# DISTRIBUTION OF LONGLEAF PINE IN THE SOUTHEASTERN UNITED STATES AND ITS ASSOCIATION WITH CLIMATIC CONDITIONS

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**Abstract--**Longleaf pine (*Pinus palustris* Mill.) has irreplaceable ecological value in the southeastern United States. However, longleaf pine-grassland ecosystems have been dramatically declining since European settlement. From the aspect of longleaf pine restoration and management, this study calculated longleaf pine importance values in each southern county and then conducted preliminary analysis based on spatial autocorrelation statistics and quantile regression. This study estimated current longleaf pine spatial distribution characteristics and the relationship between species dominance and climatic conditions. Even though longleaf pine has declined across counties over the past 40 years, clusters remain in the states of Florida, Georgia, North Carolina, Alabama, Louisana, South Carolina, and Mississippi. Quantile regression modeling predicted broader levels than conventional least square regression.

## INTRODUCTION

Longleaf pine (*Pinus palustris* Mill.)-grassland ecosystems have existed in the coastal plain for thousands of years. Historical climatic conditions influenced longleaf pine distribution (Van Lear and others 2005). Longleaf pine is one of the most important tree species in the southeastern United States because of its economic and ecological value (Brockway and others 2005, Friedenberg and others 2007, Gilliam and Platt 1999, Johnsen and others 2009, Roise and others 1991). Unfortunately, the extent of longleaf pine ecosystems has dramatically declined (Outcalt and Sheffield 1996, Van Lear and others 2005). Before European settlement, longleaf pine forests occupied over 60 million acres in the southeastern United States; only about 3 million acres remain. The loss was due to logging, land use conversion, fire exclusion, and lack of regeneration. Longleaf pine forests have become the third most endangered ecosystem in the United States (Noss and others 1995). Many approaches have been proposed for the restoration of longleaf pine, such as maintaining the overstory of longleaf pine, reducing midstory hardwood trees, reducing non-native species, and re-establishing native plant and animals (Varner and others 2005).

To assist longleaf pine-grassland restoration, ecological factors that drive species distributional response need to be considered. Iverson and others (1999) applied regression-tree analysis and identified that mean January temperature plays a significant role in affecting longleaf pine importance value in the eastern United States. Samuelson and others (2012) measured leaf physiological traits of southern pines and found that longleaf pine has higher water-use efficiency and greater drought tolerance than other pines. In general, climatic variables have the most influence in species spatial pattern at large scales (Woodward 1987), while more local effects, such as soil factors, determine the local variations in distribution (Iverson and others 1999). However, few studies investigated the relationship between longleaf pine distribution and climate effects. The objectives of this study are: (1) to assess spatial distribution of longleaf pine by decade over the past 40 years; and (2) to determine the relationship between longleaf pine importance value and minimum temperature, maximum temperature, and annual precipitation. Such information will assist future restoration efforts for longleaf pine in various climate zones and will help in planning of longleaf pine restoration.

## METHODS

The study area includes almost 2,360 counties in 13 southeastern states (fig. 1). The importance values of longleaf pine by county were calculated using the Forest Inventory and

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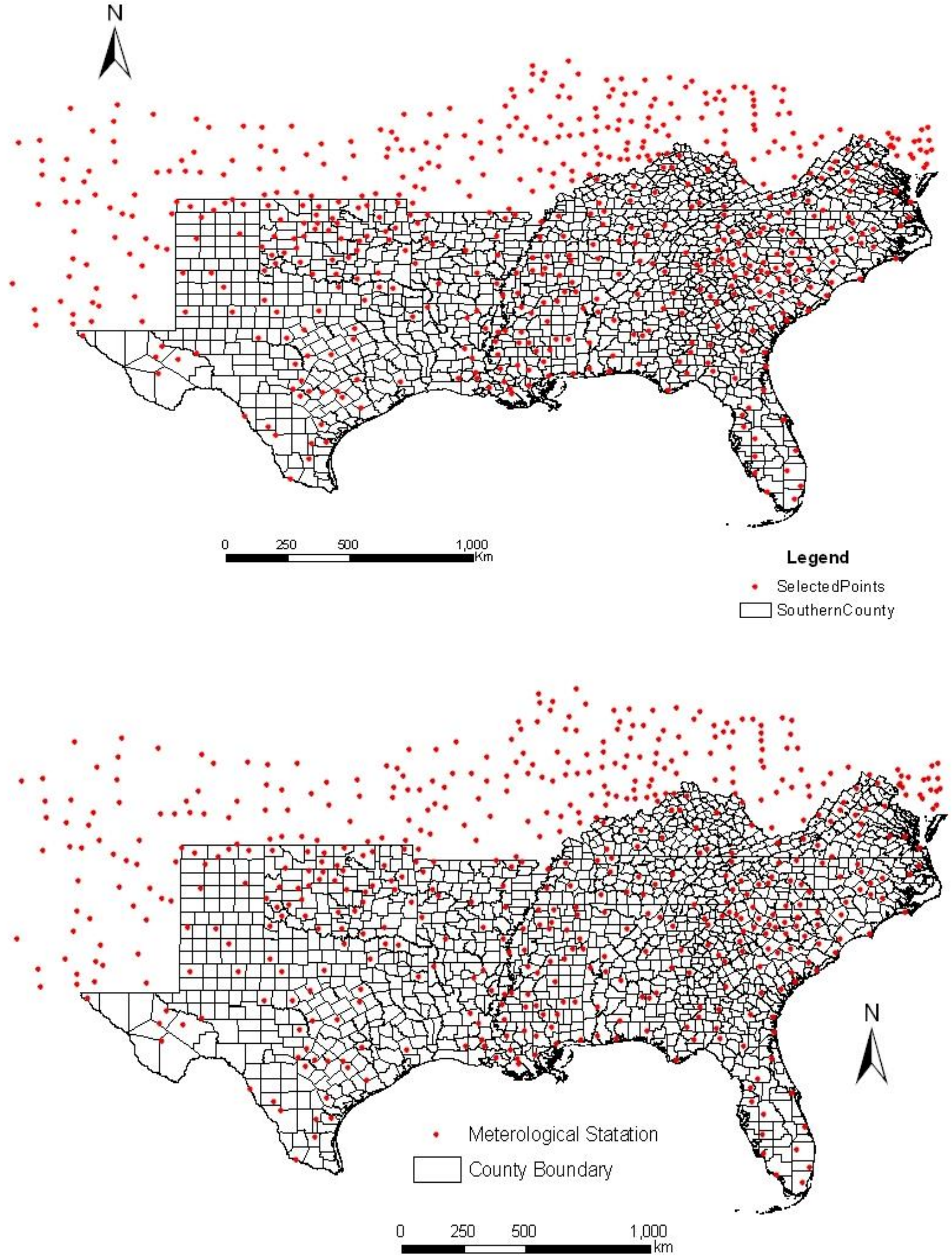


Figure 1--Study area and locations of selected meteorological stations.

Analysis (FIA) database. We divided the dataset into four decades (the 1970s, 1980s, 1990s, and 2000s). If one plot was measured twice in one decade, the latest measurements were used in our calculations.

Observed meteorological data is from the U.S. Historical Climatology Network (USHCN version 2) and contains monthly mean maximum temperature, mean minimum temperature, and total precipitation since 1897. A total of 526 meteorological stations were selected within 13 southeastern states as well as adjacent states that had data from 1970 to 2009. We then interpolated station data into climatic surfaces (raster) in ArcGIS by the Inverse Distance Weight (IDW) algorithm. Choosing stations from the adjacent states can reduce the errors from spatial interpolation of climate variables. After interpolation, zonal statistics in ArcGIS were used to aggregate climate surfaces to each county. The zonal layer was the county boundary, which was obtained from The National Atlas of the United States of America (www.nationalatlas.gov). Lastly, importance values were calculated and paired with three climatic variables by county and decade for further analysis.

Global Moran's I index estimates overall degrees of spatial autocorrelation. The index was applied in this study to test spatial autocorrelation in order to evaluate spatial clustering patterns. This index uses the randomization assumption to test for normality. In general, the values of Moran's I range from -1 to 1. Negative values of Moran's I indicate negative spatial autocorrelation; positive values of Moran's I indicate positive spatial autocorrelation; a zero value indicates no spatial autocorrelation. Moran's I is calculated by

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

where:
$N$ is the number of counties;
$w_{ij}$ is the element in the spatial weight matrix corresponding to the observation pair ($i$, $j$);
$x_i$ and $x_j$ are observations for counties $i$ and $j$, respectively;
$u$ is observed mean over all counties.

Local spatial autocorrelation statistics, or G-statistic, provide estimates of dependency relationships in different areas. In this study, the local G-statistic was used to make autocorrelation comparisons in different neighborhoods and test the statistical significance of local clusters of the importance of longleaf pine over the 4 decades. Detailed information of local G-statistic can be found in Getis and Ord (1992).

Quantile regression was used to evaluate how different parts of the dependent variable respond to predictors, in that any quantile of a response is able to be fitted by respective linear models (Cade and others 1999). Quantile regression not only specifies the predictor as the conventional regression model but also has more ecological rationale without abrupt thresholds and unexpected shapes (Austin 2007). Considering longleaf pine restoration, the primary goal is more stems and large trees. In this study, quantile regression was chosen to compare with conventional least square regression to estimate the different levels of responses of importance value to the climatic conditions.

## RESULTS AND DISCUSSION

Even though the declining dominance of longleaf pine in the southeastern United States has been reported (Oswalt and others 2012, Outcalt and Sheffield 1996, Van Lear and others 2005), few studies calculate important values at the county level. We found that longleaf pine existed in 778, 653, 668, and 649 out of 2,360 counties in the 1970s, 1980s, 1990s, and 2000s, respectively. Thus, numbers of counties occupied by longleaf pine generally decreased in the past 40 years despite a slight rebound in the 1990s. Table 1 shows the tendency of longleaf pine importance values at different quantile levels. Overall, our results showed a general decreasing trend in both the number of counties with longleaf pine and the importance values at various quantiles over the past 40 years.

Nearby counties overall have similar longleaf pine occupation conditions. For the calculation of longleaf pine importance value distribution in the southeastern United States, the results of the global autocorrelation statistics by global Moran's I are 0.2717, 0.2466, 0.3017, and 0.2292 for the 1970s, 1980s, 1990s, and 2000s, respectively. The global Moran's test related to the importance values of longleaf pine are statistically significant ($p$-value $< 0.05$) and indicate spatial heterogeneity. For the local G-statistics (fig. 2), counties shaded in red (hotspots) are spatial clusters with a 95 percent significance level from a two-tailed normal distribution. In general, most of identifed hotspots were mainly distributed in Florida, Georgia, North Carolina, Alabama, Louisana, South Carolina, and Mississippi. Hotspots provide ecological insights for longleaf pine restoration because detected counties have relatively greater degrees of longleaf pine dominance than other counties. In the future, more detailed survey of these identified hotspots may reveal suitable habitats and preservation refuges for longleaf pine restoration.

**Table 1--Statistics of longleaf pine importance value (percent; $0^{th}$ = minimum, $100^{th}$ = maximum) at various quantiles by 4 decades**

| | $0^{th}$ | $25^{th}$ | $50^{th}$ | $75^{th}$ | $100^{th}$ |
|---|---|---|---|---|---|
| 1970s | 0.07 | 2.00 | 6.00 | 14.00 | 34.00 |
| 1980s | 0.16 | 2.00 | 5.00 | 9.00 | 29.00 |
| 1990s | 0.13 | 1.00 | 4.00 | 7.00 | 28.00 |
| 2000s | 0.09 | 1.00 | 4.00 | 8.00 | 28.00 |

Multiple covariates regression was applied under 19 distinct quantiles ranging from $5^{th}$ to $95^{th}$ in order to compare estimation coefficients of quantile regression with conventional linear regression by the least square estimate. Figure 3 presents the change of intercept and partial slope with estimated conditional quantiles for three climatic variables (minimum temperature, maximum temperature, and annual precipitation) predicting longleaf pine importance value. In each panel, the solid red line shows the least squares regression line; the dashed red lines represent the 95 percent confidence interval of the least squares regression. The black dots are estimates at each conditional quantile, and the gray areas are the 95 percent confidence interval for the quantiles. For each covariate, these point estimates may be interpreted as the impact of a one-unit change of the covariate on longleaf pine important value holding other covariates fixed. From figure 3, the quantile regression estimates are outside the confidence interval of the conventional least square estimates. This indicates that the ordinary regression performs well in predicting the relationship between longleaf pine importance values and given variables of minimum temperature, maximum temperature, and annual precipitation at the quantiles of $60^{th}$-$75^{th}$, $60^{th}$-$80^{th}$, and $50^{th}$-$75^{th}$, respectively. We observed that the ordinary regression only represents the center of data distribution but fails in presenting other parts of the response distribution. Unfortunately, the center approximation is not consistent with the ecological theory of limiting factors because real limiting function is often reflected by the upper or lower boundaries. Compared to conventional regression, quantile regression is able to serve as a useful tool with considering various levels of the response. For the future management, quantile regression is helpful for identifying high dominance of longleaf pine associated with climatic conditions. Thus, quantile regression is a promising statistical

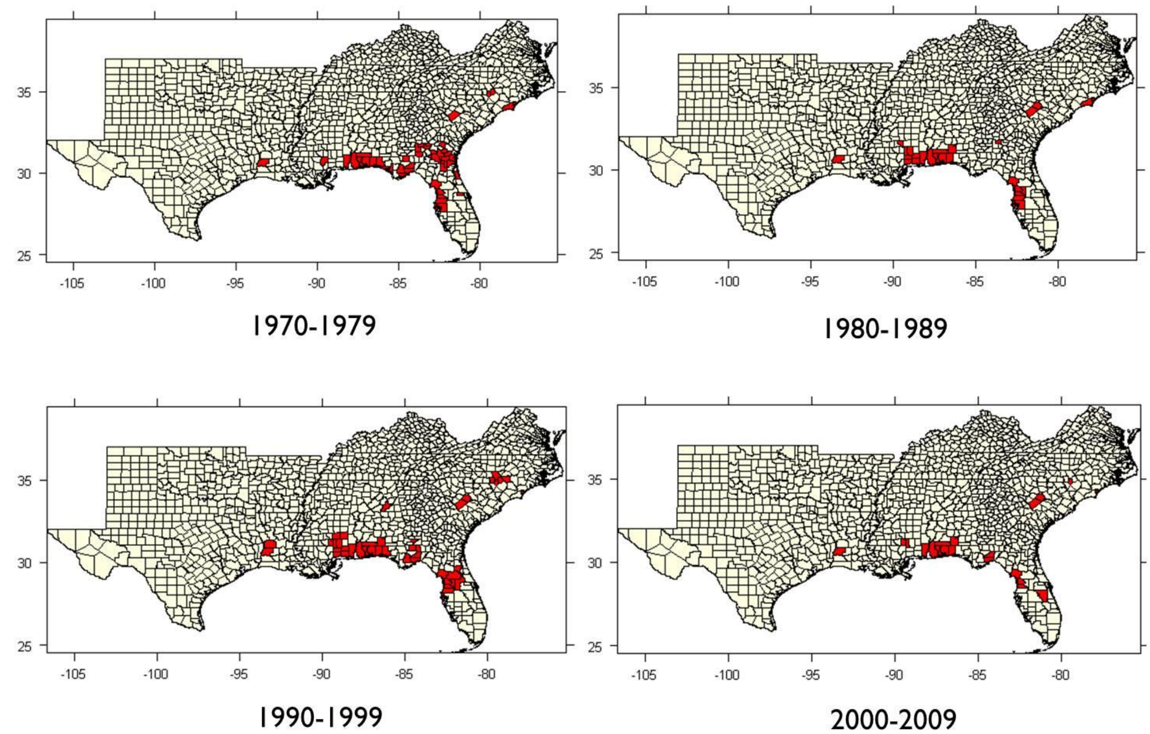


Figure 2--Shaded counties representing spatial clusters (hotspots) of longleaf pine dominance over the past 40 years.

method in selecting locations for high restoration success under changing environment.

**CONCLUSIONS**

Based on the calculation in this study, the numbers of counties with longleaf pine are decreasing over the past 4 decades in the southeastern United States. In addition, the importance values of longleaf pine are declining at various quantiles of the $0^{th}$ (minimum), $25^{th}$, $50^{th}$, $75^{th}$, and $100^{th}$ (maximum). Analyzing clusters by spatial autocorrelation statistics, we found that, in general, most of spatial clusters are distributed in Florida, Georgia, North Carolina, Alabama, Louisana, South Carolina, and Mississippi which can serve as the source of longleaf pine refuge and experimental sites for further detailed studies.

Quantile regression covered broader longleaf pine dominance levels than conventional least square regression in assessing the relationships between longleaf pine dominance and climatic variables of minimum temperature, maximum temperature, and annual precipitation. Thus, quantile regression could help with predicting longleaf pine dominance under limiting factors in future studies. In addition, we are able to utilize quantile regression modeling to evaluate potential restoration success (e.g., how much longleaf pine dominance can be achieved) before taking action.

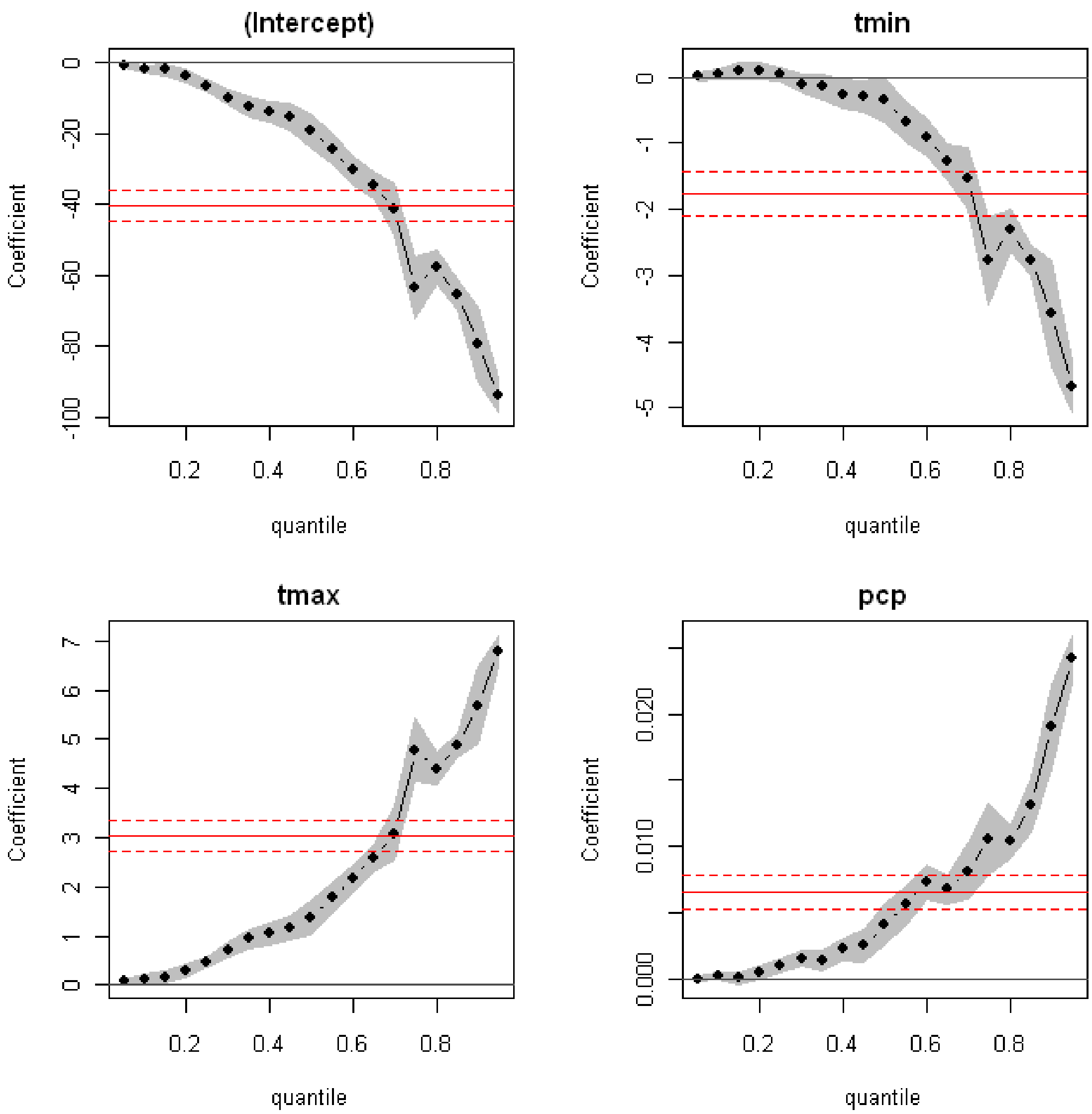


Figure 3--Coefficients of the quadratic terms for multiple quantiles. The variable names are: tmin = mean minimum temperature; tmax = mean maximum temperature; and pcp = annual precipitation.

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