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Whole Stand Survival Prediction Model in Slash Pine Plantations Infected with Fusiform Rust[1]

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銹病에 感染된 슬래쉬소나무 造林地에 대한 林分單位의 生存 豫測模型[1]

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ABSTRACT

Repeated measurement of 472 permanent subplots in slash pine (*Pinus elliottii* Engelm.) plantations were used to develop survival prediction equations for predicting future number of planted slash pine trees.

On the average, about 40 percent of the slash pines in the experimental sites had a stem cankers due to fusiform rust (*Cronartium quercuum* [Berk.] Miyabe ex Shirai f. sp. *fusiforme*) incidence. A stand level survival prediction model was developed that incorporated the incidence of fusiform rust and allowed the transition paths of trees from an uninfected stage to an infected stage. Predicted total surviving number of trees is obtained by adding together the predicted number of infected and uninfected trees.

The influence of natural hardwood density and site quality on slash pine survivals tended to show a negative effects on future survivals.

Key words : Pinus elliottii, *whole stand survival prediction model, fusiform rust disease*

要 約

美國 南部 地方의 경우, 슬래쉬소나무 (*Pinus elliottii* Engelm.) 造林地에서는 銹病 (*Cronartium quercuum* [Berk.] Miyabe ex Shirai f. sp. *fusiforme*)의 感染으로 인해 山林 所有者들에게 심각한 피해를 야기시키고 있다. 長期的으로 每年 測定된 永久實驗 plots의 資料에 의하면 平均 약 40% 정도의 슬래쉬소나무 造林地가 銹病에 感染되어 줄기 부분에 혹 (canker)이 생성되어 결국 枯死하거나 2차적 피해를 야기시키고 있다.

따라서 本 研究에서는 銹病에 感染된 슬래쉬소나무 林分에 대한 生存 豫測模型을 開發하였으며, 이 模型은 銹病의 發生率을 模型에 포함하였으며, 銹病에 感染되지 않은 段階의 林木들이 感染되는 段階로의 轉移 과정에서 발생하는 生存 本數의 변화를 파악할 수 있게 하는 特徵을 가지고 있다. 그리고 林地의 生産力과 闊葉樹의 密度가 增加함에 따라 造林된 슬래쉬소나무 林分의 未來 生存 本數는 減少하는 傾向을 나타내었다. 本 研究의 結果로 提示된 模型은 山林 經營者들에게 특히 銹病에 感染된 슬래쉬소나무 造林地 林木의 未來木 生存 本數 豫測에 중요한 情報를 提示해 줄 수 있다.

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INTRODUCTION

Infection of slash pine plantations with fusiform rust causes a serious problem to forest owners in the southern United States. An estimation of the annual financial loss due to the rust associated mortality on slash pine and loblolly pine in the southern Unite States is 28 million dollars (Adams, 1989). This includes death from girdling of the tree by the rust canker as well as incremental mortality from wind breakage, insect infestation, and other causes that exert more stress due to the weaken condition of the infected trees. On the average, about 40 percent of the slash pines had a stem cankers due to fusiform rust incidence based on field measurement surveys (Lenhart *et al.*, 1994).

Management of slash pine plantations with significant level of fusiform rust infection require accurate prediction of the timing and amount of future mortality based on current information.

Several modeling approaches to estimating the future number of trees in pine plantations have been developed. Clutter and Jones (1980) developed a survival function based on a difference model, which implied that mortality represented a change in trees per acre with a change in time. This approach was utilized by Bailey *et al.* (1985) for southern pine plantations in the southeastern United States.

The idea that survival characteristics of fusiform rust infected trees and non-infected trees might be different was modeled by Devine and Clutter (1985) for slash pine plantations in the southeastern United States. One survival equation was computed for non-infected trees, and another survival equation was computed that included the additive effects of mortality associated with fusiform rust. Borders *et al.* (1986) presented a logit model for slash pine plantations infected with fusiform rust.

Adams (1989) developed survival models for fusiform rust infected and uninfected trees that allowed for the transition of trees from an uninfected stage to an infected stage. Multinomial logistic regression models were developed by Arabatzis *et al.* (1991) to predict the possible transition paths of planted pine trees from live stems to dead stems.

Adverse effects of competition on the growth of loblolly pine have been documented by many studies (Stewart *et al.*, 1984; Shiver *et al.*, 1990; Haywood and Tiarks, 1990; Glover and Zutter, 1993; Fortson *et al.*, 1996). They found strong negative growth effects of competing hardwood competition and competing vegetation on forest trees.

Two modeling efforts with loblolly pine stands did include the hardwood competition effects in estimating the future number of planted pines (Burkhart and Sprinz, 1984; Burkhart *et al.*, 1987).

The objective of this study was to develop whole stand survival prediction model to estimate future number of planted slash pines infected with fusiform rust, and the effects of non-planted hardwood competition and forest land productivity on planted slash pine survival prediction function.

MATERIALS AND METHODS

1. Study areas

The study area consists of 22 counties in East Texas, USA. Generally, the counties are located within the rectangle from 30° - 35° north latitude and 93° - 96° west longitude.

Climatically, the study area is in a temperature latitude with humid hot summer and mild winters. Annual average rainfall varies from 30 inches in northeast to 50 inches in southeast. Fifty percent or more of annual precipitation falls April through September.

Mean annual temperature ranges from 64°F to 70°F. he soil parent materials in the southern region have been generally influenced by relatively recent Cenozoic clay and sand sediments, while the central region has been affected by the intermediate age lime-stone's, marls, sands and clays of the Mesozoic and Paleozoic Eras. The general topographic features of the study area are flat to hilly, reflecting the influence of well-defined stream patterns of erosion topography. Typically, pine and hardwood trees dominate in the study areas (Godfrey and Seymor, 1959).

2. Slash pine measurements

The ETPPRP (East Texas Pine Plantation Research Project) was initiated in 1982. Measurements are on a 3 years cycle because it takes 3 years to measure all plots. Each plot is located in a different plantation and consists of two adjacent subplots separated by a 60 ft buffer zone. Latitude and longitude coordinates are known for each plot. One subplot is designated for model development and the other for model evaluation. A subplpot is 100 ×100 ft in size, and all planted pines within a subplot are tagged and numbered. Seed source information is not available for the research plots. Typical site preparation methods for establishing the plantations in which ETPPRP plots are involved various combinations of shearing, pushing down, piling and or chopping, plus burning.

At each measurement cycle, among other tree attributes, each planted pine was examined for fusiform rust and recorded as having an infected stem if a gall occurred on a stem or on a live branch within 12 inches of the stem. The field crews were able to reliably tabulate galls occurring on trees in plantations 5 years or older. Thus, rust incidence analyses were limited to data from plantations 5 years or older. For each measurement cycle, stem rust incidence was calculated for each plot as the proportion of living trees with stem galls, irrespective of branch galls. In addition, the non-planted hardwood trees within two embedded circular 8.9 ft radius sampling areas in each subplot were tracked for twelve years or four measurement cycles.

The summary statistics of the observed variables are depicted in Table 1 for slash pine plantations.

3. Survival models

Adams (1989) developed survival models for fusiform rust infected and uninfected pine trees that allow for the transition paths from an uninfected stage to an infected stage. His work was based on Shapiro's (1946) differential equations, Shapiro (1946) presented the solutions for these differential equations and discussed methods for estimating the parameters.

In this study, slash pine plantations in the southern Unites States were considered as consisting of two components : trees infected with fusiform rust (N_i) and those uninfected (N_u). The number of trees in the infected group will have decreased due to mor-

Table 1. Summary statistics for unthinned slash pine plantations data sets.

	Model development subplots (*n* = 236)				Model evaluation subplots (*n* = 236)			
	Mean	Std Dev.	Min.	Max.	Mean	Std Dev.	Min.	Max.
A	12	4.4	5	26	12	4.4	5	26
S	74	12.6	15	109	74	11.4	22	106
T	379	170	78	1,002	390	165	91	1,032
N_u	238	151	12	842	253	151	30	764
N_i	141	74	3	340	137	72	0	421
HDT	564	601	0	3,413	608	683	0	5,425
HBA	17	10.3	0	171	12	27	0	398

Where: A= plantation age (years), S= site index (ft), T= total trees per acre, N_u= number of trees per acre without a fusiform rust stem gall, N_i= number of trees per acre with a fusiform rust stem gall, HDT= natural hardwood trees per acre, and HBA= natural hardwood basal area per acre (ft^2).

Stand age and site index (base age 25 years; Lee and Hong, 1999) for both subplots are similar. On the average, about 40 percent of the slash pines had a stem cankers due to fusiform rust incidence based on recent field survey information.

tality, but will have gained the number of uninfected trees that become infected during this time. Mortality and a change in uninfected status will both decrease the number in the uninfected component.

The basic Adams (1989) model can be expressed as :

$N_{u2}=N_{u1}\exp(-\alpha(A_2-A_1))$

$N_{i2}=(N_{i1}-\beta N_{u1})\exp(-\rho(A_2-A_1))+\beta N_{u1}\exp(-\alpha(A_2-A_1))$

where : A_2 = Subsequent age (year),

A_1 = Initial age (year),

N_{u2} = Number of surviving uninfected trees per unit (acre) at A_2,

N_{u1} = Number of surviving uninfected trees per unit (acre) at A_1,

N_{i2} = Number of surviving infected trees per unit (acre) at A_2,

N_{u1} = Number of surviving infected trees per unit (acre) at A_1,

α, β & ρ = parameters.

Properties of Model (1) are :

1) Allows for the transitions of uninfected trees to an infected stage.
2) Since only planted stems are considered, the uninfected part of the model is non-increasing.
3) However, with the possibility of uninfected trees becoming infected, the infected part is increasing.
4) The model as a whole is non-increasing.
5) Surviving trees converge to zero with extreme age values.
6) The model exhibits path invariance.
7) Mortality is assumed to occur continuously.

This survival modeling idea provided for separate estimates of mortality rates for infected and uninfected, as well as the possible transition of uninfected to infected. The parameter α is the rate at which trees are lost from the uninfected class. The parameter β allocates the number of uninfected tree to be affected by a different mortality rate in the model. The parameter ρ indicates the mortality rate in the model. Behavior of this model is consistent with the desired properties of path invariance, convergence, and surviving trees converge to zero with extreme age values. For planted pines in the southeastern United States, several studies found that as site index increased, survival tended to be decreased (Adams 1989).

In addition to the productivity of an area, another plantation parameter that could play a role in survival is the natural hardwood trees component. These hardwood trees are competing with the planted pines for survivals (Burkhart and Sprinz, 1984; Burkhart *et al.*, 1987). The influence of natural hardwood trees competitions on the survival of planted slash pines was also investigated in this study.

RESULTS AND DISCUSSION

1. Survival prediction models

Scattergrams of the survival trends depicted by the 236 development subplot values were examined. The 236 observations were used to fit the Adams model using the SYSNLIN procedure in SAS (1985) for fitting non-linear systems of equations. The option specified is SUR or seemingly unrelated regression. These two equations are seemingly unrelated since there is no obvious analytical relationship between them. A fitting procedure described in detail to account for the presence of cross equation error correlation by Borders (1989) and Hubert *et al.* (1998).

1) Models with HDT (models 2)

The survival models with HDT resulted as :

$$N_{u2}=N_{u1}\exp(-0.00039535(S*HDT/1000)(A_2-A_1))$$
$$N_{i2}=(N_{i1}-0.512333N_{u1})\exp(-0.00153205(S*HDT/1000)(A_2-A_1))+0.512333N_{u1}\exp(-0.00039535(S*HDT/1000)(A_2-A_1)) \quad (2)$$

The asymptotic standard errors for coefficients $\hat{\rho}$, $\hat{\alpha}$, β and are 0.00024, 0.00008, and 0.12290, respectively. None of the 95% confidence intervals for the parameters contained zero, and all parameters were significantly different from zero at the 0.05

level of probability ($P<0.05$). It was estimated that the uninfected component in the above model explained about 92% of the variation in the average values. But infected component in the survival model explained about 56% of the variation. Therefore, the uninfected component was more accurately predicted than the number of surviving infected trees. The tests for bias, normality, and homoscedasticity were done to check the assumptions about the errors.

Fit statistics based on the data from 236 evaluation subplots are presented in Table 2.

Table 2. Fit statistics for performance evaluation of survival model (2).

Equation	R^2	RMSE	Residual Mean	Absolute Residual Mean
N_{u2}	0.92	40.34	5.78	17.4
N_{i2}	0.56	43.55	7.98	16.5

Where : Residual Mean = $\sum_{i=1}^{n} \frac{(est_i - obs_i)}{n}$,

Absolute Residual Mean = $\sum_{i=1}^{n} \frac{|est_i - obs_i|}{n}$.

Data from the 236 evaluation subplots were utilized to compare predicted and observed values. All residual mean differences were nonsignificant from zero ($P>0.05$), and residual analyses for the fitted models showed no biases.

2) Models with HBA (models 3)

The natural hardwood basal area per acre (HBA) and the interaction of site index (S) was considered as a predictor, and the models resulted as :

$$N_{u2}=N_{u1}\exp(-0.00213856(S*HBA/100)(A_2-A_1))$$

$$N_{i2}=(N_{i1}-0.431309N_{u1})\exp(-0.00767813(S*HBA/100)(A_2-A_1))+0.431309N_{u1}\exp(-0.00213856(S*HBA/100)(A_2-A_1)) \quad (3)$$

The asymptotic standard errors for coefficients $\hat{\rho}$, $\hat{\alpha}$, $\hat{\beta}$ and are 0.00126, 0.00049, and 0.43131, respectively. None of the 95% confidence intervals for the parameters contained zero, and all parameters were significantly different from zero at the 0.05 level of probability ($P<0.05$). It was estimated that the uninfected component in the above model explained about 92% of the variation in the average values. But infected component in the survival model explained about 55% of the variation. The tests for bias, normality, and homoscedasticity were done to check the assumptions about the errors. Graphical residual analyses showed no biases. Fit statistics based on the data from 236 evaluation subplots are presented in Table 3.

Table 3. Fit statistics for performance evaluation of survival model (3).

Equation	R^2	RMSE	Residual Mean	Absolute Residual Mean
N_{u2}	0.92	41.0	7.68	31.3
N_{i2}	0.55	44.1	-0.84	32.3

All residual mean differences were nonsignificant from zero ($P>0.05$), and graphical residual analyses for the fitted models showed no biases. Compared models (2), there is no great differences in validation statistics of R^2, RMSE and Residual Mean. But in statistics of Absolute Residual Mean (ARM), the models (2) show slightly better performance. Thus, for slash pine, it is recommended that models (2) should be used in slash pine plantations because these prediction equations perform slightly better, when using Absolute Residual mean(ARM) as a magnitude of precision criterion.

2. Survival projections

1) Survivals infected with fusiform rust

Survival projections produced by equations (2) for slash pine stands are shown in Fig. 1. Slash pine stands have 500 stems per acre at age 5, site index is 70 ft which is the average value for slash pine species and the natural hardwood trees peracre is 600 which is the observed average values. Infection rate at age 5 was assumed to be 20, 30, and 40 percents of different rust level, respectively. The results shown in Fig. 1 illustrate a general tendency for predicted mortality including uninfected and infected components to decrease as the stands age increases. Predicted total mortality increases rapidly from age 5 to about 15 years of age in the survival projections and depending on initial infection level throughout the rotation.

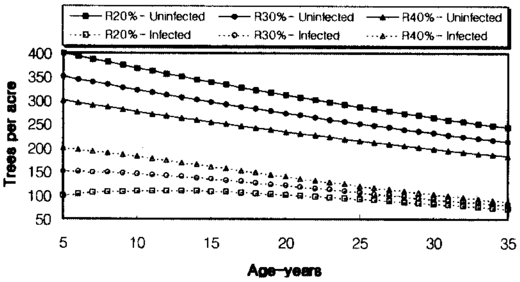

Fig. 1. Survival projections for slash pine stands infected with different level of fusiform rust.

2) Effects of site quality on survivals

Using the same scenario described above such as slash pine stands have 500 stems per acre at age 5, natural hardwood trees per acre is 600 stems, and fusiform rust infection rate is 40 percent which is the observed average value for slash pine species. Site index ranged from 50 ft to 90 ft by 20 ft classes and other factors fixed across their ranges, the surviving planted slash pine trees were computed using models (2). As site index increased, the survival of planted slash pine trees decreased.

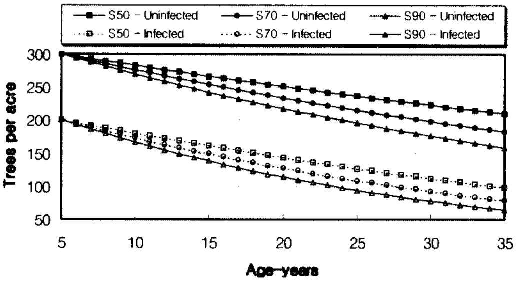

Fig. 2. The influence of the site productivity on expected future number of uninfected and infected planted slash pine trees per acre.

The future survival of the planted slash pines is obviously influenced by the forest land productivity. For a given age, as site index increases, the survival of planted slash pine tend to be decreased as shown in Fig. 2.

3) Effects of natural hardwood trees per acre on survivals

The anticipated influence of the natural hardwood tree component on slash pine planted tree survival was investigated by utilizing of the same scenarios described previously. In the scenario, plantation parameters were defined previously and the number of natural hardwood tree density ranged from 300 to 900 by 300 trees per acre classes.

Fig. 3 is based on Models (2) for slash pine. The expected impact of increasing natural hardwood tree competition expressed in trees per acre is clearly depicted in the Figure (3).

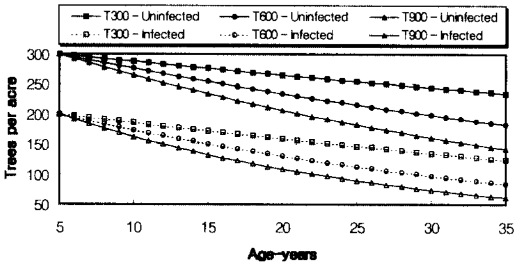

Fig. 3. The influence of hardwood tree density on expected future number of uninfected and infected planted slash pine trees per acre.

The survival of the planted slash pine is definitely influenced by the density of natural hardwood tree component. For a given age, as natural hardwood density increases, expected planted slash pine survival decreases. The relatively severe survival trends shown in the Fig. 3 might be explained by the typical character and nature of non-planted hardwood trees in slash pine plantations.

CONCLUSIONS

Stand level survival prediction equations were developed that incorporated the incidence of fusiform rust and allowed the transition paths of trees from an uninfected to an infected stage. Predicted total surviving number of trees is obtained by adding together the predicted number of infected and uninfected trees. In addition, the influence of non-planted hardwood trees density and forest land productivity on slash pine survivals tended to show a negative effects on predicted future number of slash pine trees. It considers that forest management activities that reduce the number of non-planted hardwood trees are beneficial in increasing survival of the planted slash pine trees.

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