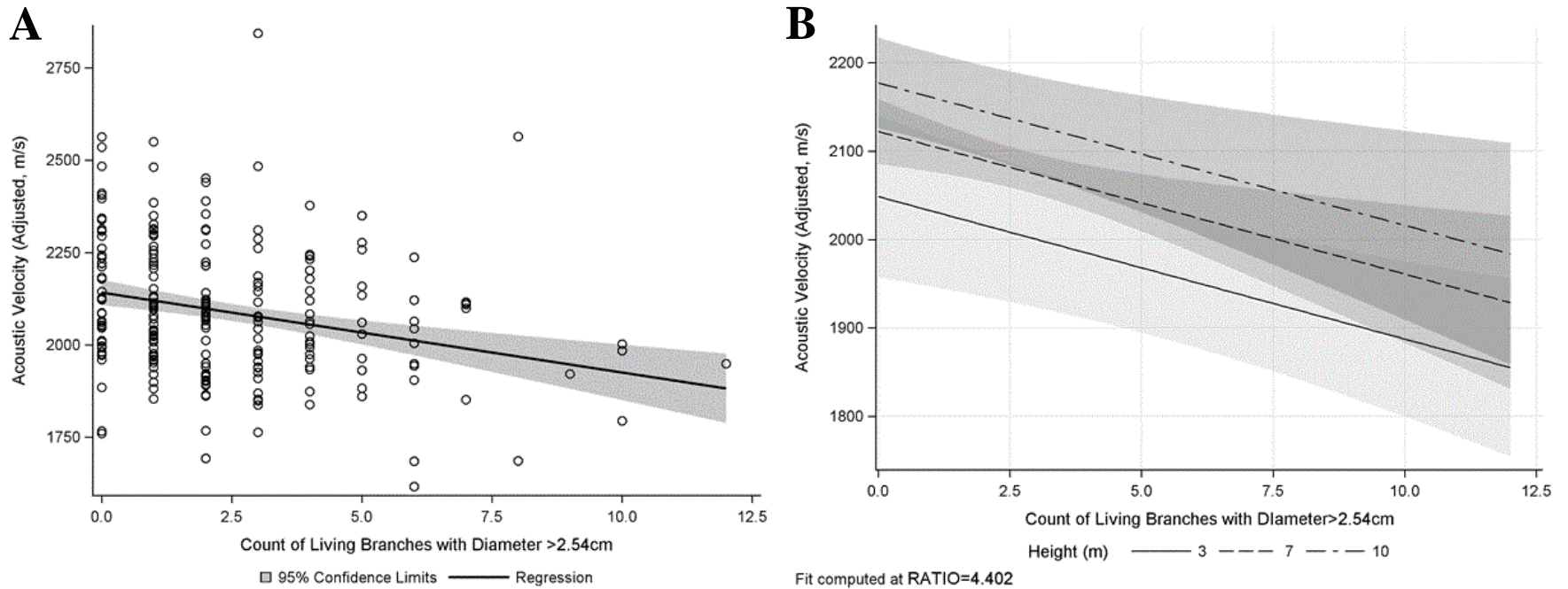


Figure 3.2 A. Regression showing AV_{adjusted} versus the number of living branches with diameter $>2.54\text{cm}$ ($r=-0.27$, $p<0.0001$). B. Regression model from Table 3.3 showing AV_{adjusted} versus the number of living branches with diameter $>2.54\text{cm}$ accounting for height and slenderness. Calculated with a slenderness ratio 4.402, series represents fits calculated for different heights ($R^2=0.11$, $p<0.0001$).

Table 3.3 Reported ranges, means, and standard deviations of AV and DBH for standing trees of six species previously reported (Wang et al., 2007) and longleaf pine measured in this study.

Species	Stand Age (years)	Sample Size (N)	AV _{adjusted} (m/s)		DBH (cm)	
			Range	Mean ± SD	Range	Mean ± SD
Sitka spruce	Mixed	30	3175-4763	3892 ±409.4	1.4-40.6	20.7 ±9.62
Western hemlock	Mixed	31	3289-4293	3721 ±264.4	1.4-32.5	18.3 ±6.92
Jack pine	40	27	3751-4618	4218 ±244.7	1.9-34.8	20.9 ±7.13
Ponderosa pine	43	114	1793-3908	2700 ±442.7	15.2-38.1	23.6 ±5.49
Radiata pine	8-25	150	1327-3771	2277 ±496.1	5-71.7	35.3±15.86
Longleaf pine (this study)	8	256	1399-2242	1786 ±204.1	4.1-20.1	14 ±2.90

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APPENDICES

Table A.1 Grading scale for visually assessing stem straightness, adapted from Prince et al. 2016

Score	Number of Straight Logs counted in 5m length			
	5m	4-5m	3-4m	2-3m
1	-	-	-	-
2	-	-	-	1
3	-	-	-	2
4	-	-	1	-
5	-	-	1	1
6	-	1	-	-
7	1	-	-	-