Predicting Survival of East Texas Loblolly and Slash Pine Plantations Infected with Fusiform Rust

J. David Lenhart
Arthur Temple College of Forestry and Agriculture, Stephen F. Austin State University

A. Beth Vaughn

Adams D.E.

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D.E. Adams, *Foley Land & Timber Company, Rt 3, Box 260, Perry, Fl 32347-9512,* **J.D. Lenhart,** *College of Forestry, SFASU, Nacogdoches, TX 75962-6109,* **A.B. Vaughn,** *Florida Division of Forestry, 7620 133rd Rd., Live Oak, FL 32060, and* **J. Lapongan,** *Forest Research Centre, Sandakan, Sabah, Malaysia.*

ABSTRACT. *Repeated measurements during 1982-1992 of East Texas Pine Plantation Research Project permanent plots in loblolly (*Pinus taeda *L.) and slash (*Pinus elliottii *Engelm.) pine plantations throughout East Texas were used to develop equations for predicting the future number of trees per acre. A typical condition of East Texas pine plantations is the incidence of fusiform rust (*Cronartium quercuum *[Berk.] Miyabe ex Shirai f. sp.* fusiforme*). A regression procedure for fitting nonlinear systems of equations was used to fit survival models that considered the possibility that trees with no rust galls on the stem could either (1) remain uninfected and alive, (2) become infected yet still alive or (3) die. For infected stems, only two possible outcomes were considered in the model: (1) remain infected and alive or (2) die. Analyses of the differences between predicted and observed values indicated no adverse trends for either of the two species. Apparently the models do represent observed survival patterns. South. J. Appl. For. 20(1):30–35.*

One of the factors influencing tree survival and wood production in loblolly (*Pinus taeda* L.) and slash (*Pinus elliottii* Engelm.) pine plantations in the southern United States is fusiform rust caused by the fungus *Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme*). Average incidence of stem galls in loblolly pine plantations 5 yr or older in East Texas has been reported as: 6% in 1969, 7% in 1984, 10% in 1987, and 10% in 1990 (Mason and Griffin 1970, Hunt and Lenhart 1986, Lenhart et al. 1988 and Lenhart et al. 1994, respectively). In contrast, average incidence of stem galls on planted slash pines 5 yr or older in East Texas has been reported as: 46% in 1984, 48% in 1987, and 41% in 1990 (Hunt and Lenhart 1986, Lenhart et al. 1988 and Lenhart et al. in press, respectively). The East Texas loblolly pine rust incidence is lower than the average southwide incidence of 12–19%, while the East Texas slash pine rust incidence is relatively high compared with average southwide incidence of 10–41% (Phelps 1977).

In East Texas pine plantations, fusiform rust incidence increases with age, and rust incidence in slash pine tends to increase faster than that in loblolly pine (Arabatzis et al. 1991). Transition of uninfected slash pine trees to an infected status increased with age, whereas an opposite trend is true for loblolly pine trees. Rust-infected East Texas slash pine trees tend to die at earlier ages than rust-infected East Texas loblolly pine trees, as Sluder (1977) also found in Georgia. The problem of rust in these plantations creates a need to investigate how tree survival will be affected.

For planted loblolly and slash pines in the southern United States, numerous survival functions, which do not consider the effects of fusiform rust, have been developed (Clutter and Jones 1980, Clutter et al. 1984a, Bailey et al. 1985, Lenhart and Clutter 1971, Lenhart 1972, Harms 1982, and Sommers et al. 1980). Specifically, several survival models that utilize fusiform rust level information have been developed. Two different survival equations, one for infected and another for uninfected trees, were determined by Devine and Clutter (1985) for rust-infected slash pine plantations. Clutter et al. (1984b) also used separate equations for the infected and uninfected trees in loblolly pine plantations. Different sets of survival functions were computed by Lenhart and Hackett (1988) for rust-infected loblolly and slash pine plantations in East Texas. Survival functions for infected and uninfected trees that allow for the transition of trees from an uninfected stage to an infected stage were developed by Adams (1989).

In this study, Adams' survival modeling concept was applied to loblolly and slash pine plantations in East Texas

The Survival Model

Shapiro (1946) described a system of differential equations to reflect the changes in two different bacteria populations Not only can each bacteria population size change at different rates, but one bacteria type can mutate to the other bacteria type. A system of differential equations that reflect this scenario, as applied to pine plantations infected with fusiform rust, was defined by Adams (1989) as:

$$dN_i / dA = -\rho_i N_i + \lambda N_u$$
$$dN_u / dA = -(\rho_u + \lambda) N_u. \qquad (1)$$

where

N_i = number of infected trees per acre.
N_u = number of uninfected trees per acre.
A = plantation age (yr).
ρ_i = instantaneous mortality rate for infected trees.
ρ_u = instantaneous mortality rate for uninfected trees.
λ = instantaneous rate of uninfected trees becoming infected.

After a period of time in a pine plantation, the number of infected trees will have decreased due to mortality but will have gained by the number of uninfected trees that became infected during this time. The number of uninfected trees will have decreased due to mortality and to becoming infected.

Adams (1989) determined a solution to the differential equations as the set of simultaneous equations, which is the survival model:

$$N_{u2} = N_{u1} e^{(-b_1(A_2 - A_1))}$$
$$N_{i2} = (N_{i1} - b_2 N_{u1}) e^{(-b_3(A_2 - A_1))} + b_2 N_{u1} e^{(-b_1(A_2 - A_1))} \qquad (2)$$

where

A_1 = initial plantation age (yr).
A_2 = projected plantation age (yr).
N_{u1} = number of uninfected trees per acre at A_1.
N_{u2} = number of uninfected trees per acre at A_2.
N_{i1} = number of infected trees per acre at A_1.
N_{i2} = number of infected trees per acre at A_2.
b_1, b_2, b_3 = regression coefficients.

Properties of the survival model [Equation (2)] are:

1. The uninfected part is a nonincreasing function, because only planted stems are considered.
2. The infected part may increase due to uninfected trees becoming infected.
3. However, the model as a whole is nonincreasing.
4. As plantation age becomes sufficiently large, the surviving number of trees per acre converges to zero.
5. The same survival estimate is found regardless of the number of periods projected, which is path invariance.
6. Mortality is assumed to occur continuously.

Plantation Measurements

Repeated measurements of East Texas Pine Plantation Research Project (ETPPRP) permanent plots between 1982–1992 were analyzed in this survival study. Since the ETPPRP has a measurement cycle of 3 yr, plantation values from either three or four consecutive visits by a field crew, which is equivalent to two or three complete cycles, respectively, were available for analyses. The ETPPRP is a long-term ongoing comprehensive research project started in 1982 by the College of Forestry at Stephen F. Austin State University and supported by East Texas forest industries.[1]

At the current time, there are 170 and 76 plots located in industrial loblolly and slash pine plantations, respectively, throughout East Texas. Each permanent plot is located in a separate plantation. A plot consists of two subplots—one for model development and one for model evaluation. The planted pines within each subplot are tagged and numbered. Genetic structure of the tagged pines is unknown. At each measurement, tree values such as dbh, total height, and crown class are determined. In addition, for plantations ≥ 5 yr old, rust infection status of each tagged pine tree is recorded. Since this survival study considered the rust infection status of the planted pines, only data from plantations 5 yr or older were analyzed. Additional procedural details are described by Lenhart et al. (1994).

Tables 1 and 2 for loblolly and slash pine, respectively, characterize observed plantation structure (age, site index-base age 25 yr and trees per acre with and without rust infections) at each of four measurement cycles by subplot. Oldest plantation age for loblolly is 24 yr, and slash pine is 22 yr. Average site index (base age = 25 yr) is relatively consistent for each species with values generally between 70–75 ft. Average total number of planted loblolly pines per acre is lower than the planted stand densities for slash pine. A larger number of slash than loblolly pine trees were infected with fusiform rust.

From the data, variables considered for a regression procedure to fit nonlinear systems of equations (SAS 1985) were:

1. A_1 = Age in years at beginning of a measurement cycle.
2. A_2 = Age in years at end of a measurement cycle.
3. S = Site index (base age 25 yr) in feet at A_1.

Plus, the variables N_{u1}, N_{u2}, N_{i1} and N_{i2} were incorporated. Total number of observations available for fitting

[1] Support from participating companies—Champion International Corporation, International Paper Company, Louisiana-Pacific Corp. and Temple-Inland Inc.—is appreciated.

Table 1 Observed stand structure characteristics based on loblolly pine East Texas Plantation Research Plots by subplot and measurement cycle.

	By measurement cycle for development subplots				By measurement cycle for evaluation subplots			
Stand structure	1	2	3	4	1	2	3	4
Age (yr)								
Mean	9.2	9.0	10.8	13.9	9.2	9.0	10.8	13.9
Range	5–17	5–19	5–21	8–24	5–17	5–19	5–21	8–24
Site index (ft)								
Mean	69	75	73	75	68	75	73	75
Range	29–100	27–125	37–113	36–111	53–106	27–115	35–110	38–118
Trees/ac								
Uninfected								
Mean	422	416	431	434	429	414	423	420
Range	122–831	74–838	70–978	74–888	148–846	105–788	112–898	122–729
Infected								
Mean	34	48	45	31	33	48	44	31
Range	0–199	0–253	0–223	0–169	0–143	0–255	0–181	0–138
Total								
Mean	456	464	476	465	462	462	467	451
Range	149–848	104–857	87–998	87–906	170–863	153–898	152–935	147–758
Number of plots	77	147	170	115	77	147	170	115

the survival model [Equation (2)] were 324 for loblolly and 138 for slash.

Survival Prediction Equations

Loblolly

The 324 loblolly observations from the model development subplots were used to fit Equation (2) in a simultaneous manner using the SYSLIN procedure in SAS (1985) to produce a survival model as:

$$\begin{aligned} N_{u2} &= N_{u1}e^{(-0.01298(A_2-A_1))} \\ N_{i2} &= (N_{i1} - 0.13072N_{u1})e^{(-0.04839(A_2-A_1))} \\ &\quad + 0.13072N_{u1}e^{(-0.01298(A_2-A_1))} \end{aligned} \tag{3}$$

Analyses of the asymptotic standard errors for the regression coefficients indicated that all three estimates were significantly different from zero ($P \leq 0.01$). For the data set used to develop the survival model, the differences between predicted and observed values were analyzed (Table 3). In addition, the data from the evaluation subplots were utilized to compare the predicted and observed values (Table 3). All mean differences were nonsignificant, plus plottings of differences over plantation age suggested no biases.

Examination of the ETPPRP data indicated that loblolly survival appears to decrease with increasing site index Following procedures described by Adams (1989), the 324 observations from the loblolly model development subplots were re-analyzed after including site index. The survival model to predict surviving trees per acre at different levels of productivity is:

Table 2. Observed stand structure characteristics based on slash pine East Texas Plantation Research Plots by subplot and measurement cycle.

	By measurement cycle for development subplots				By measurement cycle for evaluation subplots			
Stand structure	1	2	3	4	1	2	3	4
Age (yr)								
Mean	8.6	8.7	11.0	14.0	8.6	8.7	11.0	14.0
Range	5–16	5–18	6–21	9–22	5–16	5–18	6–21	9–22
Site index (ft)								
Mean	67	69	69	72	66	69	70	72
Range	27– 99	14–101	20–91	45–82	27–91	27–98	32–87	48–88
Trees/ac								
Uninfected								
Mean	204	237	243	227	229	253	260	239
Range	44–842	12–684	17–663	26–600	43–764	30–631	35–655	70–557
Infected								
Mean	152	176	141	108	146	169	138	109
Range	27–326	4–340	7–314	26–295	7–329	0–421	5–289	30–275
Total								
Mean	356	413	384	335	375	422	398	348
Range	134–1002	117–988	113–924	90–895	161–1032	116–1002	91–910	139–832
Number of plots	40	73	76	34	40	73	76	34

Table 3 Summary of residual analyses for the four survival models based on data from the East Texas Pine Plantation Research Project.

Species/Site index/Infection status	Survival model	Overall mean (pred-obs) differences[a] by subplot: Model development	Model evaluation
		(trees/ac)	
Loblolly			
Without site index	(3)		
Uninfected trees		-0.35	0.22
Infected trees		-0.40	-0.72
With site index	(4)		
Uninfected trees		0.86	1.51
Infected trees		-0.82	-1.15
Slash			
Without site index	(5)		
Uninfected trees		-0.98	-1.20
Infected trees		2.14	1.40
With site index	(6)		
Uninfected trees		0.76	0.64
Infected trees		1.35	0.86

a All mean differences were not significantly different from zero ($P \leq 0.01$)

$$N_{u2} = N_{u1} e^{(-0.00016137(S)(A_2 - A_1))}$$
$$N_{i2} = (N_{i1} - 0.12177 N_{u1}) e^{(-0.00059553(S)(A_2 - A_1))} + 0.12177 N_{u1} e^{(-0.00016137(S)(A_2 - A_1))} \quad (4)$$

Assessment of the asymptotic standard errors for regression coefficients indicated that all three estimates were significantly different from zero ($P \leq 0.01$). Both the development and evaluation data sets were utilized to compare the differences between predicted and observed surviving number of trees per acre (Table 3). No unfavorable trends were seen.

Slash

Consideration of the 138 observations from the slash pine model development subplots with the SYSLIN procedure resulted in a survival model as:

$$N_{u2} = N_{u1} e^{(-0.03465(A_2 - A_1))}$$
$$N_{i2} = (N_{i1} - 0.89135 N_{u1}) e^{(-0.07625(A_2 - A_1))} + 0.89135 N_{u1} e^{(-0.03465(A_2 - A_1))} \quad (5)$$

The asymptotic standard errors for regression coefficients indicated that all three estimates were significantly different from zero ($P \leq 0.01$). Residual analyses indicated no adverse results (Table 3). Residual plottings over plantation age showed no apparent bias.

The 138 observations from the slash pine model development subplots were re-analyzed with the parameters as a function of site index. A survival model to predict surviving trees per acre with site index as one of the predictors is:

$$N_{u2} = N_{u1} e^{-0.00045821(S)(A_2 - A_1)}$$
$$N_{i2} = (N_{i1} - 0.84777 N_{u1}) e^{(-0.0010643(S)(A_2 - A_1)} + 0.84777 N_{u1} e^{-0.00045821(S)(A_2 - A_1)} \quad (6)$$

All regression coefficients were significantly different from zero ($P \leq 0.01$). Overall mean differences are depicted in Table 3. Plottings of differences inferred no detrimental trends.

Illustrations and Applications

For each of three following examples, the data ranges match the observed data ranges with one exception. In the examples, age varies from 5 to 30 yr, and 30 yr exceeds the observed maximum value by 6 and 8 yr for loblolly and slash pine, respectively. Since a rotation age of 30 yr is reasonable for East Texas, an extrapolation to that point was not considered too extreme and should provide an useful indication of trees per acre at that point in time.

Selecting a Species to Plant

On a site in East Texas, assume a forester has the option to plant either loblolly or slash pine trees. For either species, he presupposes that 5 yr after planting there will be 500 trees surviving. Of those 500 trees, 40% are expected to have a fusiform rust stem gall, and 60% are expected to be clear of stem galls. What are the predicted future number of infected, uninfected, and total number of trees per acre between ages 5 and 30? The answer may provide assistance on deciding which species to plant.

The predicted number of trees between 5 and 30 yr were calculated using survival models (3) and (5) for loblolly and slash pine, respectively, and are depicted in Figure 1. Fifteen years later at age 20, about 357 of the loblolly pines and 316 of the slash pines are expected to be surviving. Of the 357 loblolly pine trees, about 69% are expected to be clear of galls, and about 31% are expected to have stem galls. Of the 316 slash pine trees, about 57% are expected to be clear of galls, and about 43% are expected to have stem galls. By age 30, only 293 loblolly pines and 229 slash pines are expected to be surviving. Of these surviving trees, about 74% of the loblolly pines and 55% of the slash pines are expected to be clear of stem fusiform rust galls.

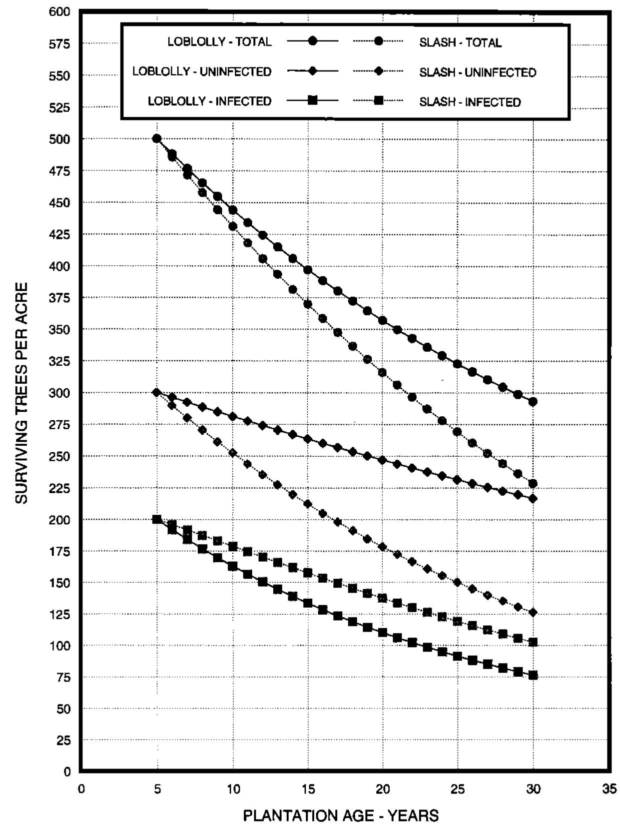

Figure 1. Comparison of predicted number of surviving trees per acre in an example East Texas loblolly and slash pine plantation with identical stand characteristics by fusiform rust stem gall infection status.

It appears that from a survival basis, the forester probably should plant loblolly pine trees on the site rather than slash pine.

Survival Percentages by Infection Status

For the same site and situation presented above, Figure 2 presents the survival percentage trends of uninfected and infected trees by species in more detail. Within this range of plantation ages, the percentages of uninfected and infected loblolly pine trees are diverging. In contrast, the percentages of uninfected and infected slash pine trees are converging.

Role of Site Productivity

An illustration of the influence of site productivity on survival is presented for the two species (Figure 3). In Figure 3, there are 12 survival prediction curves in 4 groups of 3 lines. One set of two groups represents loblolly, while the other set represents slash. Within a set, one group portrays uninfected trees, and the other group portrays infected trees. For each group, three representative site index classes are utilized.

Based on the observations used to develop Tables 1 and 2, the average total number of trees per acre at age 5 are expected to be about 446 and 372 for loblolly and slash, respectively. Of the 446 loblolly pines, about 40 are infected, and the other trees are clear. Of the 372 slash pines, about 144 are infected, while the rest are disease-free. These four points

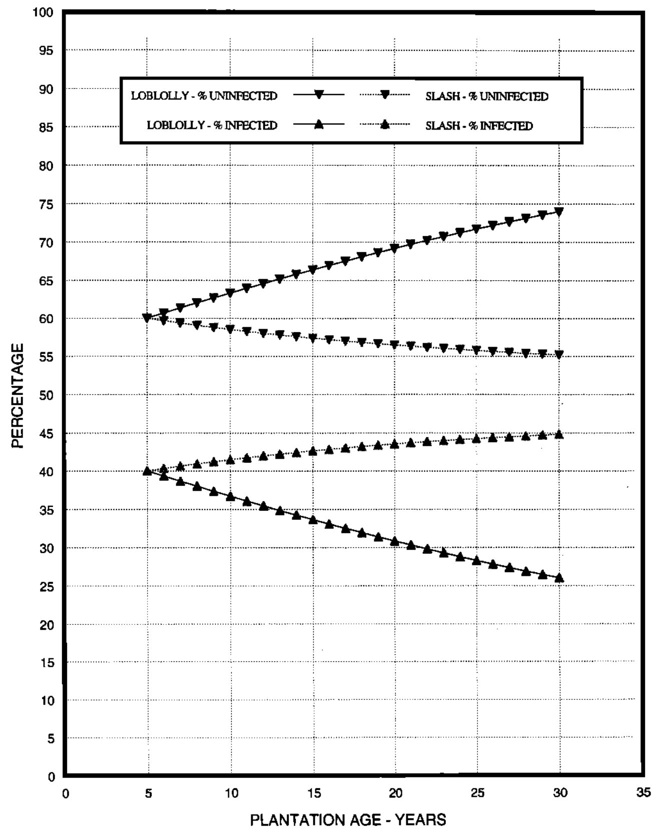

Figure 2. Comparison of predicted percentage of surviving uninfected and infected planted loblolly and slash pine trees in East Texas in an example plantation with identical stand characteristics.

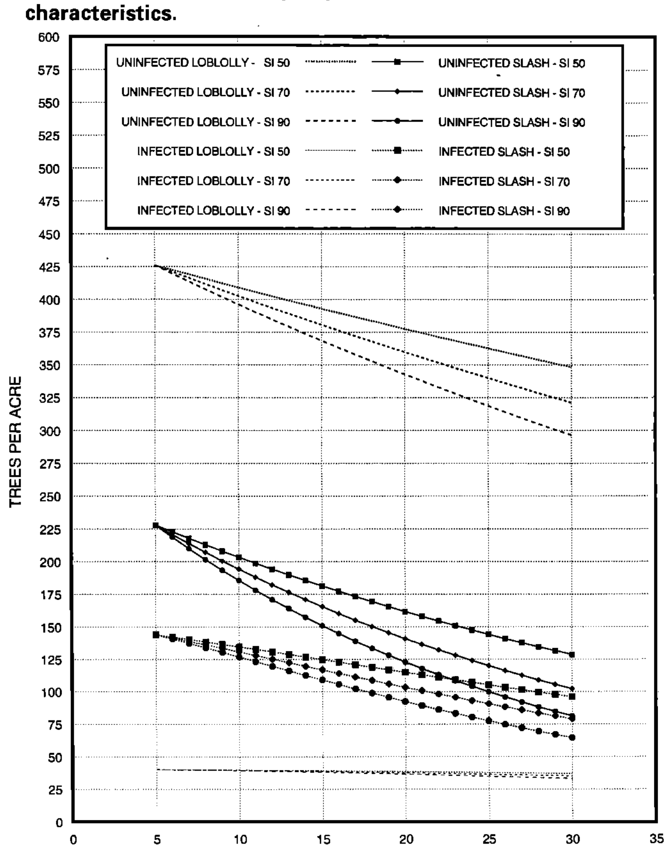

Figure 3. Comparison of predicted surviving uninfected and infected planted loblolly and slash pine trees in East Texas, while considering three different site index values.

in Figure 3 are the beginning values to compare the differences in expected survival trends as influenced by site index during a 25 yr period. Survival models (4) and (6) were utilized for loblolly and slash, respectively, for estimating future number of trees per acre.

For each of the four groups (Figure 3), it appears that the survival trends on the more productive sites are lower than the survival trends for less productive sites. At age 25, for the uninfected component of loblolly pine plantations, an increase of 40 ft in site productivity results in a reduction of about 44 trees/ac. For the infected portion of a loblolly pine plantation on site index 90 land, about 4 fewer trees are expected to survive at 25 yr than in a plantation on site index 50 land. In a similar manner, reduced survival with increasing site productivity is also expected with slash pine plantations in East Texas with the differences expected to be 48 trees less for uninfected slash pine trees and a 32 tree reduction for infected slash pines.

Conclusions

In this study, a model that reflects the survival patterns of rust-infected loblolly and slash pine plantations in East Texas was constructed. A specific advantage of the model is that it allows for an uninfected tree to either remain disease-free, become infected, or die. In contrast, an infected tree can either remain infected or die. Predicting variables are age and number of uninfected and infected trees at the beginning of a designated projection period plus age at end of the period. Site index value is also an useful predictor.

Between the two species, predicted loblolly pine survival trends were greater than slash pine. A loblolly pine is less likely to die than a slash pine tree. On a percentage basis relative to total number of trees per acre, it appears that over time, the number of uninfected loblolly pines is expected to increase, while number of infected trees decreases. In contrast, the number of uninfected and infected slash pine trees tends to approach an equal value. Survival trends in East Texas pine plantations do appear to be influenced by site productivity. With the inclusion of site index as a predictor, the model indicates that survival decreases with increasing productivity, and the pattern was similar for both species.

It is anticipated that these survival curves may be useful for plantation management decision-making such as:

- Deciding which species to plant in East Texas—loblolly or slash.
- Providing reliable estimates of future trees per acre for determining future yields.
- Selecting an optimum rotation age.
- Merchandising the planted pines by product.

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