EVALUATION OF THE EFFECT OF THINNING LEVELS, SITE INDEX, AND AGE ON SHORTLEAF PINE (*Pinus echinata* Mill.) REGENERATION AND HARDWOOD UNDERSTORY

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CHAPTER I

INTRODUCTION

Shortleaf pine (*Pinus echinata* Mill.) is the most widely distributed of all southern yellow pines in the United States with a range of more than 400,000 square meters (Lawson and Kitchens 1983). Its wide range is due to its ability to grow on different types of soils. Shortleaf pine ranges from Texas to New York and is second to loblolly pine (*Pinus taeda* L.) in terms of total softwood volume for the southern pines. The principal timber area for shortleaf pine is found in the Ouachita mountains of western Arkansas and eastern Oklahoma (Baker 1992). In maturity the tree has a tall, straight stem and an oval crown, reaching a height of about 80-90 feet and a diameter of about two to three feet. The young tree, when cut or burned back, reproduces itself by sprouting from the stump. Shortleaf pine is resistant to fusiform rust (C*ronatium fusiform*) (Hepting 1971), and is resistant to the adverse affects of ice, snow, temperatures, and resistance to fire (Jemison 1943). An adequate seed source, a suitable seedbed, and control of competing vegetation are requirements for creating shortleaf pine stands (Lawson 1978). According to Guldin (1986), it can be difficult to obtain shortleaf pine regeneration naturally or artificially, and the species is susceptible to certain pathogens such as little leaf disease (*Phytophtora cinnamoni* Rands).

Natural regeneration may be the most common method of regenerating shortleaf pine on much of the extensive forestland in private ownership throughout its range (Lawson 1978). Natural regeneration has lower establishment and capitalization costs than any other regeneration method available (Baker 1982a). Among silvicultural practices available for forest management of shortleaf pine stands, thinning has the greatest influence on the production of sawtimber, increase of product yields, and reduction of rotation length. Brinkman et al. (1965) provide information on response of shortleaf pine stands to thinning.

Problem statement

Since the 1960's, shortleaf pine has been steadily declining due to the replacement of mature stands with other southern pines, predominantly loblolly pine (McWilliams et al. 1986). Yet, there is renewed interest in the management of shortleaf pine, whether in its pure state or mixed with hardwoods or other pines due to its value. Likewise, with the tightening supply on softwood fiber in the United States, stumpage prices for yellow pine are expected to increase over the next 50 years (Haynes et al. 1995). There has been little investigation on the effects of stand density, site index, and hardwood control on shortleaf pine regeneration.

Purpose of the study

The purpose of this study is to evaluate the effect of stand density levels and hardwood control on shortleaf pine regeneration and hardwood understory in naturally regenerated shortleaf pine forests.

Objectives of the study

The present study is designed to achieve the following objectives:

1) Describe the species distribution of the understory trees;
2) Quantify the relationship between overstory shortleaf pine and stand characteristics and shortleaf pine regeneration and hardwood understory;
3) Evaluate the probability of obtaining adequate regeneration of shortleaf pine regeneration 10 years after cutting.

Definition of terms

Technical terms are defined in accordance with the Society of American Foresters (1958). Terms used frequently in this study as well as their definitions are listed as follows:

1) "Site index: An expression of forest site quality based on the height of the dominant stand at an arbitrarily chosen age" (50 years in this study).
2) "Thinning: Cutting in an immature stand to increase its rate of growth, to foster quality growth, to improve composition, to promote sanitation, to aid in litter

decomposition, to obtain greater total yield, and so recover and use material that would be lost otherwise."

3)"Understory: That portion of the trees in a forest stand below the overstory."

4)"Tolerance: The capacity of a tree to develop and grow in the shade of and in competition with other trees; a general term for the relative ability of a species to survive a deficiency of an essential growth requirement, such as light, moisture, or nutrient supply."

5)"Overstory: That portion of trees in a stand forming the upper crown cover."

6)"Seedbed: In natural regeneration, the soil or forest floor on which seed falls; in nursery practice a prepared area in which seed is sown."

7)"Seedling: A tree grown from seed. Usually the term is restricted to trees smaller than saplings. "

CHAPTER II

LITERATURE REVIEW

The effects of thinning have been studied extensively in southern pine stands. Most studies were aimed at description, measurement, treatment, and analysis of results for a specific stand over short periods of time. Often, those studies were related to growth and yield only. Few if any studies consider effects of the combination of thinning levels and stand characteristics on shortleaf pine regeneration.

Site quality and light factors

The importance of soil quality and other environmental condition effects on tree and stand development is well known (Nebeker and Hodges 1985). The quality of shortleaf pine as well as its yield varies with site quality. According to Graney (1976), researchers have noticed that soil features such as surface soil thickness, surface soil texture, and subsoil consistency are related to site quality for shortleaf pine. Generally, the best shortleaf pine sites are on well-drained, medium texture soils because they have adequate available moisture and nutrients, good soil structure, and sufficient aeration. Those factors allow the development of root systems. Research concerning soil-site relations of the southern pines has suggested that soil and topographic features, which influence soil moisture and soil aeration, were likely to be most closely related with shortleaf pine growth (Coile 1952, Ralston 1964). A strong relationship was found between site quality and soil moisture for shortleaf pine (Guldin 1986). Generally, the effects of site index reflect the availability of limited resources, especially water and nutrients. Thus regeneration levels should be influenced by site quality. Some studies have shown that on better sites, hardwood regrowth will be so rapid that shortleaf pine seedlings will have little opportunity to survive and grow, even if they are established soon after site preparation (Lawson 1960). (Shelton and Murphy 1994) suggested that uneven- aged pine stands might be better established on the poorer sites. Coile (1948) established the following relationships between site quality and soil properties for loblolly pine and shortleaf pine:

Site index (loblolly pine)= $100.04 - 75/x_1 - 1.39x_9$

Site index (shortleaf pine)= $77.32 - 45/x_1 - 1.00x_9$

Where, x_1 – depth of surface soil in inches;

x_9 – imbibitional water value of the subsoil.

Biologically, pine trees need growing space in which they compete for water, nutrients and light. Light has an important influence on natural regeneration. Light intensities of 20% or less were associated with very poor survival of pine species (Jackson 1959). Light has more impact on pine regeneration than soil moisture in limiting the establishment of shortleaf pine seedlings under forest stands in North Carolina (Oosting and Kramer 1946). This also was confirmed in the 6-year-old slash pine (*Pinus ellioti* Englm.) plantation study in Georgia (Harms 1962). Shortleaf pine as well as loblolly pine seedlings do not develop their root systems very well to compete with other vegetation; however, under ample light they become larger and supply the water and nutrients for survival and growth (Kramer 1946). Among intolerant pines, longleaf pine (*Pinus palustris* Mill.) is generally found as the most intolerant of the southern pines (Baker 1949). It is intolerant of overtopping trees. Some investigations have found that longleaf pine regeneration in old growth forests was largely confined to openings, where it was free to develop (Wahlenberg 1946). Similarly, growth rapidly declines as overstory density increases (Boyer 1963).

Factors that influence seed production

Haney (1962) and Baker (1982b) found that a good seed crop for shortleaf pine produces 80 thousand to less than 250 thousand sound seeds per acre. A ten-year study in the Ouachita and Ozark mountains on shortleaf pine seed production in natural stands, revealed that annual sound seed production in individual stands varied from 0 to more than 2 million sound seeds per acre (Shelton and Wittwer 1996). Annual variation in shortleaf pine seed production comes from biotic factors (competition, insects, mammals and birds) and abiotic factors (weather) (Shelton and Wittwer 1996). According to Barnett and Haugen (1995) there are five main factors that contribute to flowering: hormones, soil moisture, light, nutrients, and temperature. Of these factors, light, nutrients and moisture can be manipulated to enhance seed production by means of thinning (Barnett and Haugen 1995). (Smith and Stanley 1969) found that nutrients and changes in temperature and levels of light could cause response differences in the formation of the reproductive organs in pines.

Seed production and dispersal

In general, shortleaf pines do not bear seeds until they are 20 years old. Trees begin to produce a lot of seeds when their diameter is about 12 inches (Baker 1992). Shortleaf pine produces seeds in most years; yet, good seed crops occur every 3 to 10 years in the northern areas and 3 to 6 years in the southern areas (Lawson and Kitchens 1983). More than 80,000 sound seeds per acre is usually considered a good seed crop; 30,000 to 80,000 seeds per acre is an average crop; while fewer than 30,000 seeds per ace is considered marginal to poor. The minimum supply needed to adequately restock a prepared seedbed is 50,000 seeds per acre (Baker 1982a). A study of shortleaf pine seed production in Missouri showed that the most seeds were produced in stands thinned to 50 square feet of basal area, and the least were produced on unthinned stands. It was suggested that the optimum stocking for maximum seed production might be around 25 to 35 square feet of basal area per acre (Phares and Rogers 1962).

Pine seedfall starts in early October and peaks in November, and by mid December approximately 85% of the seed has fallen (Langdon 1981, Grano 1970). A ten-year study of shortleaf pine seed crops in Texas also revealed that most of the seed fell in November (Stephenson 1963).

Research has shown that seed dispersal of shortleaf pine depends on the height and stocking level of the seed source trees, magnitude of seed crop, terrain, and wind conditions at time of seedfall. It was found that for the average conditions, the effective seeding distance generally varies from 200 to 300 feet downwind from the seed source and 75 to 100 feet in other directions (Baker 1987).

Regeneration from seed

Shortleaf pine regeneration does not develop very well in closed canopy conditions since it is intolerant in nature and requires some form of great disturbance, or competition control to grow and regenerate successfully (Crow and Shilling 1980). Natural regeneration for pines in general depends on several factors including adequate seed supply, good moisture, good seedbeds during germination and establishment, and adequate control of competing vegetation. Lack of one of these requirements results in regeneration and seedling failure (Langdon 1981 and Doughterty 1990). Shortleaf pine seeds do not require exposed mineral soil for germination and seedling establishment during good seed crop years regardless of seedbed or site conditions. Yet, when the seed crop is light, seedbed preparation is recommended to allow seed contact with mineral soil and to ensure that the seedbed supply is used to the fullest extent. Generally, soil disturbance from the logging operation is enough (Baker et al. 1991).

Hardwood competition

Shortleaf pine is shade-intolerant, and hardwoods are the climax vegetation in many areas of the Southeastern United States. Thus hardwood control is important to develop shortleaf pine as a principal element of managed forests, be they naturally regenerated or planted forests. (Rogers and Brinkman 1965) found that when a dense hardwood understory is expected to hinder natural pine regeneration, eliminating hardwoods in combination with pine thinning is an excellent management practice. Regeneration often takes place under a partial forest canopy. Growth rates of residual stems also increase because thinning may show a greater increase if additional understory control is provided (Bower and Ferguson 1968, Yocom 1971). Other investigations also found that thinning and hardwood removal significantly increased shortleaf pine seed production (Phares and Rogers 1962). In fact, when competition for water and light becomes critical to nearly established seedlings, competition control should be implemented. On typical sites, many hardwoods are present and must be controlled to allow adequate natural regeneration. Single-stem injection, foliar spray, or soil application of herbicides will effectively reduce hardwood competition, especially when many very small hardwoods are present (Lloyd et al. 1978). Mechanical methods, such as hand cutting and shearing also temporarily reduce hardwood competition, but may cause problems with sprouting. Maple (1965) found that brush cutting provided higher tree percents of shortleaf pine seedlings surviving (2.9) and stocking levels than chemical treatment (1.3) and burning (0.4). Some studies have shown that on upland pine sites the competition between pines and other competing vegetation such as hardwood trees and herbaceous plants resulted in the loss of pine volume estimated to be 25 percent in natural stands and 14 percent in plantations (Fitzgerald et al. 1973). However, Crow and Shilling (1980) found that the beginning of a burning program several years before the harvest/regeneration cut reduces hardwood competition for newly established seedlings. The need to impose some control on smaller, as well as larger stems, was shown by the results of a release study in Southern Arkansas (Mann 1951). Young shortleaf pine tolerates shade relatively well; however, it gets intolerant as the stand gets older (Baker 1992).

Natural regeneration methods

Natural regeneration methods such as shelterwood, seed tree, and other systems are viable methods for establishing and maintaining shortleaf pine even-aged stands.

<u>Seed tree system</u>

The seed tree system remains undoubtedly the most widely used in natural regeneration of shortleaf pine. It involves the removal of all the overstory except 6 to 20 well-spaced, vigorous trees per acre that provide 10 to 12 square feet per acre basal area. In loblolly-shortleaf pine stands 12 to 20 trees per acre might be left where shortleaf pine comprises a majority of the stand (Baker 1982a). The number of trees required depends on tree size and site conditions (Baker 1992). Yet this system has some disadvantages. For loss of seeds after they reach the forest floor is high, but variable. It had been estimated that only 1% of the sound seed dispersed in the Ouachita Mountains produces seedlings (Yocom and Lawson 1977). To get adequate seed supply, seed trees must be released 3 to 5 growing seasons before the harvest cut by thinning the stand 60 to 70 square feet per acre basal area (Baker 1992).

<u>Shelterwood system</u>

This method is similar to the seed tree method except that stocking between 20 to 30 square feet of basal area per acre may be desirable (Baker 1982a). Baker (1992) found that this method was similar to the seed tree method except that 30 to 50 trees per acre are left to regenerate the area. It was recommended that 30 to 40 square feet of basal area should be left (Baker 1992). Phares and Rogers (1962) found that more seeds were produced at 50 square feet of basal area than at higher levels and suggested that maximum seed production per acre might occur at even lower levels of stocking. Besides resulting in greater seed production, the lower stocking levels greatly reduce competition for seedlings. For example, in Arkansas, Grano (1970) found that densities of 60 to 70 square feet of basal area per acre produced the most seeds in loblolly-shortleaf pine stands. According to Williston and Balmer (1974), the shelterwood method of regeneration specifies 30 to 60 square feet per acre basal area in loblolly pine seed trees. Though the shelterwood provides better protection than the seed tree, the greater shelterwood overstory may hinder growth of pine reproduction.

CHAPTER III

METHODOLOGY

Data

Data were obtained from plots established in a cooperative study between the USDA Forest Service Southern Research Station and the Department of Forestry at Oklahoma State University. Plot locations on the Ozark and Ouachita National Forests ranged from areas north of Interstate Highway 40 near Russellville in western Arkansas to near Broken Bow in southeastern Oklahoma (Figure 1). A total of 182 plots located in the Ouachita and Ozark National Forests were installed which covered a wide spectrum of site, age, and density classes. The study design consisted of four site index, age, and density classes (Table 1). Plots were installed during the dormant season of 1985-1987 when basic forest measurements were recorded; subsequent measurements were recorded on a four or five-year interval for each plot. For more information on plot installation and location see Murphy (1988). Summary statistics for the complete data set of the Ouachita Highlands natural even-aged shortleaf pine regeneration were computed (Table 2).

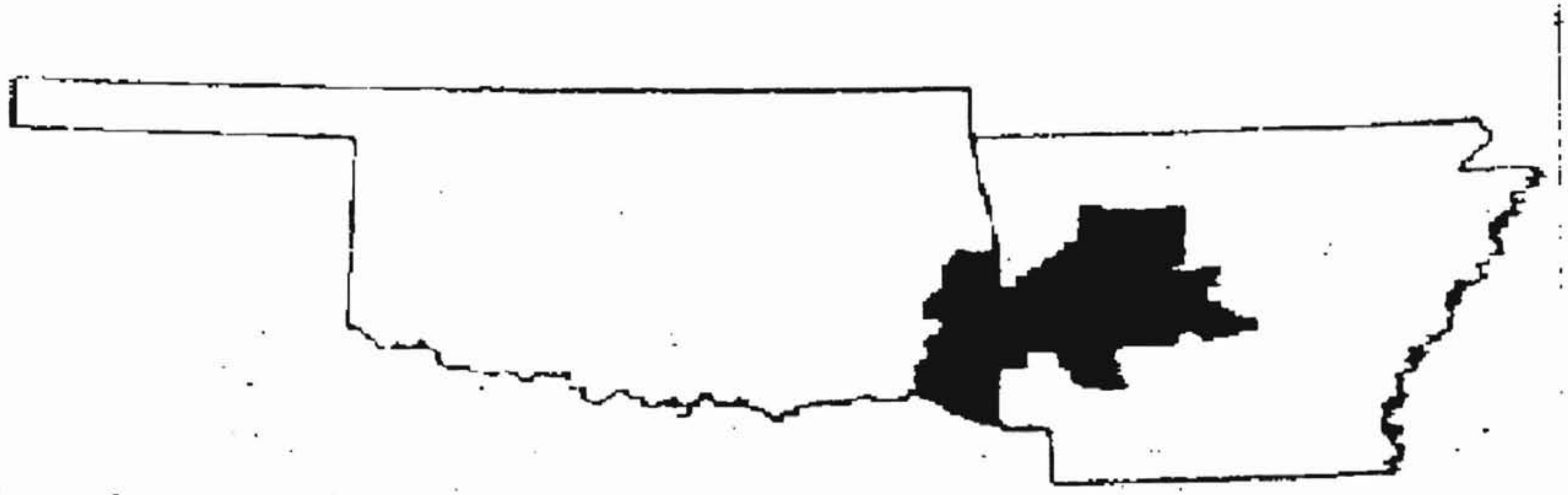


Figure 1. Region in which plots were located.

Table 1. Attributes and class ranges for the USDA Forest Service-Oklahoma State University cooperative research plots for the natural even-aged shortleaf pine growth and yield study.

Variable	Units	Class ranges	Class midpoints
Basal area	Square feet/acre	16-45	30
		46-75	60
		76-105	90
		106-135	120
Site index			
(base age 50)	Feet	<56	50
		56-65	60
		66-75	70
		>75	80
Age	Years	11-30	20
		31-50	40
		51-70	60
		71-90	80

Table 2. Summary statistics for the complete data set (N=182).

Variable	Mean	Standard error	Minimum	Maximum
Ba_o	12.50	12.66	0.00	87.64
Num_o	2778.57	1843.88	0.00	8500.00
Ba_p	1.37	4.22	0.00	26.89
Num_p	347.80	928.06	0.00	5400.00
Page_beg	54.96	20.14	18.00	93.00
Page_meas2	59.66	20.12	23.00	99.00
Pba_beg	74.89	32.64	27.32	128.99
Pba_meas2	86.16	36.41	14.87	156.46
Si_plot	61.52	11.30	38.93	87.11

Where

Ba_o = basal area of hardwood understory in the plot (ft^2/acre) 9 to 10 years after plot establishment;

Num_o = number of hardwood understory in the plot (trees/acre) 9 to 10 years after plot establisment;

Ba_p = basal area of shortleaf pine regeneration in the plot (ft^2/acre) 9 to 10 years after plot establishment;

Num_p = number of shortleaf pine regeneration in the plot (trees/acre) 9 to 10 years after plot establishment;

Page_beg = plot age at measurement 1(years) 4 to 5 years after plot establishment;

Page_meas2 = plot age at measurement 2 (years) 4 to 5 years after plot establishment;

Pba_beg = plot basal area at measurement 1(ft^2/acre) 4 to 5 years after plot establishment;

Pba_meas2 = plot basal area at measurement 2 (ft^2/acre) 4 to 5 years after plot establishment;

Si_plot = plot site index (ft).

Study design

The study design called for circular plots, 0.2 acres in size with a 52.7-foot radius, and surrounded by a 33-foot isolation buffer for each site-age-density combination. When established, each plot was thinned from below to a predetermined residual pine basal area. White-painted bands on trees just outside the boundary mark the isolation zone (Figure 2). A 33-foot buffer boundary marked by blue-painted bands on trees surround each contiguous group of plots. Plots centers are monumented with an 18-inch orange plastic surveyor's stake or steel reinforcing rod.

Herbicides were applied to control any existing hardwoods greater than or equal to 1-inch diameter at ground level and shortleaf pine were thinned when necessary to achieve the desire basal area for both the plot and buffer strip area. The isolation strip 33 feet wide was treated in the same manner as the 0.2-acre measurement plot in order to eliminate competition from forest conditions different from those in the 0.2-acre plot. The residual shortleaf pine trees on the 0.2 acre plot were measured, numbered, located from plot center, and were tallied for all trees greater than or equal to 1 inch diameter at breast height (dbh).

The plots in the USDA Forest Service-OSU Department of Forestry cooperative shortleaf pine growth study have been measured three times since their establishment. The first measurement or establishment of plots occurred from 1985-1987. The second measurement was made during the period 1990-1992. The third measurement occurred

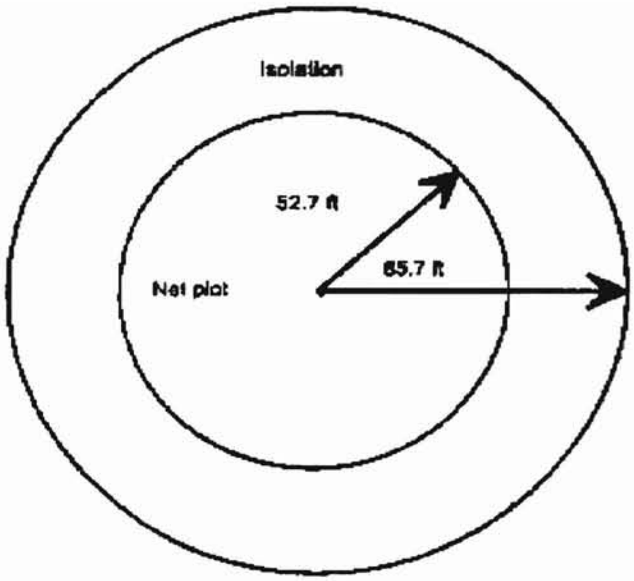


Figure 2. Layout of 0.2-acre plots for measurement of overstory shortleaf pine. Measurements are made on the net plot; the isolation plot receives the same thinning and hardwood control as the net plot.

from 1995 to 1997. During the third measurement two 0.005-acre plots were established within each 0.2 shortleaf pine growth plot to measure understory characteristics.

Each 0.2-acre net plot contains two 0.005-acre circular plots (8.3-foot radius) that are located midway between plot center and the net plot boundary and due north and south from plot center (Figure 3). The understory was measured on the 0.005-acre subplots. All shortleaf pine regeneration and hardwood understory stems 4.5 feet in height and larger were measured.

Statistical analysis

A SAS (SAS Institute Inc. 1989) subroutine was written to summarize the data (Appendix A). Descriptive statistical analysis and a matrix of simple correlation coefficients were obtained for the overstory and understory characteristics using the correlation procedure in SAS. Data summaries were performed to obtain information on distributions of species and genus. A table of the number of plots by species abundance classes was developed. Analysis of variance was conducted for the following dependent variables: understory shortleaf pine per acre, hardwood understory stems per acre, understory shortleaf pine basal area per acre, and understory hardwood basal area per acre. The analysis of variance was performed using PROC GLM (SAS Institute. Inc 1989) in SAS. The purpose was to test the main effects, which were the basal area class, age class and site index class of the stand for each understory dependent variable. Likewise, the simple effects for the basal area of shortleaf pine understory and for the basal area of hardwood understory were tested.

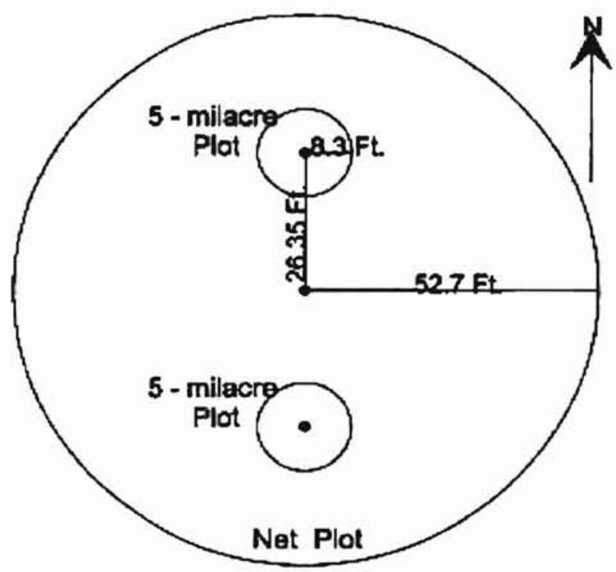


Figure 3. Location of 5-milacre plots for measurement of shortleaf regeneration and hardwood understory within 0.2-acre plot.

Stepwise regression was also used to select the best predictive variables for understory characteristics. The selected variables were then used with nonlinear regression least squares techniques to fit models for the prediction of the number and basal area of shortleaf pine regeneration as well as the number and basal area of hardwood understory stems. In addition, the number of both shortleaf pine regeneration and hardwood understory stems as well as their respective basal areas were summarized by age, basal area, and site index classes. A fit index comparable to the coefficient of determination (R^2) was computed for each model to determine how well it fits the data. The fit index has the following formula:

$$FI = 1 - \frac{\sum_{i=1}^{n} e_i^2}{\sum_{i=1}^{n} (y_i - \overline{y})^2}$$

where: FI= fit index ;

n= number of observations;

y_i = actual ith observation;

e_i = residual of the ith observation (actual minus predicted value);

$\overline{y}$ = mean of observations.

Likewise, the mean square error (MSE) for the four predictive models was computed as the sum of the squared difference between the predicted and the actual data values divided by the degrees of freedom.

$$MSE = \frac{\sum_{i=1}^{n} e_i^2}{n - p}$$

where: p = number of parameters estimated;

n and e_i are as defined previously.

Likewise, plots of the residuals against fitted values for the number of shortleaf pine regeneration as well as for the hardwood understory were done.

A probability of successful regeneration model for shortleaf pine was developed using data summarized by a SAS program (Appendix B). Successful regeneration was defined as having more than a specified number of shortleaf pine regeneration stems 10 years after thinning and hardwood control. Thus *P (regensuccsess≥T)* represents the probability of getting more than *T* shortleaf pine regeneration stems per acre 10 years after thinning and hardwood control. It was desired to develop a model, which could make predictions for levels of *T* ranging from 300 trees per acre to 700 trees per acre. Therefore, the original data set was duplicated to obtain three sets of records for the original 182 plots. The first set contains a Bernouilli variable that is 1 if there are more than 300 shortleaf regeneration stems per acre and 0 otherwise. The second set of 182 records contains a Bernouilli variable that is 1 if there are more than 500 shortleaf regenereration stems per acre and 0 otherwise. The third set contains a Bernouilli variable that is 1 if there are more than 700 shortleaf regeneration stems per acre and 0 otherwise. For parameter fitting in a logistic model described below, these three sets of 182 records are combined into one data set consisting of 546 records. The Bernouilli variables on each record are the dependent variable for fitting parameters to a logistic model for probability of regeneration success. This means, that we will have 182 records for each different level of regeneration: more than 300, 500 and 700 shortleaf pine regeneration stems per acre. An example of how the data were arranged for the purpose of computing the probability model is found in Table 3. The logistic equation was used in model development. Parameters were fitted to the model using logistic regression with a Bernoulli dependent variable in which 1 stands for shortleaf pine regeneration success and 0 for regeneration failure. The model can be used to predict the probability of getting 300, 500, and 700 or more shortleaf pine regeneration stems per acre. The following steps will explain in detais how the probability model was obtained. The need is to predict the probability of getting shortleaf pine regeneration success given basal area of the stand, site index, age, and year of establishment of plots using the model. Two dummy variables were created to represent the year of plot establishment. However, while testing those two dummy variables, it appeared both years (1985 and 1986) were significant at the level 0.05, but the difference between them was not significant at the same level of significance (0.05). Thus to make the model simple, only one dummy variable Z1 was used. Z1=1 for the year of establishment 1985 or 1986, and Z1=0 for the year of establishment 1987.

Table 3. Example of data arrangement for the parameter estimation in the probability model showing records for five plots at three levels of regeneration success.

T	Y=1 if (regn $\geq T$)	Shortleaf regeneration/ac	Basal area/ac	Site index	Age
300	1	350	35	50	45
300	0	50	100	95	50
300	1	570	40	80	60
300	1	800	38	60	45
300	0	20	110	75	86
.	.	.	.	.	.
500	0	350	35	50	45
500	0	50	100	95	50
500	1	570	40	80	60
500	1	800	38	60	45
500	0	20	110	75	86
.	.	.	.	.	.
700	0	350	35	50	45
700	0	50	100	95	50
700	0	570	40	80	60
700	1	800	38	60	45
700	0	20	110	75	86
.	.	.	.	.	.

Where Y= dependent variable;

(regn $\geq T$)= regeneration success greater than or equal to T.

The model can be written in this form:

$$(1) \quad P(regensuccess \geq T) = \frac{1}{1 + T^{Z}\exp(\beta_0 + \beta_1 x_1 + ...)}$$

Where $P(regensuccess \geq T)$ = probability of obtaining shortleaf pine regeneration stems per acre 10 years after thinning;

T= number of trees per acre;

Z= exponent of T;

x_i = explanatory variables;

β_i =parameter.

Hence for $Z \geq 0$ and T=0, the probability of regeneration success (equation 1) will be 1 as it is illustrated below:

$$P(regensuccess \geq 0) = \frac{1}{1 + 0^{Z}\exp(\beta_0 + \beta_1 x_1 + ...)}$$

$$= \frac{1}{1+0} = 1$$

And for $Z \geq 0$ and $T \rightarrow \infty$, the probability of regeneration success will be 0 as it is shown below:

$$P(regensuccess \geq \infty) = \frac{1}{1+\infty} \rightarrow 0$$

These properties of the model are biologically reasonable. One is certain that shortleaf pine regeneration stems will be greater than or equal to zero. On the other hand there is no chance of obtaining an infinite number of shortleaf pine regeneration stems. The analysis above indicates that the probability model proposed in equation 1 is consistent with these facts as long as the exponent Z of T is positive. Since equation 1 decreases monotonically as T increases, it behaves in a reasonable way. Thus the probability model (equation 1) can be written in this form:

$$(2) \qquad P = \frac{1}{1 + \exp(\beta_0 + \beta_1 BA + \beta_2 AGE + \beta_3 SI + Z \ln(T) + \beta_5 Z1)}$$

where $\ln(T)$ = natural logarithm of T.

In the process of building the model we found that the value (Z) of the exponent of T was:

$$Z = \beta_4 * SI * SI$$

To fit the model for analysis, we had to rewrite the model (equation 2) in the following form (Neter et al. 1996):

$$(3) \quad P = \frac{1}{1 + \exp(\beta_0 + \beta_1 BA + \beta_2 AGE + \beta_3 SI + \beta_4 TSSI + \beta_5 Z1)}$$

Where P= probability of regeneration success;

BA= (Pba_beg) stand basal area;

AGE= (Page_beg) stand age;

SI= (Si_plot) site index;

$TSSI = \ln(T) \times SI \times SI$;

Z1= dummy variable related to annual conditions;

Z1=1 for plots established in 1985 or 1986;

Z1=0 for plots established in 1987;

β_i= logistic regression parameters.

After evaluating the parameters in the model, chi-square goodness of fit test was used for the validation of the model by basal area class. The chi-square statistic measures how closely a set of expected frequencies fits those actually observed. The purpose here is to test the null hypothesis to find out whether or not the model fits the data for more than 300, 500, and 700 trees per acre of shortleaf pine regeneration. The model should be tested for each specified level. The formula for the test statistic is as follows:

$$\chi^2 = \sum \frac{(observed - expected)^2}{expected}$$

*s

CHAPTER IV

RESULTS AND DISCUSSION

Table 4 shows that the number of trees per acre on plots by basal area class for shortleaf pine regeneration is very small in comparison to the number of hardwood understory stems. There are a relatively good number of shortleaf regeneration stems in the lower basal area classes 30 and 60 square feet per acre, but the number decreases substantially in the higher basal area classes. Figure 4 confirms this trend. Shortleaf pine regeneration declined exponentially with increasing overstory pine basal area. Harvesting to lower basal areas encouraged more abundant shortleaf regeneration. Disturbances encourage the regeneration for shortleaf pine. Shortleaf pine appears significantly where plots were thinned because " in presence of either natural or human disturbances, shortleaf pine is likely to successfully reestablish itself" (Guldin 1986). At 30 square feet of basal area per acre the canopy is largely opened, and this favored the regeneration of shortleaf pine because this species needs light.

Table 5 shows that the number of shortleaf regeneration stems per acre on plots is relatively higher in low site classes having midpoints of 50 and 60 feet, and poor in higher sites. The competition for finite resources like water, light, growing space and nutrients from hardwood understory stems is not as high on those sites. This favors

Table 4. Number of shortleaf pine regeneration and hardwood understory stems on plots per acre by overstory plot basal area class 10 years after cutting.

Basal area class	No.plots	Number of shortleaf pine/acre	Mean	Number of hardwood/acre	Mean
30	46	39200	852.17	149900	3258.70
60	47	16900	359.57	138600	2948.94
90	48	4000	83.33	129300	2693.75
120	41	3200	78.05	87900	2143.90
All classes	182	63300	347.80	505700	2778.57

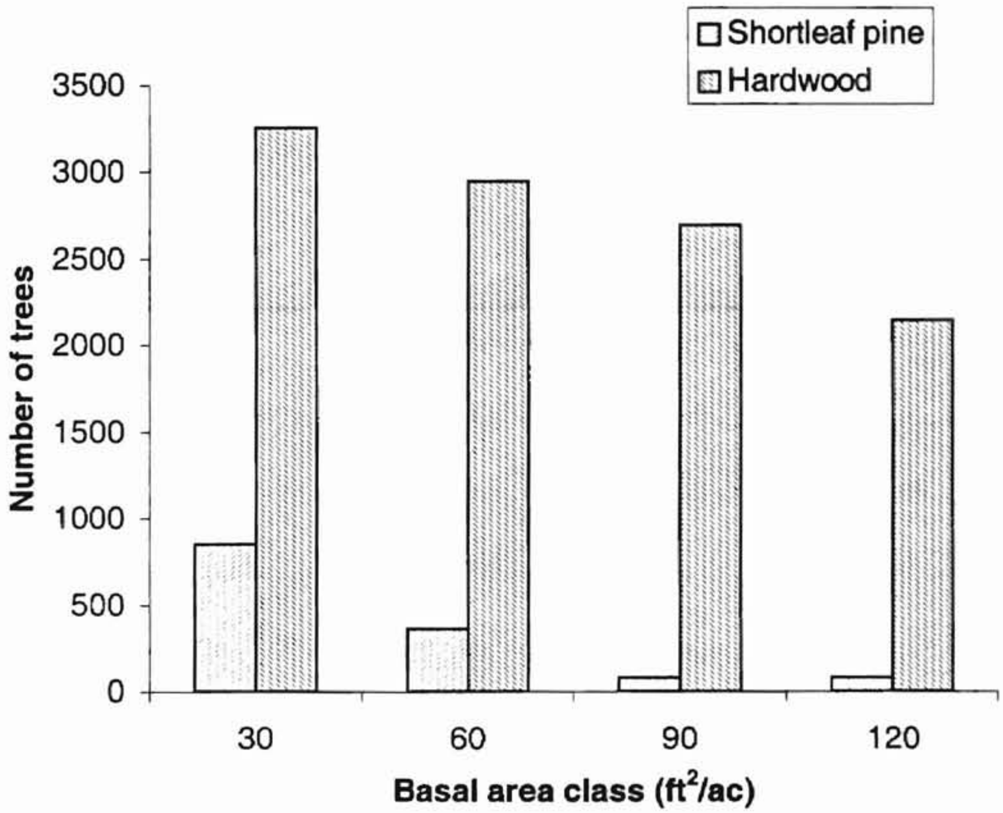


Figure 4. Number of shortleaf regeneration and hardwood understory stems per acre on plots by overstory plot basal area class 10 years after cutting.

Table 5. **Number of shortleaf regeneration and hardwood understory** stems per acre on plots by site index class 10 years after cutting.

Site index class	No.plots	Number of shortleaf pine/acre	Mean	Number of hardwood/acre	Mean
50	60	30400	506.66	86200	1436.67
60	55	27200	494.55	139900	2543.64
70	40	4900	122.50	153600	3840.00
80	27	800	29.63	126000	4666.67
All classes	182	63300	347.80	505700	2778.57

shortleaf pine regeneration. Hardwood is very abundant on the better site classes having midpoints 70 and 80 feet. This is illustrated by the graph (Figure 5). Table 6 shows that the number of shortleaf pine regeneration stems is lower at age 20, but more abundant at older ages. This occurs because around age 20 shortleaf pine starts producing seed (Baker 1992). Figure 6 shows very similar amounts of shortleaf pine regeneration from age 60 and 80.

Development of hardwood understory on the plots

Many hardwoods, mostly of tolerant species, were present in the understory of the plots at the time of establishment. When plots installed during 1985-1987 were remeasured the second time (1995 - 1997), the average number of hardwood understory stems per acre was 2,778.57 (Table 4). Although most of the hardwood understory was intensively controlled with herbicides (cut-stump treatment, tree injection, or ax frill and spray), it still developed in abundance on thinned plots often from stump sprouts. The most abundant species are hickories, blackjack oak, and dogwood (Table 7). Shortleaf pine is the tenth in terms of abundance among understory species. There appeared to be a tendency for hickory and blackjack oak species to be more abundant than other hardwoods. Quercus and Carya are the most abundant genera on plots (Table 8). Table 9 shows that 12 to 16 species are found in 20 plots, 7 to 11 in 74 plots and 2 to 6 in 77 plots.

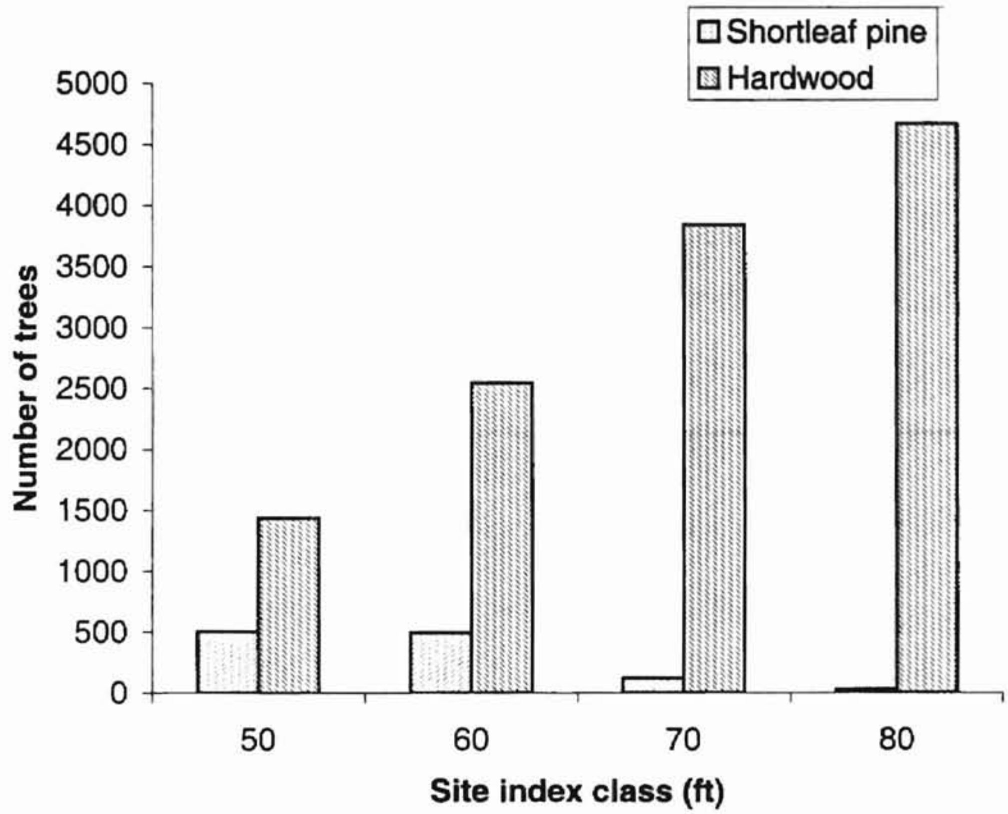


Figure 5. Number of shortleaf regeneration and hardwood understory stems per acre on plots by site index class 10 years after cutting.

Table 6. Number of shortleaf pine regeneration and hardwood understory stems per acre on plots by overstory plot age class 10 years after cutting.

Plot age class	No.plots	Number of shortleaf pine/acre	Mean	Number of hardwood/acre	Mean
20	28	4400	157.14	65900	2353.57
40	54	24300	450.00	133800	2477.78
60	53	17300	326.42	161100	3039.62
80	47	17300	368.09	144900	3082.98
All classes	182	63300	347.80	505700	2778.57

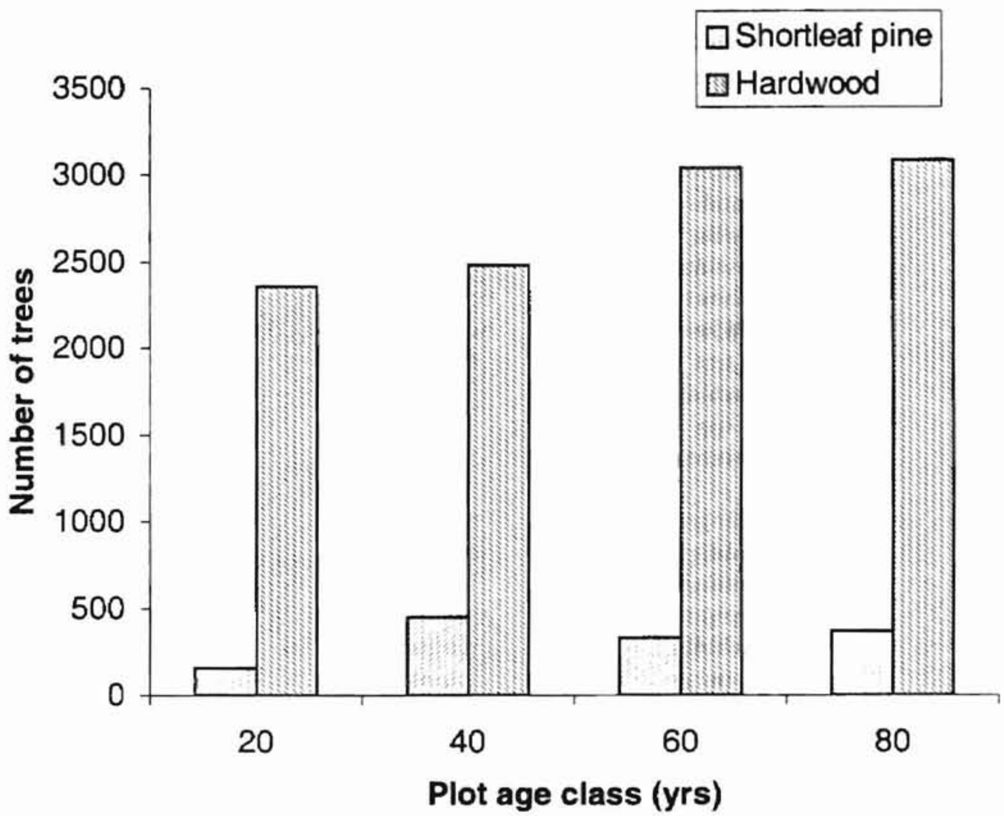


Figure 6. Number of shortleaf regeneration and hardwood understory stems per acre on plots by overstory plot age class 10 years after cutting.

Table 7. Summary of understory species distribution by the most abundant based on 5-miliacre plots located in 182 of 0.2-acre overstory plots in natural, even–aged shortleaf pine forests.

Common name	Genus	Species	Number of plots
Hickory	*Carya*	*spp.*	106
Blackjack oak	*Quercus*	*marilandica*	98
Flowering dogwood	*Cornus*	*florida*	84
Sumac	*Rhus*	*spp.*	77
Red mapple	*Acer*	*rubrum*	74
Black tupelo	*Nyssa*	*sylvatica*	71
Post oak	*Quercus*	*stellata*	68
Winged elm	*Ulmus*	*alata*	74
White oak	*Quercus*	*alba*	60
Shortleaf pine	*Pinus*	*echinata*	55
Northern red oak	*Quercus*	*rubra*	47
Sweetgum	*Liquidambar*	*styraciflua*	41
Blueberry	*Vaccinium*	*spp.*	42
Southern red oak	*Quercus*	*falcata*	39
Ash	*Fraxinus*	*spp.*	42
Black cherry	*Prunus*	*serotina*	38
Other species			34
Common persimmon	*Diospyros*	*virginiana*	24
Eastern hophornbeam	*Ostrya*	*virginiana*	23
Eastern redcedar	*Juniperus*	*virginiana*	21
Water oak	*Quercus*	*nigra*	20
Sassafras	*Sassafras*	*albidum*	18
Black oak	*Quercus*	*velutina*	17
Willow oak	*Quercus*	*phellos*	16
Hawthorn	*Crataegus*	*spp.*	12
Serviceberry	*Amelanchier*	*spp.*	12
Slippery elm	*Ulmus*	*rubra*	11
American hornbeam	*Carpinus*	*caroliniana*	10
Viburnum	*Viburnum*	*spp.*	9
Eastern redbud	*Cercis*	*canadensis*	8
American holly	*Ilex*	*opaca*	8
White mulberry	*Morus*	*alba*	7
Chinkapin	*Castonopis*	*spp.*	6
Wild plum	*Prunus*	*americana*	6
Devil's walking stick	*Aralia*	*spinosa*	6
Chestnut oak	*Quercus*	*prinus*	3
Buckthorn	*Rhamnus*	*spp.*	3
Sugarberry	*Celtis*	*laevigata*	1
Black walnut	*Juglans*	*nigra*	1
Black locust	*Robinia*	*pseudoiacacia*	1
American elm	*Ulmus*	*americana*	1

Table 8. Summary of understory genus frequency based on 5-miliacre plots located in182 of 0.2-acre overstory plots in natural, even-aged shortleaf pine forests.

Genus	Number of plots
Quercus	169
Carya	106
Cornus	84
Rhus	77
Acer	74
Nyssa	71
Ulmus	69
Pinus	55
Prunus	44
Vaccinium	42
Liquidambar	41
Fraxinus	42
Unknowm	34
Diospyros	24
Ostrya	23
Juniperus	21
Sassafras	18
Crataegus	12
Amelanchier	12
Carpinus	10
Viburnum	9
Cercis	8
Ilex	8
Morus	7
Castonopis	6
Aralia	6
Rhamnus	3
Celtis	1
Juglans	1
Robinia	1
Tilia	1

Table 9. Number of plots by species abundance classes, based on 5-miliacre plots located in 182 of 0.2-acre overstory plots in natural, even-aged shortleaf pine forests.

Species classes	Number of plots
>17 species	1
12-16 species	20
7-11 species	74
2-6 species	77
1 species	10

Analysis of variance

Analysis of variance was conducted to determine the effects of the overstory variables including basal area class, site index class, and age class on the following dependent variables: number of shortleaf pine regeneration stems, hardwood understory stems, shortleaf pine regeneration basal area, and hardwood understory basal area. It is found that the basal area class is significant at the probability 0.05 level for the number of shortleaf pine regeneration while plot age class and site index classes are not significant at the same level (Table 10). The basal area class and the site index class are significant at the probability 0.05 level for the number of hardwood understory stems while the plot age is not significant at the same level (Table 11). For the basal area of shortleaf pine regeneration, it is found that the basal area class and site index classes are significant (Table 12a), while the plot age class is not at the 0.05 level of significance. The simple effects of site index class given basal area class and basal area class given site index class in the model for the basal area of shortleaf pine understory were tested (Table 12b). For the basal area of hardwood understory, basal area class and plot site index were significant, while the plot age class is not significant at the 0.05 level (Table 13a). The effect of site index class given basal area class and plot age class (Table 13b) as well as the effect of plot age class given basal area class and site index class for the basal area of hardwood understory were tested (Table 13c). Likewise, the effect of basal area class given site index class and plot age class for the basal area of hardwood understory was tested (Table 13d). The effect of site index class given basal area class and basal area class given site index class is found in Table 13e.

Table 10. Analysis of variance results for factors affecting the number of shortleaf pine regeneration stems (dependent variable).

Source	Df	F value	Pr>F
Ba_class	3	4.53	0.0047
Pa_class	3	0.53	0.6605
Ba_class*Pa_class	9	0.54	0.8436
Si_class	3	2.78	0.0440
Ba_class*Si_class	9	1.74	0.0871
Pa_class*Si_class	8	1.53	0.1542
Ba_class*Pa_class*Si_class	19	1.10	0.3611

Where

Ba-class= basal area class;

Pa_class= plot age class;

Ba_class*Pa_class= two way interaction term;

Si_class= site index class;

Ba_class*Si_class= two way interaction term;

Pa_class*Si*class= two way interaction term;

Ba_class*Pa_class*Si_class= three way interaction term.

Table 11. Analysis of variance results for factors affecting the number of hardwood understory stems (dependent variable).

Source	Df	F value	Pr>F
Ba_class	3	5.32	0.0017
Pa_class	3	2.81	0.0423
Ba_class*Pa_class	9	1.17	0.3218
Si_class	3	35.39	0.0001
Ba_class*Si_class	9	1.15	0.3322
Pa_class*Si_class	8	1.34	0.2274
Ba_class*Pa_class*Si_class	19	0.83	0.6709

Where Ba_class, Pa_class, and Si_class are as previously defined.

Table 12a. Analysis of variance results for factors affecting the basal area of shortleaf pine regeneration stems (dependent variable).

Source	Df	F value	Pr>F
Ba_class	3	8.13	0.0001
Pa_class	3	0.77	0.5152
Ba_class*Pa_class	9	1.43	0.1831
Si_class	3	3.48	0.0180
Ba_class*Si_class	9	3.89	0.0002
Pa_class*Si_class	8	0.95	0.4785
Ba_class*Pa_class*Si_class	19	0.68	0.8363

Table 12b. The simple effect of Si_class given Ba_class and Ba_class given Si_class.

Effect of Si_class given	Ba_class	P-value
	30	0.0001*
	60	.
	90	0.7972
	120	0.9879
Effect of Ba_class given	Si_class	P-value
	50	0.0001*
	60	0.0004*
	70	.
	80	.

Where Ba_class, Pa_class, and Si_class are as previously defined.
* significant effect (α=0.05).

Table 13a. Analysis of variance results for factors affecting the basal area of hardwood understory stems (dependent variable).

Source	Df	F value	Pr>F
Ba_class	3	17.08	0.0001
Pa_class	3	2.22	0.0886
Ba_class*Pa_class	9	1.54	0.1407
Si_class	3	31.08	0.0001
Ba_class*Si_class	9	3.38	0.0009
Pa_class*Si_class	8	1.82	0.0787
Ba_class*Pa_class*Si_class	19	2.07	0.0093

Table 13b. The simple effect of Si_class which was significant (α=0.05) at the following levels of Ba_class and Pa_class.

Ba_class	Pa_class	P-value
30	20	0.0014
30	40	0.0001
30	60	0.0255
30	80	0.0001
60	40	0.0179
60	80	0.0001
90	60	0.0148
120	80	0.0095

Table 13c. The simple effect of Pa_class which was significant (α=0.05) at the following levels of Ba_class and Si_class.

Ba_class	Si_class	P-value
30	70	0.0001
30	80	0.0017
60	70	0.0011
120	80	0.0215

Table 13d. The simple effect of Ba_class which was significant (α=0.05) at the following levels of Si_class and Pa_class.

Si_class	Pa_class	P-value
70	40	0.0014
80	40	0.0001
70	80	0.0255

Table 13e. The simple effect of Si_class given Ba_class and Ba_class given Si_class.

Effect of Si_class given	Ba_class	P-value
	30	0.0001*
	60	.
	90	0.2991
	120	0.5121
Effect of Ba_class given	Si_class	P-value
	50	0.7489
	60	0.0974
	70	.
	80	.

Where Ba_class, Pa_class, and Si_class are as previously defined.
* significant effect (α=0.05).

Correlation coefficients

A matrix of simple correlation coefficients were obtained using correlation procedure in SAS for all variables listed in Appendix C. Inspection of these coefficients indicates that the number of shortleaf pine as well as its basal area is negatively correlated with the number of hardwood understory, the plot basal area of the shortleaf pine overstory, and plot site index. The number of hardwood understory is positively correlated with plot site index, but negatively correlated with the plot basal area of the shortleaf pine overstory.

Regression analysis

Four exponential models similar to those of Shelton and Murphy (1994) were developed for the purpose of predicting the number of shortleaf pine regeneration and hardwood understory stems as well as their respective basal areas. The stepwise procedure was used to select independent variables. Variables were eliminated from the full model if their coefficient did not significantly differ from zero at the probability level 0.15 (SAS default).

Model 1

The model for predicting the number of shortleaf pine regeneration is:

$$Num\_p = \exp(\underset{(0.94389)}{7.33604} - \underset{(0.00637)}{0.03795}Pba\_meas2 - \underset{(0.00006)}{0.00032}Num\_o + \underset{(0.89895)}{2.32191}Z1)$$

$$(FI = 0.42 \qquad MSE = 528773.89)$$

Standard errors are in parentheses below parameter estimates. The correlation coefficient between the number of shortleaf pine regeneration and the plot basal area at measurement 2 is negative and significantly different from zero (Appendix C). Likewise, the correlation coefficient between the number of shortleaf pine regeneration and the number of hardwood is negative and significantly different from zero. The sign of plot basal area at measurement 2 and the number of hardwood is consistent with this negative correlation. This is expected since trees within a plot are ecologically interdependent and competing for finite resources such as water and nutrients. Due to pine's shade intolerance, seedling development will, to some extent, be stopped or retarded in any regeneration cutting method retaining a large overstory. In this model the year of establishment represented by the dummy variable Z1 has a positive significant effect on seedlings. This may suggest that a good seedyear is an important factor in getting adequate shortleaf pine regeneration. The plot basal area at measurement 2, the number of hardwood understory, and the year of establishment explain 42 percent of the total variation in number of pine regeneration stems, which is relatively reasonable. The fit index for the number of shortleaf pine regeneration is close to the one (0.45) found in the 5-year study described by Shelton and Murphy (1994). The plot of the residuals for this model against the plot overstory basal area at measurement 2 (Figure 7) shows that some groups along the basal area axis are clustered about basal area treatment levels. No trends appear with respect to the vertical axis. However the plot of the residuals against the number of hardwood (Figure 8) shows no trend according to the data. Figure 9 does not show a trend in the residuals with respect to levels of the dummy variable Z1.

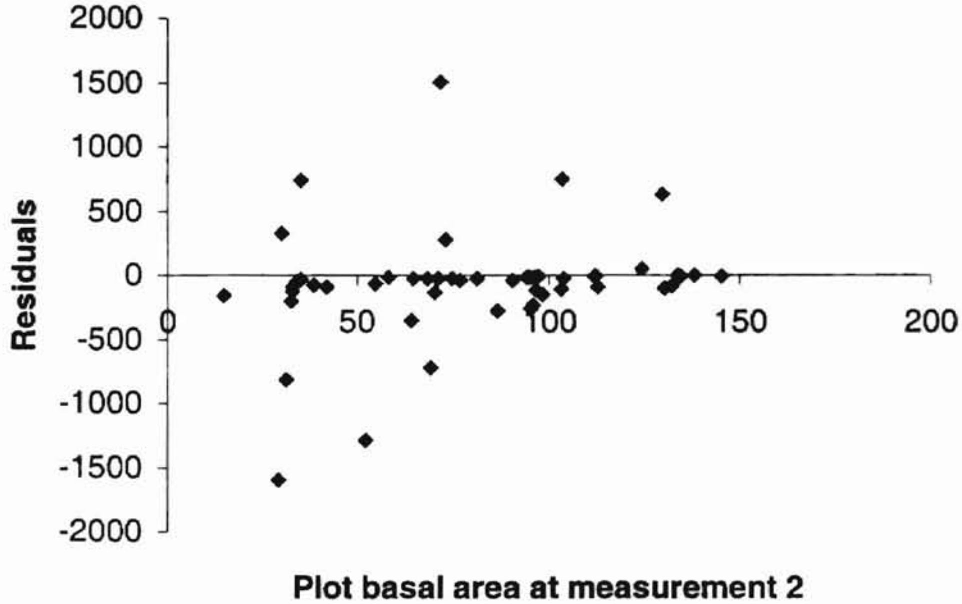


Figure 7. Residuals for number of shortleaf regeneration stems vs. overstory plot basal area (ft^2/acre) at measurement 2.

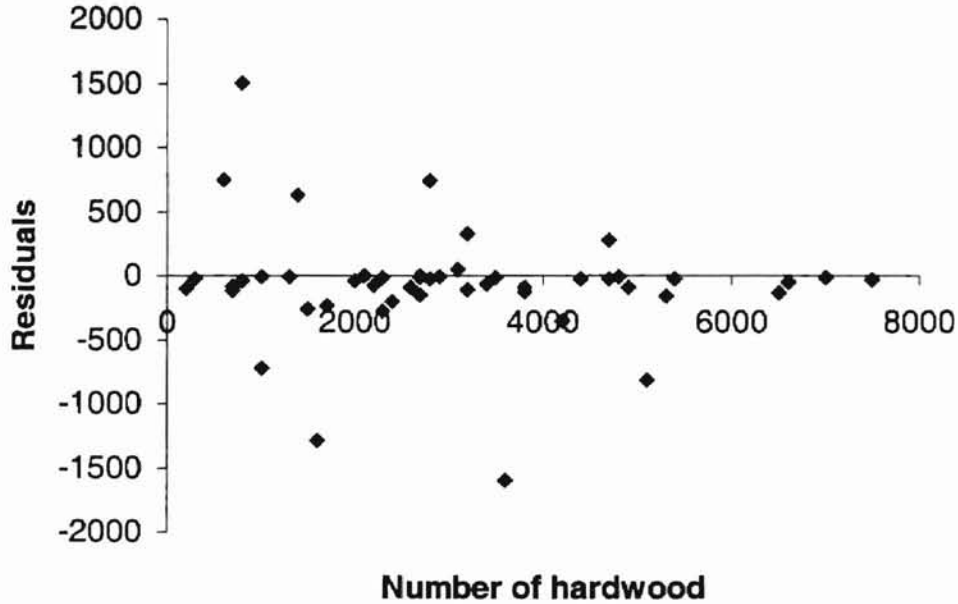


Figure 8. Residuals for number of shortleaf regeneration stems vs. number of hardwood understory stems.

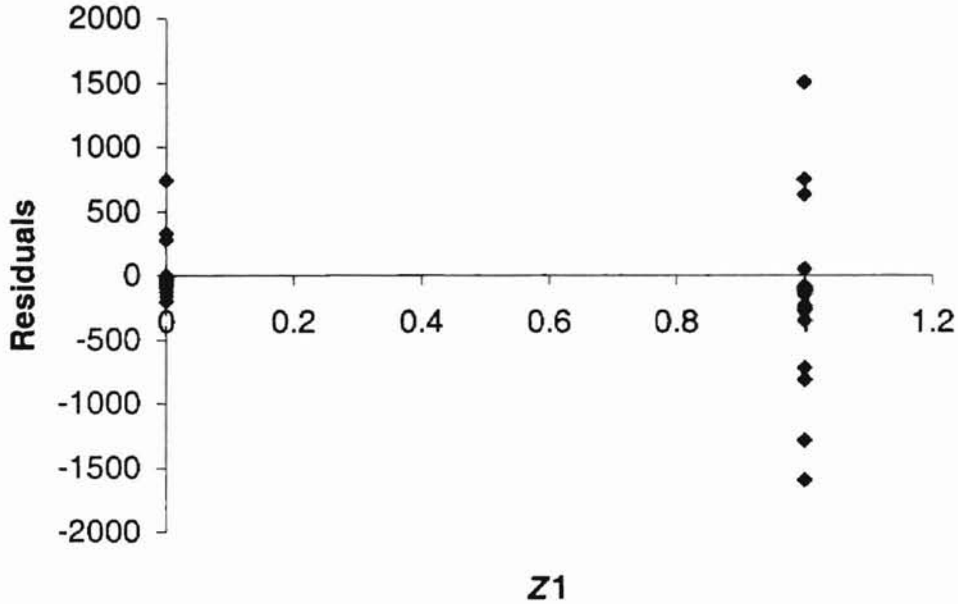


Figure 9. Residuals for number of shortleaf regeneration stems vs. Z1=1 if year of establishment is 1985 or 1986 and Z1=0 if year of establishment is 1987.

Model 2

The model for predicting the number of hardwood understory stems is:

$$Num\_o = \exp(6.06501 - 0.00404 Pba\_beg + 0.03398 Si\_plot)$$
$$(0.23776) \qquad (0.00105) \qquad (0.00321)$$
$$(FI = 0.43 \qquad MSE = 1929782.30)$$

The correlation coefficient between the number of hardwood understory and the plot basal area at measurement 1 is negative and significantly different from zero (Appendix C). The sign of plot basal area at measurement 1 in the model is consistent with this negative correlation. However, the correlation coefficient between the number of hardwood understory and plot site index is positive and significantly different from zero. The sign of plot site index in the model is consistent with this positive correlation. This agrees with the theory that better sites encourage hardwood understory at the expense of shortleaf pine regeneration. The plot basal area at measurement 1 and the plot site index explain 43 percent of the total variation in number of hardwood understory stems. The fit index for the number of hardwood understory stems is higher in this study compared to the one (0.15) found in the 5 year-study (Shelton and Murphy 1994). The plot of the residuals of number hardwood against site plot index (Figure 10) shows no trend at all. However, it shows that some groups along the basal area axis are clustered about basal area treatment levels (Figure 11). No trends appear with respect to the vertical axis.

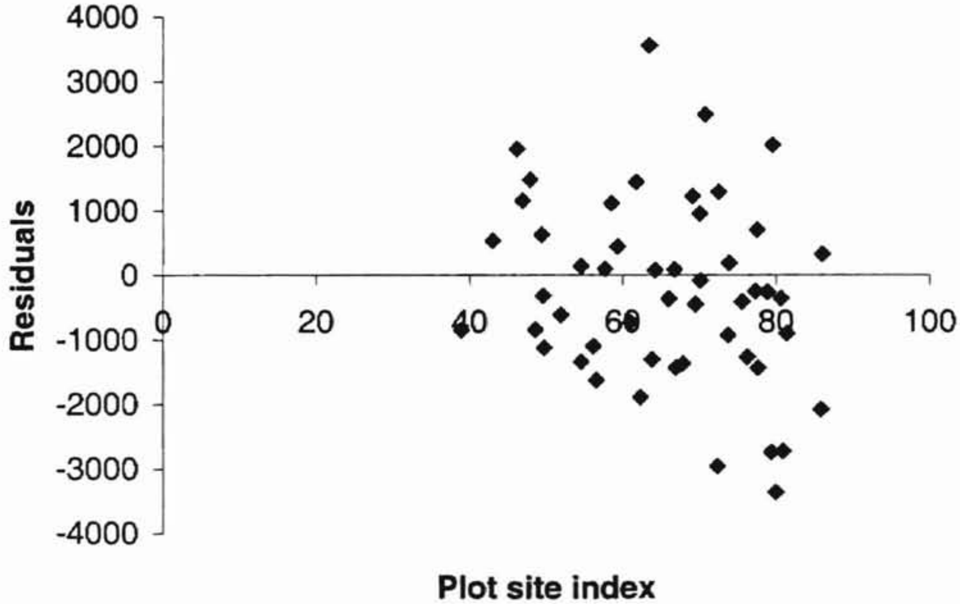


Figure 10. Residuals for number of hardwood understory stems vs. plot site index.

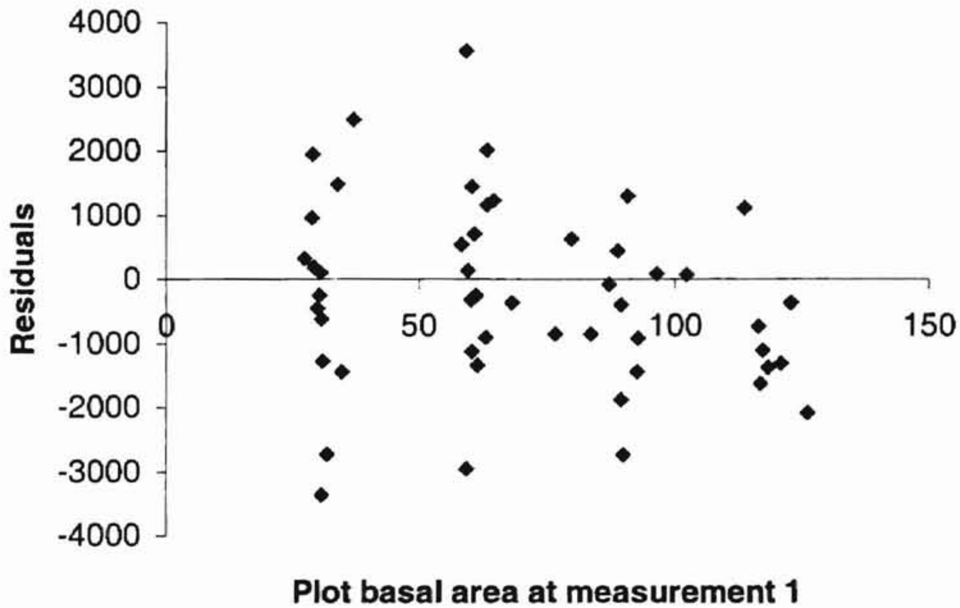


Figure 11. Residuals for number of hardwood understory stems vs. plot overstory basal area (ft^2/acre) at measurement 1.

Model 3

The model for predicting the basal area of shortleaf pine regeneration is:

$$Ba\_p = \exp(7.86213 - 0.20937Pba\_beg - 0.00035Num\_o + 1.33976Z1)$$

(1.77119) (0.05709) (0.00007) (0.44093)

(FI= 0.43 MSE=10.33252)

The correlation coefficient between the basal area of shortleaf pine understory and the plot basal area at measurement 1 was negative and significantly different form zero. The sign of plot basal area at measurement 1 is consistent with this negative correlation. Likewise, the correlation between the basal area of shortleaf pine understory and the number of hardwood understory was negative. The sign of the number of hardwood understory is consistent with expectations due to the competition with shortleaf pine trees. The plot basal area at measurement 1, the number of hardwood understory, and the regeneration conditions explain 43 percent of the total variation in the basal area of shortleaf pine regeneration.

Model 4

The model for predicting the basal area of hardwood understory stems is:

$$Ba\_o=\exp(0.43218-0.01246Pba\_beg+0.04576Si\_plot)$$

(0.34009) (0.00159) (0.00447)

(FI= 0.50 MSE=80.76)

The correlation coefficient between the basal area of hardwood understory and the plot basal area at measurement 1 is negative and significantly different from zero. The sign of plot basal area at measurement 1 is consistent with this negative correlation.

However, the correlation coefficient between the basal area of hardwood understory and plot site index is positive and significantly different from zero. The sign of site index in this model is consistent with this positive correlation. This is biologically reasonable, since the basal area growth for hardwood understory should increase as the site increases in quality. The plot basal area at measurement 1 and plot site index explain 50 percent of the total variation in the basal area of hardwood understory.

Probability model

The parameter estimates, standard errors, and descriptions for the probability model of obtaining shortleaf pine regeneration success are presented in Table 14. The parameter estimates can be used in the model (equation 3) to determine the probability of getting more shortleaf pine regeneration stems than a given level *T*. It is recommended that predictions be made for levels of regeneration success *T* between 300 and 700 stems per acre, the range of values used for parameter estimation. The results of fitting the probability model (equation 3) show that the dummy variable Z1, basal area of the stand as well as the interaction term of the natural logarithm of tree by the square of the site index plot are very significant with P-values less than 0.05. This means that the basal area of the stand and the year of establishment of plots have a significant effect in predicting the probability of shortleaf pine regeneration success. The year of establishment variable in part reflects the seed production, which greatly influences the

Table 14. Parameter estimates, standard errors, and description for the probability model.

Parameter	Estimate	Standard error	Description
β_0	3.4357	2.0131	*Intercept*
β_1	0.0288	0.00433	*BA*
β_2	-0.0154	0.00629	*AGE*
β_3	-0.1251	0.0664	*SI*
β_4	0.000244	0.000091	*TSSI*
β_5	-1.3958	0.3043	Z1

success of shortleaf pine regeneration. The dummy variable for the year of establishment could also reflect conditions for seedling establishment. It is possible that the seed year was good, but a hot dry summer was poor for seedling establishment. From the results it is found that 21 percent of plots have 300 or more shortleaf pine regeneration (Table 15), 18 percent of plots have 500 or more shortleaf pine regeneration (Table 16), and 14 percent have 700 or more shortleaf pine regeneration (Table 17). The chi-square test can be used to evaluate the model at each level of regeneration success threshold based on the number of shortleaf regeneration: more than 300, 500, and 700. Table 15 indicates a greater disparity between observed and expected frequencies at basal area class 90 square feet per acre, possibly because of seedling mortality. Table 16 shows a disparity between observed and expected frequencies at basal area class 30 square feet per acre. In this case, the data show more regeneration than expected. This might happen due to better than average seedfall on some plots. Chi-square statistics can be calculated using observed vs. expected values in Tables 15, 16, and 17. The chi-square value for obtaining more than 300, 500, and 700 trees per acre of shortleaf pine regeneration are 1.96081, 2.76982, and 0.96778 respectively. These chi-square values are less than the critical value of the chi-square distribution (5.99) under the null hypothesis at the 0.05 level of significance. Thus we fail to reject the null hypothesis that this model fits the data at each above specified levels. Neter et al. (1996) indicate that when the data used for fitting parameters is used in a chi-square evaluation of a logistic model, the degrees of freedom should be calculated by subtracting two (2) from the number of categories used to calculate chi-square.

Table 15. Goodness of Fit for logistic regression fucntion-shortleaf pine regeneration (300 or more trees/acre of shortleaf pine regeneration).

		Success		Failure	
Basal area class	No.plots	Observed	Expected	Observed	Expected
30	46	19	19.22037	27	26.77960
60	47	12	12.30304	35	34.69700
90	48	3	6.02997	45	41.97000
120	41	4	3.21991	37	37.78010
Total	182	38	40.77329	144	141.22671

$X^2 = 1.96081$ P-value = 0.37

Table 16. Goodness of Fit for logistic regression fucntion-shortleaf pine regeneration (500 or more trees/acre of shortleaf pine regeneration).

		Success		Failure	
Basal area class	No.plots	Observed	Expected	Observed	Expected
30	46	18	15.22943	28	30.77060
60	47	8	9.13842	39	37.86160
90	48	3	4.18485	45	43.81510
120	41	4	2.23562	37	38.76440
Total	182	33	30.78832	149	151.21168

$X^2 = 2.76983$ P-value = 0.25

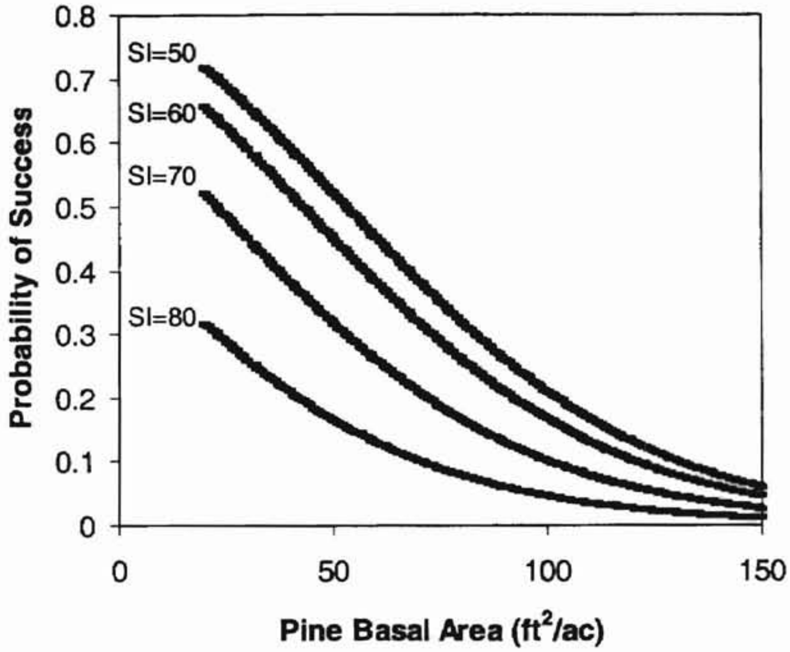
Table 17. Goodness of Fit for logistic regression fucntion-shortleaf pine regeneration (700 or more trees/acre of shortleaf pine regeneration).

		Success		Failure	
Basal area class	No.plots	Observed	Expected	Observed	Expected
30	46	13	12.94284	33	33.05720
60	47	7	7.44680	40	39.55320
90	48	3	3.28666	45	44.71330
120	41	3	1.76207	38	39.23790
Total	182	26	25.43837	156	156.56163

$X^2 = 0.96778$ P-value = 0.61

The chi-square test can be used to evaluate the model at each level of regeneration success threshold based on the number of shortleaf regeneration: more than 300, 500, and 700. Table 15 indicates a greater disparity between observed and expected frequencies at basal area class 90 square feet per acre, possibly because of seedling mortality. Table 16 shows a disparity between observed and expected frequencies at basal area class 30 square feet per acre. In this case, the data show more regeneration than expected. This might happen due to better than average seedfall on some plots. Chi-square statistics can be calculated using observed vs. expected values in Tables 15, 16, and 17. The chi-square value for obtaining more than 300, 500, and 700 trees per acre of shortleaf pine regeneration are 1.96081, 2.76982, and 0.96778 respectively. These chi-square values are less than the critical value of the chi-square distribution (5.99) under the null hypothesis at the 0.05 level of significance. Thus we fail to reject the null hypothesis that this model fits the data at each above specified levels. Neter et al. (1996) indicate that when the data used for fitting parameters is used in a chi-square evaluation of a logistic model, the degrees of freedom should be calculated by subtracting two (2) from the number of categories used to calculate chi-square. P-values were calculated for tables 15, 16, and 17 using this rule. Their p-values are respectively 0.37, 0.25, and 0.61, which are higher than the probability level 0.05. This confirms the conclusion that the model fits the data throughout the specified range, that is the difference between observed and expected frequencies are not statistically significant. Examples of computing the probability of getting 300, 500, and 700 or more shortleaf pine regeneration stems per acre at age 50 for good annual conditions (Z1=1), and bad annual conditions (Z1=0) are found on Figures 12, 13, and 14 respectively. It appears that by holding the age at 50 years and changing the level of number of trees per acre from 300 to 700, the probability decreases also. This confirms that the greater the number of overstory shortleaf pine trees per acre retained, the less the probability to obtain a given amount of regeneration. From Figures 12, 13, and 14, we found that at lower sites and lower overstory pine basal area, the probability of regeneration success is higher and decreases monotonically as the site index and basal area increase. Likewise, it appears clearly that annual conditions have a great impact on the regeneration of shortleaf pine. For example, the probability of obtaining 300 shortleaf pine trees per acre during good conditions at 30 square feet basal area, 50 feet site index is approximately 0.66, while it is only 0.32 during bad annual conditions. This confirms the results of regression model 1 for predicting number of shortleaf regeneration stems per acre. The coefficient of Z1 in model indicates that the number of shortleaf pine stems per acre is greater by a factor of exp(2.3)=10 when Z1=1(good conditions for shortleaf regeneration) than when Z1=0 (poor conditions for shortleaf regeneration). This shows how great is the impact of annual conditions on the regeneration of shortleaf pine.

Z1=1, *AGE*=50



Z1=0, *AGE*=50

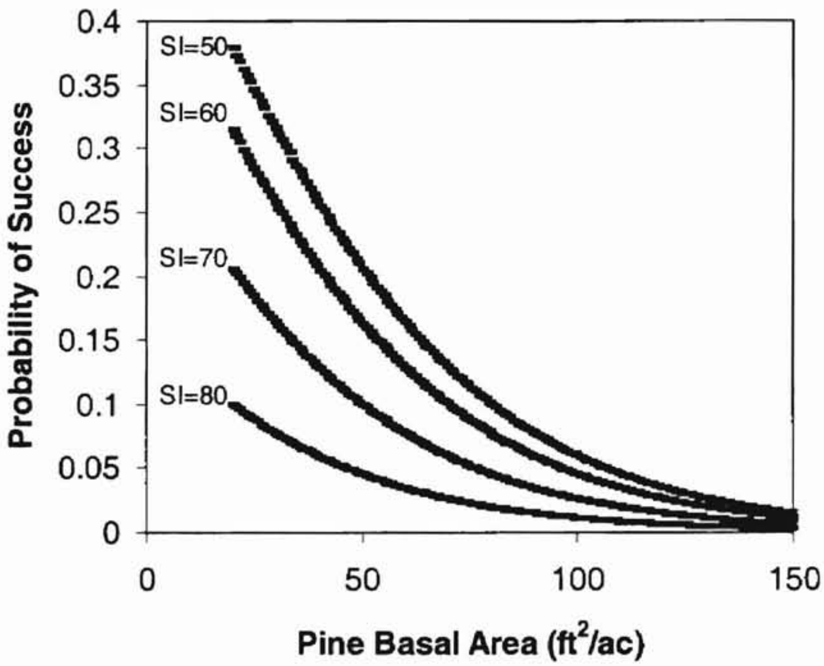
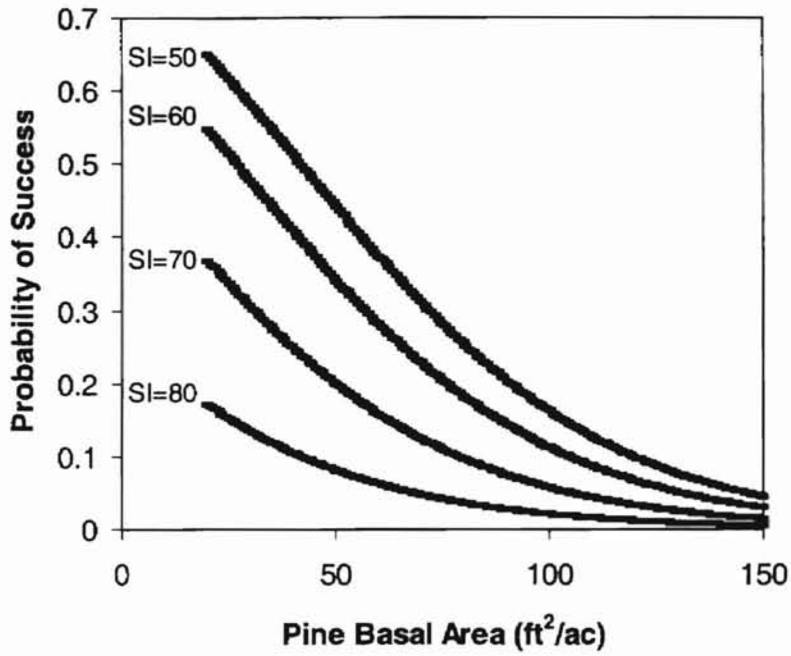


Figure 12. Probability of obtaining 300 or more shortleaf pine regeneration stems per acre at age 50, Z1=1(good regeneration conditions) and Z1=0 (bad regeneration conditions).

Z1=1, *AGE*=50



Z1=0, *AGE*=50

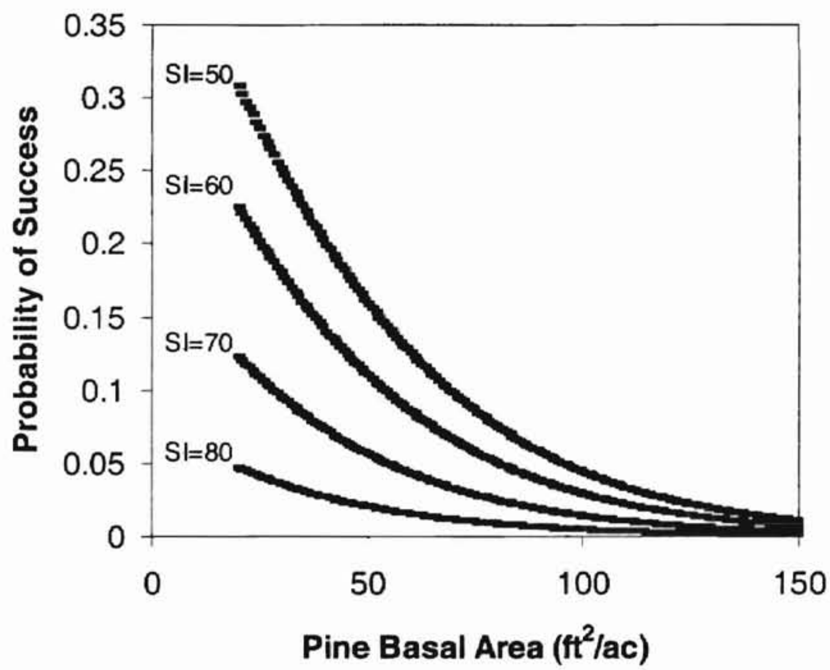


Figure 13. Probability of obtaining 500 or more shortleaf pine regeneration stems per acre at age 50, Z1=1(good regeneration conditions) and Z1=0 (bad regeneration Conditons).

Z1=1, *AGE=50*

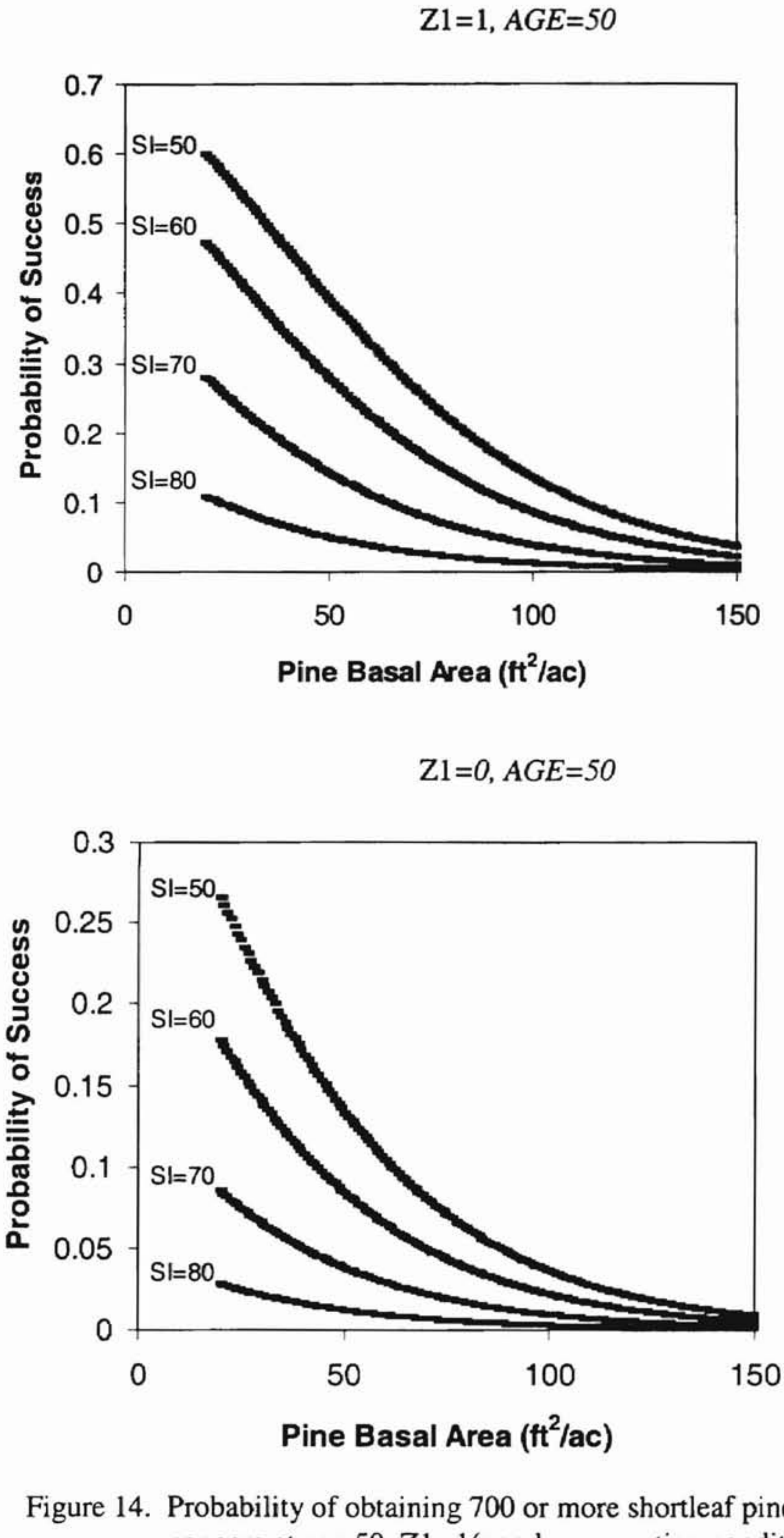


Figure 14. Probability of obtaining 700 or more shortleaf pine regeneration stems per acre at age 50, Z1=1(good regeneration conditions) and Z1=0 (bad regeneration condition).

CONCLUSION

The aim of any reproduction cutting system is to ensure conditions that favor the establishment and development of the desired species. The results of the present study indicate that hardwood control applied in this study was not as effective as desired in delaying reinvasion by woody species because we have less shortleaf pine regeneration than hardwood understory. This in part might be due to high mortality resulting from fast-growing hardwood sprouts suppressing shortleaf seedlings. There might not be enough moisture as well as exposed mineral soil to allow the germination. In addition, it should be noticed that blackjack oak, hickory and flowering dogwood are among the most abundant species on plots.

Shortleaf pine is negatively correlated with the overstory basal area and hardwood understory. It appears that the overstory basal areas of more than 90 square feet are not conductive to the regeneration of shortleaf pine in the understory, unless they are released from the shade of pine overstory and hardwood competition. For basal area over than 100 square feet, the chance of obtaining shortleaf pine regeneration is small because at that level, there was almost no disturbance due to thinning operations.

Year of plot establishment significantly affected abundance of shortleaf pine regeneration. This could be due to variation in seedcrops and/or conditions for seedling establishment.

The four models developed might be used to predict the numbers of shortleaf pine and hardwoods as well as their respective basal areas. However, a careful interpretation should be given to these predictions.

The probability model developed is appropriate to similar shortleaf pine stands throughout the area from which data were obtained. It is helpful in predicting the possibility of success of shortleaf pine regeneration given values for the explanatory variables.

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APPENDICES

APPENDIX A

```
/*COMBINE. SAS
THIS PROGRAM COMBINES PLOT-LEVEL VARIABLES WITH NUMBERS OF
TREES AND BASAL AREA BY PLOT AND ASSIGNS INITIAL BA AND AGE AND
SITE INDEX CLASSES*/

LIBNAME PATH.'C:\NKOUKA';
TITLE;
*MERGE 1995 DATA;
PROC SORT DATA=PATH.DBH95;
BY PLOT;
RUN;
PROC SORT DATA=PATH.BA95;
BY PLOT;
RUN;
DATA DS1995; MERGE PATH.DBH95 PATH.BA95;
BY PLOT;
RUN;
*MERGE 1996 DATA;
PROC SORT DATA=PATH.DBH96;
BY PLOT;
RUN;
PROC SORT DATA=PATH.BA96;
BY PLOT;
RUN;
DATA DS1996; MERGE PATH.DBH96 PATH.BA96;
BY PLOT;
RUN;
*MERGE 1997 DATA;
PROC SORT DATA=PATH.DBH97;
BY PLOT;
RUN;
PROC SORT DATA=PATH.BA97;
BY PLOT;
RUN;
DATA DS1997; MERGE PATH.DBH97 PATH.BA97;
BY PLOT;
RUN;
*CONCATENATE 1995 1996 AND 1997 DATASETS;
DATA ALL; SET DS 1995 DS1996 DS1997;
RUN;
PROC SORT DATA=ALL;
BY PLOT;
```

```
RUN;
*MERGE PLOT-LEVEL VARIABLES ONTO THE FIFTIETH-ACRE PLOT INFO;
DATA PATH.COMBINED; MERGE PATH.PLOTS (IN=P) ALL (IN=B);
BY PLOT;
IF P AND B THEN DO;
IF      PBA_BEG <=45 THEN BA_CLASS=30;    *CREATE BA CLASSES;
IF 45< PBA_BEG<=75   THEN BA-CLASS=60;
IF 75< PBA_BEG<=105 THEN BA_CLASS=90;
IF      PBA_BEG>105   THEN BA_CLASS=120;

IF      SI_PLOT <=55 THEN SI_CLASS=50;    *CREATE SI CLASSES;
IF 55< SI_PLOT<=65   THEN SI_CLASS=60;
IF 65< SI_PLOT<=75 THEN SI_CLASS=70;
IF      SI_PLOT>80   THEN SI_CLASS=80;

IF      PAGE_BEG <=30 THEN PA_CLASS=20;    *CREATE AGE CLASSES;
IF 30< PAGE_BEG<=50   THEN PA_CLASS=40;
IF 50< PAGE_BEG<=70 THEN PA_CLASS=60;
IF      PAGE_BEG>70   THEN PA_CLASS=80;
OUTPUT;
END;
RUN;
PROC PRINT DATA=PATH.COMBINED SPLIT='_';
VAR PLOT BA_CLASS PA_CLASS SI_CLASS NUM_P NUM_O BA_P BA_O ;
RUN;
```

APPENDIX B

```
/* CREATE STACKED DATA SET CONTAINING VARIABLE REGENSUC (FOR
REGENERATION SUCCESS)*/
DATA DS 300;
MERGE PATH.COMBINED PATH.YR_ESTAB; BY PLOT;
IF NUM_P>=300 THEN REGENSUC=1;
IF NUM_P<300 THEN REGENSUC=0;
LN_MT(300);
BA=PBA_BEG;
AGE=PAGE_BEG;
SI=SI_PLOT;
TSSI=LN_MT*SI*SI;
RUN;
DATA DS500;
MERGE PATH.COMBINED PATH.YR_ESTAB; BY PLOT;
IF NUM_P>=500 THEN REGENSUC=1;
IF NUM_P<500 THEN REGENSUC=0;
LN_MT(500);
BA=PBA_BEG;
AGE=PAGE_BEG;
SI=SI_PLOT;
TSSI=LN_MT*SI*SI;
RUN;
DATA DS700
MERGE PATH.COMBINED PATH.YR_ESTAB; BY PLOT;
IF NUM_P>=700 THEN REGENSUC=1;
IF NUM_P<700 THEN REGENSUC=0;
LN_MT(700);
BA=PBA_BEG;
AGE=PAGE_BEG;
SI=SI_PLOT;
TSSI=LN_MT*SI*SI;
RUN;
DATA
DATA STACKED;
SET DS300 DS500 DS700;
Z1=0;
IF YR_ESTAB=1985 THEN Z1=1;
IF YR_ESTAB=1986 THEN Z1=1;
RUN;
LIBNAME PATH'C:\NKOUKA';
PROC LOGISTIC DATA=STACKED;
MODEL REGENSUC=BA AGE SI TSSI Z1;
OUTPUT OUT=ONE P=PHAT;
```

```
RUN;
DATA PROBA; SET ONE;
PROC SORT DATA=PROBA; BY BA_CLASS;
RUN;
PROC MEANS DATA=PROBA SUM; BY BA_CLASS;
VAR PHAT REGENSUC;
RUN;
```

APPENDIX C: CORRELATION COEFFICIENTS.

Variables	Ba_o	Num_o	Ba_p	Num_p	Page_beg	Page_meas2	Pba_beg	Pba_meas2	Si_plot
Ba_o	1.00	0.69 *	-0.09	-0.07	0.19 *	0.18 *	-0.34 *	-0.40 *	0.55 *
Num_o	0.69 *	1.00	-0.14	-0.16 *	0.15 *	0.15 *	-0.20 *	-0.24 *	0.63 *
Ba_p	-0.09	-0.14	1.00	0.85 *	0.01	0.02	-0.36 *	-0.35 *	-0.20 *
Num_p	-0.07	-0.16 *	0.85 *	1.00	0.06	0.07	-0.31 *	-0.32 *	-0.17 *
Page_beg	0.19 *	0.15 *	0.01	0.06	1.00	0.99 *	-0.01	-0.19 *	0.23 *
Page_meas2	0.18 *	0.15 *	0.02	0.07	0.99 *	1.00	-0.01	-0.19 *	0.22 *
Pba_beg	-0.34 *	-0.20 *	-0.36 *	-0.31 *	-0.01	-0.01	1.00	0.96 *	0.01
Pba_meas2	-0.4 *	-0.24 *	-0.35 *	-0.32 *	-0.19 *	-0.19 *	0.96 *	1.00	-0.08
Si_plot	0.55 *	0.63 *	-0.20 *	-0.17 *	0.23 *	0.22 *	0.01	-0.08	1.00

Where cells with * indicate that the P-value was significant from zero ($\alpha = 0.05$).

VITA

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Candidate for the Degree of

Master of Science

Thesis: EVALUATION OF THE EFFECT OF THINNING LEVELS, SITE INDEX, AND AGE ON SHORTLEAF PINE (*Pinus echinata* Mill.) REGENERATION AND HARDWOOD UNDERSTORY

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