1991

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Fusiform Rust Incidence in Loblolly and Slash Pine Plantations in East Texas

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*ABSTRACT. A method to predict the incidence of fusiform rust (*Cronartium quercuum *[Berk.] Miyabe ex Shirai f. sp.* fusiforme*) in unthinned loblolly (*Pinus taeda *L.) and slash pine (*Pinus elliotti *Englem.) plantations located on non-old-fields in East Texas is presented. In addition, procedures are described to estimate changes in rust incidence over time as:*

1. *A rust-free tree remains rust free, develops stem or branch galls, or dies.*
2. *A tree with branch galls remains with branch galls only, develops stem galls, or dies.*
3. *A tree with stem galls remains with stem galls, or dies.*

Multinomial logistic regression models utilizing basic plantation parameters as predictors were fit to estimate current rust incidence and, then, the change in rust condition over time.

South. J. Appl. For. 15(2):79–84.

Fusiform rust, caused by the fungus *Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme*, is the most damaging disease of loblolly and slash pines, the two major pine species in the southern United States. Annual losses in the order of $130 million (Anderson and Mistretta 1982) underscore the need for assessing the incidence of this disease so that detection, control, and prevention practices can be efficiently deployed.

The purpose of this study was to predict the incidence of fusiform rust in planted stands of loblolly and slash pine in East Texas. By incidence we mean the proportion of trees in a stand in each infection-level category; and the change in these proportions over time, henceforth called the *transition proportions.* Shoulders and Nance (1987) compiled statewide summaries of similarly defined transition proportions and observed that transition proportions may vary widely among stands. Our modeling effort was intended to provide more precise estimators of stand-level transition proportions by including stand attributes as explanatory factors.

Within a timber stand, rust proportions follow a multinomial distribution. Accordingly, multinomial logistic regression (MLR) models were fit. The MLR model estimates the probability of an event. When applied to a stand of trees, this probability is interpreted as the estimated proportion of trees in a certain class. MLR models can accommodate an arbitrary number of classes; when only two classes are recognized, the MLR reduces to the binary logistic model, which has been widely used in forestry to model mortality (see, for example, the work by Monserud 1976, Hamilton 1974 and 1986, and Hamilton and Edwards 1976).

DATA

Data from the East Texas Pine Plantation Research Project (ETPPRP) were available for analysis. The ETPPRP is a long-range project initiated in 1982 by the School of Forestry at Stephen F. Austin State University and participating forest industries[1] (Lenhart et al. 1985). Each of the 252 ETPPRP permanent plots (173 in loblolly and 79 in slash) is located

[1] The continuing support from the participating companies—Champion International Corporation, International Paper Company, Louisiana-Pacific Corp. and Temple-Inland Forest Products Inc.—is appreciated.

in a separate plantation throughout 24 counties of East Texas. A permanent plot consists of two subplots, each 100 ft square. Within each subplot, the planted pines are tagged and numbered for remeasurement on a 3-year cycle. Seed sources for the planted pines are not known.

At the time of plot installation (first measurement), among other factors, the occurrence of fusiform rust symptoms on each planted pine was visually classified. Listed in an order which signifies an increasing level of disease severity, these classification categories are:

1. CLEAR—Free of fusiform rust.
2. BRANCH—Fusiform rust galls on a live or dead branch more than 12 in. from the stem.
3. STEM—Galls on a stem or on a live branch within 12 in. of the stem.

During the second measurement, each planted pine was again visually classified into one of the categories listed above or a fourth category: DEAD—A tree alive at first measurement but dead upon remeasurement. ETPPRP field crews were able to reliably note only those fusiform rust galls occurring on planted pines 5 years or older. As a result, data from 70 loblolly and 38 slash pine plots were available for analysis. In addition, for each plot, data from only one of the two subplots were considered.

Descriptive statistics for both species at both measurements are listed in Table 1. Table 2 presents the distribution of the sample plots by age classes. Lenhart et al. (1988) present a quantitative summary of the rust incidence at each measurement.

The proportions that were used to model fusiform rust incidence were the number of trees in each of the classes listed above divided by the total number of trees. The transition proportions used to model changes in incidence depended on the initial number of trees in the CLEAR, BRANCH, and STEM classes, respectively. For example, the four transition proportions for trees initially classified as CLEAR are the numbers of trees in the four classes at second measurement, each divided by the number of initially CLEAR trees. The transition proportions for BRANCH and STEM initial infection levels are similarly defined; however we assume that there is zero probability that a tree will move from an initial state of infection to a state of lesser infection. Consequently, there are only three transition proportions associated with the initial BRANCH class; and only two transition proportions associated with the initial STEM class.

Age, site index at base age 25, number of trees per acre, and basal area per acre were recorded at the time of plot establishment and at the second measurement. Other information available for each plot included the method of site preparation, aspect, geographic location, and landform characteristics.

Table 2. Age distribution of permanent sample plots by species at first measurement.

	Plantation age (yr)													
Species	5	6	7	8	9	10	11	12	13	14	15	16	17	Total
Loblolly	11	4	11	9	3	9	8	7	2	1	2	2	1	70
Slash	3	9	8	4	2	1	4	1	1	4	0	1	0	38

Table 1. Loblolly and slash pine plot summary statistics at the first and second measurement.

Plot variables	First measurement			Second measurement		
	min.	mean	max.	min.	mean	max.
			Loblolly			
Site index (ft)[1]	29	69	100	32	72	101
Trees/ac	139	444	749	139	436	740
Basal area/ac (ft²)	0	50	116	10	77	140
Age (yr)	5	9	17	8	12	20
			Slash			
Site index (ft)[1]	27	66	99	37	69	84
Trees/ac	133	345	1002	112	152	989
Basal area/ac (ft²)	0	35	107	5	53	129
Age (yr)	5	9	16	8	12	19

[1] Base age = 25 yr.

METHODOLOGY

Multinomial Logistic Regression Model

A distinction must be made between the multinomial logistic regression (MLR) model used in this study and another, known as the ordered multinomial logistic regression (OMLR) model. The first does not connote any necessary natural ordering of the values the response variable can take, whereas the latter is designed to account for such an ordering. Arabatzis (1990) discusses the relative advantages and disadvantages of the two models. A brief description of the MLR model follows.

Let p_{ij} be the proportion of trees growing on the ith plot ($i = 1, 2, \ldots, n$) in the jth category ($j = 1, 2, \ldots, m$). The MLR model expresses p_{ij} as

$$p_{ij} = \frac{\exp(\underline{\beta}_j' \underline{x}_i)}{\sum_{j=1}^{m} \exp(\underline{\beta}_j' \underline{x}_i)} \qquad (1)$$

where $\underline{\beta}_j$ is a vector of unknown parameters unique to each category and $\underline{x}_i$ is the vector of explanatory variables observed at the ith plot. Since each tree must fall into one of the mutually exclusive categories, the proportions must sum to one. To satisfy this condition $\underline{\beta}_1 = \underline{0}$ is customarily set to zero, thereby obtaining

$$p_{ij} = \frac{\exp(\underline{\beta}_j' \underline{x}_i)}{1 + \sum_{j=2}^{m} \exp(\underline{\beta}_j' \underline{x}_i)} \quad (j = 2,3,\ldots,m) \qquad (2)$$

and $p_{i1} = 1 - \Sigma_{j=2}^{m} p_{ij}$. With estimates of the coefficient vectors $\underline{\beta}_j$, one can predict the proportion of trees in the ith category for a plantation with independent variable values given by $\underline{x}_i$.

Maximum likelihood is a commonly used method for the estimation of the unknown coefficient vectors $\underline{\beta}_j$; the maximum likelihood estimators are statistically consistent and can be derived via nonlinear weighted least squares (Amemiya 1985). Arabatzis and Gregoire (1991) discuss attractive properties of the MLR model in further detail, e.g., the fact that predicted proportions are naturally bounded between 0 and 1. They also present methodology for hypothesis testing, construction of approximate confidence intervals, and list several goodness of fit criteria.

Modeling Fusiform Rust Incidence

To predict the proportion of loblolly and slash pine trees in a stand which are CLEAR, BRANCH, STEM, or DEAD at a given age, Equation (2) was fit to the data of each species. Site index, average height of dominant and codominant trees, geographic location (north or south East Texas), number of trees per acre, basal area per acre, quadratic mean diameter, relative spacing, type of plantation terrain (flat or slope), including interactions and transformations of the above variables, were considered during the model fitting stage. Variable screening criteria were sum of squared residuals, weighted sum of squared residuals, pseudo-R^2, Akaike's information criterion and the maximized value of the log-likelihood, all of which are described by Arabatzis and Gregoire (1990).

Modeling Changes in Fusiform Rust Incidence

To predict the transition proportions of fusiform rust in loblolly and slash pine the following MLR models were considered:

1. A quatrinomial logistic regression model for the proportion of initially unaffected trees, which either remained unaffected, became branch infected, became stem infected, or died.
2. A trinomial logistic regression model for the proportion of branch infected trees, which either remained at the same level of infection, moved to a higher infection level or died.
3. A binomial logistic regression model for the proportion of stem infected trees, which either remained at the same level of infection or died.

In addition to the regressor variables described above, the initial proportion in each infection category was used as a regressor.

RESULTS AND DISCUSSION

For both species, plantation age (AGE), site index on a 25-year base (SI), basal area per acre (BA), and an indicator of terrain type (FLAT)[2] were selected as regressor variables. For loblolly only, an indicator of geographic location (NORTH)[3] and a variable for a BA, FLAT interaction were also included.

Corresponding to an estimated coefficient vector $\hat{\underline{\beta}}$, the estimated proportion is derived algebraically from the function $\hat{\underline{\beta}}'\underline{x}$ as shown in (2). For loblolly pine the $\hat{\underline{\beta}}'\underline{x}$ functions for incidence categories are:

BRANCH:

$$\hat{\underline{\beta}}'\underline{x} = -2.7123 - 0.5050(\text{NORTH}) - 1.6731(\text{FLAT}) + 0.0320(\text{AGE}) + 0.0036(\text{SI}) - 0.0112(\text{BA}) + 0.0176(\text{BA})(\text{FLAT}) \quad (3)$$

STEM:

$$\hat{\underline{\beta}}'\underline{x} = -3.0140 - 0.4167(\text{NORTH}) - 0.3874(\text{FLAT}) + 0.0930(\text{AGE}) + 0.0094(\text{SI}) - 0.0107(\text{BA}) + 0.0049(\text{BA})(\text{FLAT}) \quad (4)$$

DEAD:

$$\hat{\underline{\beta}}'\underline{x} = -5.5961 - 0.5931(\text{NORTH}) - 0.6094(\text{FLAT}) + 0.0352(\text{AGE}) + 0.0034(\text{SI}) + 0.0156(\text{BA}) + 0.0128(\text{BA})(\text{FLAT}) \quad (5)$$

For slash pine the $\hat{\beta}'x$ functions for incidence categories are:

BRANCH:

$$\hat{\underline{\beta}}'\underline{x} = -1.9983 - 0.0599(\text{FLAT}) + 0.0543(\text{AGE}) - 0.0139(\text{SI}) + 0.0144(\text{BA}) \quad (6)$$

STEM:

$$\hat{\underline{\beta}}'\underline{x} = -3.8697 - 0.2944(\text{FLAT}) + 0.2478(\text{AGE}) + 0.0406(\text{SI}) - 0.0261(\text{BA}) \quad (7)$$

DEAD:

$$\hat{\underline{\beta}}'\underline{x} = -6.6413 + 0.0449(\text{FLAT}) + 0.2879(\text{AGE}) + 0.0412(\text{SI}) - 0.0267(\text{BA}) \quad (8)$$

Standardized residuals for each level of rust infection were plotted against age, site index, and basal area per acre, as a check against model misspecification. No untoward trends were detected in these graphs. The $\hat{\underline{\beta}}'\underline{x}$ functions for the transition proportions of both species are shown in the Appendix.

The geographic location of loblolly pine plantations significantly affected the incidence of fusiform rust. As indicated by the coefficient estimates of the NORTH variable, loblolly pine trees in North-East Texas plantations are more likely to be clear of rust, on average, than trees in plantations located in South-East Texas. Also, the effect due to geographic location seems to influence whether healthy loblolly pine trees become branch or stem infected (see Appendix); in contrast, geographic location is not a significant factor

[2] A value of one was assigned to the variable FLAT if a plantation was located on flat terrain; a value of zero was assigned otherwise.

[3] A value of one was assigned to the indicator variable NORTH if a plantation was located in Cass, Harrison, Marion, Panola, Red River, or Rusk counties of North-East Texas; a value of zero was assigned otherwise.

influencing the transition of branch or stem infected trees to a more severe level of infection or death (Appendix). Wells and Dinus (1978) also reported that geographic location of a plantation was an important factor affecting the incidence of fusiform rust on loblolly pine. No geographic trend could be detected for slash pine plantations, because all available survey plots were located in South-East Texas.

Soil drainage was an important factor influencing the incidence of fusiform rust in both species. Trees on poorly drained (flat) sites are more likely to be clear of rust; and on such sites, the proportion of initially clear trees that later become infected is smaller than that on better drained sites; however, once a tree is infected, the disease is more severe on flat sites. Previous studies have also reported lower fusiform rust incidence on poorly drained sites and higher incidence on well-drained sites (May et al., 1973, Hollis et al. 1975, Hollis and Schmidt 1977, Schmidt et al. 1990).

Fusiform rust incidence increases with age in both species but at a faster rate in slash pine, as the magnitude of the corresponding coefficient estimates indicate. The transition of CLEAR loblolly pine trees to infected trees decreased with age, whereas the opposite is true for slash pine. The transition of branch infected trees to stem infected trees is negatively related to increasing age in both species, whereas at the transition to death of a tree the relationship becomes positive for loblolly pine and remains negative for slash pine. These observations agree with what is generally accepted, namely that slash pine can be decimated by the disease at earlier ages than loblolly pine, which can survive to normal rotation ages (Geron and Hafley 1988). Devine and Clutter (1985) also reported decreasing mortality rates of infected slash pine trees with increasing age. Similar conclusions were reached by Hunt and Lenhart (1986) after compiling data from four surveys on loblolly and slash pine plantations in East Texas between 1969 and 1984, the 1984 survey containing the initial measurements used in this study. The difference in transition rates from branch infection to stem infection seems to be the critical point in the progression of the disease in the two species.

The transition from one category of rust infection to a more severe category is influenced by the initial proportion of trees that are clear (CLEAR0P), have branch (BRANCH0P) galls, or have stem (STEM0P) galls. For loblolly pine, the higher the initial proportion of CLEAR0P trees, the larger the proportion that are CLEAR three years later, and the smaller the proportion that later are branch or stem infected (see Appendix). Similarly the higher the proportion of BRANCH0P trees, the higher the proportion that later become stem infected. For slash pine opposite trends are suggested for the roles of CLEAR0P and BRANCH0P. In addition, STEM0P was positively related to the proportion of stem infected slash pine trees which subsequently die. For stem infected loblolly pine trees, STEM0P did not significantly affect mortality rate.

With few exceptions, site index coefficients were positive, indicating that higher site index corresponds to increased rust incidence, a result which concurs with that reported by Nance et al. (1981) and Borders and Bailey (1986).

Stand density, expressed as basal area per acre, significantly affected fusiform rust incidence. For both species, it was negatively related to the proportion of stem infected pines and, also, to the transitional proportions of healthy trees to trees with infection on the stem. The remaining coefficient estimates were not significantly different from zero. Several studies have failed to establish a significant relationship between stand density and rust occurrence (Wakeley 1969, Miller 1972, Borders and Bailey 1986). However, our results support Siggers's (1955) reasoning that close spacing enhances the natural pruning of branch galls.

The interaction between stand density and soil drainage is positively related to the proportion of loblolly pine trees infected and to the proportion of initially CLEAR trees that become infected. This interaction effect was not significant in slash pine. Although difficult to interpret, it seems that high density stands growing on poorly drained sites are more susceptible to rust occurrence than stands growing on other sites.[4] Of course, other confounding factors might have contributed to this result, even though subsequent examination did not reveal any trends. We included this term in the models because it improved model performance.

APPLICATION

To illustrate how fusiform rust incidence and transitional proportions can be estimated, consider a 10-year-old loblolly pine plantation growing in South-East Texas on well drained soil, BA = 50 ft^2/ac, 450 trees/ac, and SI = 90 ft. To predict the proportions of infected trees at the current age, solve Equations (3)–(5) and exponentiate to obtain.[5]

BRANCH:

$$\exp[-2.7123 + 0.0320(10) + 0.0036(90) - 0.0112(50)] = 0.0722$$

STEM:

$$\exp[-3.0140 + 0.0930(10) + 0.0094(90) - 0.0107(50)] = 0.1698$$

DEAD:

$$\exp[-5.5961 + 0.0352(10) + 0.0034(90) - 0.0156(50)] = 0.0156$$

Substituting the above terms into Equation (2) obtains:

[4] A referee suggested that perhaps slow growth on these sites due to poor drainage and high density presents more opportunities for rust infection, whereas in the absence of this slow growth the chance of infection is lessened.

[5] Note that for this example, the NORTH and FLAT dummy variables equal zero.

$$P_{\text{branch}} = \frac{0.0722}{1 + 0.0722 + 0.1698 + 0.0156} = 0.0574$$

$$P_{\text{stem}} = \frac{0.1698}{1 + 0.0722 + 0.1698 + 0.0156} = 0.1350$$

$$P_{\text{dead}} = \frac{0.0156}{1 + 0.0722 + 0.1698 + 0.0156} = 0.0125$$

$$P_{\text{clear}} = - P_{\text{branch}} - P_{\text{stem}} - P_{\text{dead}} = 0.7951$$

Thus, the status of the 450 current trees per acre is estimated to be: about 26 trees have galls on branches, 61 have galls on stem, 357 trees are clear, and 6 trees are dead.

The 3-year transition of the 357 clear trees from age 10 to age 13 can be predicted using Equations (1)–(3) from the Appendix and the value $P_{\text{clear}} = 0.7951$, as:

BRANCH:
$$\exp[0.7657 - 0.0961(10) + 0.0015(90) - 0.0063(50) - 2.3303(0.7951)] = 0.1077$$

STEM:
$$\exp[2.1661 - 0.0156(10) + 0.0039(90) - 0.0187(50) - 4.3641(0.7951)] = 0.1295$$

DEAD:
$$\exp[-7.6082 + 0.0914(10) + 0031(90) + 0.0124(50) + 1.3891(0.7951)] = 0.0092$$

Substituting into Equation (2) obtains:

$$P_{\text{clr-bra}} = \frac{0.1077}{1 + 0.1077 + 0.1295 + 0.0092} = 0.0860$$

$$P_{\text{clr-stem}} = \frac{0.1295}{1 + 0.1077 + 0.1295 + 0.0092} = 0.1039$$

$$P_{\text{clr-dead}} = \frac{0.0092}{1 + 0.1077 + 0.1295 + 0.0092} = 0.0074$$

$$P_{\text{clr-clr}} = 1 - P_{\text{clr-bra}} - P_{\text{clr-stem}} - P_{\text{clr-dead}} = 0.8029$$

Of the 357 trees that were clear of galls at age 10, it is now estimated that 3 years later at age 13 the status is: about 31 now have galls on branches, 37 have galls on stem, 3 have died, and 286 are still clear of galls.

In a similar manner, the 3-year transition of the 26 trees with branch galls from age 10 to age 13 can be estimated using Equations (4)–(5) from the Appendix, the value $P_{\text{branch}} = 0.0574$, and Equation (2). Of the 26 trees, approximately 12 now have galls on the stem and 13 still have galls located only on branches. One of the 26 trees is expected to die during this period.

Likewise, the 3-year transition of the 61 trees with stem galls from age 10 to age 13 can be predicted using Equation (6) from the Appendix, the value $P_{\text{stem}} = 0.1350$, and Equation (2). The status of the 61 stem infected trees is now: about 4 are dead and 57 remain with stem galls.

In summary, by the end of this 3-year period in the life of a Southeast Texas loblolly pine plantation, it is estimated:

1. Trees remaining clear of galls = 286, which is a decrease of 71 trees.
2. Trees with branch galls = 44. At the beginning of the 3-year period, 13 of these 44 initially had branch galls and 31 were clear of galls. Net increase over the period is 18 trees.
3. Trees with stem galls = 106. At the beginning of the 3-year period, 57 of the 106 trees initially had stem galls, 12 had branch galls and 37 were clear of galls. Net increase over the period is 45 trees.
4. Trees dying = 8.

CONCLUSIONS

All models indicated that fusiform rust infection increases with time in both species but at a higher rate in slash pine. Loblolly pines in plantations in South-East Texas more frequently had fusiform rust galls than those in North-East Texas. Rust incidence was lower on poorly drained soils. Site quality was positively related to rust incidence. Increased stand density reduced the frequency of stem infection.

The amount of rust infection can be explained only partially by the usual survey stand variables used in the models above (Borders and Bailey 1986). Additional factors, omitted from the present models, may influence rust incidence and spread. For instance, it has been reported (Froelich and Snow 1986, Hollis et al. 1975) that the presence of large numbers of oaks (*Quercus* spp.) scattered among the planted pines is often associated with a high incidence of fusiform rust infection. Thus, it is possible that the inclusion of variables to account for oak volume or oak leaf area would explain additional variation in the pattern of rust incidence.

Because basal area per acre is likely to depend on rust induced mortality, estimation of future transition proportions beyond the 3-year range of the data used to fit these models is risky. At the very least, it will be necessary to incorporate a projection of future basal area into the transition model and to base the model on a longer time-series of measurements. Future work along these lines is planned. □

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APPENDIX

For loblolly pine the $\hat{\beta}'\underline{x}$ functions for three year transition proportions are:

a. Initially CLEAR trees

BRANCH:

$$\hat{\beta}'\underline{x} = 0.7657 - 0.6040(\text{NORTH}) - 1.8551(\text{FLAT}) - 0.0961(\text{AGE}) + 0.0015(\text{SI}) - 0.0063(\text{BA}) + 0.0178(\text{BA})(\text{FLAT}) - 2.3303(\text{CLEAR0P}) \quad (1)$$

STEM:

$$\hat{\beta}'\underline{x} = 2.1661 - 0.7026(\text{NORTH}) - 0.6422(\text{FLAT}) - 0.0156(\text{AGE}) + 0.0039(\text{SI}) - 0.0187(\text{BA}) + 0.0098(\text{BA})(\text{FLAT}) - 4.3641(\text{CLEAR0P}) \quad (2)$$

DEAD:

$$\hat{\beta}'\underline{x} = -7.6082 - 0.2626(\text{NORTH}) - 0.1266(\text{FLAT}) + 0.0914(\text{AGE}) + 0.0031(\text{SI}) + 0.0124(\text{BA}) + 0.0084(\text{BA})(\text{FLAT}) + 1.3891(\text{CLEAR0P}) \quad (3)$$

b. Initially BRANCH trees

STEM:

$$\hat{\beta}'\underline{x} = 2.3465 + 0.8494(\text{FLAT}) - 0.1038(\text{AGE}) - 0.0176(\text{SI}) + 3.1156(\text{BRANCH0P}) \quad (4)$$

DEAD:

$$\hat{\beta}'\underline{x} = -14.4421 + 1.8264(\text{FLAT}) + 0.3412(\text{AGE}) + 0.0962(\text{SI}) - 10.2581(\text{BRANCH0P}) \quad (5)$$

c. Initially STEM trees

DEAD:

$$\hat{\beta}'\underline{x} = -5.0577 + 0.9932(\text{FLAT}) + 0.0761(\text{AGE}) + 0.0176(\text{SI}) \quad (6)$$

Equations to predict transition proportions for slash pine:

a. Initially CLEAR trees

BRANCH:

$$\hat{\beta}'\underline{x} = -6.1697 + 0.2169(\text{FLAT}) + 0.1287(\text{AGE}) + 0.0182(\text{SI}) + 0.0027(\text{BA}) + 2.0773(\text{CLEAR0P}) \quad (7)$$

STEM:

$$\hat{\beta}'\underline{x} = -3.1762 + 0.2305(\text{FLAT}) - 0.0710(\text{AGE}) + 0.0201(\text{SI}) - 0.0062(\text{BA}) + 0.7542(\text{CLEAR0P}) \quad (8)$$

DEAD:

$$\hat{\beta}'\underline{x} = -4.0027 - 0.0229(\text{FLAT}) + + 0.0346(\text{AGE}) - 0.0056(\text{SI}) + + 0.0169(\text{BA}) - 0.9425(\text{CLEAR0P}) \quad (9)$$

b. Initially BRANCH trees

STEM:

$$\hat{\beta}'\underline{x} = 3.3829 - 0.6711(\text{FLAT}) - 0.1341(\text{AGE}) + 0.0168(\text{SI}) - 3.4127(\text{BRANCH0P}) \quad (10)$$

DEAD:

$$\hat{\beta}'\underline{x} = -5.3000 + 0.1900(\text{FLAT}) - 0.0435(\text{AGE}) + 0.0823(\text{SI}) - 9.3939(\text{BRANCH0P}) \quad (11)$$

c. Initially STEM trees

DEAD:

$$\hat{\beta}'\underline{x} = -1.9572 + 0.2917(\text{FLAT}) - 0.0060(\text{AGE}) - 0.0116(\text{SI}) + 1.5364(\text{STEM0P}) \quad (12)$$