PLANTATION MANAGEMENT
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SURVIVAL PREDICTIONS FOR FUSIFORM INFECTED LOBLOLLY PINE PLANTATIONS ON PREPARED SITES IN THE COASTAL PLAIN OF SOUTH CAROLINA, GEORGIA, AND NORTHERN FLORIDA

by

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PREFACE

This research was initiated by the late Dr. Jerome L. Clutter who was working on the statistical analysis of these data at the time of his death on November 22, 1983. The authors have attempted to complete the analysis. The basic form of the models was conceived by Jerry. We have fit the models to the data and validated the models with an independent data set. While most of the ideas were Jerry's, we accept responsibility for errors of omission or commission.

INTRODUCTION

Forest owners in the southeastern United States annually suffer significant timber losses due to fusiform rust (*Cronartium fusiforme* Hedge and Hunt excumm.) infections. Powers et al. (1975) estimated this loss to approach 100 million cubic feet in slash (*Pinus elliottii* Engelm.) and loblolly pine (*Pinus taeda* L.) in 1970. Lloyd (1982) estimates the yield loss for loblolly plantations on site index 70, base 25, to be 265 cubic feet per acre between ages 10 and 20 years. Lloyd further indicates that each increase of 10% in fusiform infected trees at age 3 will reduce growth from age 10 to 20 by 82 cubic feet per acre. When compared to a disease free plantation, a 30% infection at age 3 could reduce growth by 242 cubic feet per acre during this ten-year period. Losses of this magnitude will substantially reduce the economic return of slash and loblolly plantations. Powers et al. (1975) estimate that fusiform infections can reduce profitability by one-third in pulpwood rotations.

It is generally recognized (Jones, 1972) that the major component of this loss is mortality induced by the disease. Mortality can be caused directly by the pathogen or indirectly by wind breakage, insect damage or other factors resulting from the reduced vigor of the fusiform infected trees. While Powers (1975) has shown that slash is more susceptible than loblolly to this disease, loblolly pines do suffer extensive damage. Czabator (1971) concluded that direct control of fusiform infection in plantations is impossible with current technology.

Sound management decisions are based on accurate projections of product flows, and the product yield is a function of the number of surviving stems at any point in time. Thus, there is a clear need for the ability to predict survival with an acceptable degree of precision.

The objective of this study is to develop an equation which predicts the number of surviving stems per acre in loblolly plantations infected with fusiform rust. The model should have separate mortality equations for infected and uninfected stems so that managers of fusiform infected stands can more accurately evaluate alternative management regimes.

A review of relevant publications by Clutter and Devine (1982) includes most of the published work on the mortality of infected and uninfected southern pine stands. They concluded that the surviving number of infected slash pine trees per acre is a function of (1) the number of trees per acre with fusiform rust at some initial age, and (2) the projection interval or time period between the initial age and the prediction age. They also developed an equation to predict the surviving number of infected slash pine stems in Lower Coastal Plain plantations:

$$N = N_o e^{\{-0.01206061(A-A_o) - 0.02794954(A-A_o) - 0.34938068(Ln(A) - Ln(A_o))\}}$$

where N = the surviving number of trees per acre at age A that had a stem infection at age A_o,

N_o = the number of trees per acre that had a stem infection at age A_o,

A = projection age, and

A_o = initial age.

The surviving number of uninfected stems is given by the previous equation with the last two terms of the exponent deleted or

$$N = N_o \, e^{-0.01206061(A - A_o)}$$

where

N = the surviving number of trees per acre at age A that did not have a stem infection at age A_o,

N_o = the number of uninfected trees per acre at age A,

A = projection age, and

A_o = initial age.

These models are independent of site index, and the equation for the number of surviving uninfected stems resembles a continuous discounting function. The additional terms for the fusiform rust infected stems serve to decrease the survival rate.

DATA COLLECTION AND SUMMARY

During the summer of 1976, 206 permanent plots were established in South Carolina, Georgia and northern Florida. Of these plots, 39 were located in loblolly pine plantations. The geographic locations of these plots are shown in Figure 1. All plots were located on lands owned by PMRC[1] members at the time of the study. They were rectangular in shape and designed to contain five original planting spaces in each of five rows. At the time of plot establishment, all trees in every plot were tagged for permanent identification. On each plot, every tree

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[1]The Plantation Management Research Cooperative was composed of the following firms: Continental Forest Industries, Union Camp, Brunswick Pulp Land Co., Owens-Illinois, Container Corporation of America, St. Regis Paper Co., ITT Rayonier Inc., Gilman Paper Co., and St. Joe Paper Co. at the time of the study.

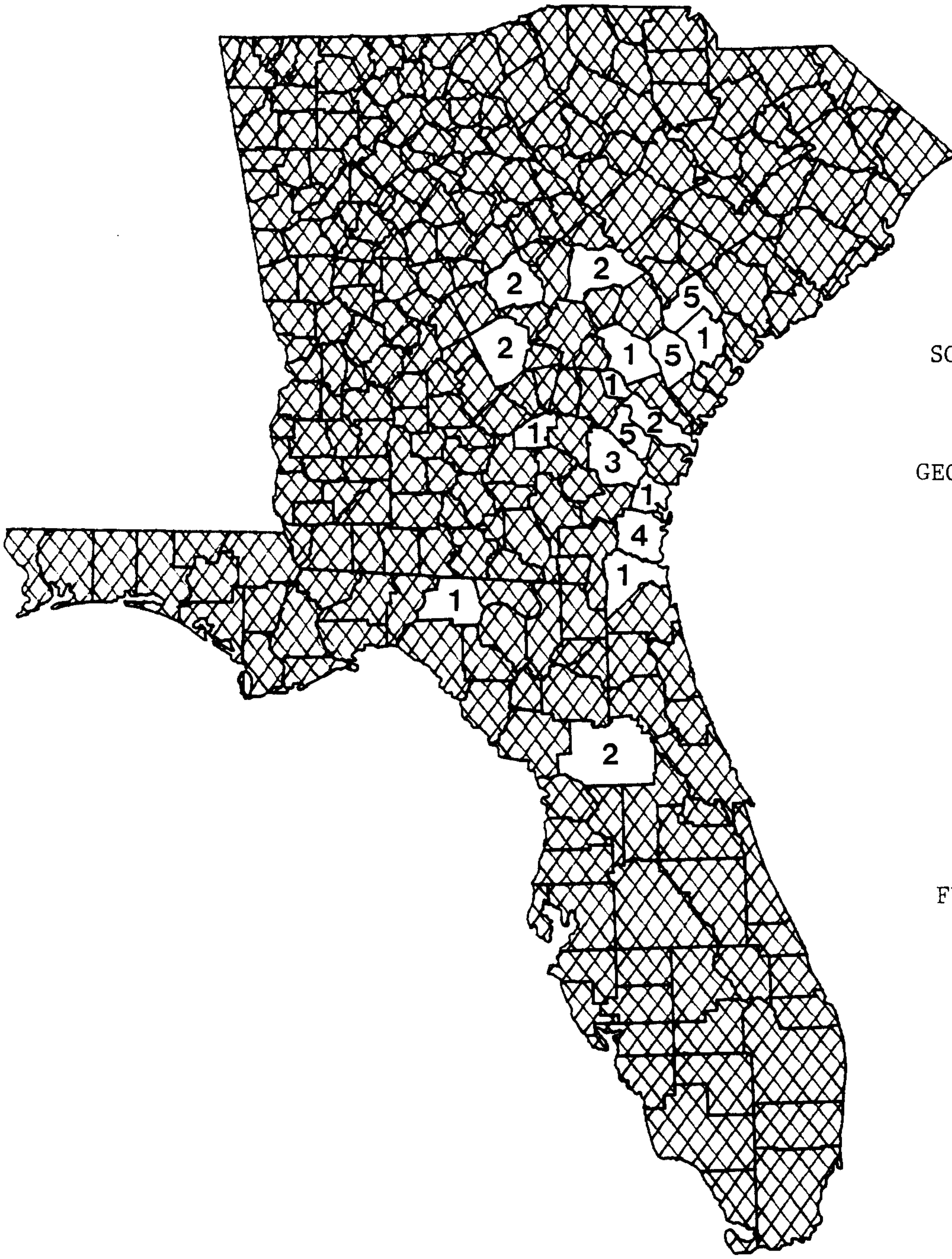

Figure 1. Location of sample plots.

was measured for dbh and the presence or absence of fusiform rust on the stem. Branch cankers were considered to constitute a stem canker if they occurred within one foot of the main stem. Total height and crown class were recorded on five infected and five uninfected trees across the range of dbh classes. Following a soil profile examination, each plot was assigned a Soil Conservation Service (SCS) drainage classification. The SCS drainage classification for the loblolly cronartium plots is shown in Table 1.

Table 1. Distribution of Sample Plots by Drainage Class

Drainage Class	SWE	WD	MWD	SWP	PD	VPD
Number of Plots	3	3	5	6	19	3

where SWE = somewhat excessively drained

MWD = moderately well drained

WD = well drained

SWP = somewhat poorly drained

PD = poorly drained

VPD = very poorly drained

All plots were first measured during the summer of 1976. Subsequent measurements were made during the summers of 1979 and 1982. The same tree measurements were made after each of the three-year growth periods. The number of trees that died during each of the two growth periods was recorded.

The total number of stems per acre in each of the three measurement periods was calculated. Trees were classified as infected or uninfected according to the presence or absence of stem infection in 1976. The number of infected stems in 1979 was calculated as the number of infected stems in 1976 less the number of infected trees which died during the 1976-1979 growth period. The number of infected stems in 1982 was calculated as the number of infected trees in 1979 less the number of infected trees which died during the three year growth period ending in 1982. Distribution of total stems per acre, infected stems per acre and uninfected stems per acre in 1976 are shown in Tables 2 through 4.

The planting date for each plot was obtained from the respective land owners. Fractional ages were calculated for each of the three measurement years as the number of days from the first of January divided by 365. Ages of the sample plots are shown in Table 5.

Site index values were estimated for each plot (Table 6) using the average height of dominant and codominant trees for the measurement period when the age of the plantation was nearest 25 years. Site index was calculated using the site index equation developed by Clutter, Harms, Brister and Rheney (1984):

$$Ln(S) = -0.81238 + (1.20676\ Ln(H_d) + 44.91596/A - .81630)\ e^{-4.69839/A}$$

where

H_d = average height of dominant and codominant trees, and

A = age of the trees in the measurement period when the stems are nearest 25 years.

$Ln(S)$ = natural log of site index (base age 25).

Table 2. Distribution of the Sample Plots by Total Stems Per Acre in 1976.

Total Stems Per Acre in 1976	200-400	400-500	500-600	600-700	700-800	800+
Number of Plots	2	5	10	10	5	7

Table 3. Distribution of Sample Plots by Infected Stems Per Acre in 1976.

Infected Stems Per Acre in 1976	100-200	200-300	300-400	400-500	500+
Number of Plots	13	9	9	6	2

Table 4. Distribution of Sample Plots by Uninfected Stems Per Acre in 1976.

Uninfected Stems Per Acre in 1976	0-200	200-300	300-400	400-500	500+
Number of Plots	7	7	14	6	5

Table 5. Distribution of Sample Plots by Age Class in 1976

Age in 1976	4-5	6-7	8-9	10-11	12-13	14-15	16-17	18-19	20-21
No. of Plots	3	3	12	6	4	4	5	0	2

Table 6. Distribution of Sample Plots by Site Index Class

Site Index	40-50	51-60	61-70	71-80	81-90
No. of Plots	1	3	16	8	8

MODEL DEVELOPMENT

The basic assumption inherent in the development of the model is that a loblolly pine plantation is comprised of two components: infected trees and uninfected trees, which have different rates of mortality. The models developed are path invariant which implies that the predicted number of stems is independent of the number of steps used to reach the projected value. For example, if the number of stems per acre at age 10 is known, predicting the number of survivors from age 10 to 25 in one step gives the same value as predicting the number of survivors in three steps: from 10 to 15, then from 15 to 20 and finally from 20 to 25. The models also have the property known as convergence which ensures that as the length of the projection interval approaches zero, the number of predicted stems approaches the number of stems at the initial age.

Survival Model for the Infected Trees

The expected instantaneous rate of change in surviving trees per acre is obtained as the product of an instantaneous mortality rate at a given age and the number of trees present at a given age. In equation form this can be represented as:

$$\frac{dN}{dA} = \frac{\beta}{A}(N) \tag{1}$$

where $\frac{dN}{dA}$ = the expected instantaneous rate of change in the number of trees,

N = the number of trees present,

A = the age of the trees present,

$\frac{\beta}{A}$ = the instantaneous mortality rate at age A, and

$\beta \leq 0$ is a parameter to be estimated from the data.

This equation implies that mortality rate is directly related to the number of stems present and inversely related to age.

The survival function is found by solving the differential equation (1). The solution can be written as

$$N = N_o \left(\frac{A}{A_o}\right)^{\beta} \tag{2}$$

where

N_o = the number of infected trees per acre present at age A_o,

A = age at the end of the projection period,

A_o = age at beginning of the projection period,

N = number of infected trees per acre present at age A.

It can be shown that this equation has the two desirable properties of path invariance and convergence.

Non-linear regression techniques were used to estimate β in equation (2). As seen in Table 7, the model fits quite well. The standard error is 31 trees per acre, and 91 percent of the variation about the mean number of surviving infected trees is explained by the model.

Table 7. Analysis of Variance for Equation 2.

Source	DF	Sum of Squares	Mean Square	R^2
Regression	1	4,583,534.1		.91
Residual	73	69,870.2	957.125	
Uncorrected Total	74	4,653,404.3		
Corrected Total	73	798,316.5		

The parameter estimate for β is -.506749. The predicted number of surviving infected stems is therefore

$$\hat{N} = N_o \left(\frac{A}{A_o}\right)^{-.506749} \qquad (3)$$

where

$\hat{N}$ = the predicted number of surviving infected stems at age A and the other variables are as defined above.

The instantaneous mortality rate for the infected stems is estimated by $N^{-1} dN/dA = \beta/A$. As seen in Table 8, the instantaneous mortality rate for the infected loblolly stems decreases from 10% at age 5 to 2.5% at age 20.

Table 8. Instantaneous Mortality Rates for Infected Loblolly Stems

Age	Instantaneous Mortality Rate
5	.10135
10	.05068
15	.03378
20	.02534
25	.02027
30	.01689

Survival Model for the Uninfected Stems

The established trees which are uninfected are likely to experience lower mortality prior to the onset of competition than their infected counterparts. After the onset of competition, mortality of the uninfected stems usually increases.

The basic survival model used for the uninfected stems was developed by Clutter and Bailey (1984) and is of the following form:

$$N = N_o \left(\frac{A}{A_o}\right)^{\beta_1} e^{\beta_2 (S)(A - A_o)} \qquad (4)$$

where

N = the number of surviving uninfected stems at age A,

N_o = the number of uninfected stems at age A_o,

A = the age of the stand at the end of the projection period,

A_o = the age of the stand at the beginning of the projection period,

S = site index (base 25) for the stand, and

β_1 and β_2 are parameters to be estimated.

This model has the "convergence property" and is "path invariant". As seen in Table 9, the model shown in equation (4) fits the data well.

Table 9. Analysis of Variance for Equation 4.

Source	d.f.	Sum of Squares	Mean Square	R^2
Regression	2	9,472,368	4,736,184	.98
Residual	70	37,971	542	
Uncorrected Total	72	9,510,339		
Corrected Total	71	1,697,406		

The coefficient of determination, R^2, indicates that 98 percent of the variation in the projected number of surviving uninfected stems is attributed to the model. The standard error is 23 trees per acre. Residuals were plotted against N_o, A, A_o, and S. No discernable trends were detected. The survival function for the uninfected trees is:

$$\hat{N} = N_o \left(\frac{A}{A_o}\right)^{.191538} e^{-.00055856(S)(A - A_o)} \tag{5}$$

Inclusion of the site index significantly improved the predictive power of the model for uninfected loblolly stems, but did not improve the fit of the model for the infected stems. Clutter and Devine (1982) did not find site index to be significant for either the infected or uninfected slash pine trees; however, Clutter, Harms, et al. (1984) found site index to be significant for loblolly pine.

The model for the uninfected loblolly pine stems conforms with the previously stated logic concerning the relationship between mortality and age. As shown in Table 10, the mortality rate is very low at early ages. This indicates that for the uninfected trees there is little mortality prior to the onset of competition. The rate of mortality is also higher on the better sites. This implies that stands experiencing fast growth also experience competition mortality at an early age. By contrast, the model used for slash pine by Clutter and Devine (1982) indicates that the mortality rate for uninfected trees is constant at around 1.2% across sites and ages.

Table 10. Instantaneous Mortality Rates for Uninfected Loblolly Stems

	Instantaneous Mortality Rate			
	Site Index			
Age	50	60	70	80
10	.00878	.01435	.01995	.02553
15	.01516	.02073	.02633	.03191
20	.01835	.02393	.02952	.03511
25	.02027	.02584	.03144	.03702
30	.02154	.02718	.03271	.03830

The model shown in Equation (5) will result in negative instantaneous mortality rates (number of trees increasing over time) for very young plantations on low sites, and should therefore not be used to predict survival in plantations when the initial age is less than seven years.

Use of the Model

The predicted number of surviving trees for a plantation which contains rust infections can be calculated using Equations (3) and (5). Suppose 700 trees per acre survive at age 10. The stand has site index 70 and 20% of the stand, or 140 trees, are infected; 560 are uninfected. The number of infected stems (N_i) surviving at age 20 is estimated as

$$N_i = 140\left(\frac{20}{10}\right)^{-.506749} = 99.$$

The number of uninfected stems (N_u) surviving is estimated as

$$N_u = 560\left(\frac{20}{10}\right)^{.191538} e^{-.00055856(70)(20-10)} = 433$$

The total number of surviving stems ($N_i + N_u$) is projected to be 532. As seen in Table 11, if the stand had 50% fusiform rust infection at age 10, the estimated number of stems surviving at age 20 would be 516. The model developed by Clutter and Jones (1980), and reported in Clutter, Harms, et al. (1984) which does not include percent cronartium, projects 525 surviving trees. This indicates that the Clutter-Harms model gives results similar to ours on stands with cronartium infection in the range of 20 to 50 percent.

Figure 2 compares, in graphic form, the survival trends produced by the model developed in this paper and the Clutter-Harms model. For low and medium stocking, i.e. 400 and 600 stems per acre at age 7, the models developed in this paper predict lower total survival than the Clutter-Harms model for all ages up to 25. With low density, high site index and a 50 percent infection rate, the difference is substantial, around 70 trees at age 25. For medium stocking, i.e. 600 trees per acre, the difference decreases over time, but our model consistently estimates greater mortality. With high stocking, 800 trees per acre at age 7, the Clutter-Harms model predicts slightly lower mortality at age 25. Without exception the model developed in this paper predicts lower survival between ages seven and seventeen. This conforms to expectations as an infected stand is likely to have higher mortality at ages less than 10 years.

Equations (3) and (5) are based on data from plots less than 28 years of age. As reported in Table 5, only two plots were over 17 years old in 1976. Consequently, the user is cautioned that projection of surviving trees beyond age 28 is extrapolation.

VALIDATION OF THE MODEL

The model was tested for validity by comparing the observed and predicted survival rates for an independent data set consisting of 109 remeasured loblolly plots located in the coastal plain of South and North Carolina. These plots had an average site index of 61.9 feet with a standard deviation of 9.25 feet. The average age of the stands was 15.7 years in 1977 and the interval between measurements was 4 years. At the time of the first measurement, the average percent rust infection was 15.5 percent. The average density in 1977 was 613 trees per acre and the average number surviving was 512 trees. Thus, on an average, 101 trees died during the period.

The mean residual, i.e. observed minus predicted number of stems, was -11.2 or an average error of 11.1%. The standard deviation was 87 trees. The correlation between the observed and predicted number of trees was .83 (Table 12).

The data set used to validate the model contained 68 plots with less than 20% infected stems. The plots used to develop the model had infection rates of at least 20%. As seen in Table 13, the correlation between the observed and predicted number of surviving trees was indentical for the two infection groups. However, the mean residual of total trees was less for the group with greater than 20% infection. The correlation coefficient was higher for the uninfected group in both cases.

CONCLUSION

We have developed models that predict survival for fusiform rust infected site prepared loblolly pine plantations in the Lower Coastal Plain and have validated them with an independent data set. Analysis of residuals showed no correlation with age, site index and initial density. Predicted survival is consistent with our expectations. The models have the desirable properties of path invariance and convergence.

Previously published survival equations for loblolly pine in the Lower Coastal Plain ignore the impact of fusiform rust. Consider two loblolly pine plantations identical in all respects except one stand has 10% fusiform rust infection and the other stand has 40% infection. Surely the survival patterns would be expected to be different. Our model recognizes this and should be useful to forest resource managers who must make decisions concerning loblolly pine stands which are heavily infected with fusiform rust. If subsequent research reveals that the diameter distributions of infected and uninfected trees in a plantation differ significantly, such a survival model will be essential for predicting total yield and yield from the infected and uninfected components.

Table 11. Predicted Survival for Loblolly Pine Stands Using Equations 3 and 5 for Site Index 70.

	Percent Rust at Age 10						
	20			50			
	Stems Per Acre						
Age	Infected	Uninfected	Total	Infected	Uninfected	Total	PMRC*
10	140	560	700	350	350	700	700
11	133	548	681	333	343	676	691
12	128	536	664	319	335	654	679
13	123	524	647	306	327	633	665
14	118	511	629	295	319	614	650
15	114	498	612	285	311	596	632
16	110	485	595	276	303	579	613
17	107	471	578	267	295	562	592
18	104	458	562	260	286	546	571
19	101	445	546	253	278	531	548
20	99	433	532	246	270	516	525
21	96	420	516	240	262	502	503
22	94	407	501	235	255	490	480
23	92	395	487	229	247	476	458
24	90	383	473	225	239	464	436
25	88	371	459	220	232	452	415

*Survival model developed by Clutter, Harms, et al. (1984).

Table 12. Analysis of Residuals and Correlation Between Observed and Predicted Survival for an Independent Test (109 plots).

	Mean	Standard Deviation	Correlation*
Uninfected Stems	-18.5	82.8	.83
Infected Stems	7.3	45.1	.70
Total Stems	-11.2	87.4	.82

* The simple correlation between the observed and predicted number of surviving stems.

Table 13. Analysis of Residuals and Correlation Between Observed and Predicted Survival by Infection Group for an Independent Test.

≤ 20% Infection (68 plots)

	Mean	Standard Deviation	Correlation
Uninfected Stems	-42.7	77.9	.82
Infected Stems	19.3	35.2	.49
Total Stems	-23.3	79.7	.83

> 20% Infection (41 plots)

	Mean	Standard Deviation	Correlation
Uninfected Stems	21.4	75.8	.87
Infected Stems	-12.7	52.5	.48
Total Stems	8.7	96.5	.83

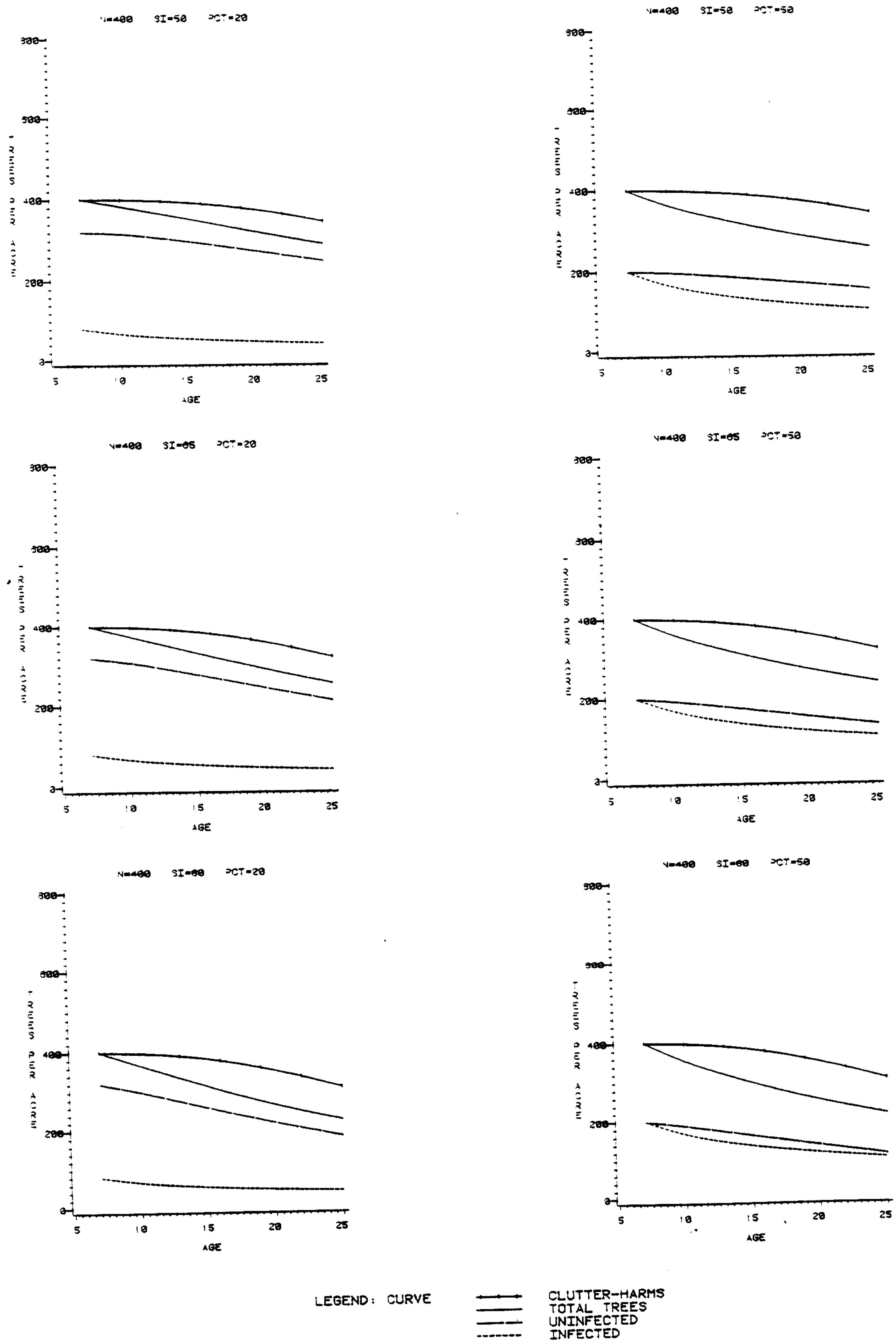

Figure 2. Survival trends for various combinations of site index (SI) and number of trees per acre at age 7 (N) assuming cronartium infection levels (PCT) of 20% and 50%.

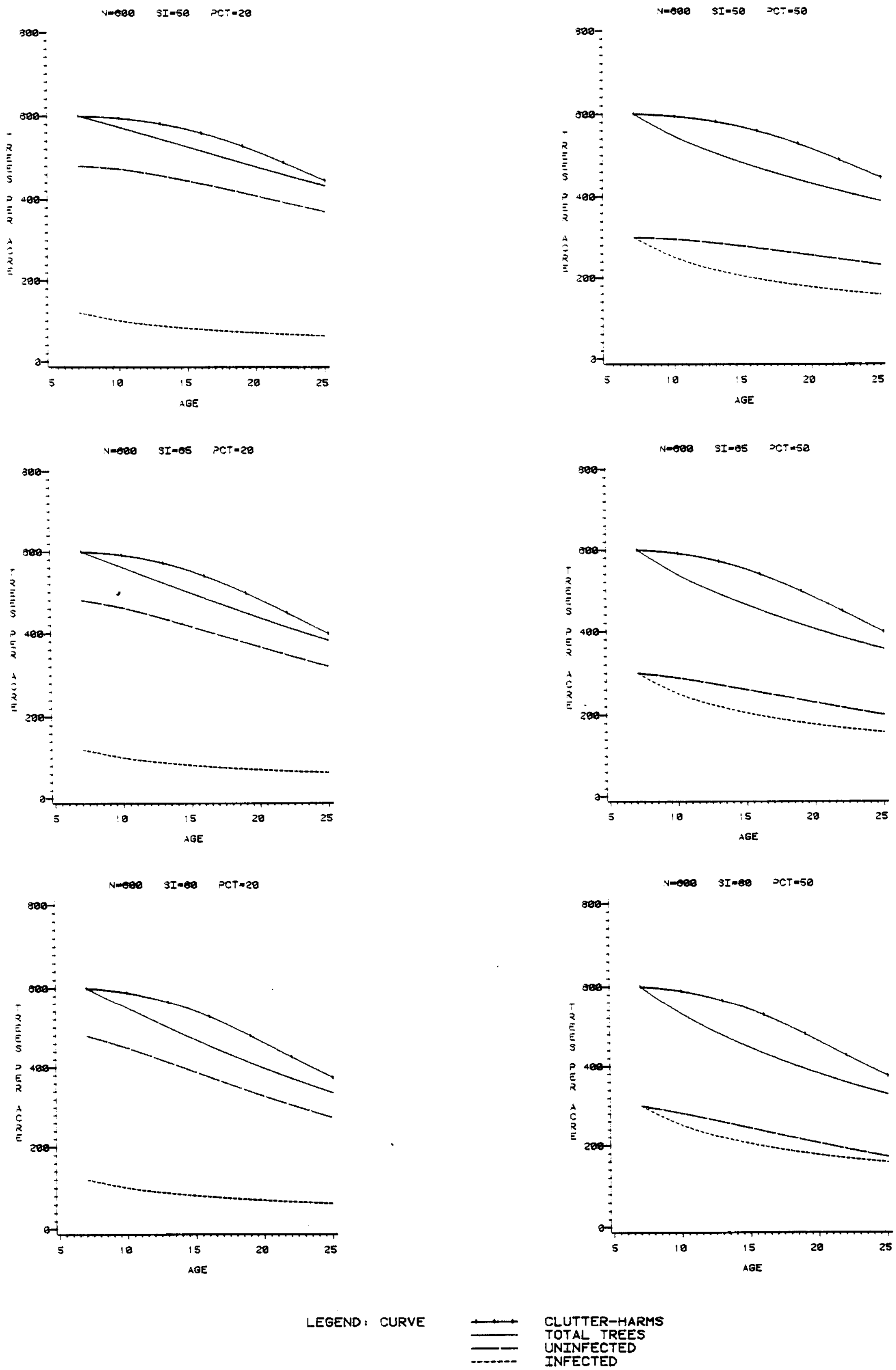

Figure 2. (Continued)

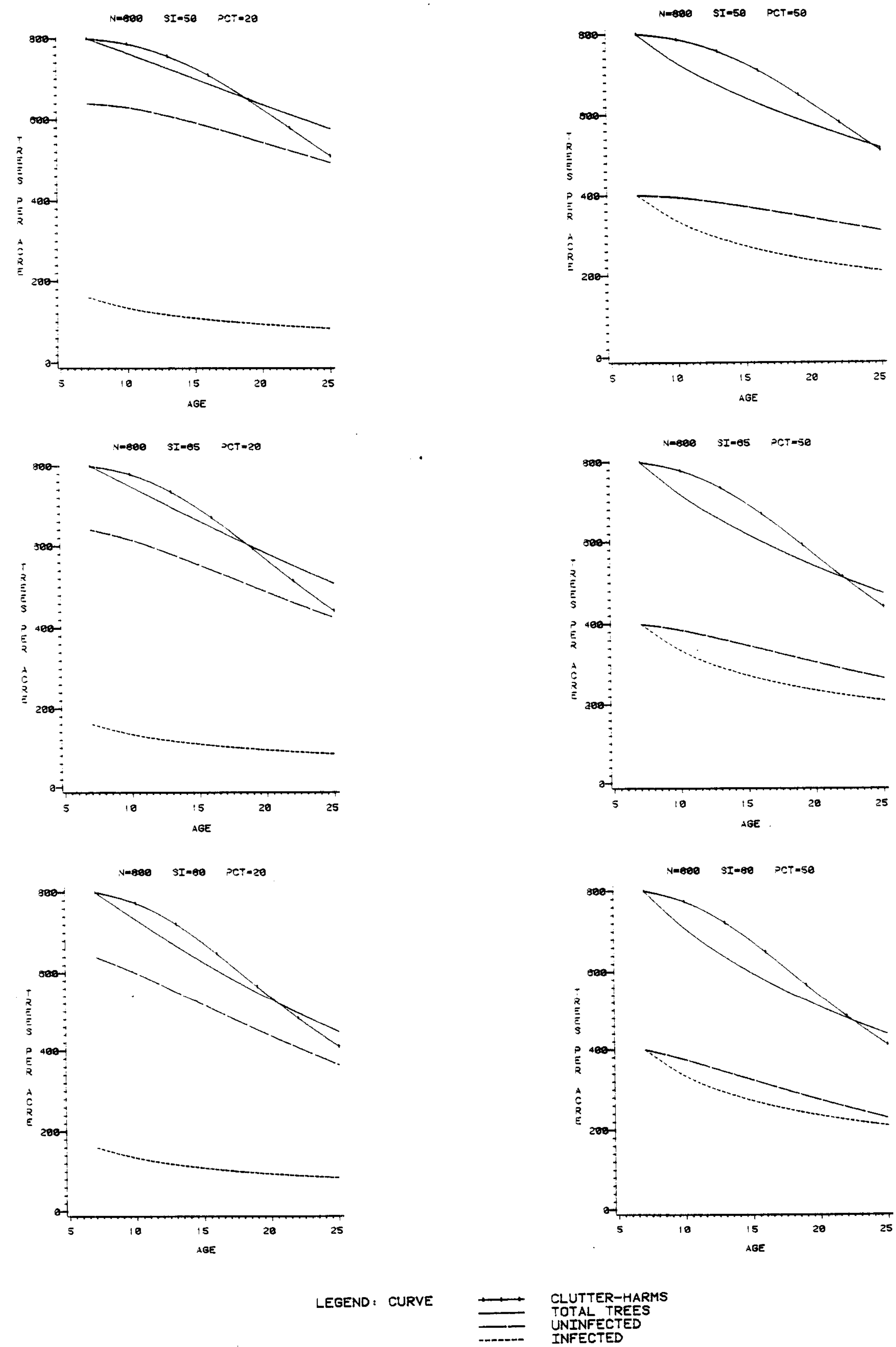

Figure 2. (Continued)

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