INCLUSION OF CLIMATIC VARIABLES IN LONGLEAF PINE GROWTH MODELS

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Abstract—The Regional Longleaf Growth Study was established by the USDA Forest Service to study the dynamics of naturally regenerated, even-aged longleaf pine (*Pinus palustris* Mill.) stands. The study accounts for growth change over time by adding new sets of plots in the youngest age class every 10 years. To detect possible changes in productivity with time, a series of timerep plots in youngest age class were established and periodically re-measured. Stand level and growth models were fitted to individual timerep data sets. Parameter stability analyses indicated that model parameters changed significantly from one time period to the next. Further tests identified particular parameters that were most sensitive to time and in need of modification. Climate variables were added as covariates to models to improve stability of modeling parameters, since climatic indices are correlated with residuals. There have been changes in productivity of these plots which may be related to changes in climate.

BACKGROUND

From 1964 to 1967, the USDA Forest Service established the Regional Longleaf Pine Growth Study (RLGS) in the Gulf States. The original objective of the study was to obtain a database for the development of growth and yield predictions for naturally regenerated, even-aged longleaf pine stands. Plots were installed to cover a range of ages, densities, and site qualities. The plots are inventoried on a 5-year cycle and are thinned at each inventory, as needed, to maintain the assigned density level. The study accounts for growth change over time by adding a new set of plots in the youngest age class every 10 years.

Plots cover a range of age classes from 20 to 130 years, 6 site index classes ranging from 40 to 80 feet at 50 years, and 5 density classes ranging from 30 to 150 square feet acre^{-1}. A new class, "free to grow", has recently been added to determine the maximum density longleaf pine stands can attain prior to onset of mortality. Densities are established and maintained by low thinning. Within this distribution are five time replications of the youngest age class. All five replications are located on the Escambia Experimental Forest (EEF) in Brewton, AL.

TIMEREP PLOTS

The increasing concerns in recent years by researchers and the public about the changes in forest growth can be explained by examining the stability of growth and yield model parameters. In order to detect possible changes in productivity over time, a series of plots termed "timereps" were established on the EEF in Brewton, AL, in young, naturally regenerated longleaf pine stands that have been periodically measured (Kush and others 1987). The basic purpose of these plots was to investigate potential differences in growth due to differences in climatic factors (represented by different time periods) after reducing the differences in initial stand characteristics as much as possible. The controlled nature and the close proximity of the timerep plots already isolate concomitant effects induced by the stand characteristics.

The timerep plots are the subset of periodically measured growth data obtained from the RLGS (Kush and others 1987). The study was initiated in the mid-1960s to monitor growth and yield of naturally regenerated, even-aged longleaf pine stands (Farrar 1978); three periods of timerep plots were available for the following analyses. In a study by Rayamajhi and others (1998), the parameters of projection models were tested and found to be unstable and in need of modification by incorporating suitable variables that will account for the change.

METHODS

In order to measure the effect of climate on longleaf pine productivity, groups of 3 timerep plots were established every 10 years on the EEF in Brewton, AL. A subset of timerep band plots were selected in which all stand variables (site index, trees acre^{-1}, and age) were isolated; the difference of basal area increment year^{-1} (BAIPYR) among the timereps could then be measured without confounding the measurement. For statistical analysis of data, timerep-period differences were compared using analysis of covariance (ANCOVA), containing terms for timerep (treatment) and basal area, with and without the climate variables of precipitation and maximum and minimum temperature (as covariates). Primary treatment comparisons were pairwise comparisons between the different timereps (1, 2, and 3) based on least-squares means from the ANCOVA. The assumptions of these analyses were to observe effect of climate in the very basic basal area model consisting of stand characteristics. Based on the results, longleaf pine growth and yield models are provided with predictor variables to account for changes in climatic variables.

RESULTS AND DISCUSSIONS

The observed mean basal area acre^{-1} (BA), its statistics, and the change from one period to another are presented in table 1. The sample sizes were not the same among the timereps; however, the stand characteristics were controlled to be homogeneous. The change column exhibits an increased BAIPYR for timerep 3, differentiating it from other two timereps. The observed means and its statistics for precipitation in inches, and maximum and minimum temperatures in °F are presented in table 2 for each timerep.

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Table 1—Average basal area (square feet acre^{-1}) for the first time period of each timerep and the average change in basal area (square feet acre^{-1} year^{-1}) at the start of the second time period. Timerep plots are located on the Escambia Experimental Forest in Brewton, AL

Timerep	N	Period 1					Change				
		Mean	STD	Median	Min	Max	Mean	STD	Median	Min	Max
1	28	47.29	24.9	51.5	11.4	97.3	4.70	1.22	4.29	2.64	7.10
2	60	59.21	20.1	59.2	23.9	101.2	5.24	1.38	5.26	3.07	8.33
3	21	57.75	16.7	60.4	24.8	81.5	7.42	1.49	7.34	4.18	9.55

Table 2—Observed means of climatic variables for the three timereps on the Escambia Experimental Forest in Brewton, AL

Timerep	Variable	N	Mean	STD	Median	Min	Max
1	Precip (*in*)	20	70.27	6.4	11.4	56.7	77.0
2		60	76.33	13.8	59.2	65.1	98.6
3		21	63.90	—	60.4	63.9	63.9
1	Max temp (*°F*)	20	76.39	0.27	66.4	76.0	77.6
2		60	77.07	0.26	70.8	76.8	77.5
3		21	77.92	—	63.9	77.9	77.9
1	Min temp (*°F*)	20	50.24	0.96	49.8	49.3	51.7
2		60	51.07	1.09	51.4	49.4	52.1
3		21	53.01	—	53.0	53.0	53.0

A mean change analysis of covariance is performed to find the difference among the three timereps so that the effect of any climate variable could be compared with and without climatic variables. The dependent variable was BAIPYR; the independent variable consisted of basal area at period 1, as a covariate, and the timereps. The mean change analysis showed overall significance among the timereps and non-significance for covariate (table 3). Least Square (LS) mean pairwise change indicates timerep 3 was different from timereps 1 and 2. However, the mean change analysis including climatic variables, such as mean minimum temperature, showed that the timereps were not different (table 4). The LS means pairwise change was not significantly different among the timereps. This indicates significance of including climatic variables in the very basic growth model. The ongoing changes can be explained by including some form of climatic variables

Table 3—Analysis of mean change for the three timereps (without climatic variables) on the Escambia Experimental Forest in Brewton, AL

Main effects (type II SS)	ndf[a]	ddf[b]	p-value
Basal area at Period 1	1	105	0.3535
Timerep	2	105	<0.0001

Treatment	LS means for change	Std. error
Timerep 1	4.7515	0.2636
Timerep 2	5.2156	0.1775
Timerep 3	7.4072	0.2980

Pairwise Comparison of LS Means

Treatment	Difference	Two-sided 95% CI	p-value
Timerep1-Timerep2	-0.4641	(-1.1013, 0.1732)	0.1518
Timerep1-Timerep3	-2.6557	(-3.4478,-0.86.5)	<0.0001
Timerep2-Timerep3	-2.1916	(-2.8779,-1.5053)	<0.0001

[a] Numerator degrees of freedom.
[b] Denominator degrees of freedom.

Table 4—Analysis of mean change (including mean minimum temperature) for the three timereps on the Escambia Experimental Forest in Brewton, AL

Main effects (Type II SS)	df[a]	ddf[b]	p-value
Basal area at Period 1	1	104	0.0002
Timerep	2	104	0.1031
Mean minimum temperature	1	104	<0.0001

Treatment	LS means for change	Std. error
Timerep 1	5.7666	0.2675
Timerep 2	5.3002	0.1493
Timerep 3	5.8120	0.3443

Pairwise Comparison of LS Means			
Treatment	Difference	Two-sided 95%CI	p-value
Timerep1-Timerep2	0.4664	(-0.1341, 1.0669)	0.1265
Timerep1-Timerep3	-0.0454	(-1.0613, 0.9704)	0.9295
Timerep2-Timerep3	-0.5118	(-1.2707, 0.2470)	0.1839

[a] Numerator degrees of freedom.
[b] Denominator degrees of freedom.

or indices. Timereps 1 and 2 were more similar when precipitation was included, but timerep 3 remained unchanged (table 5).

Since climatic variables are correlated with residuals of the basal area projection or increment models (Rayamajhi 1996), the following climate models were obtained using the full RLGS dataset. Climatic variables were represented by a climatic index $f_i(x)$, representing precipitation and the mean minimum temperature.

Climate Models

(1) Basal Area Projection Model:

$$BA_2 = BA_1 \left(\frac{A_1}{A_2}\right)^{-1.637+4.046f_1(x)} e^{5.3752\left[1-\left(\frac{A_1}{A_2}\right)^{-1.637+4.046f_1(x)}\right]}$$

Table 5—Analysis of mean change for the three timereps (including total precipitation) on the Escambia Experimental Forest in Brewton, AL

Main effects (Type II SS)	ndf[a]	ddf[b]	p-value
Basal area at Period 1	1	104	0.0006
Timerep	2	104	<0.0001
Total Precipitation	1	104	<0.0001

Treatment	LS means for change	Std. error
Timerep 1	4.9786	0.2337
Timerep 2	4.9222	0.1632
Timerep 3	7.9424	0.2765

Pairwise Comparison of LS Means			
Treatment	Difference	Two-sided 95% CI	p-value
Timerep1-Timerep2	0.0564	(-0.5287, 0.6414)	0.8489
Timerep1-Timerep3	-2.9638	(-3.6643,-2.2632)	<0.0001
Timerep2-Timerep3	-3.0201	(-3.6840,-2.3562)	<0.0001

[a] Numerator degrees of freedom.
[b] Denominator degrees of freedom.

(2) Basal Area Increment Model:

$$BAI = 0.2349 + 0.0036\left(\frac{BA_1}{A_1}\right) - 0.1511\left(\frac{N_1}{A_1}\right) + 0.7152\left(\frac{S}{A_1}\right) + 0.2094 f_2(x)\left(\frac{N_1}{A_1}\right)$$

(3) Individual Tree Growth Model:

$$bai = 19.83 e^{-0.0941 BA^{0.5}} e^{-0.0037 BAL} e^{\left[0.3048\left(1 - e^{-0.3498 DBH}\right) - 0.3119\right]A} e^{-0.4261 f_3(x)}$$

where

$f_1(x) = \sum$ Precipitation(01,10,11,12)/$\sum$ Min. Temp.(04,07,08,09)

$f_2(x) = \sum$ Precipitation(02,4,11,12)/$\sum$ Min. Temp.(04,06,07,12)

$f_3(x) = \sum$ Precipitation(02,06,08,09)/$\sum$ Min. Temp.(04,09,11)

Summary of Findings

A subset (band) of three time replication plots were selected from time replication plots on the EEF. The stand characteristics, age, density, and site quality were isolated in order to make a comparison of BAIPYR over three time periods. The analysis of variance showed a statistically significant difference among the three timereps. An ANCOVA was performed, adding the climatic variables total precipitation and minimum and maximum temperatures, as covariates. The results reduced the statistical significance, resulting in non-significance when a climatic variable like minimum temperature was considered. This shows that climatic variables such as total precipitation and minimum and maximum temperature can be used to account for variation in the timereps. Based on the correlation of climatic variables with the residuals, growth models containing climatic variables are suggested.

CONCLUSIONS

There was an increased growth trend in terms of BAIPYR for longleaf pine due to changes in climatic factors based on these data. Parameters of growth and yield models do not remain stable for long projection periods and need to be modified to account for the variable that is responsible for the change. Climatic variables, such as precipitation, and maximum and minimum temperatures, or climatic indices derived from these variables should be used in the growth and yield model. The model then incorporates, rather than ignores, any changes ongoing because of the effects of climate. Furthermore, addition of climatic variable strengthens the robustness of the predictability of the models.

LITERATURE CITED

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