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Positive Returns from Investment in Fusiform Rust Research

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Cover:

Research plot in Olustee, FL--control group (L), rust resistant family (R).

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Summary

Fusiform rust [*Cronartium quercuum* (Berk.) Miy. ex Shirai f. sp. fusiforme Burdsall et Snow] is a widespread and damaging disease of loblolly and slash pine across much of the Southern United States. Research by government and university scientists has identified families of these species with improved genetic resistance to infection by the disease, allowing production and planting of resistant seedlings in areas at risk. This paper describes an evaluation that compared the cost of fusiform rust research to the simulated benefits of rust resistant seedlings in plantations established Southwide between 1970 and 2020.

Forest Inventory and Analysis (FIA) records from 1968 to I986 provided the frequency of various infection rates and site qualities among young plantations before substantial effects of improved resistance. These site quality and infection levels formed the inputs to stand-level yield models that simulated the disease's effects on mortality and product degrade as stands mature. Yields at successive ages were merchandised to three products and valued to permit identification of optimal rotation age. We extrapolated stand-level yields to regional levels using the FIA frequency data plus historical and projected planting rates, The value of these regional yields indicated plantation values in the absence of improved resistance and formed our baseline scenario.

To estimate the impact of genetically improved resistance on this baseline, we asked seedling producers from across the South to estimate their production of resistant seedlings and associated gains in resistance since 1970 and to project those gains forward to 2020. We used these estimates to reduce infection rates in the various years of the baseline scenario to simulate the effect of improving resistance over time.

We handled selected uncertainties by running three separate sets of simulations based on different assumptions. First, we tested the impact of rotations longer than economically optimal by adding a set of simulations that assumed a fixed 35-year rotation. Second, because we had no empirical information on how well the industry is able to target resistant seedlings into areas at greatest risk, we simulated two different resistance scenarios: (I) uniform, where resistant seedlings were placed uniformly across plantations of the South; and (2) optimal, where resistant seedlings first went to conditions where resistance would yield the greatest benefit. An additional resistance scenario, total resistance, separately valued rust damage and showed the maximum potential benefits achievable fromfuture research. Third. in the absence of clear evidence on how efficiently loggers and mills utilize infected stems, we simulated stand and regional yields under four different levels of utilization: poor, pulpwood, sawtimber, and full.

From the information supplied by seedling producers, we found that production of rust-resistant seedlings rose rapidly beginning around 1980, although gains in resistance were initially small. By 1990, approximately 66 million resistant slash and 144 million resistant loblolly seedlings were being produced annually, representing 39 percent of slash seedling production and 17 percent of loblolly. For those resistant seedlings, the gains in resistance in 1990 were about 39 and 28 percent for slash and loblolly, respectively. Seedling producers anticipated that both production and resistance numbers would continue to improve for the next decade or two.

Forest Inventory and Analysis data from three surveys between 1968 and 1993 indicated fusiform infection has been widespread although rarely severe. About one-third of young plantations have experienced fusiform infection rates of 5 percent or more, but infection rates of more than 45 percent have typically occurred on less than 10 percent of the plantation acres. For most of the period surveyed, infection incidence in plantations was greater on high-quality sites but similar for loblolly and slash pine once these site-quality summary differences were taken into account. Neither of these patterns was apparent in the most recent survey, however, possibly due to increased deployment of resistant seedlings and a southwestward shift in planting activity within the region. Site quality of new plantations generally improved over the three surveys.

Stand-level simulations showed rust affects both product mix and gross yield. High rates of rust infection shifted harvest volumes away from sawtimber and into lower valued products, and except under full utilization in Ioblolly, also lowered total harvested volumes. Changes in product mix and volume resulted in reduced harvest values with the largest losses occurring on higher quality sites and when infected stems were poorly utilized. In slash pine, stands with low infection levels at age 5 eventually produced financial returns equal to or greater than similar uninfected stands. Generally, only when initial infection rates exceeded 20 to 30 percent did rust result in a net damage to stand value and yield. This presumed competitive release effect was less common in loblolly simulations, where low levels of rust generally produced at least some financial damage.

The effect of genetically improved resistance on Southwide plantation values depended on the year and on the assumptions regarding rotation standard, resistance deployment, and utilization efficiency, but several broad conclusions are warranted. The total resistance scenario showed that fusiform rust had a relatively small effect on region-wide plantation volumes, generally less than 1 percent, although product shifts caused additional loss of value. Rust effects on the value of plantations Southwide depended on how efficiently the industry utilizes infected stems. Rust reduced total plantation values by 2.1 percent under the full utilization assumption but by 12.7 percent under poor utilization. Small shifts in supply imply small price effects, suggesting that plantation owners would capture most of the benefits of improved resistance.

Improvements in resistance resulted in gradually increasing benefits over time but the amount depended on the assumptions used. Regional benefits for plantations established in 1990 were $4 to $55 million but rose to $8 to $67 million for planting in the year 2020. Placing resistant seedlings optimally resulted in benefits 2% to 4 times higher than deploying them uniformly. For most scenarios, projected improvements in resistance did not capture all potential benefits of rust elimination, indicating substantial room for improvement through further research and development,

When annual benefits were aggregated over time with appropriate discounting, region-wide benefits of improved resistance totaled $108 to $999 million, depending on assumptions of rotation length, utilization, and resistance deployment. Such benefits were the direct result of investments in research and development-investments that cost government, universities, and industry an estimated $49 million in 1992 constant dollars. Comparing the various benefit estimates with these costs showed net returns to investment were $58.9 to $949.5 million with benefit:cost ratios ranging between 2.2 and 20.4, We conclude that even under our most conservative assumptions, past investments in fusiform rust research have resulted in substantial benefits to owners of loblolly and slash pine plantations across the South.

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Abstract

Fusiform rust ***[Cronartium quercuum (Berk.)*** **Miy. ex Shirai f. sp.** *fusiforme* **Burdsall et Snow] is a widespread and damaging disease of loblolly and slash pine in the South. Research has identified families of these pines with improved genetic resistance to the disease, allowing production and planting of resistant seedlings in areas at risk. This study compared the cost of fusiform rust research to the simulated benefits of rust-resistant seedlings in plantations established Southwide between 1970 and 2020, Seedling producers provided estimates of resistant seedling production and gains in resistance over the period. Stand-level simulations evaluated the impact of various infection rates on financial yield on low-, medium-, and high-quality sites of each species, taking into account both motility and product degrade effects of the disease. Two rotation regimes and four levels of infected stem utilization were explored. Stand-level yields were extrapolated to regional values using long-term distributions of plantation conditions from Forest Inventory and Analysis surveys. Simulation results showed that past investments in fusiform rust research of $49 million will return benefits to plantation owners of between $108 and $999 million in 1992 constant dollars. Expected improvements in resistance will not eliminate all financial damages from the disease; simulation results indicate substantial financial benefits yet remain for additional research and development.**

Keywords: *Cronartium fusiforme,* **disease control,** disease resistance, economic damages, **fusiform rust, loblolly pine, plantation valuation, research benefits, slash pine.**

Introduction

Fusiform rust [Cronartium ***quercuum*** (Berk.) Miy. ex Shirai f. sp. ***fusiforme*** Burdsall et Snow] has long been recognized as the most damaging disease of southern pine forests. Occurring in a band across the heart of the South, the disease is prevalent in the most productive stands-loblolly (Pinus *taeda* L.) and slash (P. *eliottii* Engelm.) plantations on higher quality sites (Anderson and others 1986a, Borders and Bailey 1986). Galls on seedlings can cause early mortality, while survivors with resulting stem cankers are subject to breakage and are unsuitable for solid wood products (Get-on and Hafley 1988, Holley and Veal 1977). The most effective means of reducing damage from this pathogen has been to plant genetically resistant seedlings.

For three decades, the U.S. Department of Agriculture, Forest Service (Forest Service), academic institutions, and forest industry have maintained extensive research efforts to improve resistance of planted growing stock to fusiform rust. Research has included characterizing the basic biology of the disease, identifying resistant genotypes, establishing rust-resistant orchards, and developing standardized methods for screening seedlings for rust susceptibility. A casual evaluation suggests that fusiform rust research has achieved considerable success-increasing amounts of planted stock embody improved genetic resistance, and infection rates in planted southern pine stands appear to have waned during the 1980's.

A more thorough evaluation of this apparently successful research program would analyze its economic benefits and *costs.* Although a considerable body of literature exists on the productivity of agricultural research expenditures, we found fewer studies examining forestry research productivity, and most of these investigate technical change in the forest products industry. We are aware of two studies that examine the productivity of research investments in timber growing technology. Hyde and others (1992) examined aggregate research investment effects on southern pine productivity, Huang and Teeter (1990) evaluated net economic returns from research on a single factor influencing pine productivity-herbaceous weed control. Our analysis is more similar to the latter study because it focuses on a single factor--fusiform rust.

Fusiform rust affects both the quantity and quality of timber produced per unit area; therefore, increased rust resistance translates directly to increased economic value. Because rotation ages in southern pine plantations are relatively short, financial gains from genetic improvements are realized quickly. Moreover, discounting in short rotation species affects these gains less than in species with long rotations, We expect the benefits of improved resistance to fusiform rust in southern pine to be greater than the benefits of research investments in many other timber types.

The methods we develop to evaluate fusiform rust research in the South are applicable to other timber types and timber investments. In this approach, we simulate timber production and merchandising processes at the stand level and then aggregate quantities and values across the region to estimate aggregate production and value functions. By comparing a base level scenario representing no investments in fusiform rust research with a variety of scenarios representing potential impacts of fusiform rust research, we can estimate the aggregate production and value impacts of fusiform rust research. Using data collected on research program costs, we evaluate the economic efficiency of this research by computing a benefit:cost ratio for each of the potential outcomes.

In reporting our research, we divide this paper into five sections. First, we present the overall goals and objectives. Second, we review previous work related to fusiform rust evaluations. Third, we describe our research methods. Fourth, we present the results of our analysis. Finally, we discuss our conclusions and their implications.

Objectives

The overall goal of this study is to evaluate the economic efficiency of historical fusiform rust resistance programs. This research evaluation includes the following specific objectives:

1. Estimate the aggregate biological effects of fusiform rust resistance breeding programs.

2. Estimate the stand-level (microeconomic) impacts of fusiform rust on timber yields and timber growing investments.

3. Estimate the resulting aggregate (macroeconomic) increases in volume and value of southern softwood timber supply, resulting from improved rust resistance.

4. Estimate the costs of fusiform rust research.

5. Compute benefit:cost ratios and discuss their implications for future research strategies.

Previous Research

Several studies have valued the impacts of fusiform rust, its control, or other issues related to the economic effectiveness of forestry research. Studies made use of a variety of empirical and simulation approaches. Some studies were conducted at the stand level, while others evaluated regional impacts.

Powers and others (1974) used Forest Inventory and Analysis (FIA, previously Forest Survey) data from South Carolina, Georgia, and Florida to extrapolate an estimated loss from fusiform rust of $28 million across the South in 1972. Gross volume losses to galls in plantations and natural stands were valued without explicit treatment of product shifts or mortality effects. The authors considered the estimated loss conservative because it excluded the costs of spraying protective fungicide in tree nurseries and replacing infected trees in seed orchards and did not separately account for losses of higher value products.

Holley and Veal (1977) concluded that the amount of quantitative data on the effects of fusiform rust on growth, yield, and degrade in pine stands across the South was insufficient to estimate the economic impacts of fusiform rust. However, they concluded the major effect of rust-associated mortality is a reduction in yield. Lowered quality of the infected stem also results in loss. They speculated that damage from fusiform rust, on a Southwide basis, would run into the tens of millions of dollars annually and would increase over time.

Anderson and others (1986b) also used FIA data to estimate the economic losses caused by fusiform rust. They estimated that total losses for the South Central States (Texas and Oklahoma through Tennessee and Alabama) equaled $35 million per year based on a discounted cash flow, The harvest volumes estimated were gross volumes because they only merchandised the individual stems into sawtimber and pulpwood products.

Busby and Haines (1989) developed a model to estimate the damage of fusiform rust infection in slash pine stands. The model required the user to specify the percent reduction in sawtimber to account for degrade from fusiform rust but this information was unobtainable; therefore, degrade was not included in their evaluation. Geron and Hafley (1988) used the North Carolina State University (NCSU) Managed Loblolly Pine Plantation Growth and Yield Simulator to examine the stand-level impacts of fusiform rust on loblolly yields with two different merchandising assumptions. They concluded that the majority of the stem galls occur below 8 feet (It), the most valuable portion of the stem. As the percentage of infection increases, solid wood losses increase as well.

Redmond and Anderson (1986) examined the economic benefits of the fusiform rust screening center in Asheville, NC. They concluded that the screening process can identify superior resistant seedlots and reduce the growth, yield, and degrade losses due to fusiform rust when these seedlings are planted in high-hazard fusiform rust areas.

Hyde and others (1992) and Newman (199 1) used a statistical model to estimate research-driven improvements in forest productivity across the South between 1952 and 1985. Using FIA data aggregated to the State level as units of observation, they were able to run regressions on a set of explanatory variables including dummy variables for different time periods. After accounting for the variation explained by other biological and ownership variables, the variation in the aggregate inventory variable explained by the dummy variables was attributed to productivity gains from research expenditures. Because the dummy variable approach simply captures temporal variation that is not explained by other explanatory variables, attribution to a single causal factor is somewhat tenuous.

None of these studies satisfactorily estimated the regional economic benefits and costs of fusiform rust research itself, tracking the effects of such research through seedling production, planting, growth, harvesting, merchandising, and sale. The lack of such a comprehensive analysis of this research's effectiveness led to the evaluation reported here.

Methods

We chose a simulation approach over empirical alternatives for this evaluation for several reasons. Simulation offers unambiguous assignment of causality, ability to estimate market effects yet to occur, and discrimination of marginal effects despite fluctuations in the market. The availability of growth and yield models for slash and loblolly pine that incorporate effects of fusiform rust infection was also important to our decision. Using our own routines and data from other sources, we were able to design a simulation model that projects the impacts of changing fusiform rust resistance on regional timber supplies.

The Simulation System

To evaluate the benefits of genetically improved resistance, we must contrast the values of southern plantations without rust-resistant technologies against the values of these plantations *with the* improved rust resistance. The difference between plantation values for these two scenarios provides our measure of the benefit of the fusiform rust research program.

The modeling scheme we developed simulates the establishment of new plantations and their growth to rotation age, harvesting, merchandising into products, and valuation. The sequence is simulated separately for loblolly and slash and across a range of initial site qualities and early fusiform rust infection levels to reflect the diversity of plantation conditions across the region. Southwide production is calculated by multiplying the simulated per-acre yields and values for each initial condition with that condition's corresponding area in the region and then summing across the South.

This sequence provides the basis for the without scenario, The *with* scenario is simulated by modifying the *without* scenario to reflect the deployment of genetically resistant seedlings. Resistant seedlings are assigned to particular site conditions and their resulting infection rates reduced to reflect their higher resistance. The deployment of seedlings and the establishment and growth of plantations are repeated across a range of years for the *with* and *without* scenarios to reflect changing planting rates and the improving availability and resistance of genetically resistant seedlings over time. The simulation encompasses loblolly and slash pine plantations established throughout the South between 1970 and 2020.

We can illustrate the simulation system as a mathematical formula. Let Y_{ijk} represent the yield per acre and let V_{ijk} represent the economic value per acre from a site planted with species i, on site quality j, with infection level k. Then the aggregate production functions for the South can be represented by multiplying the number of acres planted to species i on site quality j with infection level k in year t, A_{ijkt}, by the appropriate yield values Y_{ijk}, and summing across historical and anticipated values for the arguments represented by the subscripted variables:

$$Volume^{without} = \sum_i \sum_j \sum_k \sum_t A_{ijkt} Y_{ijk}, \qquad (1)$$

where

$Volume^{without}$ = aggregate production from timber stocks without genetic improvement.

Aggregate values for the South can be computed by substituting V_{ijk} for Y_{ijk} in equation (1).

$$Value^{with} = \sum_i \sum_j \sum_k \sum_t \sum_r A_{ijktr} V_{ijk}. \qquad (2)$$

To reflect the introduction of resistant seedlings, equation (2) is modified to include a resistance factor r. The subscript only appears on *A* because the increased resistance is simulated as a shift in the distribution of acres toward lower infection rates.

The benefits attributable to introduction of rust-resistant planting stock can be computed as the difference between values with and without the use of genetically improved stock:

$$Volume\ Benefits = Volume^{with} - Volume^{without}, (3)$$

$$Value\ Benefits = Value^{”‘”} - Value^{without}. (4)$$

Stand-Level Simulations

Impacts of infection at early ages were projected through to yields at various ages for a range of initial site conditions. The range of initial site conditions for loblolly and slash pine was represented by 3 levels of site quality, termed “site classes,” and 11 levels of rust infection at age 5, termed “infection classes.” The combination of 3 site classes and 11 infection classes resulted in 33 initial conditions for each species.

Growth and yield-To generate yield tables for the 33 initial conditions for slash pine, we used the University of Georgia **GAPPS** model, developed from extensive growth and yield research by their Plantation Management Research Cooperative (Burgan and others 1989, Pienaar and others 1988). We used a second model developed by the North Carolina State University (NCSU) Loblolly Yield Model (Hafley and Smith 1989) to produce a similar set of yield tables for loblolly pine. Both models project fusiform rust-associated mortality over time and infection rates of surviving stems through the life of the stand.

For the simulations, we specified no thinning and an initial planting density of 700 seedlings per acre. We assumed early survivorship varied with site quality: 75 percent survival for low-quality sites, 80 percent for medium, and 85 percent for high. Infection classes for the simulations were indicated as 0, 10,20, . . . 90, 100 percent infection at age 5. The three site classes were termed low, medium, and high, defined for loblolly as site index and 80 ft at base age 25. Corresponding site indices for slash pine were 50, 60 and 70.

We estimated even-aged pine plantation yield tables for each species and each of the 33 initial conditions, calculating yield at 5-year increments starting with stand age 10 and ending with stand age 35. For each age, the model reported volume yield in cubic feet by breast height diameter class, as well as an overall percentage of rust-infected trees. We applied this overall stand infection rate to the number of stems in each of the diameter classes to distribute infected stems to the different diameter classes.

Model outputs were less reliable for extreme input values. Volume predictions were more tenuous at the oldest ages than for younger ages where empirical data were more readily available, and prediction of yield at 100 percent infection rates was also problematic. Because the model used for loblolly pine calculations did not permit 100 percent initial infection as an input, we substituted 99 percent. For slash pine, the model’s results proved unstable at 100 percent infection so we used quadratic regression to estimate outputs under these conditions. In a few cases, this approach yielded either negative product volumes or implausibly high pulp yields. When this occurred, negative volumes were reset to zero and each of the three product volumes was rescaled so their sum matched a similarly extrapolated total stand volume.

Product merchandising-While both yield models incorporated mortality effects of rust, additional merchandising simulations were needed to capture how galls affected wood utilization on the surviving stems. Because empirical information was unavailable on logger responses to galls, we used four timber utilization scenarios to account for a range of possible merchandising intensities. Case I (poor utilization) assumed any tree with a stem gall is left in the woods. Case II (pulpwood utilization) assumed any tree with a stem gall is pulped. Case TII (sawtimber utilization) assumed the tree was pulped unless at least a 16-q gall-free log is present. Case IV (full utilization) assumed optimal utilization of all trees, even those with galls.

Within these constraints, we used the following rules to merchandise logs. Sawtimber required at least an 8-ft, gall-free log with a small end diameter outside bark (sedob) $\geq$ **8** inches (in.) or a small end diameter inside bark (sedib) $\geq$ 6 in. Sawtimber log lengths ranged from 8 ft to 16 ft in 2-ft increments. Longer log lengths were preferred. Chip-n-saw required at least an 8-ft, gall-free log with a sedob $\geq$ 4 in. or a sedib $\geq$ **3** in. The log lengths were the same as sawtimber. There were no length restrictions for pulp. All trees were merchandised to a 4-in. top sedob or 3-in. top sedib. In loblolly, we assumed the gall was 2 ft in length; in slash, 4 ft in length. In all but Case I, galls were pulped. We based the small end diameters on personal communications with knowledgeable loggers from the area of concern and developed and programmed our own merchandising routines to do these analyses because existing software was inadequate.

The loblolly merchandiser incorporated the model 4 plantation taper equations used by the NCSU Loblolly Yield Model (Max and Burkhart 1976). Loblolly yields were estimated using Newton’s volume formula for a paraboloid frustum.[1] We assumed the only stem defect was fusiform rust galls.

Merchandising infected stems required information on where the stem galls occurred and how many galls occur on an individual stem. Geron and Hafley (1988) defined the probability of a gall occurring at a given height on the stem. To account for occurrences of more than one gall segment on a stem, we used a 0.75 probability of one segment, 0.15 for two

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[1] Personal communication. 1993. William D. Smith, Assessment Coordinator, Southern Research Station, 3041 Cornwallis Road, Research Triangle Park, NC 27709

segments, and 0.10 for three segments on any given infected tree.[2] We used a uniform variate random number generator combined with these frequency distributions to determine the number of galls and the height of the segments on any given stem. Therefore, merchandised yields of infected stands reflect some degree of unreplicated stochasticity. Following allocation of gall segments, each infected tree within a stand-age class and diameter at breast height (d.b.h.) class was merchandised individually.

The slash merchandiser incorporated the yield and taper equations used by GAPPS (Pienaar and others 1988). We used the same assumptions as in the loblolly merchandiser, with two exceptions. The number of gall segments on a slash stem was based on research by Belanger and others (1985), and their height on the stem was based on research by Webb and Patterson (1984).

Product prices-Because fusiform rust infection greatly affects timber utilization, detailed product price information was critical in the valuation process. We recognized three product classes: pulpwood, chip-n-saw, and sawtimber. For sawtimber, we included the effect of log length on price,

Base product prices were computed using 1992 average prices (Norris 1992) for the Southern States and sub-State regions where fusiform rust is prevalent: Alabama, Arkansas (region 2), Florida, Georgia, Louisiana, Mississippi, North Carolina (region 2), South Carolina, and Texas. State product prices were weighted by removal rates to compute a weighted average price per cubic foot. Using this method, the following base prices were used in the economic analysis: (1) pulpwood = \$0.32 per cubic foot, (2) chip-n-saw = \$0.66 per cubic foot, and (3) sawtimber = \$0.94 per cubic foot.

To account for the effect of galls on sawtimber log length and therefore value, it was necessary to compute sawtimber values for various log lengths. We assumed that lumber price relations by length adequately represented log price relations by length. Relations were calculated using reported prices (Random Lengths Price Report 1993) for kiln-dried southern yellow pine *(P. echinata* Mill.) averaged over the west, central, and east reporting regions for dimensions ranging from 2 by 6 to 2 by 12 in. and lengths ranging from 8 ft to 24 ft.

Linear models were estimated by regressing lumber prices on lumber length. The estimated regression line was: price = \$302.91 + \$6.45 x length. The t-statistics on the intercept and length variable were 15.333 and 4.025, respectively, and the adjusted r-square was 0.128. This regression can be interpreted to mean that the base lumber price is \$302.91 and increases \$6.45 with each foot increment in length. Therefore, we used this relationship to estimate lumber prices for 8-, 10-, 12-, 14-, and 16-ft lengths. A relative price index was then computed using 12 ft as the standard length. The index ranged from 0.932 for 8-ft boards to 1.068 for 16-ft boards.

Finally, the relative lumber prices were applied to the base stumpage prices to estimate log prices by length. We assumed that the average prices were computed for 12-A logs (i.e., the relative price index = 1). Multiplying the relative price indices by the base timber price yielded stumpage prices in terms of log lengths. Assuming a conversion rate of 200 ft^3 per thousand board feet, the following log values were computed and used in the analysis:

Log length	Value/ft^3
8 ft	\$0.88
10 ft	\$0.91
12 ft	\$0.94
14 ft	\$0.97
16 ft	\$1.00

This pricing scheme provided a higher price per cubic foot for longer logs than for shorter logs. No similar price premium was provided for log diameter. For a given length sawtimber log, larger diameter stems were valued at the same per-cubic-foot price as those with smaller diameters.

Plantation establishment costs-Regeneration costs were based on cost trends published by Belli and others (1993). We assumed the costs of establishing lobloly and slash pines were equal; however, better quality sites required more intensive site preparation because they supported greater vegetative competition. Initial site preparation consisted of combinations of shearing, chopping, raking, disking, and piling, with all site classes receiving a prescribed bum. A herbicide treatment was included on high-quality sites. Seedlings were hand planted on low-quality sites, hand and machine planted on medium-quality sites, and machine planted on high-quality sites. With seedling costs included, these activities led to regeneration costs of \$139, \$155, and \$197 for the low-, medium-, and high-quality sites, respectively.

Economic value calculations-We chose two financial measures of impact at both the stand and regional levels: net present value at time "t" (**PV_t**) and soil expectation value (SEV). Present value (PV) describes the value of a single rotation and consists of the gross revenue at harvest less the costs of stand establishment t-years earlier, shown in equation (5). To keep revenues and costs commensurate, establishment

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[2] Personal communication. 1993. Charles Walkinshaw, Plant Pathologist, Southern Forest Experiment Station, Alexandria Forestry Center, 2500 Shreveport Highway, Fineville, LA 71360

costs were compounded forward to harvest date. Harvest date was chosen over planting date because harvest is when management decisions finally influence timber markets. In this evaluation, PV's from individual stands were summed across the region and then over time to calculate the regional benefits of improved resistance, following the approach used by Löfgren (1988) to value genetic improvements. As with other calculations in this evaluation, we assumed a discount rate of 4 percent, per Row and others (1981).

$$PV_t = V_t - C(1+r)^t, \qquad (5)$$

where

V_t = the value (gross revenue) of the stand at stand age t,
r = the discount rate, and
C = the costs of regenerating the stand.

Soil expectation value represents the combined PV of an infinite sequence of rotations, all discounted back to a common stand establishment date and summed. Soil expectation value is useful for comparing the long-term, "bare-land" value of a given system of management at time of plantation establishment, the time genetically resistant seedlings would be produced and deployed. We used SEV to compare stand-level conditions and to compare the "with" and "without" scenarios at selected points in time, an approach previously used to evaluate impacts of fire and insect outbreaks (Holmes 1991, Matte.11 1980, Reed 1983, Routledge 1980). Because SEV includes future rotations as well as the present rotation, it is not useful for aggregating across changing technology. Therefore, in this evaluation it described aggregate conditions at individual points in time. Present value was used to aggregate regional benefits across time.

$$SEV_t = \frac{V_t(1+r)^{-t} - C}{1-(1+r)^{-t}}. \qquad (6)$$

Two rotation standards were evaluated in this study. The first system assumed a fixed rotation length of 35 years, referred to as the sawtimber rotation. Product yields at 35 years were used as input to the PV and SEV equations. The results of fixed rotations are relatively easy to interpret but imply an uncommonly long rotation and simplistic stand management. The fixed rotation standard is most useful for illuminating simulation processes in the absence of shifts in rotation length.

The second rotation standard maximizes SEV, referred to as the optimal economic rotation. Under this standard, each combination of species and site condition was evaluated separately to determine its own year of maximum SEV. Because the generated yield tables were computed using 5-year intervals, SEV values were interpolated to determine the maximum, using a three-step process, First, the SEV's were calculated for stand ages 10 through 35 in 5-year increments, using the yield data. Second, the six calculated SEV' were used to estimate the coefficients of a fourth order polynomial:

$$SEV_t = \beta_0 + \beta_1 t + \beta_2 t^2 + \beta_3 t^3 + \beta_4 t^4 + \epsilon_t, \qquad (7)$$

where
t = stand age.

Third, coefficients of the regressions were used to predict SEV annually between the stand ages 10 to 35. These were compared to find the maximum SEV and corresponding optimal rotation age T:

$$SEV_T = Max\ SEV_t, \qquad (8)$$

where
$t = 10, \ldots 35.$

Simple linear interpolation was used to estimate volumes of pulp, chip-n-saw, and sawtimber for optimal rotation ages that fell between calculated ages, Present value was calculated from SEV:

$$PV = SEV[1-(1.04)^{-t}]. \qquad (9)$$

Aggregate Benefit Simulations

We estimated regional harvest volumes and plantation values over time by extrapolating from the stand-level yields previously described. Cross-scale extrapolations are subject to various forms of extrapolation error (Rastetter and others 1992). which we minimized by partitioning conditions into classes and calibrating selected parameters to regional scale measures.

For each of the 66 initial stand conditions, the fine-scaled processes of stand establishment, growth, yield, and harvesting were simulated. We then used region-wide information on historical and projected planting and the diffusion of rust resistance through the industry to aggregate these simulations to regional measures of timber supply and value.

Region-wide information needed to perform aggregate simulations included information on acreages planted and species mix over time, dissemination of rust-resistant planting stock, amount of reduction in infection in that stock, and information on baseline infection rates in the absence of genetic selection. Several assumptions about fusiform rust resistance and technology helped structure the simulations.

Evidence from field trials indicated that genetic gains in resistance tend to be proportional across sites of differing risk (Hodge and others 1993), i.e., genetic resistance conveys a proportional reduction in infection rates. We assumed this proportional reduction in infection in early years is the sole effect of selection for genetic resistance to fusiform rust. Having accounted for this genetic impact on early infection, we assumed that plantations of similar infection rate and site quality would all grow at the same rate and suffer the same dynamics of new infections and mortality regardless **of** their genetic source.

Assuming that resistance only affects infection rates implies that selection for resistance can be attained without sacrifice of growth. Conversations with tree improvement researchers indicated no consensus on this issue. Some reported that their resistant families showed growth equal to their other improved lines, while others indicated that tradeoffs between resistance and growth have been necessary. Because no definitive scientific studies on such tradeoffs could be found, we chose to assume that no tradeoff exists.

We also assumed that once resistant genotypes are identified, **their production and planting technologies are no different than those of improved, nonresistant seedlings, Seed orchards for resistant and nonresistant seedlings should cost the same and be** equally **productive.** We assumed nursery and planting costs for both types of seedlings were also equal. Any additional costs incurred in genetic selection for resistance were included as costs for research, including the study of fusiform rust biology and risk, the development of methods for screening, and the evaluation **of fusiform rust resistance.**

Distribution of conditions across the region-we obtained data on the distribution of stand conditions from the southeastern FIA (SEFIA) unit in Asheville, NC, and from the southern FIA (SOFIA) unit in Starkville, MS. Plot-level information with appropriate area expansion factors was obtained for all FIA loblolly- and slash pine-dominated plots in the South collected since 1968 (southeastern) and 1974 (southern) and described the three most recent cycles of measurement of the six completed to date. Dates of data collection for the fourth survey were 1968 to 1977; for the fifth, 1978 to 1986; for the sixth, 1986 to 1993.

Standard FIA variables from the 33,036 plot records describe forest type, survey cycle, expansion area, site class, stand origin, and age. Forest Inventory and Analysis calculated two additional measures for this study: quadratic mean d.b.h. and percentage of stems infected with fusiform rust. These calculations used only a plot's dominant (pine) species to simplify interpretation of species differences and projections of yield. Thus, infection rates for a loblolly pine stand refer only to infection rates among the loblolly stems. Although we obtained records for all ages of stands and for both planted and natural pine stands, the extrapolation process focused on young plantations, those less than 10 years old, forming a subset of 6,117 records over the three survey cycles.

Plot records were used to generate area distributions for each survey cycle, with groupings corresponding to those used in the yield simulations and separate tables for loblolly and slash pines. Infection rates were rounded into 11 classes for tabulation: 0-4,5-14, 15-19, . . .95-100. For site-quality classes, SEFIA and SOFIA recognize five and six classes, respectively, but some of these are rarely reported. Those categories with the least acres were collapsed into adjoining categories to form the three final site-quality classes used in the evaluation and defined in table 1.

We attempted to maximize comparability both between the two FIA collecting units and across the three survey cycles. However, two discrepancies remain in the fourth cycle:

- While fifth and sixth cycle data span the entire South, fourth cycle data were not available for three States-Arkansas, Mississippi, and Tennessee.
- Survey coding changed during the fourth cycle from the general "disease" category to the more specific "fusiform rust stem gall." Only North Carolina and Virginia used the more specific category in this cycle,

The potential impact of omitting three States was examined by temporarily dropping the three States from the fifth and sixth

Table 1-Correspondence between site classes reported in Forest Inventory and Analysis (FIA) surveys by southern FIA (SOFIA) and southeastern FIA (SEFIA) and site indices (SI) used in the stand-level yield simulations

	FIA surveys		Simulation	
Site quality	SOFIA	SEFIA	Loblolly	Slash
	Site class codes		*SI base age 25*	
High	1-3	1-2	80	70
Medium	4	3	65	60
Low	5-6	4-5	50	50

cycle tallies and recalculating plantation acres by site-quality and infection rates. Relative shifts in distributions were small, indicating that relative frequencies were fairly insensitive to the omission. For the change in disease coding, we followed the advice of FIA staff and assumed that all of the early fourth cycle “disease” cases were, in fact, fusiform rust. This overstates actual fusiform rust incidence but apparent rates of infection in the fourth cycle were still lower than those observed in the fifth and sixth cycles.

To separate the “with” from the “without” conditions, the “without” selection scenario used data only from the fourth and fifth surveys, before substantial deployment of genetically resistant seedlings, which might have reduced the infection rates observed in the FIA data. However, empirical analyses were conducted for all three surveys to provide insight into actual patterns of infection and their variability over time. Evaluating the causes of empirical disease patterns is simplified when incidence is stratified by principal causal factors. For fusiform rust, these factors include species, age, stand origin, site quality, alternative host availability, climatic suitability, and genetic resistance of the host, although not all can he addressed using FIA data To minimize impacts of age, our empirical analyses were confined to stands less than 10 years in age at the time of survey, referred to here as "young."[3] All analyses were stratified by dominant species and stand origin, and most analyses were also stratified by site quality. We analyzed infection patterns by survey cycle, although this stratification inevitably reflects a number of causal factors, including availability of oak hosts and year-to-year variations in weather. At least for plantations, changes over time also included genetic changes in seedlings.

Accounting for total pine plantation area-Recent decades have seen dramatic increases in area of southern pine plantations. Sources indicate a doubling from 1970 to 1990, with projections suggesting perhaps a threefold to fourfold increase by the year 2020.’ This historic increase was corroborated by the FIA inventory records, which indicated that young, planted loblolly and slash area increased 75 percent from fifth to sixth survey cycles (roughly 1982 to 1990). However, our extrapolation process is based on acres planted per year, by species and over time, rather than on total plantation area.

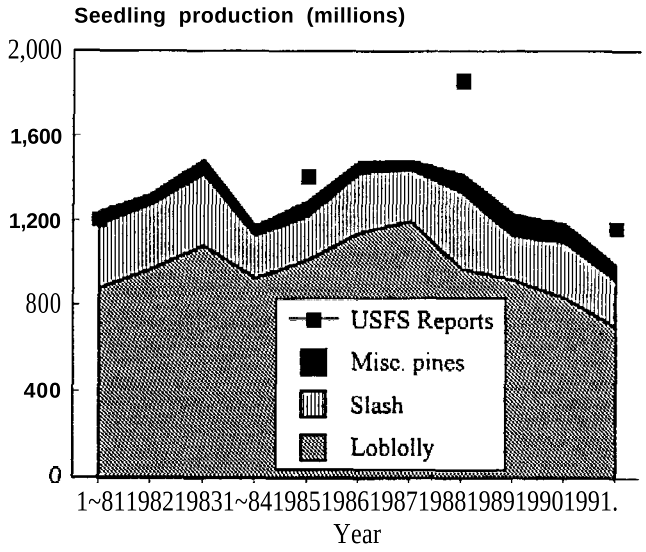

Figure I-Southern pine seedling production estimates (Carey and Kelley 1993). Diamonds indicate southern seedling production estimates (all species) derived from annual USDA Forest Service Planting Reports.

For the years 1970, 1975, 1980 and 1985, we estimated planted area using Forest Service tree planting reports (e.g., Mangold and others 199 1; USDA Forest Service 198 1, 1982; Williston 1980), summing the acres reported planted in the 13 Southern States: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia. Figures did not include seeded acres. For the years from 1990 to 2020, we used unpublished ATL.AS/TAMM projections provided by John Mills.[5]

Because both planting sources described aggregate softwood plantation acres, acres had to be apportioned by species before use. For the years from 1980 through 2020, we used the relative frequencies from a survey of seedling producers reported in Carey and Kelley (1993) to apportion aggregate planted acres to species (fig. 1). Early survey reports indicated an annual average of 74 percent loblolly and 2 1 percent slash for the years 198 1-9 1; we applied these seedling frequencies to total planted pine acres. However, analyses of FL4 data

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[3] Infection rates typically change with stand age due to the interacting processes of new infection and mortality. operational surveys of rust incidence are ideally conducted at age 5, and measures taken at this age are typically used as inputs for yield projections. Because FIA data do not consistently support this more precise age measure across all three cycles, we assumed that infection rates reported over the broader age category (0 to 9 years) are equivalent to infection at age 5. Note that extremely young stands do not contribute to FIA calculations of infection rates, because only stems of 1 in. d.b.h. or greater are tallied. Analysis shows that among those young plantations for which infection rates could be calculated, only 10 percent were coded as younger than 5 years of age.

[4] Personal communication. 1994. David N. Wear, Project Leader, Southeastern Forest Experiment Station, 3041 Cornwallis Research Triangle Park, NC 27709

[5] Personal communication. 1993. John Mills, Research Forester, Pacific Northwest Station, 1221 outhwest Yamhill, Suite 200, Portland, OR 97208-3890

indicated that this distribution had not always prevailed. Therefore, for the years 1970 and 1975, we calculated the relative shares of newly established loblolly and slash plantations from fourth and fifth cycle FIA plot data. Loblolly's share was 63 percent; slash's was 37 percent. Plantations of other softwood species were assumed to be negligible for these years.

Estimation of rust resistance adoption-Forest Inventory and Analysis data from the fourth and fifth forest survey cycles provided the infection rates for the baseline "without" scenario, Simulating the changes in these infection rates under the "with" scenario required information on technology diffusion and selection gain. We needed to know how quickly industry adopted rust resistant selection into their seedling production activities, and how effective that genetic selection has been. To obtain this information, we collaborated with the major southern tree improvement cooperatives in surveying the principal producers of loblolly and slash seedlings, both State and industry.

We surveyed producers of loblolly and slash seeds and seedlings for estimates of their historical and planned production of resistant and total pine seedlings for selected years from 1970 to 2020. We also requested an estimate of the gain in resistance for those resistant seedlings produced in the same years. Gain was defined in the questionnaire as "the relative reduction in infection in your resistant seedlings when compared with infection rates which would have occurred had nonresistant seedlings been planted instead."[6] We also asked for estimates of past expenditures for fusiform rust resistance research and development. Survey questions were developed cooperatively and reviewed by additional Forest Service and university specialists for clarity and relevance, Appendix A shows the questionnaire for slash pine,

The Western Gulf Forest Tree Cooperative and the Florida State Tree Improvement Cooperative sent survey forms for slash pine to their entire memberships. Their combined memberships comprise virtually all slash pine seedling producers in the South. The NCSU-Industry Cooperative Tree Improvement Program sent out questionnaires to loblolly seedling producers. Because industry is more fragmented among loblolly producers, this cooperative surveyed only those members thought to produce fusiform rust-resistant stock. We also contacted two additional nonmember loblolly producers. We made followup phone calls to improve response rate, answer questions, and minimize double counting that could arise from contract production of seedlings. Tree improvement cooperatives provided additional information on gain, diffusion, and research costs.

The slash pine survey provided information that allowed us to calculate the Southwide weighted average resistance gain by year and the proportion of resistant slash seedlings. Because the loblolly pine sampling strategy did not provide complete coverage of total loblolly pine seedling production, we derived estimates of total loblolly seedling production from other sources. For the years 1980,[7] 1985, and 1990, we used direct estimates of regional loblolly seedling production from the Auburn University nursery survey (Carey and Kelley 1993). For the remaining years, estimates of loblolly planting acres were converted to seedlings assuming 768 seedlings per acre, an average derived from a sample of USDA Forest Service Planting Reports from that period.

We obtained estimates of gain for a given species and year by calculating the average gain reported by the different producers, weighted by the number of resistant seedlings they reported for a given year. Thus, the number represents an average across all resistant seedlings for that species. For this survey, resistant seedlings are seedlings where (1) resistance to fusiform rust was an important factor in their genetic selection, and (2) their perceived resistance probably resulted in planting them in areas at risk to fusiform rust infection.

Rust-resistant seedling deployment--The benefit of using resistant seedlings depends on the degree to which those seedlings are planted in locations where their resistance will do the most good, in short, on their deployment. In lieu of explicit empirical information on deployment, we chose to simulate three scenarios: (1) uniform-assumed no information on areas at risk, (2) optimal---assumed perfect knowledge of areas at risk, and (3) total resistance--assumed all plantations were free of infection. The uniform and optimal scenarios were chosen to bracket industry abilities to target resistant seedlings effectively. The total resistance scenario was added to help delimit the maximum benefits possible from increased fusiform rust resistance in these species.

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[6] Gains in resistance are expressed in percentage terms, where 0 percent gain indicates no improvement in resistance over nonresistance-selected stock, and 100 percent indicates total immunity to infection. Thus, if genetically resistant seedlings with a 50 percent gain in resistance are planted in an area that normally experiences 30 percent infection rates, 15 percent of the resistant seedlings should become infected. The terms "gains in resistance" and "resistance gains" are synonymous

[7] The earliest year for which seedling production estimates were available was 1981. The survey's 1981 count was used for 1980 in the absence of a more timely estimate.

Under uniform deployment, resistant seedlings were assigned equally to all combinations of site quality and infection. Uniform deployment simulated the distribution of seedlings that might be expected if seedlings were distributed without regard to their rust resistance, or without any knowledge of which sites were more at risk to fusiform rust infection.

Under optimal deployment, resistant seedlings were assigned to those combinations of site quality and initial infection that benefit the most from gains in resistance. To accomplish this, we calculated for each combination of site quality and infection (“cell”) the change in SEV that would result from a hypothetical 50-percent gain in resistance and ranked thecells from most to least improvement in SEV. The resistant seedlings reported in the producer survey were allocated first to those cells with the greatest benefit and continued through the ranking until the resistant seedlings ran out. Remaining cells received nonresistant seedlings.

Under total resistance, all plantations were assumed to have zero infection levels. This assumption was imposed over all simulation years-past, present, and future--to allow flexibility in constructing hybrid scenarios. For example, the consequences of deploying a breakthrough discovery in the year 2005 might be evaluated by combining the benefits under the optimal deployment scenario for years before 2005 with those from the total resistance scenario for subsequent years.

For the total resistance scenario, adjusting for increased resistance was straightforward-initial infection levels were set to 0 percent on all acres, simulating a 100~percent gain in resistance. For both the uniform and optimal deployment scenarios, adjusting for gains in resistance was only slightly more involved. For those acres planted with resistant seedlings. initial infection rates were adjusted downward based on the average gains in resistance for that species and year. That is, the original infection rates were proportionally reduced by an amount corresponding to the reported resistance gain for that species and year. The resulting infection level was then rounded to the nearest lo-percent infection level, allowing resistant acres to be merged with yield numbers based on their site quality and revised infection level, the same approach used with nonresistant acres.

The aggregation process-To recap, we first defined the base case (“without” selection) by distributing planting acres for each species and each simulation year across the 66 site conditions, using the distributions from the FIA data. We then modified the base-case acres three different ways to represent alternative “with” resistance scenarios {uniform, optimal, and total resistance). Each modification consisted of dividing the acres in each site condition into resistant and nonresistant acres.’ For the resistant acres, we adjusted their resulting infection level downward based on the gains in resistance reported for that year. We repeated this process for each combination of four utilization and two rotation standards.

The next step in the aggregation process was to assign yields to those acres. We merged the per-acre outputs from the stand-level simulations with the corresponding acre figures to yield output numbers suitable for aggregation. For the baseline case, product outputs can be summarized:

$$Volume_{lmt}^{without} = \sum_{i=1}^{2}\sum_{j=1}^{3}\sum_{k=0,10...}^{100} A_{ijkt}\, Y_{ijklm}, \qquad (10)$$

where

i = loblolly or slash;
j = high, middle, or low site quality;
k = fusiform rust infection percentage at age 5;
l = poor, pulpwood, sawtimber, or full utilization scenario;
m = economically optimal or fixed 35-year rotation;
t = simulation year of 1970, 1975, . . .2020.

This equation is modified to include resistant seedlings, representing the various ‘With” resistance scenarios:

$$Volume_{lmnt}^{with} = \sum_{i=1}^{2}\sum_{j=1}^{3}\sum_{k=0,10...}^{100}\sum_{r=0}^{1} A_{ijknrt} Y_{ijklm}, \qquad (11)$$

where

n = uniform, optimal, or total resistance deployment scenario,
r = planted with genetically resistant seedlings or not.

Calculations for SEV and PV used the Same formulas except that the dependent variable represents values rather than volumes.[9]

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[8] For the total resistance scenario, the amount of nonresistant acres was always zero. Only under uniform allocation did every cell have both resistant and nonresistant acres. For the optimal scenario, some cells had resistant acres and some nonresistant, with only one cell having both types of acres. That cell indicated where resistant seedlings ran out with the remainder receiving nonresistant seedlings.

[9] For PV, some timing adjustments were required to account for differences between planting and harvest dates. The regional benefits evaluation simulates planting and harvesting activities every 5th year. For PV calculations, planted acres must be "aged" to harvest year by adding rotation length to their planting year. This addition places some harvests between simulation years. Such years were rounded to the nearest S-year interval (2000,2005,2010. . .) to ensure a complete population of acres for each simulation year.

Summing values over time-To sum SEV’s and PV's over time, annual values must be interpolated between simulation years, and future values discounted to a common year. To fill in the 4 intervening years between each simulation year, SEV’s and PV's are interpolated to generate annual values. These are then discounted back to 1992 using our standard 4-percent discount rate before aggregating. For SEV's, we discounted back from planting date; for PV's, from harvest date.

Timber prices were assumed constant over time, a reasonable assumption when supply effects are small enough to have modest impacts on regional prices. The aggregate volume estimates were used later to check the validity of this assumption. Discounting to a common year adjusted for the future value of money and is necessary when comparing costs and benefits that occur at different times.

Implementation details--Our simulation scheme resulted in 726 separate base-case acreage figures, corresponding to 2 species by 3 site-quality classes by 11 infection levels by 11 simulation years. We replicated each base-case acreage record eight times to provide for the different “with resistance” scenarios evaluated, corresponding to the different combinations of utilization and rotation standards employed.[10] We merged these acreage records with the corresponding stand-level yield records and multiplied the per-acre volumes and values by the *acres* in that class, then summed the resulting values across site classes and infection classes to provide totals by species and simulation year for each simulation scenario.

We computed aggregate volume and value for each combination of utilization (poor, pulpwood, sawtimber, and full) and rotation standard (economic, optimum, and fixed). Within each of these combinations, separate aggregate values were calculated for each deployment option, permitting comparison of timber supplies and values “without” rust protection (the base case) with those of different scenarios of increased rust resistance (the cases “with” fusiform rust research improvements).

Benefits calculations-Benefits were. calculated for each simulation year by subtracting SEV for a “without” base case from the SEV for one of its corresponding “with” deployment scenarios. These comparisons were possible for each of the three deployment scenarios in each of the eightutilization-by-rotation standards, and for each of the 11 simulation years. Soil expectation value provided a useful comparison for such “point-in-time” comparisons.

To compare benefits with costs, both benefits and costs must be summed over time. We used PV to prevent the double counting of future rotations that occurs when aggregating SEV’s over time. Summing PV over time requires some adjustments in time. To simplify data and processing requirements, we simulated planting activity every 5th year, from 1970 through the year 2020, To aggregate PV by harvest year, we first computed the harvest year for each set of acres, adding rotation length to their planting year. Because such years could fall between the 5-year simulation intervals, we reassigned each to the nearest simulation year, a rounding process which ensured compatible totals of PV for each simulation year.” Once aggregated to these simulation years, annual benefits can be calculated by subtracting the PV's of the base case from those of the different deployment scenarios. For aggregation over time, these annual benefits were interpolated to fill in the intervening years between simulation years before discounting and summing.

Note that the various utilization and rotation standards represent alternative assumptions of prevailing forestry practices in the South. Each combination of utilization and rotation standards has one “without” case (base) plus three “with” improved resistance cases (uniform, optimal, and total resistance). The choice of uniform or optimal deployment represents a third set of alternatives about prevailing practices, which together bracket real world conditions. The total resistance scenario is an entirely hypothetical condition where fusiform rust never existed. Summing the values of this unattainable condition enables estimation of total fusiform rust damages Southwide over the simulation period.

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[10] The base-case acres are the same between the different utilization and rotation standards, and the total number of acres per species is the same across all the deployment scenarios. Thus, reproducing the base-case acres across all these scenarios would seem unnecessary. However, each utilization and rotation standard produces different yields for the different site conditions and hence, different marginal benefits of resistance. The different site conditions might, therefore, rank differently and result in different allocations of resistant seedlings under the optimal deployment scenario. Therefore, we used separate base-case acre estimates for each scenario.

[11] The 15-year spread in rotation ages that occurs across conditions in the economic rotation scenario has implications for the aggregated numbers in the beginning and ending years of the simulation period. For example, some of the stands planted in 1970 were harvested as early as 1990, while those with longer rotations were not harvested until 2005. For the same reason, harvests reported in the year 1990 did not include harvests from plantations with long rotations that were planted before 1970. Similar processes affected the aggregate values for the ending harvest years. Because this evaluation involves differences from baseline, where this process also occurs, the “priming effect” does not affect conclusions over the differences from baseline (benefits) but should be kept in mind when examining the detailed information from which these differences were derived.

Research Costs

Research costs for the fusiform rust program evaluation were collected from seedling producers, research cooperatives, the Forest Service, and other unpublished data sources. The survey canvassing the university cooperatives and principal producers of loblolly and slash pine seedlings included questions on past annual resources they expended on fusiform rust research or development in 1970, 1975, 1980, 1985, and 1990 (Appendix A). To simplify this task, respondents could specify resources in either dollars or scientist-years. We used other sources to obtain expenditures for Forest Service research and to translate scientist-years into dollars.

The Forest Service provided a precise estimate of the full-time equivalents (FTE's) and total budgets spent annually for fusiform rust research from 1976 to 1993, based on an historical tally of the research work units and scientists in the South.” In addition, we obtained estimates of university forestry research expenditures and research FTE's from the Southern National Association of Professional Forestry Schools and Colleges (NAPFSC) summaries.” We used the Southern NAPFSC data to calculate an average annual cost per forestry research FTE (or scientist-year). Similarly, the Forest Service data were used to calculate an average annual fusiform rust research cost per FTE. Because neither the Forest Service nor the NAPFSC data covered all the relevant years for which fusiform rust research was performed, simple linear regressions of the average research cost per FTE as a function of year were performed to fill in data for missing years. To calculate the average research costs per FTE for the industry, we computed a simple average of the (lower) Forest Service costs and (higher) university costs.

Simple linear interpolation was used to estimate the annual research expenditures for both university cooperatives and seedling producers. For each sector, we used costs per FTE times the number of FTE's, plus research expenditures, to calculate the total research costs for each sector and for the South per year.

Benefit:Cost Computations

Once we had estimated all the stand-level financial impacts, regional aggregate economic benefits, and regional research costs of fusiform rust research, we were able to compute the regional cost and benefits of fusiform rust research. The benefit:cost (B/C) ratios and net benefits were calculated with all benefits and costs indexed to a common year. We compounded the research costs for the region to 1992, the base year used for the financial analyses, at a 4 percent real interest rate. Similarly, we discounted all the benefits of improved fusiform rust protection back to 1992 using a 4-percent real discount rate,

Calculating the B/C ratios and the net benefits was computationally simple. For the B/C ratio, we divided the aggregated research benefits by the single regional research cost term for the various scenarios. For the net benefits, we subtracted the single aggregated regional research cost term from the aggregated research benefits for the various scenarios. Given the detailed analyses made to calculate the biological, financial, and regional impacts of increased fusiform rust resistance in southern pines, the estimated total research benefits should be reasonably accurate. The cost estimates, while simpler to obtain, may not be as precise. Simple sensitivity analyses of costs could be performed by merely multiplying the base costs by some factor to examine the effects of their variation on the net benefits associated with fusiform rust research.

Results and Discussion

The results of this research are summarized in five sections: (1) adoption of rust resistance, based on the data provided by southern tree improvement cooperatives and forest industry; (2) regional fusiform rust infection patterns, based on analysis of the FIA data; (3) stand-level fusiform rust physical and financial impacts; (4) aggregate regional. impacts of fusiform rust protection research; and (5) overall B/C analyses for rust resistance research.

Adoption of Rust Resistance

The response rate from the questionnaire sent to seedling producers was generally good. Over four-fifths of the organizations contacted provided at least some quantitative information on seedling production or resistance gain, with only one nonrespondent. For slash, comparisons with other estimates of production indicate the responses covered about half of total slash seedling production. Responses to questions addressing recent accomplishments were the most complete, with somewhat fewer responses for the earliest period (1970) and even fewer for projections far in the future. Questionnaires where estimates for all dates were provided indicated a pattern of rising gains in resistance and production of resistant and total seedlings in the 1970's and 1980's. These increases

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[12] Personal communication. 1994. Richard S. Smith, retired, USDA Forest Service, P.O. Box 96090, Washington, DC 20090-6090.

[13] Personal communication. 1994. Arnett Mace, Dean, D.B. Warnell School of Forest Resources, University of Georgia, Athens, GA 30602

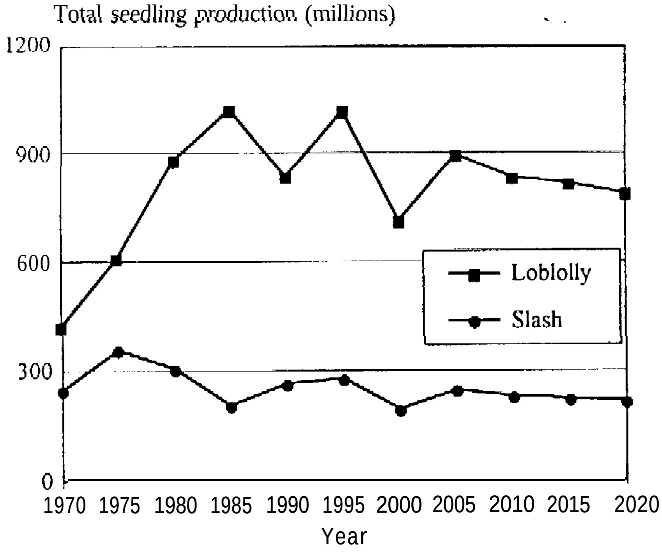

Figure 2–Southwide loblolly and slash pine seedling production, reconstructed using responses from a survey of seedling producers and other data.

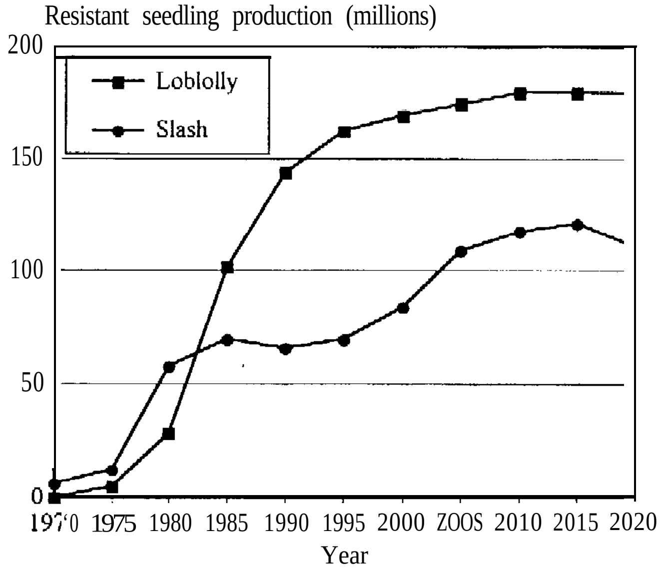

Figure 3–Southwide production of loblolly and slash pine seedlings genetically selected for their resistance to fusiform rust, based on a survey of seedling producers,

leveled off in later years, We used this general pattern to avoid problems caused by missing values in incomplete survey responses. In cases where organizations declined to project future production levels, we assumed the last production rates provided would be maintained. No substitutions were made for missing estimates of resistance gain; calculation of average gain was based solely on actual responses.

Total seedling production-Figure 2 shows the reconstructed estimate of total loblolly and slash seedling production over time, based on survey results and external estimates of seedling production. They show a dramatic rise in production for loblolly from 1970-85, rising to 1 billion seedlings per year. This rise is followed by modest declines. Responses from slash seedling producers indicate gradually declining production through the period.

Resistant seedling production-Figure 3 shows the reported production of resistant loblolly and slash seedlings over time, showing steadily increasing production of resistant seedlings. Starting from virtually zero in 1970, production of resistant seedlings exceeded 210 million seedlings Southwide by 1990. Production of resistant slash began more quickly than for resistant loblolly but was numerically outstripped in the early 1980's as loblolly increased in popularity.

Adoption rates appear somewhat different when adjusted for each species' total production (fig. 4). Using this measure, adoption of genetic resistance in slash pine has been more rapid than in loblolly. In slash, resistant lines now apparently account for more than 40 percent of production and are expected to plateau at between 70 percent and 80 percent by the year 2010. In loblolly, the diffusion of resistance has been much less complete. Currently, just over 15 percent of loblolly seedling production is identified as fusiform rust resistant, and resistant seedlings are not expected to account for more than 25 percent in the foreseeable future. Note, however, that respondents expressed difficulty projecting future production decisions, and their responses represent their best judgments. For loblolly, the adjusted percentage is a ratio of two independently derived measures: survey responses and planting acreage projections. Its accuracy should, therefore, be viewed as the more tenuous.

Resistance gain-Equally important to total production of resistant seedlings is the increased resistance in those seedlings. Producers thought resistance increased continually over the survey period (fig. 5). The expected gains in resistance for both species began at low levels in the early 1970's. However beginning in the late 1980's, gains in slash pine resistance surpassed loblolly and were expected to maintain greater gains in the foreseeable future. Industry experts expected gains in resistance in slash to eventually exceed 60 percent, compared to just above 40 percent for loblolly. For seedlings currently being produced, average gains in resistance were estimated to be around 45 percent for slash and 30 percent for loblolly.

These gain numbers were averaged across seedling lines designated as fusiform rust resistant. Many respondents,

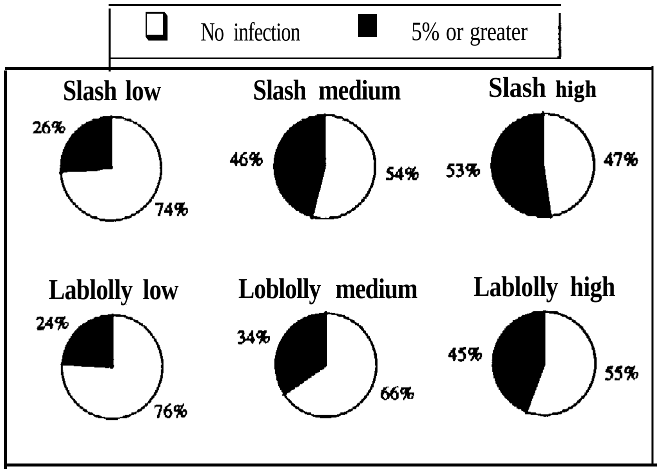

Figure &Proportion of young planted pine acres with 5 percent or more of stems infected in FL4 survey cycle 4 (1968-1977), broken out by site quality.

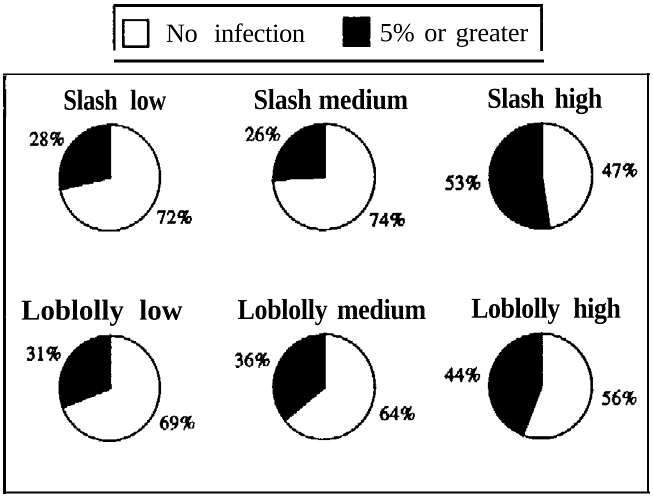

Figure 9-Proportion of young planted pine acres with S percent or more of sterns infected with fusiform rust in FIA survey cycle 5 (1978-1986), broken out by site quality.

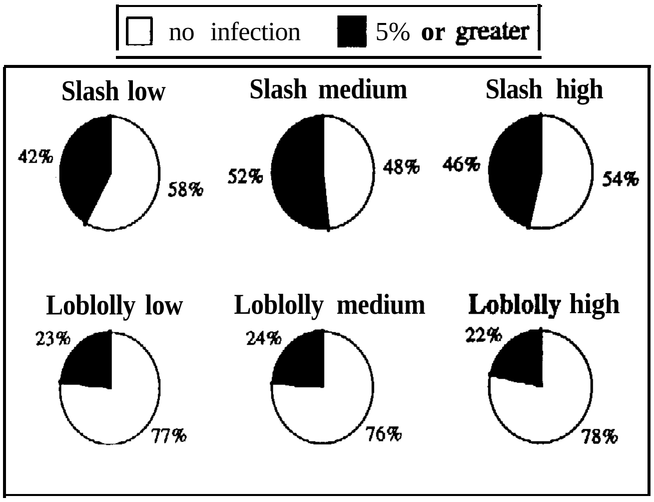

Figure I&-Proportion of young planted pine acres with 5 percent or more of stems infected with fusiform rust in FIA survey cycle 6 (1986-1993), broken out by site quality.

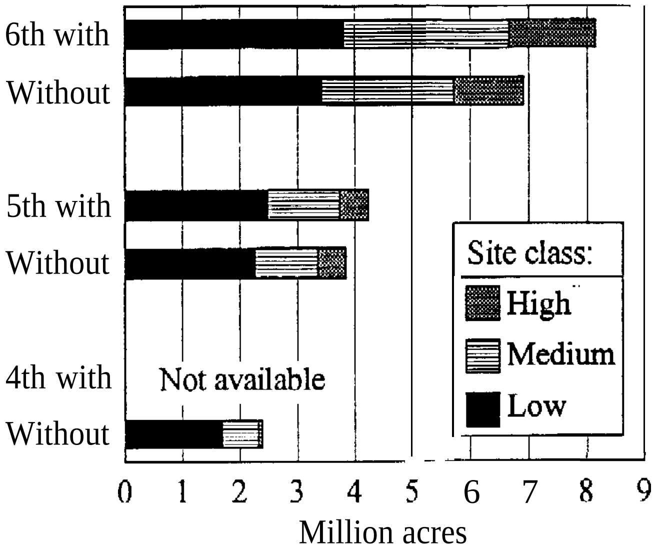

Figure 1 l-Acres of young slash pine plantations by survey cycle and site quality class. The "with" indicates Southwide tallies, "Without" indicates that AR, MS, and TN are omitted.

for each of the three survey cycles. To remove population differences from the comparisons, the table contains two sets of numbers for the fifth cycle, The "Without AR, MS, and TN" set contains the same population of States available for the fourth cycle. The "With all States" set matches the complete sample reported in the sixth cycle.

Table 3 shows that in the fourth cycle young, natural slash stands were located farther south than young slash plantations, but this difference was eliminated by the fifth cycle. As infection rates for slash are higher at more northern latitudes, the location difference would have acted to reduce infection rates in natural slash in the fourth cycle relative to those in plantations. It is not clear, however, whether the l-degree latitude shift sufficiently explains the twofold infection difference.

Site class-When infection patterns in plantations are broken out by site quality as shown in figures 8,9, and 10, three patterns emerge:

1. Infection rates increased consistently with increasing site quality for both slash and loblolly plantations in both the fourth and fifth cycles. This agrees with the widespread belief that better quality sites are generally at greater risk to fusiform rust.

2. In young plantations, infection rates in slash and loblolly were quite similar once site quality was taken into account. These are, however, aggregate statistics based on only one of various ways of defining site classes. The aggregation process obscures differing distributions of the species across the South, differing patterns of development of the disease as stands age, and differences that might occur for infection levels higher than 5 percent.

3. Similarity in infection rates between species, and increasing infection with improving site quality, held for the fourth and fifth cycles but disappeared in the sixth. In the sixth cycle, infection rates for slash were twice those for loblolly, and infection rates for both species were nearly constant across different quality sites.

The loss of site-quality differences in cycle 6 might have resulted from increased deployment of resistant seedlings to the highest quality sites. Given the past correlations between site quality and infection and the patterns of economic impacts explored later in this paper, such a strategy makes economic sense. However, shifts in the genetic makeup of planting stock do not explain the more recent difference in infection rates between species. Seedling producers thought genetic selection and production of resistant seedlings were more successful in slash than in loblolly, but infection rates are substantially higher in slash plantations.

Class and location--Shifts in latitude can be tested for their role in the divergence of infection rates between species. Such a divergence would be consistent with a northward shift in either loblolly or slash plantations. However, table 3 shows that plantations of both species shifted southward rather than northward over the three cycles.

Shifts in longitude are somewhat more promising. Both species have shifted westward over the period of interest. As was shown earlier, the statistical correlation between longitude and infection was marginal in the simple model used, However, the sign of the correlations implies that westward shifts would be associated with increased infection for slash and reduced infection for loblolly, as has been observed. Because this is a qualitative comparison, it is not clear whether the spatial shift in distributions quantitatively accounts for the divergence between species' infection rates.

Shifts in site class and species-The different species and site classes described here are not equally common in the South, nor has their relative importance remained constant over time. Figures 11 and 12 show the acres of young slash and loblolly plantations for each survey cycle subdivided by site class. The graphs also illustrate the impact of omitting Arkansas, Mississippi, and Tennessee from the Southwide tallies. Including both "with" and "without" totals for cycles 5 and 6 allowed us to compare populations across all three survey cycles and estimate the probable impacts of excluding these States from fourth cycle totals.

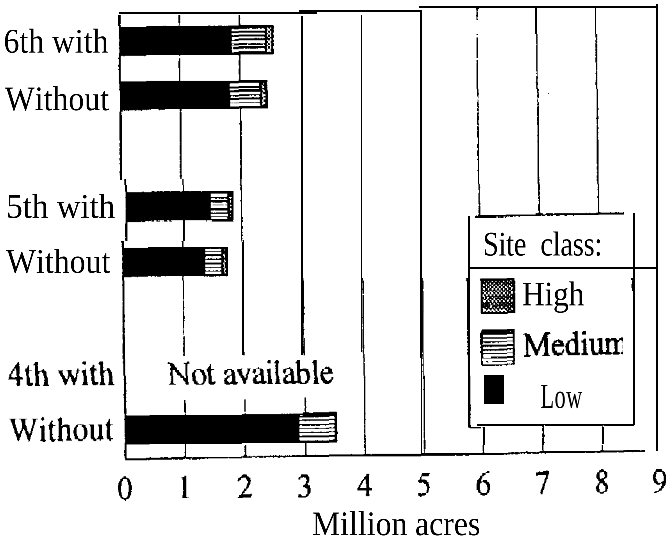

Figure 12--Acres of young loblolly pine plantations by survey cycle and site quality class. The "with" indicates Southwide tallies, "Without" indicates that AR, MS, and TN are omitted.

Forest Inventory and Analysis data (figs. 11 and 12) on young plantations (aged less than 10 years) support several conclusions:

1. Slash pine has enjoyed varying popularity over the period surveyed, with slash plantation acreage dropping from 3.5 million acres in cycle 4 to 1.9 million acres in cycle 5 but rebounding to 2.6 million acres by cycle 6. These figures understate the early decline in slash plantations because the fourth cycle figures omitted Mississippi, a State where later surveys reported significant amounts of slash pine.

2. Young loblolly plantation acreage has climbed steadily, almost tripling over the three survey cycles.

3. Combined acreage of young plantations dropped slightly from fourth to fifth cycles (5.7 percent) but increased by three-quarters by the sixth.

4. Shifting preferences moved loblolly from a minority 40-percent share of combined plantation acreage to a dominant three-quarters share by the sixth cycle.

5. Most plantations occurred in the lowest site-quality class, especially for slash. However, this dominance weakens over time as more new plantations appeared in the better site quality classes. The shift over time may be due to afforestation on better quality sites or improvements **in management.** Because FIA crews base site-quality estimates on the early growth of seedlings, any of a number of factors may be responsible for the apparent improvement, including changes in genetic stock, fertilization, or weed control.

6. The distribution of site qualities for a given species and time period was fairly insensitive to inclusion of Arkansas, Mississippi, and Tennessee. However, the three States together accounted for 6.4 and 4.8 percent of young slash pine plantation acreage in the fifth and sixth cycles and 10.5 and 17.8 percent of young loblolly plantation acreage.

Regional distributions-We generated distributions of young plantation acreage by site quality and infection level from FIA data for slash and loblolly for each survey cycle. Tables 4 and 5 show the relative distributions. The tables reiterate the correlation between lower quality sites and lower infection rates, and show distributions skewed toward, the lower infection levels, Stands with greater than 50 percent infections generally make up less than 10 percent of acreage for a given species, cycle, or site quality. Table 6 shows the distribution we used for the regional extrapolation, calculated from the combined FL4 records for cycles 4 and 5. The distribution was calculated by pooling all young plantation plot records from the fifth and sixth cycles and calculating a distribution weighted by each plot's expansion factor. This approach produced an area-weighted frequency distribution somewhat biased toward the more recent survey because planting activity increased over that period.

Stand-Level Impacts

The tables in Appendix B show product yields and SEV's for stands with different initial conditions. In the absence of rust, the simulations showed markedly increasing yield for the higher site qualities, particularly for sawtimber volumes. The merchandising routines placed most of the timber in the chip-n-saw and sawtimber products, with relatively little volume going directly to pulp in uninfected stands. Economically optimal rotations were always less than the 35 years assumed for the fixed rotation. Consequently, the economic rotation tables all have smaller yields but larger SEV's than in the corresponding fixed rotation tables. Volumes and SEV's at zero infection are identical across the different utilization standards because these standards only affect merchandising of infected stems.

Increasing levels of rust infection shifted volumes away from sawtimber and into pulp, illustrated in figure 13 for loblolly, Under the highest utilization standard, total loblolly stand volumes may actually remain fairly constant across different infection levels. However, for loblolly's three lesser utilizations and for all of the cases for slash, high levels of rust brought lower total stand yields and product quality (figs. 13 and 14). Generally, the decline in yield and product quality at higher infection levels resulted in greater drops in value at the lesser utilizations (fig. 15). Although high infection levels proved damaging, infection levels of around 10 to 20 percent sometimes resulted in increases in value compared with the no-rust case. This generally occurred in slash plantations and particularly on high-quality sites at high utilizations.

Total volume per acre increased with infection on slash pine stands up to about 30 percent infection on high-quality sites and up to about 20 percent infection on low-quality sites. This increase was apparently due to a competitive release of infected and uninfected trees, allowing more volume accretion on fewer stems. The stand-level economic benefits of reductions in fusiform rust infection rates can be computed from these tables by subtracting the SEV at the *initial* infection rate from the SEV at the *subsequent* infection rate. For example, in table Bl-Loblolly pine plantation yields for differing site qualities and age-5 fusiform infection rates under the full utilization and economic rotation assumptions-the economic benefits of reducing fusifonn rust infection rates from 60 to 30 percent in loblolly pine stands (i.e., rcprcsenting a 50-percent gain) with a high site index and full timber

Table 4--Percentage of 0- to 9-year-old loblolly pine plantations Southwide by site quality and infection class for fourth through sixth survey cycles

	Infection (percent)										
Cycle/site quality	0	10	20	30	40	50	60	70	80	90	100
	Acres in cycle (percent)										
Fourth cycle[a]											
High	1.7	0.6	0.8	0	0	0	0	0	0	0	0
Middle	18.5	2.5	2.9	2.3	.8	0	.5	.5	0	0	.2
Low	52.2	4.5	4.2	2.7	.7	1.0	.6	1.3	.5	.2	.8
Fifth cycle											
High	8.8	1.7	1.8	1.6	.6	.5	.2	0	.2	0	.2
Middle	21.0	3.4	2.6	1.9	1.2	1.3	.3	.4	.2	0	.3
Low	35.7	3.5	3.4	3.1	2.2	2.3	.3	.5	0	0	.4
Sixth cycle											
High	16.2	1.3	1.3	.7	.1	.3	.3	.1	.1	0	.2
Middle	28.1	4.5	2.4	1.4	.3	.1	0	.2	0	0	.1
LOW	32.5	3.9	1.4	2.0	1.2	.5	.2	.1	.2	.1	.2

[a] Fourth cycle data omits Arkansas, Mississippi, and Tennessee and for some States includes infections other than fusiform rust.

Table 5--Percentage of 0- to 9-year-old slash pine plantations Southwide by site quality and infection class for fourth through sixth survey cycles

	Infection (percent)										
Cycle/site quality	0	10	20	30	40	50	60	70	80	90	100
	Acres in cycle (percent)										
Fourth cycle											
High	0.4	0.2	0.2	0	0	0	0	0	0	0	0
Middle	9.6	2.2	2.2	.8	1.4	.7	.2	.2	.3	0	.1
Low	60.5	3.6	4.7	5.4	2.1	2.1	.8	.4	.8	.3	.7
Fifth cycle											
High	2.7	0	.5	1.5	0	0	0	.5	.5	0	0
Middle	13.8	.5	.5	1.4	0	.5	0	0	1.0	.5	.5
Low	54.4	6.3	4.6	3.4	1.8	1.4	1.4	1.0	.2	.3	1.1
Sixth cycle											
High	4.0	0	1.9	0	.8	0	.4	.4	0	0	0
Middle	11.4	1.7	3.3	2.2	1.5	2.0	.8	0	.2	0	.8
Low	39.9	6.8	6.1	6.0	2.6	2.4	2.1	1.4	.2	.5	.6

[a] Fourth cycle data omits Arkansas, Mississippi, and Tennessee and for some States includes infections other than fusiform rust.

Table 6--Percentage of 0- to 9-year-old slash pine and loblolly plantations Southwide by site quality and infection class **for combined survey cycles 4 and 5**

	Infection (percent)										
Cycle/site quality	0	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
	Acres in cycle (percent)										
Slash											
High	1.1	0.1	0.3	0.5	0	0	0	0.1	0.1	0	0
Middle	10.9	1.7	1.7	1.0	1.0	.6	.1	.2	.5	.1	.3
LOW	58.7	4.4	4.6	4.8	2.0	1.9	1.0	.6	.6	.3	.8
Loblolly											
High	6.1	1.3	1.4	1.0	.4	.3	.1	0	.1	0	.2
Middle	20.1	3.1	2.7	2.1	1.0	.8	**.4**	.5	**.1**	**0**	.3
LOW	41.9	3.9	3.7	3.0	1.7	1.8	.4	.8	.2	.1	.5

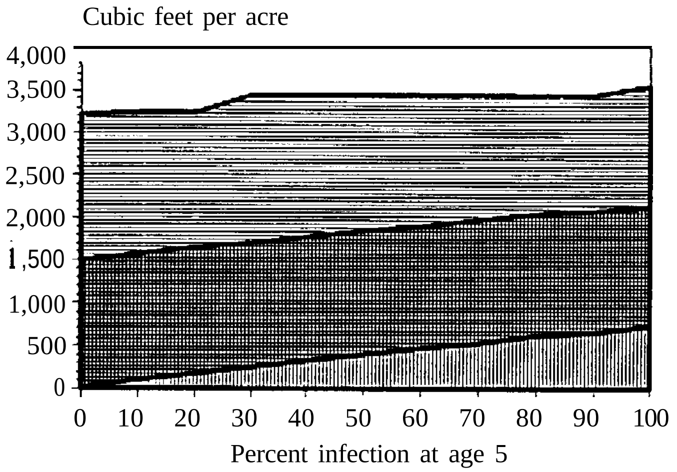

Figure 13--Pulpwood, chip-n-saw, and sawtimber volumes harvested from loblolly pine plantations under different levels of early fusiform rust infection. Data were obtained from simulations of growth, yield, and merchandizing that assumed economically optimal rotation age, full utilization of infected stems, and a medium-quality site (SI 65).

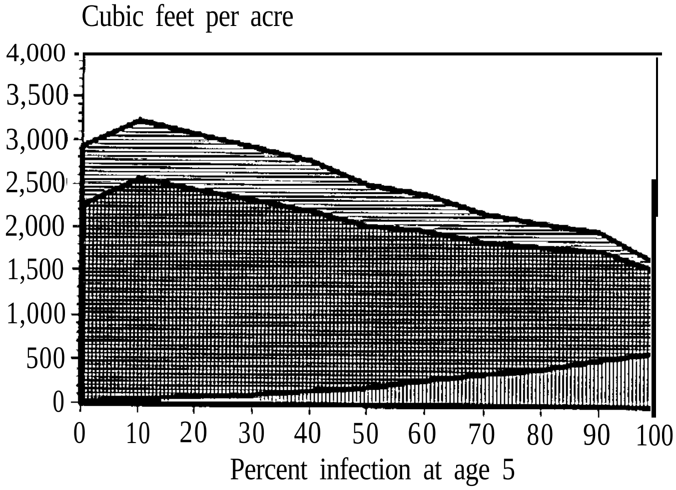

Figure 14--Pulpwood, chip-n-saw, and sawtimber volumes harvested from slash pine plantations under different levels of early fusiform rust infection. Data were obtained from simulations of growth, yield, and merchandizing that assumed economically optimal rotation age, full utilization of infected stems, and a medium-quality site (SI 60).

utilization are $90 per acre ($2,243-$2,153). In loblolly plantations, reducing rust virtually always yielded a positive economic benefit.

In slash plantations, the economic benefits to reduced rust infection were often negative at the low initial levels of infection. Managers predicting infection rates that fall in this range have little economic incentive to reduce infection. On the other hand, the incremental benefits of reducing fusiform rust infection increase with site index over the high range of infection levels. Therefore, managers must be able to predict infection rates to determine their best planting strategy.

As expected, utilization standard had a large effect on the magnitude of physical and economic damages from fusiform rust infection. The absolute level of damage was generally higher for stands managed on short rotations than on long rotations for poor utilization standards; the opposite was true for full utilization.

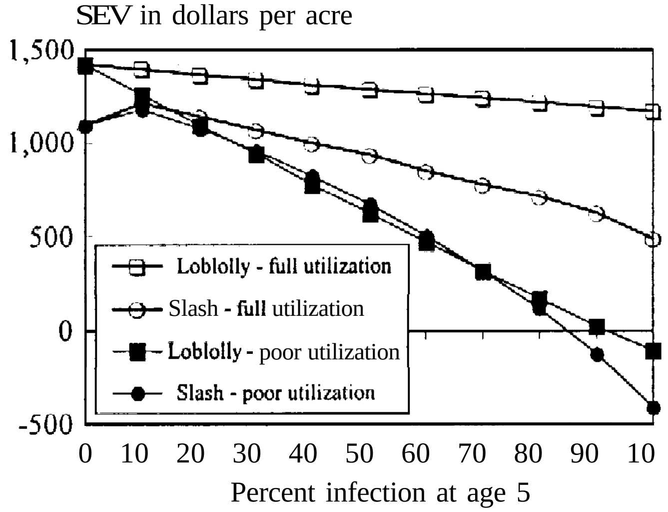

Figure 15–Soil expectation values (SEV) for loblolly and slash plantations assuming either full or poor utilization of infected stems across a range of early fusiform rust infection rates. Results shown are for economically optimal rotations on medium-quality sites.

The marginal benefits of reducing infection rates on loblolly and slash pine stands managed on short rotations with high utilization standards generally increased with site index. Marginal benefits of reductions in infection rates increased with site index for loblolly stands with poor utilization standards, regardless of rotation length. The marginal benefits of reductions in infection rate were higher on short rotation stands than on long rotation stands, regardless of site index.

Two cautions are warranted regarding these tables. First, simulation results at the highest infection levels and for the 35-year rotations push the limits of the yield models and their underlying data and should be viewed as less reliable than those for conditions more commonly encountered in the field. Second, stochasticity in the merchandising routines may be responsible for modest anomalies in individual numbers but do not alter the general patterns discussed.

Aggregate Benefits

Aggregating the volumes and SEV's in tables B 1-B 16 using the acres in the various base-case scenarios produced eight sets of regional totals that varied over time, one for each combination of utilization and rotation standards. While the volume estimates do not directly contribute to a financial evaluation of benefits and costs, they highlight the importance of valuing product shifts and permit reappraisal of constant price assumptions.

Volume benefits by year-The regional plantation harvest volumes show patterns that echo those from the stand-level evaluation. First, rust resistance had a negligible effect on total harvest volume. Even complete resistance to rust failed to change total plantation harvests by more than 1 percent under all scenarios except one. Under the poor utilization standard, where infected stems were assumed left in the woods, harvests increased in the final simulation years by as much as 5 percent under the optimal allocation scenario and 9 percent for the total resistance case.

Second, relatively little harvest volume went to the pulp product class. Pulp represented about 3 percent of baseline harvest volumes for most scenarios and years simulated, jumping to 9 percent in the pulpwood utilization case. Although generally small in absolute terms, pulp volumes were sensitive to rust resistance, dropping to even lower shares of harvest under the uniform, optimal, and especially the total resistance scenarios compared with the no-resistance, baseline case. Pulpwood harvests dropped to near zero in the total resistance scenarios.

Third, chip-n-saw and sawtimber products were important products under all scenarios investigated, but their relative dominance depended on rotation assumptions. Chip-n-saw accounted for roughly 55 to 60 percent of harvest volume under economically optimal rotations but under the fixed 35-year rotation, sawtimber volumes accounted for the dominant share.

Fourth, rust resistance shifted harvests toward higher valued products, but these shifts were generally small. Except in the pulpwood utilization scenario, shifts were limited to only a few percentage points of overall volume, moving from pulpwood into the higher valued products.

Because chip-n-saw constitutes an intermediate product class, it ultimately contributes wood to both sawtimber and pulp chip markets. Accounting for this contribution alters the apparent effects of resistance on overall pulp and sawtimber supplies. If we assume that chip-n-saw supplies equal volumes to pulp and sawtimber markets (Koch 1972), we can evaluate the relative pulp and sawtimber shifts from the baseline case implied by the genetic resistance scenarios.

Under the higher utilization scenarios, projected increases in resistance resulted in shifts in pulp and dimension wood supplies of less than 3 percent assuming optimal deployment, and even less under uniform deployment. Total eradication of infection would reduce pulp supplies to the market by 6 to 9 percent under these assumptions and increase sawtimber supplies 2 to 3 percent above those in the baseline.

If the industry pulps all infected stems, supply shifts would be more responsive to resistance. Pulp supplies could drop 19 percent under economic and 26 percent under 35-year rotations, balanced by increases in sawtimber supplies of 9 to 10 percent. Should the industry leave infected stems in the woods, both pulp and sawtimber supplies would be increased by improved resistance. Projected improvements in resistance would ultimately increase supplies by 1 to 5 percent, while eradication would increase them by 9 percent.

These supply shifts apply only to outputs from loblolly and slash plantations. Southern pine plantations accounted for only 14 percent of southern softwood supplies in 1984, although this share is projected to increase to 65 percent by 2030 (USDA Forest Service 1988). Even so, the modest supply shifts projected to result from genetic resistance to fusiform rust are generally small enough to support our assumption of constant prices.

Financial benefits by year-Variations over time for the different base cases were driven primarily by changes in planting activity. Figure 16 illustrates this finding for the full utilization, economic rotation base case. Aggregate SEV's and planted acres more than doubled between 1970 and 1985 but then dropped sporatically back to intermediate levels. Figure 16 also shows that loblolly made up most of these aggregate values, in keeping with its much larger share of plantation acres, Aggregate base-case values under fixed rotations and less intense utilization were somewhat less, but followed similar dynamics.

The simulations of improved genetic resistance produced three additional trend lines for each base case. Figure 17 repeats the base-case aggregate value from figure 16 and adds lines for the corresponding uniform deployment, optimal deployment, and total resistance scenarios. Several general patterns were apparent. First, regardless of variations over time, the deployment scenarios consistently ranked the same, with base case the least valuable followed by uniform and optimal, with total resistance the most valuable. Second, the uniform and optimal cases started out the same as the base case in 1970, but diverged upward over time as resistance technology was increasingly adopted by industry. Third, total resistance SEV's roughly paralleled those of the base case and provided a cap that the uniform and optimal values approached but never reached. The differences between these scenarios were small relative to the overall value of plantations. For the full utilization and economic rotation scenario, resistant seedlings ultimately increased aggregate plantation values by only 0.6 percent under uniform deployment and 1.3 percent if deployment was optimal. Under these assumptions, even total eradication of rust would increase plantation values by only 2.1 percent, although under poor utilization, total resistance could increase SEV's by as much as 12.7 percent.

While the relative differences between the scenarios may be small, their absolute differences are more central to this "with versus without" comparison, specifically the differences between the three resistant seedling scenarios and the base case. The differences for two scenarios are shown graphically in figures 18 and 19. Benefits were much higher under poor utilization (fig. 18), but in both scenarios increasing resistance over time resulted in a gradual rise in benefits under the uniform case, a more rapid rise under optima! deployment, but in neither case attaining the maximum, represented by the total resistance line.

Table 7 reports the base-case values plus the differences above base for four of the eight scenarios. Patterns for the four cases not shown were always intermediate between these four extremes. Not surprisingly, aggregate base-case values were larger under more intensive management, represented by full utilization and/or economic rotation. Base-case SEV's varied over time but paralleled each other.

The improvements in SEV shown under total resistance measure the economic damages fusiform rust causes across the region and represent the maximum annual benefit achievable from genetic resistance to fusiform rust. Such benefits differed substantially depending on the utilization and rotation standards evaluated, but year-to-year fluctuations were much smaller. This occurred because under the assumptions we used, year-to-year fluctuations were caused by changes in species mix and Southwide planting area; genetic resistance and fusiform rust infection rates remained constant for both the base case and total resistance standards.

For the uniform and optimal standards, changes in genetic resistance and resulting infection levels led to longer-term shifts in plantation value and benefits over the base case. Under optimal deployment, these benefits climbed steadily toward the total resistance benefits, eventually reaching full potential benefits only under the assumptions of full utilization and fixed rotations. Under other conditions, benefits from optimal deployment remained below those from total resistance, indicating that under most sets of assumptions, substantial improvements were still unrealized. When seedlings were distributed randomly rather than optimally,- benefits remained substantially lower, generally less than half those achieved under optimal deployment.

Present values were also aggregated by year (not shown), but their aggregation was by harvest date. Thus, while both PV and SEV followed the same dynamics and trends, patterns for aggregate PV were shifted roughly 20 to 35 years later, depending on the rotation assumption.

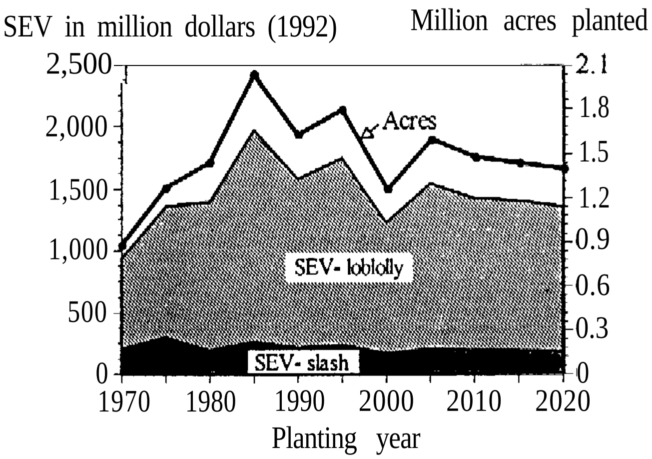

Figure 16--Southwide aggregate soil expectation values (SEV) for loblolly and slash pine plantations under the baseline scenario of no genetic selection for resistance to fusiform rust. The line indicates Southwide planting activity assumed in the simulation, the major determinant of the year-to-year variations shown.

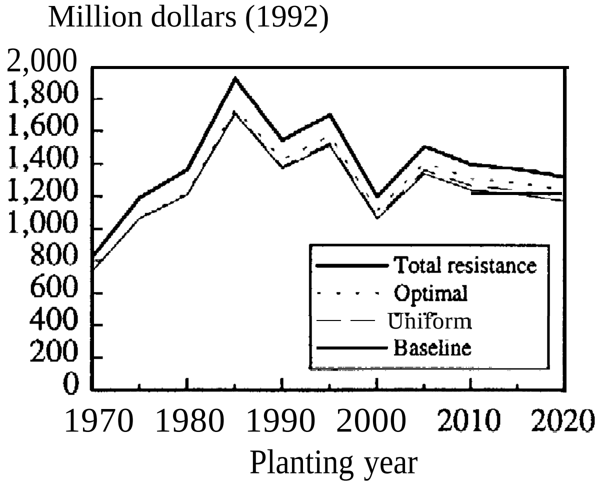

Figure 17-Aggregate soil expectation values of southern loblolly and slash plantations for the four deployment scenarios investigated. Values shown assume economically optimal rotations and poor utilization of infected stems.

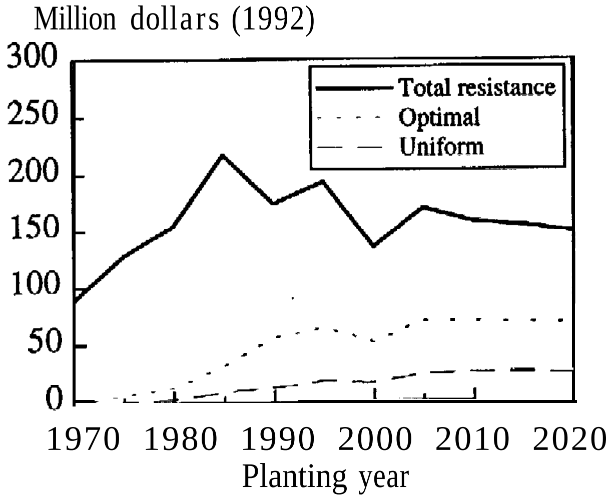

Figure 18--The annual benefits of genetic resistance to fusiform rust **assuming** uniform or optimal deployment of genetically resistant seedlings or total resistance to fusiform rust Poor utilization and economically optimal rotations are assumed, and benefits are calculated as the difference in aggregate soil expectation values from those in the baseline scenario.

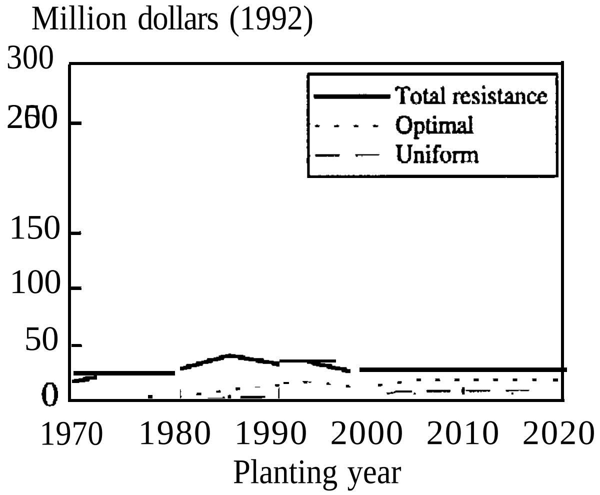

Figure 19--The annual benefits of genetic resistance to fusiform rust assuming uniform or optimal deployment of genetically resistant seedlings or total resistance to fusiform rust. Full utilization and economically optimal rotations are assumed, and benefits are calculated as the difference in aggregate soil expectation values from those in the baseline scenario.

Table 7-Annual soil expectation values (SEV) for Southwide loblolly and slash pine plantations

Planting year	Economic rotation				Fixed rotation			
	Base case’	Uniform	Optimal	Total resistance	Base case	Uniform	Optimal	Total resistance
	Million constant dollars							
		Difference from *base*[b]				*Difference from baseb*		
Poor utilization								
1970	**733**	0	0	**89**	**549**	0	0	**64**
1975	**1064**	1	**7**	**128**	**796**	0	**5**	**92**
1980	**1210**	**3**	**13**	**154**	**902**	**2**	**10**	110
1985	**1710**	**9**	**32**	**217**	**1275**	**7**	**27**	156
1990	**1372**	13	**55**	**174**	**1022**	**10**	**42**	125
1995	**1513**	17	**64**	**193**	**1128**	**13**	**48**	138
2000	1064	16	**51**	**135**	**794**	**12**	**39**	97
2005	1340	23	**70**	**170**	**1000**	**17**	**53**	122
2010	1242	25	**70**	**158**	**926**	**19**	**53**	113
2015	1216	25	**69**	**155**	**906**	**19**	**52**	111
2020	1175	24	**67**	**149**	**877**	**18**	**51**	107
Full utilization								
1970	**804**	0	0	**18**	**601**	0	0	12
1975	**1166**	0	3	**25**	**871**	0	**2**	**18**
1980	**1335**	1	**4**	**28**	**999**	1	**4**	**14**
1985	**1888**	**3**	**10**	**40**	**1411**	**2**	**7**	**20**
1990	**1514**	**4**	**14**	**32**	**1132**	**4**	**12**	15
1995	**1670**	**5**	**17**	**35**	**1248**	**5**	**13**	17
2000	**1175**	**5**	**12**	**25**	**878**	**5**	11	12
2005	**1479**	**8**	**17**	**32**	**1107**	**8**	15	15
2010	**1370**	**8**	**17**	**29**	**1025**	**8**	14	14
2015	**1341**	**8**	**17**	**28**	**1004**	**8**	14	14
2020	**1298**	**8**	**17**	**27**	**971**	**8**	15	14

[a] Base case values assume no genetic selection for fusiform rust resistance

[b] “Difference from base” columns indicate increases in SEV from the base case given genetic selection assuming uniform or optimal targeting of resistant seedlings or complete resistance (‘Total resistance”) in all seedlings.

The data in table 7 can alternatively be viewed on a per-acre basis, removing the effects of changing planting activity over time (table 8). Dividing the base case SEV values from table 7 by total loblolly and slash planting acres gives an average of the yields from Appendix B, weighted by their relative frequency of occurrence. Repeating this process with the total resistance SEV’s shows how much higher the average per-acre value would be without any fusiform rust infections. Given the assumptions of the simulation, these two measures are virtually constant over time except for the shift in species allocations between 1975 and 1980. For the uniform and optimal deployment cases, the aggregate improvements in SEV were divided by those acres where resistant seedlings were planted. This measure indicates the per-acre marginal value of resistant seedlings under uniform and optimal deployment. These two measures vary over time because of changes in resistant seedling supply **and** resistance.

The per-acre SEV’s for the base case ranged from $626 to $931 depending on utilization and rotation assumptions. Total resistance SEV’s were anywhere from $9 to $108 higher, but these values were spread across all plantations. Under the optimal allocation regime, the added benefits of resistant seedlings were about $20 to $25 per acre under full utilization and $70 to $100 under poor utilization for plantations established over the next several decades. Per-acre benefits

Table 8--Annual per-acre soil expectation values (SEV) for Southwide loblolly and slash pine plantations in constant dollars per acre

	Economic rotation				Fixed rotation			
Planting Year	Base case”	Total resistance	Uniform[b]	Optimal	Base case	Total resistance	Uniform	Optimal
				Poor utilization				
1970	836	937	0	0	626	699	0	0
1975	836	937	15	103	626	698	0	74
1980	843	950	12	53	628	705	8	41
1985	843	950	13	45	628	705	10	38
1990	843	950	24	100	628	705	18	76
1995	843	950	24	92	628	705	19	69
2000	842	949	34	109	629	705	26	83
2005	843	950	31	94	629	706	23	71
2010	843	950	36	100	629	705	27	75
2015	843	951	36	100	628	705	28	75
2020	842	949	38	107	629	705	29	81
				Full utilization				
1970	917	937	0	0	685	699	0	0
1975	917	936	0	44	685	699	0	29
1980	930	949	4	16	696	705	4	16
1985	931	950	4	14	695	705	3	10
1990	931	950	7	25	696	705	7	22
1995	930	950	7	24	695	705	7	19
2000	930	950	11	26	695	705	11	23
2005	930	950	I1	23	696	706	11	20
2010	930	950	11	24	696	705	11	20
2015	930	949	12	25	696	706	12	20
2020	930	950	13	27	696	706	13	24

[a] Numbers under the base case and total resistance columns are weighted average SEV's across all loblolly and slash plantations.

[b] Numbers under the uniform and optimal columns represent increased SEVs above the base case for the two deployment regimes indicated, but spread only across those plantations that received rust-resistant seedlings

under uniform allocation were substantially lower than under optimal allocation. Their difference indicates the value of targeting resistant seedlings, a difference that was highest in the early years but declined somewhat in later years as resistant seedling supplies increased.

Benefits summed over time-Tables 9 to 11 show the Southwide PV's, discounted to 1992 and summed across years, for loblolly and slash plantations separately and for both combined. As anticipated, PV's were greater for economic rotations than for fixed rotations within each merchandising scenario. Also, PV increased with improvements in the utilization and deployment standards. In general, marginal efficiency gains were more difficult to attain as utilization efficiency increased. For example, the difference in PV between pulpwood and poor utilization standards was greater than the difference in PV between full and sawtimber utilization standards.

The benefits of improved resistance to fusiform rust were obtained by subtracting the PV of a particular base ease from the PV of one of the three ‘With resistance” scenarios on the same row, shown in tables 12, 13, and 14. For example, the total benefit of improved resistance assuming uniform deployment, poor utilization, and a fixed rotation age for loblolly pine was (29,683 ~ 29,547 =) $137 million (table 12). For a different combination of utilization and rotation type (i.e., full utilization and an economic rotation age), the benefit was (36,887 – 36,872 =) $14 million. Computed research benefits were greater for slash pine than loblolly. Although various aspects of host-pathogen relations may have contributed to the species difference, greater adoption of resistance technology by slash producers doubtless played a major role. Table 14 gives the research benefits for the two species combined. These benefits ranged from $108 to $999 million depending on rotation length and utilization and

Table 13--Present value of the research benefits for slash pine, planted from 1970 to 2020

Utilization/ rotation type	Deployment		
	Uniform	Optimal	Total resistance
	Million constant dollars (1992)		
Poor			
Economic	128	249	342
Fixed	145	286	562
Pulp wood			
Economic	125	251	381
Fixed	126	247	500
Sawtimber			
Economic	95	187	308
Fixed	110	212	446
Full			
Economic	91	184	273
Fixed	105	203	432

Table 14--Present value of the combined research benefits for slash and loblolly pine, planted from 1970 to 2020

Utilization/ rotation type	Deployment		
	Uniform	Optimal	Total resistance
	Million constant dollars (1992)		
Poor			
Economic	269	991	4,619
Fixed	282	999	4,394
Pulpwood			
Economic	214	708	3,037
Fixed	211	687	2,728
Sawtimber			
Economic	114	281	973
Fixed	134	337	835
Full			
Economic	108	261	850
Fixed	123	294	614

deployment standards. In most cases, economic damages were higher for economic rotations than under the longer fixed case. The one exception was for slash stands with high utilization standards-here damages were higher for long rotations.

The values in table 14 represent benefits relative to the base case, and caution should be exercised when making comparisons across scenarios. For example, a comparison of the combined research benefit for the poor utilization standard with a fixed rotation age and uniform deployment ($282 million) with the research benefit for the full utilization standard with an economic rotation age given optimal deployment ($261 million) does not suggest that the former scenario is more desirable from an economic perspective, because hvo different base cases were used to calculate the research benefits ($40.7 and $45.1 billion, respectively). However, our results indicate that efficiency gains associated with the introduction of genetically improved planting stock are greatest for producers with the lowest utilization standard and lowest for producers with the highest utilization standards.

Research Costs

Table 15 shows the costs of fusiform rust research and development of resistant genotypes, with scientist-years and expenditures by the Forest Service, university-industry research cooperatives, and forest industry and other seedling producers.

Forest Service research costs per FTE were greater than the universities in the early to middle 1970’s. By the late 1970’s to the middle 1980’s, university research costs per FTE had increased as university scientists expanded their overall research efforts. Forest Service total costs on fusiform rust research increased until the middle 1980’s then started to decline. The estimated university total fusiform rust research effort increased until the early 1980’s then started to decline, but by the late 1980’s and early 1990’s research costs increased again, primarily from increased costs per FTE. The estimated industry total costs on fusiform rust research have increased steadily.

Benefit:Cost Analysis

Table 16 gives a summary of the B/C analysis. The calculations of the B/C ratios and the net present values were straightforward. The PV of the research costs was $48.8 million (table 15). The B/C ratios for each scenario

Table 15--Fusiform rust research costs by sector from 1970 to 1992

	Forest Service			University (coops only)[a]				Industry				Total				
Year	FTE's	$/FTE	Total ($,000's)	FTE's	$/FTE	Expen-diture	Total ($1,000's)	FTE's	$/FTE	Expen-diture	Total ($1,000's)	FTE's	$/FTE	Expen-diture	Total ($1,000's)	PV total research costs ($1,000's 1992)
1970	6	$ 50,292	$318	3	$ 29,300	$ 6,663	$102	0.3	$ 39,796	$120,000	$ 132	10	$119,387	5126,663	$ 552	$ 1,307
1971	6	57,089	347	3	37,535	7,398	129	.3	47,312	126,400	141	10	141,937	133,798	617	1,406
1972	6	63,887	376	3	45,770	8,133	157	.3	54,829	132,800	149	9	164,486	140,933	682	1,495
1973	6	70,685	405	3	54,005	8,868	184	.3	62,345	139,200	158	9	187,035	148,068	748	1,575
1974	6	77,482	435	3	62,240	9,603	212	.3	69.861	145,600	167	9	209,584	155,203	813	1,647
1975	6	84,280	464	3	70,476	10,338	239	1	77,378	152,000	198	9	232,133	162,338	902	1,756
1976	7	98,923	643	3	78,711	12,742	269	1	88,817	162,600	216	10	266,451	175,342	1,127	2,112
1977	5	86,415	458	3	86,946	15,146	298	1	86,680	173,200	225	9	260,041	188,346	981	1,767
1978	6	88,103	511	3	95,181	17,550	327	1	91,642	183,800	239	10	274,927	201,350	1,077	1,864
1979	5	96,875	465	3	103,416	19,954	356	1	100,146	194,400	254	9	300,437	214,354	1,076	1,791
1980'	5	104,167	500	3	111,651	22,358	329	2	107,909	205,000	453	10	323,727	227,358	1,283	2,053
1981	3	164,118	558	3	115,444	22,977	340	2	139,781	273,264	595	8	419,342	296,241	1,493	2,299
1982	4	121,190	509	2	128,121	23,596	248	2	124,656	341,528	628	8	373,968	365,124	1,385	2,050
1983	5	122,667	552	2	126,070	24,215	245	2	124,368	409,792	696	9	373,105	434,007	1,493	2,125
1984	4	133,182	586	2	144,592	24,834	278	2	138,887	478,056	797	8	416,660	502,890	1,661	2,274
1985	5	158,235	807	1	152,827	25,453	216	3	155,531	546,320	951	9	466,593	571,773	1,974	2,598
1986	7	196,567	1,317	1	153,253	26,896	218	3	174,910	543,056	998	11	524,730	569,952	2,533	3,205
1987	7	173,636	1,146	1	177,332	28,339	250	3	175,484	539,792	996	10	526,453	568,131	2,392	2,910
1988	5	215,600	1,078	1	212,581	29,783	296	3	214,091	536,528	1,093	9	642,272	566,311	2,467	2,886
1989	5	195,769	1,018	1	185,767	31,226	263	3	140,768	533,264	1,029	9	572,305	564,490	2,311	2,599
1990	5	192,308	1,000	1	194,003	32,669	275	3	193,155	530,000	1,129	10	579,465	562,669	2,404	2,600
1991	4	179,524	754	1	202,238	32,669	285	3	390,881	530,000	1,122	9	572,642	562,669	2,161	2,248
1992	4	176,905	743	2	197,857	32,669	428	3	187,381	530,000	1,111	9	562,143	542,669	2,282	2,282

Present value of research cost = $48,851

FTE = full-time employee; PV = present value

[a] University and industry totals calculated as (FTE's x $/FTE) + direct expenditures.

Table 16--Benefit:cost ratio and net present value of fusiform rust research in loblolly pine and slash pine

		Deployment	
Utilization/ rotation type	Benefit measure	Uniform	Optimal
Poor			
Economic	B/C[a]	5.51	20.29
	PV[b]	220.36	942.47
Fixed	B/C	5.77	20.44
	PV	232.80	949.68
Pulpwood			
Economic	B/C	4.37	14.49
	PV	164.79	659.07
Fixed	B/C	4.31	14.06
	PV	161.74	638.18
Saw-timber			
Economic	B/C	2.33	5.75
	PV	64.95	232.13
Fixed	B/C	2.74	6.89
	PV	85.03	287.93
Full			
Economic	B/C	2.21	5.33
	PV	58.93	211.68
Fixed	B/C	2.53	6.02
	PV	74.55	245.03

[a] B/C is defined as the benefit:cost ratio.
[b] PV is defined as the net present value, in million constant dollars (1992).

were calculated as the aggregate research benefit (table 14) divided by $48.8 million. For example, the B/C ratio under poor utilization with an economic rotation age and uniform deployment was (269 / 48.8 ≈) 5.5 1. If the B/C ratio is greater than 1, then the benefits were greater than the costs, implying the research program was economically efficient. In table 16, the B/C ratios were all greater than 1.

The net benefits for each scenario were calculated as the PV of the aggregate research benefits (table 14) minus the PV of the research cost ($48.8 million). For example, the net benefit under poor utilization with an economic rotation age and uniform deployment was (269 - 48.85 1 ≈) $220 million. If the net benefit was greater than zero, then the PV of the benefits was greater than the PV of the costs, implying the research program was economically efficient. Research costs could double and, in some scenarios, increase by a factor of 10, and net benefits would remain positive.

Conclusions

The above results provide information on five aspects of fusiform rust: (1) the speed of adoption of rust-resistant technology across the South; (2) the historical distribution of fusiform rust infection across sites of different quality and location; (3) fusiform rust's probable financial effect on individual landowners across stands of differing infection and site quality, and for different utilization and rotation standards; (4) the aggregate timber supply effects of improved fusiform rust resistance in southern pines; and (5) B/C ratios for the fusiform rust research. Several implications of our analyses and findings bear discussion.

Resistance Gains and Regional Conditions

By 1980, results of research into selection methods for resistance to fusiform rust began to be implemented on the ground as producers of loblolly and slash seedlings began producing and planting resistant stocks in steadily increasing numbers. These first resistant seedlings yielded minor gains in resistance but these improved over time. The biggest gains in resistance and most rapid changeover to resistant lines occurred in slash, where mortality effects are more severe and where a greater share of the planting range is at risk of infection. Today, resistant lines account for almost half of slash seedling production and a sixth of loblolly, with resistance gains around 40 and 30 percent, respectively. Both production of resistant lines and the resistance achieved in those lines are expected to increase through the next several decades, increasing by half again before leveling off, Thus, the benefits of past research are by no means fully realized in current seedling nurseries.

The production of resistant seedlings (fig. 5) can be compared with the historical measures of risk shown (fig. 7 or tables 4 through 6) as a rough measure of production success relative to plantations at risk. This comparison suggests that the slash pine seedling industry adopted resistance technology so rapidly in the 1970's, that by 1980 they were essentially producing enough resistant seedlings to cover all areas of even minor (5 percent) risk to infection. The projections for loblolly indicate that nurseries will not produce enough resistant seedlings for areas at risk even by the year 2020.

However, comparison of "sufficiency" is rather limited because landowners have limited ability to determine which planting sites will be at risk to fusiform rust. Many landowners may plant sites with resistant stock anticipating conditions favorable to fusiform rust, but such conditions may not occur. Thus, planting resistant seedlings can provide insurance against risk especially when resistant seedlings are abundant.

These are rough physical indicators of sufficiency of production. Financial indicators provide a more relevant test, but these would need to consider the predictability of infection for individual locations in a risk framework.

Tree improvement specialists anticipate limits to gains in resistance based on current research. For slash this limit is thought to be just over 60 percent but for loblolly closer to 40 percent. The reasons for such anticipated limits are unclear, but could involve genetic tradeoffs or limitations, financial considerations, or limited benefits to be gained by much higher resistance levels.

Extrapolation of historical infection patterns to future conditions must recognize the limitations of our measurement period. While the empirical infection rates represent the longest consistent record obtainable, the rates are inevitably subject to various edaphic conditions. Thus, there is no guarantee that the infection patterns reflected in the three FIA survey cycles will prevail in the next decade, much less in any particular year. We did not forecast alternate host availability or spring periods of high humidity, conditions that favor fusiform rust infection in pine hosts (Froelich and Snow 1986).

Empirical analyses confirmed the importance of site quality and regional location to fusiform rust incidence, although stand origin appeared less important once differences in site quality were considered. In the 1970's and early 1980's, slash and loblolly plantations appeared to experience similar incidences of fusiform rust infection once site quality was taken into account. However, slash plantations experienced high infection rates more often, and site correlations dissolved in the most recent survey. Over the two decades for which data are available, plantations shifted toward higher quality sites and to the south and west, factors that should influence the risks of infection. However, accounting for shifts in risk factors was beyond the scope of the present evaluation.

Financial Analyses and Management Implications

The volume and SEV projections represent the first consistent examination of fusiform rust effects on merchandised yield and return on investment in slash and loblolly under optimal economic and fixed rotations, By allowing a range of site conditions and harvesting-utilization intensities, owners of young plantations can compare the likely future returns for their stand under a wide range of conditions.

The financial returns show that stand compensation for mortality at lower levels of infection can significantly ameliorate financial damage from fusiform rust, primarily for slash. The dispersed nature of fusiform rust mortality in stands is particularly well suited to such compensation, creating patches of mortality, which under light infection rates might be isolated individuals. It is, of course, also advantageous for the mortality to occur early in the stand's life. Should other stresses create additional dispersed mortality, the compensation seen in our simulations would not be possible, and financial losses from fusiform rust would be correspondingly greater. Similarly, planting at substantially lower densities would increase the financial loss if moderate infections developed.

The financial results show that the absolute levels of economic damage are greater for slash than loblolly pine at all but the lowest infection levels. Generally, economic damage increases with site index, Because most pine acres in the South experience low to moderate infection, we conclude that the greatest economic damages are occurring on the most common sites (i.e., low to moderate site index).

Thinning represents an alternative means of stocking control and can be a useful strategy for alleviating damages in infected stands (Nance and others 1983, Powers and Brender 1977). Including the option of thinning could increase financial returns and total harvested volumes but not uniformly across stand conditions or species. Increases would probably be greater on higher quality sites, and because infections in loblolly are less likely to kill the stem than in slash, thinning would increase yields more in infected loblolly than slash stands, Such differential shifts affect the relative benefits of reduced infection in complex ways and could not be evaluated in this study.

Our results show that under some conditions of extremely high infection, planting and harvesting pine trees promises financial losses, not gains. Under these cases, landowners might reasonably choose to replant their stands, although the returns in such cases have not been evaluated in this study. No empirical information is available on how often stands are replanted, but Williston (1980) cites one 30-year program in Mississippi where 18 percent of the stands had to be replanted. To what degree fusiform rust may have been involved in some of those planting failures is unknown.

Regional Research Benefits

We found that the aggregate economic impacts of genetic improvements in rust resistance vary widely depending on utilization and deployment assumptions. In general, the economic gains from improved resistance are less when infected stems are utilized efficiently. Likewise, the marginal economic benefits of improved rust resistance were generally higher for long rotations than economic rotations. While the total value of rotations that maximize economic value were higher than long rotations, our results indicate that gains from improved biotechnology are more valuable on economically "inefficient" stands.

More generally, the alternative assumptions used in the analysis of rotation and utilization standards and seedling deployment show the sensitivity of Southwide plantation revenues to these factors. Comparing the PV totals under different sets of assumptions provides dollar estimates of their aggregate importance to plantation owners across the region.

The study found that moving from the least intensive to most intensive utilization of infected stems increases aggregate net revenues by roughly $3.8 to $4.4 billion over the study period, representing about $76 to $88 million per year over the 50-year simulation period (table 11). Unfortunately, there are no data to tell how close industry currently comes to full utilization. We can say, however, that aggregate revenues of southern plantations depend strongly on how efficiently rust infected stems are utilized.

Rotation standards also exert a strong effect on net revenue for southern pine producers. For example, a shift from uniform 35-year rotations to economically optimal rotations for the variety of site indices and rust infection levels found throughout the South would increase net revenues by about $5.1 billion (table 1 l), representing about $102 million per year. However, based on FIA data, 35-year-old pine plantations are rare in the South.

We found that the research benefits of improved rust resistance depend on how accurately resistant seedlings can be deployed (table 14). For example, the returns with optimal deployment over uniform deployment range from about $ 153 to $722 million over the study period. This represents an average annual gain from about $3.1 to $14.4 million per year.

The sensitivity of results to utilization, deployment, and rotation practices demonstrates the importance of research and technology transfer in areas such as milling and logging practices, fusiform rust hazard assessment, and economic guidelines to landowners. We know that these factors are economically important to the industry but cannot say where current practices lie within the range of conditions explored. Only with information on current practices can we quantify the potential benefits available from improvements in logging practices, hazard assessment, and harvest timing.

We found that, in general, the investments made in fusiform rust research have been efficient when gauged by computed B/C ratios. If the sawtimber utilization standard is "typical" in the South, B/C ratios range from 2.33 to 6.89, depending on rotation length and seedling deployment. Likewise, the total net PV (research benefits minus research costs) for this utilization standard range from about $65 million to $288 million. Other utilization standards yielded different measures of efficiency, but all scenarios led to the same conclusion-fusiform rust research in the South has been a good investment from an economic efficiency standpoint.

Our conclusion about the positive returns of fusiform rust research differ from those of Hyde and others (1992) for all research investments in southern pine productivity. They state that "The net PV results are negative throughout most of the range of feasible benefit and cost estimates" (p. 190) and "timber growth and management has not been an outstanding historic achievement" (p. 192). The different conclusions may result from differences in approach (simulation versus empirical), scope of the research evaluated, and quality of the data on costs.

First, our analysis is forward looking and uses simulation analysis to gauge productivity changes, while their analysis is backward looking and uses statistical estimates of changes in productivity. Using statistical analysis on historical data is difficult because the data available to estimate changes in timber productivity are of poor quality. Because productivity was measured as a residual effect after the inclusion of various biologic and ownership variables, the residual approach simply detects "other" changes in the biologic production function occurring over time. If the production function is changing for reasons not captured in the model, such as changes in land or atmospheric quality, the residual approach cannot isolate the effects of research versus these other factors on timber growth. Simulation avoids this problem by imposing a true *ceteris paribus* condition-everything is held constant except for the productivity modifying factor under consideration.

Second, we consider the efficiency of a single timber research program in the South, whereas Hyde and others (1992) consider all timber research programs. The particular case we studied is probably one of the more promising timber research programs for traditional market analysis because improvements in genetic resistance to fusiform rust translate directly into increased tree survival, wood quality, and therefore economic value. Furthermore, we assume productivity gains will not influence per unit price, whereas the model by Hyde and others includes both price and quantity impacts.

Third, the data we used for computing research costs, while imperfect, was specific to the fusiform rust research program and could be considered generally reliable. Hyde and others (1992) noted that the quality of the research cost data they used was of questionable quality and could not be correlated with a specific timber research program.

Maximum Potential Gains

The uniform and optimal deployment scenarios in our analyses measured the potential benefits that could be achieved from implementation of existing and anticipated fusiform rust protection research. Fully targeting all rust-resistant seedlings to the highest risk sites could generate research benefits ranging from $261 million if all trees were fully merchandised with economic rotation to $999 million if poor utilization and fixed rotation prevailed (table 14). These numbers translate into annual benefits of about $5 million to $20 million per year.

Table 14 can be used to compute the maximum potential economic gains that could be achieved if fusiform rust were eliminated-as represented by the total column. Again, depending on the existing utilization standards, the net PV of total benefits could range from a low of $0.6 billion to a high of $4.6 billion. These values translate into annual figures of about $12 million to $92 million-and represent the imputed annual loss to fusiform rust infection in southern pines. If we assume that the economic sawtimber rotation represents the most typical combination of forest management and timber utilization regimes, the maximum potential net research benefits (or total fusiform rust losses) are about $1 billion in net PV, or $20 million per year. This sum compares reasonably well with the annual loss estimates of $28 million per year from Powers and others (1974), $35 million per year from Anderson and others (1986b), and tens of millions from Holley and Veal (1977). The poorer utilization pulpwood scenarios would roughly triple our loss estimates, making them somewhat higher than those in previous studies.

The potential annual benefits of completely eliminating fusiform rust-perhaps $20 to $40 million per year-could be used when considering further investments in fusiform rust research. The existing tree breeding and selection programs were implicitly considered by our survey respondents when they made estimates of future gain and rust protection. To achieve something closer to the maximum potential benefits, significant breakthroughs in rust prevention research and implementation must occur, such as identifying genetic markers of resistance (Wilcox and others 1994). Will we be able to support this research in the future and who will pay, public organizations or private firms, are the key questions for the future.

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Appendix A

Sample Questionnaire
Sent by Tree Improvement Cooperatives to Pine Seedling Producers:
Version for Slash Pine Producers

Benefits of Selecting for Fusiform Rust-Resistant Slash Pine

This survey is part of a study estimating the benefits and costs of selecting for resistance to fusiform rust. Benefits to selection depend on when and to what extent resistant seedlings have been used in plantations, and how successful genetic selection has been in reducing infection rates in those resistant plantations. Costs refer to the additional resources needed to enable production of specific fusiform resistant lines over and above costs which would have been necessary to produce nonresistant stock. Please answer as much of the survey as YOU can.

1. **Please estimate selection effectiveness and annual seedling production figures for the selected years shown.** GAIN refers to the relative reduction in infection in your resistant seedlings when compared with infection rates which would have occurred had nonresistant seedlings been planted instead.[1] For the RESISTANT and TOTAL seedling-production estimates as well as estimates of gain, include slash pine seedlings produced in your own organization's nurseries or produced under contract for your organization, regardless of who ultimately plants the seedlings. Seedling production estimates are necessary for calculating the relative contribution of resistant seedlings to total slash pine production for the region. Projecting production and gain several decades into the future will enable estimation of anticipated benefits of genetic selections which have already occurred.

Year	Expected GAIN in fusiform resistance in your resistant slash seedlings (%)[1]	Number of RESISTANT slash seedlings produced by your organization	TOTAL number of slash seedlings produced by your organization [resistant + nonresistant)
1970			
1975			
1980			
1985			
1990			
1995			
2000			
2005			
2010			
2015			
2020			

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[1] For example, suppose infection rates are 80 percent for nonresistant stock, while infection in resistant stock in the same area is only 20 percent. Gain in this case would be (80 - 20)/80 or 75 percent.

Please estimate for the selected years below the approximate annual resources your organization has devoted to research into selection, breeding, or screening specifically for resistance to fusiform rust in loblolly or slash pine. Resources can be expressed either as dollar expenditures or as scientist-years, whichever is most convenient. Costs of research conducted by tree improvement cooperatives will be obtained directly from the cooperatives and should not be included here.

Year	Expenditures or scientist-years
1970	
1975	
1980	
1985	
1990	

Thank you for your assistance.

Appendix B

Financial Analyses of Impacts of Fusiform Rust

Table B1--Loblolly pine plantation yields for **differing site qualities and age-5 fusiform infection rates under the full utilization and economic rotation assumptions**

Infection	Pulp	Chip-n-saw	Saw	Rotation	SEV[a]
Pct	Ft^3/ac	Ft^3/ac	Ft^3/ac	Yr	$(1992)
		Site class[b] (high)			
0	11	1,531	3,090	23	2,313
10	109	1,522	3,043	23	2,307
20	193	1,514	2,967	23	2,273
30	270	1,519	2,885	23	2,243
40	381	1,469	3,096	24	2,205
50	481	1,481	2,983	24	2,164
60	535	1,468	2,941	24	2,153
70	658	1,483	2,803	24	2,109
80	704	1,479	2,763	24	2,096
90	802	1,474	2,670	24	2,053
100	867	1,481	2,596	24	2,021
		Site **classb (medium)**			
0	18	1,482	1,725	24	1,422
10	102	1,469	1,670	24	1,396
20	174	1,468	1,598	24	1,368
30	250	1,453	1,735	25	1,341
40	321	1,457	1,661	25	1,312
50	400	1,441	1,599	25	1,286
60	463	1,431	1,544	25	1,261
70	534’	1,445	1,461	25	1,239
80	615	1,423	1,401	25	1,212
90	662	1,428	1,349	25	1,192
100	724	1,392	1,441	26	1,164
		Site class[b] (low)			
0	7	1,388	998	29	687
10	82	1,374	927	29	662
20	135	1,370	879	29	646
30	188	1,361	835	29	631
40	195	1,354	716	28	626
50	320	1,351	711	29	591
60	372	1,326	681	29	578
70	456	1,307	616	29	555
80	493	1,318	568	29	541
90	562	1,300	516	29	524
100	575	1,314	490	29	516

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[a] SEV (soil expectation value).
[b] Site class includes different assumptions of site index, site preparation, and early survivorship.

Table B2–Loblolly pine plantation yields for differing site qualities and age-5 fusiform infection rates under the full utilization and fixed rotation assumptions

Infection	Pulp	Chip-n-saw	Saw	Rotation	SEV[a]
Pct	*Ft^3/ac*	*Ft^3/ac*	*Ft^3/ac*	*Yr*	*$(1992)*
		Site class[b] (high)			
0	1	1,017	4,931	35	1,463
10	95	1,069	5,344	35	1,601
20	1x2	1,072	5,251	35	1,586
30	260	1,069	5,174	35	1,574
40	351	1,069	5,079	35	1,557
50	477	1,075	4,944	35	1,532
60	497	1,083	4,913	35	1,529
70	655	1,066	4,750	35	1,495
80	811	1,072	4,551	35	1,453
90	855	1,077	4,532	35	1,457
100	895	1,075	4,492	35	1,452
		Site class[b] (medium)			
0	8	1,030	3,197	35	1,002
10	76	1,017	3,178	35	1,001
20	167	1,020	3,086	35	984
30	231	1,024	3,018	35	972
40	251	1,029	2,994	35	967
50	390	1,033	2,849	35	944
60	459	1,025	2,784	35	929
70	534	1,026	2,707	35	914
80	569	1,010	2,689	35	913
90	603	1,007	2,658	35	908
100	727	1,019	2,521	35	879
		Site class[b] (low)			
0	13	1,152	1,604	35	579
10	72	1,156	1,540	35	566
20	140	1,143	1,482	35	553
30	204	1,155	1,409	35	540
40	246	1,157	1,364	35	530
50	296	1,142	1,330	35	522
60	372	1,145	1,250	35	506
70	427	1,169	1,171	35	493
80	503	1,143	1,121	35	481
90	555	1,150	1,063	35	469
100	613	1,151	1,003	35	457

[a] SEV (soil expectation value).

[b] Site class includes different assumptions of site index, site preparation, and early survivorship

Table B3--Loblolly pine plantation yields for differing site qualities and age-5 fusiform infection rates under the sawtimber utilization and economic rotation assumptions

Infection	Pulp	Chip-n-saw	Saw	Rotation	SEV[a]
Pct	*Ft^3/ac*	*Ft^3/ac*	*Ft^3/ac*	*Yr*	*$(1992)*
		Site class[b] (high)			
0	11	1,531	3,090	23	2,313
10	125	1,539	3,011	23	2,295
20	223	1,560	2,891	23	2,243
30	374	1,503	3,070	24	2,195
40	498	1,556	2,891	24	2,139
50	585	1,579	2,781	24	2,104
60	686	1,570	2,689	24	2,057
70	812	1,595	2,539	24	2,013
80	908	1,600	2,436	24	1,981
90	1,011	1,563	2,642	25	1,933
100	1,065	1,672	2,480	25	1,911
		Site class[b] (medium)			
0	18	1,482	1,725	24	1,422
10	118	1,484	1,638	24	1,386
20	218	1,468	1,752	25	1,352
30	283	1,481	1,676	25	1,323
40	440	1,473	1,525	25	1,266
50	495	1,528	1,416	25	1,242
60	585	1,500	1,354	25	1,203
70	678	1,540	1,220	25	1,180
80	722	1,503	1,333	26	1,146
90	834	1,542	1,181	26	1,104
100	910	1,502	1,145	26	1,081
		Site class[b] (low)			
0	7	1,388	998	29	687
10	92	1,376	916	29	658
20	163	1,382	838	29	636
30	261	1,359	764	29	609
40	338	1,371	675	29	584
50	389	1,410	698	30	567
60	497	1,364	519	29	534
70	564	1,432	500	30	513
80	652	1,430	413	30	490
90	745	1,358	275	29	461
100	793	1,430	273	30	446

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[a] SEV (soil expectation value).

[b] Site class includes different assumptions of site index, site preparation, and early survivorship.

Table B4—Loblolly pine plantation yields for differing site qualities and age-5 fusiform infection rates under the sawtimber utilization and fixed rotation assumptions

Infection	Pulp	Chip-n-saw	Saw	Rotation	SEV[a]
Pct	*Ft^3/ac*	*Ft^3/ac*	*Ft^3/ac*	*Yr*	*$(1992)*
		Site **class[b](high)**			
0	1	1,017	4,931	35	1,463
10	127	1,075	5,306	35	1,595
20	262	1,083	5,159	35	1,568
30	366	1,083	5,055	35	1,549
40	382	1,092	5,024	35	1,545
50	580	1,097	4,820	35	1,508
60	677	1,107	4,708	35	1,488
70	832	1,106	4,531	35	1,452
80	894	1,095	4,480	35	1,444
90	1,028	1,122	4,315	35	1,414
100	1,075	1,114	4,272	35	1,405
		Site **class[b](medium)**			
0	8	1,030	3,197	35	1,002
10	103	1,034	3,136	35	994
20	206	1,027	3,038	35	975
30	271	1,046	2,956	35	961
40	375	1,055	2,841	35	941
50	423	1,062	2,789	35	931
60	540	1,078	2,649	35	906
70	623	1,073	2,572	35	891
80	692	1,111	2,465	35	874
90	796	1,111	2,359	35	855
100	903	1,125	2,239	35	834
		Site **class[b](low)**			
0	13	1,152	1,604	35	539
10	94	1,172	1,501	35	560
20	178	1,176	1,413	35	543
30	252	1,202	1,314	35	525
40	315	1,213	1,238	35	510
50	377	1,236	1,154	35	496
60	482	1,286	999	35	469
70	542	1,237	988	35	461
80	613	1,326	829	35	439
90	746	1,294	728	35	414
100	812	1,335	618	35	397

[a] SEV (soil expectation value)

[b] Site class includes different assumptions of site index, site preparation, and early survivorship.

Table B5--Loblolly pine plantation yields for differing site qualities and age-5 fusiform infection rates under the pulpwood utilization and economic rotation assumptions

Infection	Pulp	Chip-n-saw	saw	Rotation	SEV[a]
Pct	*Ft^3/ac*	*Ft^3/ac*	*Ft^3/ac*	*Yr*	*$(1992)*
		Site **class**[b] (high)			
0	11	1,531	3,090	23	2,313
10	479	1,371	2,824	23	2,180
20	945	1,216	2,513	23	2,015
30	1,360	1,079	2,234	23	1,868
40	1,839	924	1,909	23	1,699
50	2,238	792	1,643	23	1,557
60	2,720	637	1,316	23	1,390
70	3,140	499	1,035	23	1,241
80	3,546	366	761	23	1,100
90	4,023	215	436	23	930
100	4,393	90	190	23	800
		Site **class**[b] {medium)			
0	18	1,482	1,725	24	1,422
10	336	1,329	1,575	24	1,328
20	668	1,181	1,392	24	1,225
30	954	1,047	1,238	24	1,134
40	1,277	899	1,065	24	1,032
50	1,559	771	911	24	943
60	1,860	634	746	24	849
70	2,147	501	593	24	759
80	2,435	367	438	24	667
90	2,720	236	283	24	578
100	2,985	118	138	24	495
		Site class' (low)			
0	7	1,388	998	29	687
10	248	1,245	890	29	630
20	461	1,122	801	29	583
30	696	984	703	29	531
40	908	860	616	29	485
50	1,118	732	531	29	437
60	1,363	594	423	29	382
70	1,578	467	333	29	334
80	1,703	344	214	28	288
90	1,903	219	139	28	243
100	2,084	108	69	28	201

[a] SEV (soil expectation value).

[b] Site class includes different assumptions of site index, site preparation, and early survivorship.

Table B6--Loblolly pine plantation yields for differing site qualities and age-5 fusiform infection rates under the pulpwood utilization and fixed rotation assumptions

Infection	Pulp	Chip-n-saw	Saw	Rotation	SEV[a]
Pct	*Ft ^{3}/ac*	*Ft ^{3}/ac*	*Ft ^{3}/ac*	*Yr*	*$(1992)*
			Site class[b] (high)		
0	1	1,017	4,931	35	1,463
10	674	958	4,875	35	1,496
20	1,302	856	4,346	35	1,382
30	1,890	754	3,858	35	1,276
40	2,539	652	3,307	35	1,157
50	3,127	551	2,819	35	1,051
60	3,756	453	2,284	35	935
70	4,326	352	1,793	35	826
80	4,904	255	1,309	35	721
90	5,562	148	754	35	601
100	6,067	66	329	35	509
			Site **class**[b] (medium)		
0	8	1,030	3,197	35	1,002
10	446	911	2,916	35	936
20	881	811	2,581	35	858
30	1,229	726	2,318	35	797
40	1,684	618	1,971	35	716
50	2,063	525	1,685	35	649
60	2,466	427	1,374	35	576
70	2,831	339	1,096	35	511
80	3,218	247	802	35	442
90	3,586	164	517	35	377
100	3,917	81	269	35	318
			Site class’ (low)		
0	13	1,152	1,604	35	579
10	294	1,034	1,440	35	532
20	540	930	1,297	35	490
30	821	813	1,133	35	443
40	1,062	714	991	35	402
50	1,300	611	856	35	362
60	1,582	494	691	35	314
70	1,823	395	549	**35**	274
80	2,084	283	399	**35**	229
90	2,332	183	252	**35**	188
100	2,544	92	130	**35**	152

’ Site class includes different assumptions of site index, site preparation, and early survivorship.

’ SEV refers to soil expectation value.

Table B7--Loblolly pine plantation yields for differing site qualities and age-5 fusiform infection rates under the poor utilization and economic rotation assumptions

Infection	Pulp	Chip-n-saw	Saw	Rotation	SEV[a]
Pct	*Ft ^{3}/ac*	*Ft* -l/m	Ft ‘/ac	YP	*$(1992)*
Site classb(high)					
0	11	1,531	3,090	23	2,313
10	13	1,371	2,824	23	2,078
20	11	1,216	2,513	23	1,808
30	10	1,079	2,234	23	1,569
40	8	924	1,909	23	1,294
50	6	771	1,812	24	1,066
60	5	619	1,447	24	793
70	4	484	1,140	24	550
80	3	355	838	24	321
90	1	197	554	26	**50**
100	1	68	299	31	**(147)**
Site class (medium)					
0	18	1,482	1,725	24	1,422
10	17	1,329	1,575	24	1,262
20	15	1,181	1,392	24	1,091
30	14	1,030	1,395	25	941
40	12	884	1,200	25	773
50	11	758	1,027	25	625
60	9	623	840	25	471
70	7	492	668	25	321
80	4	351	534	26	170
90	3	224	343	26	**23**
100	1	100	219	30	**(107)**
Site class (low)					
0	7	1,388	998	29	687’
10	10	1,245	890	29	594
20	9	1,122	801	29	514
30	8	984	703	29	427
40	7	862	688	30	348
50	6	732	593	30	269
60	5	596	474	30	177
70	4	467	373	30	96
80	3	332	297	31	**18**
90	2	204	207	32	**(58)**
100	1	92	130	35	(125)

‘SEV (soil expectation value).

[b] Site class includes different assumptions of site index, site preparation, and early survivorship.

Table B8--Loblolly **pine plantation yields for differing site qualities and age-5 fusiform infection rates under the poor utilization and fixed rotation assumptions**

Infection	Pulp	Chip-n-saw	saw	Rotation	SEV[a]
Pct	*Ft^3/ac*	*Ft^3/ac*	*Ft^3/ac*	Yr	*$(1992)*
		Site class[b] (high)			
0	1	1,017	4,931	35	1,463
10	3	958	4,875	35	1,423
20	3	856	4,346	35	1,241
30	2	754	3,858	35	1,071
40	2	652	3,307	35	881
50	2	551	2,819	35	711
60	1	453	2,284	35	528
70	1	352	1,793	35	357
80	1	255	1,309	35	189
90	0	148	754	35	(3)
100	0	66	329	35	(150)
		Site class (medium)			
0	8	1,030	3,197	35	1,002
10	8	911	2,916	35	888
20	7	811	2,581	35	763
30	6	726	2,318	35	664
40	5	618	1,971	35	534
50	4	525	1,685	35	425
60	4	427	1,374	35	308
70	3	339	1,096	35	203
80	2	247	802	35	93
90	1	164	517	35	(13)
100	1	81	269	35	(107)
		Site class (low)			
0	13	1,152	1,604	35	579
10	12	1,034	1,440	35	501
20	11	930	1,297	35	433
30	9	813	1,133	35	354
40	8	714	991	35	287
50	7	611	856	35	222
60	6	494	691	35	143
70	4	395	549	35	76
80	3	283	399	35	3
90	2	183	252	35	(65)
100	1	92	130	35	(124)

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[a] SEV (soil expectation value).

[b] Site class includes different assumptions of site index, site preparation, and early survivorship,

Table B9--Slash pine plantation yields for differing site qualities and age-5 fusiform infection rates under the full utilization and economic rotation assumptions

Infection	Pulp	Chip-n-saw	saw	Rotation	SEV[a]
Pct	*Ft³/ac*	*Ft³/ac*	*Ft³/ac*	*Yr*	*$(1992)*
		Site **class**[b] (high)			
0	20	2,694	1,489	23	1,830
10	34	3,317	1,726	24	2,104
20	81	3,031	1,461	23	1,988
30	137	2,815	1,401	23	1,867
40	194	2,632	1,324	23	1,744
50	286	2,395	1,087	22	1,629
60	354	2,234	999	22	1,514
70	462	2,072	892	22	1,392
80	524	1,885	851	22	1,295
90	613	1,747	651	21	1,193
100	732	1,362	489	21	964
		Site **class**[b] (medium)			
0	19	2,238	666	24	1,098
10	50	2,518	655	24	1,216
20	83	2,358	638	24	1,145
30	111	2,216	604	24	1,074
40	161	2,049	568	24	996
50	200	1,839	478	23	932
60	285	1,689	423	23	848
70	367	1,490	322	22	772
80	416	1,378	282	22	706
90	521	1,235	218	22	618
100	614	923	103	21	486
		Site class (low)			
0	8	1,651	192	25	543
10	32	1,760	187	25	589
20	61	1,645	174	25	544
30	71	1,540	170	25	502
40	115	1,428	156	25	458
50	148	1,247	135	24	417
60	188	1,144	124	24	376
70	238	1,031	111	24	331
80	313	865	70	23	281
90	375	756	59	23	240
100	445	537	29	22	168

[a] SEV (soil expectation value).

[b] Site class includes different assumptions of site index, site preparation, **and early** survivorship.

Table B10--Slash pine plantation yields for differing site qualities and age-5 fusiform infection rates under the full utilization and fixed rotation assumptions

Infection	Pulp	Chip-n-saw	Saw	Rotation	SEV[a]
Pct	*Ft ^{3}/ac*	*Ft ^{3}/ac*	*Ft ^{3}/ac*	Yr	*$(1992)*
		Site class[b] (high)			
0	23	2,754	3,267	35	1,358
10	10	3,473	3,372	35	1,549
20	22	2,957	3,254	35	1,399
30	12	2,544	3,078	35	1,248
40	9	2,119	2,961	35	1,118
50	15	1,686	2,856	35	991
60	39	1,315	2,738	35	874
70	134	1,001	2,529	35	753
80	314	797	2,172	35	619
90	518	627	1,788	35	490
100	641	41	1,496	35	286
		Site class[b] (medium)			
0	10	2,486	1,561	35	825
10	23	2,843	1,571	35	909
20	9	2,498	1,530	35	818
30	10	2,151	1,505	35	732
40	13	1,886	1,416	35	649
50	4	1,581	1,398	35	574
60	36	1,267	1,373	35	502
70	145	966	1,299	35	425
80	252	754	1,157	35	349
90	433	603	883	35	253
100	536	142	800	35	139
		Site class[b] (low)			
0	32	1,921	555	35	4io
10	27	2,042	532	3s	440
20	29	1,849	505	35	388
30	13	1,641	515	35	343
40	0	1,438	533	35	302
50	10	1,244	523	35	257
60	21	1,083	492	35	213
70	93	916	419	35	162
80	160	702	423	35	122
90	285	554	312	35	70
100	353	288	278	3s	8

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[a] SEV (soil expectation value).

[b] Site class includes different assumptions of site index, site preparation, and early survivorship.

Table B11—Slash pine plantation yields for differing site qualities and age-5 fusiform infection rates under the sawtimber utilization and economic rotation assumptions

Infection	Pulp	Chip-n-saw	Saw	Rotation	
Pct	*Ft ^{3}/ac*	*Ft ^{3}/ac*	*Ft ^{3}/ac*	*Yr*	*$(1992)*
		Site class[b] (high)			
0	20	2,694	1,489	23	1,830
10	58	3,305	1,713	24	2,097
20	152	2,998	1,421	23	1,962
30	212	2,785	1,358	23	1,839
40	329	2,595	1,226	23	1,693
50	445	2,334	1,169	23	1,560
60	537	2,213	995	23	1,426
70	711	2,018	698	22	1,287
80	828	1,818	614	22	1,171
90	1,027	1,647	335	21	1,019
100	1,197	1,265	78	21	768
		Site class[b] (medium)			
0	19	2,238	666	24	1,098
10	63	2,506	654	24	1,213
20	105	2,355	619	24	1,140
30	42	2,211	520	23	1,092
40	269	1,984	525	24	970
50	315	1,841	488	24	891
60	442	1,583	373	23	801
70	565	1,416	293	23	706
80	594	1,227	336	23	657
90	833	1,014	127	22	519
100	976	658	78	22	374
		Site class[b] (low)			
0	8	1,651	192	25	543
10	42	1,750	187	25	587
20	87	1,624	171	25	539
30	125	1,493	164	25	489
40	162	1,383	154	25	443
50	211	1,274	134	25	403
60	338	1,083	114	25	339
70	370	978	100	25	292
80	536	761	71	25	225
90	610	599	35	24	171
100	742	358	9	24	83

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[a] SEV (soil expectation value).

[b] Site class includes different assumptions of site index, site preparation, and early survivorship.

Table B12—Slash pine plantation yields for differing site qualities and age-5 fusiform infection rates under the sawtimber utilization and fixed rotation assumptions

Infection	Pulp	Chip-n-saw	Saw	Rotation	SEV[a]
Pct	*Ft³/ac*	*Ft³/ac*	*Ft³/ac*	*Yr*	*$(1992)*
		Site **class**[b] **(high)**			
0	23	2,754	3,267	35	1,358
10	10	3,473	3,372	35	1,549
20	22	2,957	3,254	35	1,399
30	12	2,544	3,078	35	1,248
40	9	2,119	2,961	35	1,118
50	15	1,686	2,856	35	991
60	43	1,320	2,731	35	874
70	231	1,048	2,384	35	727
80	121	804	2,356	35	649
90	731	720	1,481	35	434
100	754	136	1,286	35	245
		Site class (medium)			
0	10	2,486	1,561	35	825
10	23	2,343	1,571	35	909
20	9	2,498	1,530	35	818
30	10	2,151	1,505	35	732
40	13	1,886	1,416	35	649
50	4	1,581	1,398	35	574
60	52	1,262	1,362	35	499
70	165	999	1,245	35	416
80	365	790	1,008	35	323
90	606	674	639	35	209
100	751	231	497	35	84
		Site **class**[b] (low)			
0	32	1,921	555	35	426
10	27	2,042	532	35	440
20	29	1,849	505	35	388
30	13	1,641	515	35	343
40	0	1,438	533	35	302
50	10	1,244	523	35	257
60	35	1,082	479	35	210
70	149	890	389	35	153
80	285	693	308	35	97
90	426	526	197	35	40
100	552	253	112	35	(33)

[a] SEV (soil expectation value).

[b] Site class includes different assumptions of site index, site preparation, and early survivorship.

Table B13--Slash pine plantation yields for differing site qualities and age-5 fusiform infection rates under the pulpwood utilization and economic rotation assumptions

Infection	Pulp	Chip-n-saw	Saw	Rotation	SEV[a]
Pct	*Ft^3/ac*	*Ft^3/ac*	*Ft^3/ac*	*Yr*	*$(1992)*
Site **class**[b] (high)					
0	20	2,694	1,489	23	1,830
10	143	3,235	1,698	24	2,073
20	341	2,895	1,594	24	1,907
30	526	2,561	1,495	24	1,746
40	821	2,203	1,333	24	1,555
50	1,104	1,840	1,184	24	1,371
60	1,457	1,438	850	23	1,169
70	1,859	1,032	536	22	960
80	2,274	632	355	22	748
90	2,580	252	85	20	539
100	2,269	0	0	19	183
Site class” (medium)					
0	19	2,238	666	24	1,098
10	105	2,572	740	25	1,202
20	206	2,341	708	25	1,111
30	341	2,096	654	25	1,012
40	508	1,820	588	25	906
50	716	1,463	464	24	791
60	950	1,166	393	24	672
70	1,196	816	262	23	545
80	1,459	489	128	22	406
90	1,671	188	45	21	281
100	1,467	0	0	19	72
Site **class**[b] (low)					
0	8	1,651	192	25	543
10	50	1,742	187	25	583
20	123	1,587	171	25	531
30	169	1,474	196	26	474
40	260	1,303	183	26	418
50	376	1,108	170	26	357
60	519	894	148	26	292
70	706	642	100	25	225
80	888	366	53	24	143
90	1,046	129	17	23	71
100	997	0	0	22	(37)

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[a] SEV (soil expectation value).

[b] Site class includes different assumptions of site index, site preparation, and early survivorship.

Table B14--Slash pine plantation **yields** for differing site qualities and age-5 fusiform infection rates under the pulpwood utilization and fixed rotation assumptions

Infection	Pulp	Chip-n-saw	Saw	Rotation	SEV[a]
Pct	*Ft³/ac*	*Ft³/ac*	*Ft³/ac*	*Yr*	*$(1992)*
		Site class[b] (high)			
0	23	2,754	3,267	35	1,358
10	10	3,473	3,372	35	1,549
20	22	2,957	3,254	35	1,399
30	12	2,544	3,078	35	1,248
40	9	2,119	2,961	35	1,118
50	15	1,686	2,856	35	991
60	173	1,259	2,661	35	853
70	848	766	2,049	35	628
80	1,662	381	1,238	35	382
90	2,801	28	104	35	78
100	2,177	0	0	35	(225)
		Site class[b] (medium)			
0	10	2,486	1,561	35	825
10	23	2,843	1,571	35	909
20	9	2,498	1,530	35	818
30	10	2,151	1,505	35	732
40	13	1,886	1,416	35	649
50	4	1,581	1,398	35	574
60	116	1,207	1,352	35	490
70	555	766	1,089	35	358
80	1,127	378	658	35	203
90	1,849	27	43	35	13
100	1,479	0	0	35	(162)
		Site class” (low)			
0	32	1,921	555	35	420
10	27	2,042	532	35	440
20	29	1,849	505	35	388
30	13	1,641	515	35	343
40	0	1,438	533	35	302
50	10	1,244	523	35	257
60	88	1,037	471	35	203
70	324	734	369	35	131
80	669	361	255	35	47
90	1,124	15	10	35	(58)
100	917	0	0	35	(149)

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[a] SEV (soil expectation value).

[b] Site class includes different assumptions of site index, site preparation, and early survivorship

Table B15-- Slash pine plantation yields for differing site qualities and age-5 fusiform infection rates under the poor utilization and economic rotation assumptions

Infection	Pulp	Chip-n-saw	Saw	Rotation	SEV[a]
Pct	*Ft^3/ac*	*Ft ^{3}/ac*	*Ft ^{3}/ac*	*Yr*	*$(1992)*
		Site **class**[b] (high)			
0	20	2,694	1,489	23	1,830
10	15	3,235	1,698	24	2,046
20	18	2,974	1,796	25	1,844
30	14	2,673	1,858	26	1,655
40	20	2,325	1,852	27	1,421
50	14	1,923	1,660	27	1,179
60	10	1,486	1,562	28	907
70	9	1,020	1,203	28	589
80	3	575	782	28	252
90	2	219	195	24	(121)
100	0	0	0	24	(608)
		Site **class**[b] **(medium)**			
0	19	2,238	666	24	1,098
10	25	2,572	740	25	1,186
20	25	2,341	708	25	1,077
30	15	2,146	744	26	956
40	7	1,902	779	27	824
50	11	1,619	794	28	673
60	12	1,277	673	28	501
70	4	905	608	29	317
80	2	513	456	30	113
90	2	167	98	26	(126)
100	0	0	0	27	(410)
		Site **class**[b] (low)			
0	8	1,651	192	25	543
10	19	1,794	219	26	577
20	17	1,641	205	26	515
30	15	1,532	22s	27	449
40	16	1,394	254	28	380
50	8	1,219	277	29	301
60	6	1,023	323	31	219
70	2	736	225	30	110
80	3	415	166	31	(12)
90	1	115	33	28	(152)
100	0	0	0	29	(303)

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[a] SEV (soil expectation value).

[b] **Site** class includes different assumptions of site index, site preparation, and early survivorship.

Table B16– **Slash pine plantation yields for differing site qualities and age-5 fusiform infection rates under the poor utilization and fixed rotation assumptions**

Infection	Pulp	Chip-n-saw	Saw	Rotation	SEV[a]
Pct	*Ft³/ac*	*Ft³/ac*	*Ft³/ac*	*Yr*	*$(1992)*
		Site class* (high)			
0	23	2,754	3,267	35	1,358
10	10	3,473	3,372	35	1,549
20	22	2,957	3,254	3s	1,399
30	12	2,544	3,078	35	1,248
40	9	2,119	2,961	35	1,118
50	15	1,686	2,856	35	991
60	4.	1,259	2,661	35	834
70	11	766	2,049	35	537
80	0	381	1,238	35	201
90	0	28	104	35	(226)
100	0	0	0	35	(605)
		Site class[b] (medium)			
0	10	2,486	1,561	35	825
10	23	2,843	1,571	35	909
20	9	2,498	1,530	35	818
30	10	2,151	1,505	35	732
40	13	1,886	1,416	35	649
50	4	1,581	1,398	35	574
60	11	i ,207	1,352	35	479
70	6	766	1,089	35	299
80	2	378	658	35	80
90	0	27	43	35	(188)
100	0	0	0	35	(414)
		Site class* (low)			
0	32	1,921	555	35	420
10	27	2,042	532	35	440
20	29	1,849	505	35	388
30	13	1,641	515	35	343
40	0	1,438	533	35	302
50	10	1,244	523	35	257
60	8	1,037	471	35	195
70	1	734	369	35	95
80	3	361	255	35	(25)
90	0	15	10	35	(180)
100	0	0	0	35	(301)

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[a] SEV (soil expectation value).

[b] Site class includes different assumptions of site index, site preparation, and early survivorship.

Pye, John M.; Wagner, John E.; Holmes, Thomas P.; Cubbage, Frederick W. 1997. Positive returns from investment in fusiform rust research. Res Pap. SRS-4 Asheville, NC U.S. Department of Agriculture, Forest Service, Southern Research Station 55 p.

Fusiform rust [*Cronartium quuercuum* (Berk.(Miy. ex Shirai f sp. *fusiforme* Burdsall et Snow] is a widespread and damaging disease of loblolly and slash pine in the South. Research has identified families of these pines with improved genetic resistance to the disease, allowing production and planting of resistant seedlings in areas at risk. This study compared the cost of fusiform rust research to the simulated benefits of rust-resistant seedlings in plantations established Southwide between 1970 and 2020. Seedling producers provided estimates of resistant seedling production and gains in resistance over the period. Stand-level simulations evaluated the impact of various infection rates on financial yield on low-, medium-, and high-quality sites of each species, taking into account both mortality and product degrade effects of the disease. Two rotation regimes and four levels of infected stem utilization were explored. Stand-level yields were extrapolated to regional values using long-term distributions of plantation conditions from Forest Inventory and Analysis surveys. Simulation results showed that past investments in fusiform rust research of S49 million will return benefits to plantation owners of between $108 and $999 million in I992 constant dollars. Expected improvements in resistance will not eliminate all financial damages from the disease; simulation results indicate substantial financial benefits yet remain for additional research and development.

Keywords: *Cronartium fusiforme*, disease control, disease resistance, economic damages, fusiform rust, loblolly pine, plantation valuation, research benefits, slash pine.