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An Integrated Approach Toward Reducing Losses from Fusiform Rust in Merchantable Slash and Loblolly Pine Plantations

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Abstract

The primary objective of this study was to evaluate the selective thinning of trees with rust galls as a means of reducing losses to the fusiform rust (*Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme*) disease in merchantable slash (*Pinus elliottii* Engelm. var. *elliottii*) and loblolly (*P. taeda L.*) pine plantations. Additional objectives were to assess the post-thinning occurrence and impacts of southern pine beetles (*Dendroctonus frontalis* Zimm.) and annosum root rot (*Heterobasidion annosum* Fr.). Nineteen rust-infected plantations were selected in Alabama, Georgia, and South Carolina to represent a wide range of stand and rust conditions. Thinnings were based primarily on the removal of trees with severe and moderate stem girdling caused by fusiform rust galls. Approximately 750 acres were thinned operationally to salvage potential mortality; 2,250 nonthinned acres served as controls. Study plots were surveyed annually for 10 years to determine the amount and causes of mortality. Stand growth and development were evaluated at the end of 5- and 10-year periods after treatment. Removal of rust-infected stems greatly improved the quality of trees in the residual stands. The periodic diameter growth of individual dominant and codominant slash and loblolly pine trees was affected by the extent of stem girdling. Trees with severe stem girdling (≥50 percent) grew significantly less than gall-free trees or trees with small or moderate stem girdling. Trends in periodic stand growth and total volume production were similar for slash and loblolly pine. Standing volume at the end of 10 years was greater in nonthinned portions of the plantations than in thinned portions. However, periodic stand growth and ingrowth of rust-free sawtimber (≥9 inches in diameter at breast height) were greater in thinned portions of the plantation. Rust-associated mortality was the primary factor that reduced volume growth and production in slash pine plantations. Losses from fusiform rust and the southern pine beetle had a severe impact on total production in the loblolly plantations. Thinning significantly reduced losses from both of these forest pests. Management implications can be incorporated into conventional thinning procedures for regulating stand density, increasing growth, and improving stand health.

Keywords: Annosum root rot, forest health, integrated pest management, *Pinus elliottii* Engelm. var. *elliottii*, *Pinus taeda* L. southern pine beetle, thinning.

Introduction

There are over 25 million acres of pine plantations in the Southern United States. Recent assessments indicate the total area in pine plantations will more than double by the year 2030 (U.S. Department of Agriculture 1988). Slash pine (*Pinus elliottii* Engelm. var. *elliottii*) and loblolly pine (*P. taeda* L.) are the species planted most commonly in the South. These two species are also the most susceptible to damage caused by fusiform rust (*Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme*). Recent surveys show that slash and loblolly pine plots with ≥10 percent rust incidence are distributed over nearly the entire range of each species (Starkey and others 1997). Losses to fusiform rust result from mortality, stem defect, and a reduction in the growth of trees with severe stem galls. A high incidence of rust in pine plantations severely limits management options and objectives.

Significant advances have been made during the past 20 years in the development of management strategies to reduce losses from fusiform rust. Methods have been developed for predicting the relative rust hazard of sites for both slash and loblolly pines (Anderson and others 1986, Borders and Bailey 1986, Froelich and Snow 1986, Starkey and others 1997). Rust resistant planting stock is available for use in high-rust hazard areas (Powers and Kraus 1986, Schmidt and others 1981). Models provide the opportunity for assessing the combined effects of site quality, stand density, age, and level of fusiform rust infection on future yields of infected slash and loblolly pine plantations (Nance and others 1983, 1985). These models emphasize the importance of preventing rust during stand establishment (0–5 years), when the potential impact of rust infection is the greatest.

Forest surveys, completed at about the time this study was initiated, indicate that more than 50 percent of the slash and loblolly pine plantations—approximately 15 million acres—were greater than 10 years of age (Sheffield and Knight 1982, Sheffield and others 1983, U.S. Department of Agriculture 1988). Many plantations, especially those located in high-hazard rust areas, continue to be heavily infected with fusiform rust (Starkey and others 1997). The selective thinning of trees with severe stem galls has been proposed as a means of reducing losses to rust in merchantable pine plantations (Malac 1978, Powers and others 1974). Yet, little is known about the value, practicality, and response of stands subjected to thinning based on the incidence and severity of fusiform rust. In 1981, several members of the

newly-formed Integrated Forest Pest Management Cooperative requested a research study to determine whether or not merchantable-aged plantations of slash and loblolly pines with moderate to high incidences of fusiform rust could or should be treated. From 1981 to 1992, a 10-year study was conducted in Alabama, Georgia, and South Carolina to better understand and manage fusiform rust in merchantable slash and loblolly pine plantations. Silvicultural options, pest management principles, and operational practices were integrated to meet the following objectives:

- Assess improvements in stand quality after thinning;
- Quantify mortality caused by fusiform rust, the southern pine beetle (*Dendroctonus frontalis* Zimm.) (SPB), and annosum root rot (*Heterobasidion annosum* Fr.) over the 10-year study period;
- Determine whether severity of stem girdling by fusiform rust affects the periodic diameter growth of individual trees;
- Evaluate periodic volume growth and total yield in thinned and nonthinned plantations;
- Compare differences in treatment responses between slash and loblolly pine;
- Assess advantages and disadvantages of selective thinning in rust-infected plantations; and
- Develop management recommendations for assessing and reducing losses from fusiform rust in merchantable slash and loblolly pine plantations.

Study Plantations and Methods

A long-term cooperative study was established in the early 1980's to determine the biological responses and cultural options associated with thinning stands infected with fusiform rust (Belanger and others 1985, Miller and others 1985). Study plantations were selected to represent a wide range of stand and rust conditions.

Ten slash pine plantations were located in the Coastal Plain of Georgia and South Carolina—3 in Georgia and 7 in South Carolina. Nine loblolly pine plantations were located in the Coastal Plain of Georgia and Alabama—two in Georgia and seven in Alabama. Plantation size ranged from 50 to 200 acres. Four 1/4-acre permanent plots were established in randomly designated thinned and nonthinned portions of each plantation (randomized block design). All trees in the 1/4-acre plots were numbered to maintain their identities throughout the study. Diameter at breast height (d.b.h.), number of stem and branch galls, crown class, and a risk class based on rust severity were recorded for each tree. The fifth tree in each diameter class was selected to record detailed rust characteristics and tree heights. The stem gall characteristics measured and recorded in this 20-percent subsample were (1) the height aboveground, (2) the estimated percentage of stem circumference affected by each gall, and (3) the estimated proportion of each rust gall with sunken areas usually containing areas of decay, insect activity, or both that are referred to as cankers. Tree heights were measured to determine site index and develop volume equations for individual plantations.

Guidelines for Tree Removal

The success of selective thinning in rust-infected plantations is based on anticipated mortality. The following criteria—based on rust severity—were used to mark and remove trees with stem infections:

High risk: trees likely to die before rotation: number of stem galls ≥ 2, stem girdling ≥ 50 percent by at least one gall;

Moderate risk: tree survival to rotation age questionable: number of stem galls = 1, stem girdling ≥ 50 percent;

Low risk: trees likely to survive through rotation: stem girdling < 50 percent.

The proportion of gall cankering was not used in the final rust severity index because obtaining an objective assessment of the extent of cankering is difficult.

Most high-risk trees were marked for removal; low-risk trees were not marked. Moderate-risk trees provided flexibility in the selection process; their removal was based on the potential value of individual trees, spacing within the stand, and yield requirements for thinning. Trees were cut and removed throughout the year. Scheduling was strongly dependent on the availability of logging crews, weather, and local demands for pulpwood. Cutting to provide access rows for logging equipment removed trees from all diameter and risk classes.

Assessing Pest Damage and Treatment Differences

Study plots were surveyed annually to determine amount and causes of mortality. Rust-associated mortality (RAM) was defined as any dead tree with a stem gall and included stem-breakage if the break occurred at a gall. Additional mortality was attributed to SPB and a category classified as other (e.g., root diseases, climatic effects, logging, fire, cutting for access roads, other insects).

Annosum root rot hazard ratings were determined for plantations based on soil types. During the seventh growing season, a total of 3,832 roots were sampled from thinned and nonthinned plots. These roots were washed, scraped, and examined for symptoms of root diseases. A sub-sample (12 percent) of symptomatic roots was cultured in the laboratory to determine the occurrence of *H. annosum* in damaged tissue.

The d.b.h. of all trees in the thinned and nonthinned portions of the study plantations was remeasured at 5-year intervals to evaluate the effects of treatment, fusiform rust, and other pests on individual tree growth, stand growth and development, and total yield over a 10-year period. To reduce the confounding effect of crown position on individual tree growth, only dominant and codominant trees were used to assess the influence of treatment, rust occurrence, and risk class on periodic diameter growth. Periodic yields were estimated using local volume tables developed for individual plantations. Analyses of variance were used to compare thinning and nonthinning treatments and to separate the influence of rust severity on tree growth. Significant differences between means were tested at the 0.05 probability level.

Results—Slash Pine

Stand and rust characteristics—Ages of the 10 slash pine plantations averaged 16 years when the study was established and ranged from 13 to 21 years. Average site quality at 25 years was 62 (Bennett and others 1959). Study plots contained an average of 437 live trees per acre and an average total volume (Bennett and others 1959) of 2,398 cubic feet (ft^3) per acre. Average d.b.h. was 6.1 inches (in.). Approximately 9 percent of the stems were sawtimber-sized trees (d.b.h. ≥9.0 in.). Susceptibility of the sites to *H. annosum* infection was ranked as intermediate to low for eight plantations. Hazard rankings for the other two plantations were intermediate and high.

The slash pine study plots contained an average of 207 infected stems per acre. Incidence of stem infections averaged 47 percent and ranged from 35 to 70 percent. The average stem gall girdled 63 percent of the stem circumference. Forty-six percent of infected stems was classified as high-risk trees.

Southern pine beetle activity was endemic in the Atlantic Coastal Plain when the study was initiated. Beetle-caused mortality was not evident in the slash pine plantations before or immediately after thinning operations.

Immediate returns—materials salvaged—Table 1 shows average stand and individual tree characteristics after the selective thinning of rust-infected stems. Most of the trees removed (85 percent) were from the high- and moderate-risl rust classes. High-risk trees represented approximately 46 percent of the total slash pine volume harvested. High-risk trees that were not cut were generally too small for efficien and effective harvest.

Rust profiles developed for high-, moderate-, and low-risk trees indicate infections were equally and proportionally distributed over all diameter classes. Because rust severity

Table 1—Average stand structure and individual tree characteristics after the selective thinning of fusiform rust-infected stems in 10 slash pine plantations in the Coastal Plain of Georgia and South Carolina

	Stand structure			Tree characteristics	
Treatment	Basal area	Volume	Live trees	D.b.h.	Height
	Ft^2/acre	*Ft^3/acre*	*No./acre*	*In.*	*Ft*
Thinned					
Initial	97	2,403	437	6.1	47.2
Removed	30	731	141	5.9	46.5
Residual	67	1,672	296	6.2	47.5
Nonthinned	95	2,391	308	6.4	47.8

D.b.h. = diameter at breast height.

was the primary basis for marking and removal, thinning did not significantly change the average diameter, average tree height, or diameter distribution of slash pine.

Improvement in stand quality—The average number of rust-infected stems, rust incidence, total number of stem galls, and severity of rust infection was high in the slash pine plantations before thinning (table 2). Thinning removed 77 percent of the high-risk trees. Thinning reduced incidence of stem galls by 22 percent, total number of stem galls by 70 percent, and average gall severity by 15 percent. Residual stem galls were small and had little cankering.

Periodic responses—mortality—Total mortality during the 10-year study period was significantly higher in nonthinned portions of slash pine plantations than in thinned portions (table 3). Rust-associated mortality accounted for 78 percent of the total volume losses in nonthinned areas. Most of the remaining mortality was attributed to other causes and factors that could not be identified. High-risk trees accounted for 65 percent of total RAM.

Net differences in total volume losses between thinned and nonthinned plots averaged 329 ft^3 per acre. This equates to an annual gain of approximately 0.35 cords of wood per acre. The major portion (91 percent) of this volume gain resulted from the salvage removal of rust-infected trees. The average d.b.h. and total height of trees killed by SPB attack were greater than those of trees killed by fusiform rust (table 4). Much of the remaining mortality in the thinned plots occurred in small trees that sustained mechanical injury during thinning operations. Other mortality in nonthinned

Table 2—Average fusiform rust characteristics after the selective thinning of rust-infected stems in 10 slash pine plantations in the Coastal Plain of Georgia and South Carolina

	Stem infections				Gall characteristics	
Treatment	Infected stems	Incidence	Total stem galls	High risk trees	Circumference[a]	Max.[b]
	No./acre	*Percent*	*No./acre*		*Percent*	
Thinned						
Initial	207	47	372	96	63	71
Removed	132	94	258	74	72	82
Residual	75	25	114	22	48	52
Nonthinned	191	48	339	110	63	71

[a] Average percentage of stem circumference girdled.
[b] Percentage of stem circumference girdled by most severe gall.

Table 3—Average 10-year mortality and volume losses caused by fusiform rust, the southern pine beetle, and other factors in thinned and nonthinned portions of 10 slash pine plantations in the Coastal Plain of Georgia and South Carolina

	Thinned		Nonthinned	
Cause	Tree mortality	Volume loss	Tree mortality	Volume loss
	No./acre	*Ft^3/acre*	*No./acre*	*Ft^3/acre*
Fusiform rust	17.8	74.3	73.7	373.7
SPB	1.6	7.8	5.4	28.6
Other and unknown	22.8	66.2	24.1	74.8
Total	42.2	148.3	103.2	477.1

SPB = Southern pine beetle.

Table 4—Average diameter at breast height and total height of trees killed by fusiform rust, the southern pine beetle, and other factors in thinned and nonthinned portions of 10 slash pine plantations in the Coastal Plain of Georgia and South Carolina

Cause	Thinned		Nonthinned	
	D.b.h.	Height	D.b.h.	Height
	In.	*Ft*	*In.*	*Ft*
Fusiform rust	5.2	42.4	5.8	46.4
SPB	5.6	46.4	6.1	48.1
Other and unknown	4.3	39.7	4.3	39.8

D.b.h. = diameter at breast height; SPB = southern pine beetle.

plots was mostly in intermediate and suppressed trees in gradual decline from crown competition.

Accumulative annual tree mortality and associated volume losses caused by fusiform rust were low during the 2 years immediately after thinning but increased at a relatively constant rate during years 3 through 10 (figs.1, 2). This trend was particularly evident in the nonthinned plots.

Losses attributed to SPB attack and spot spread were minimal during the 10-year study period. No visible signs of disturbance were associated with any of the SPB outbreaks in slash pine plantations.

Symptoms of root diseases were evident in approximately 16 percent of the roots sampled (table 5). There were no significant statistical differences between the percentages of symptomatic slash pine roots from thinned and nonthinned areas. The annosum rust rot fungus was isolated from less than 1 percent of the symptomatic roots (table 6). No mortality in thinned or nonthinned plots was attributed to root decay fungi.

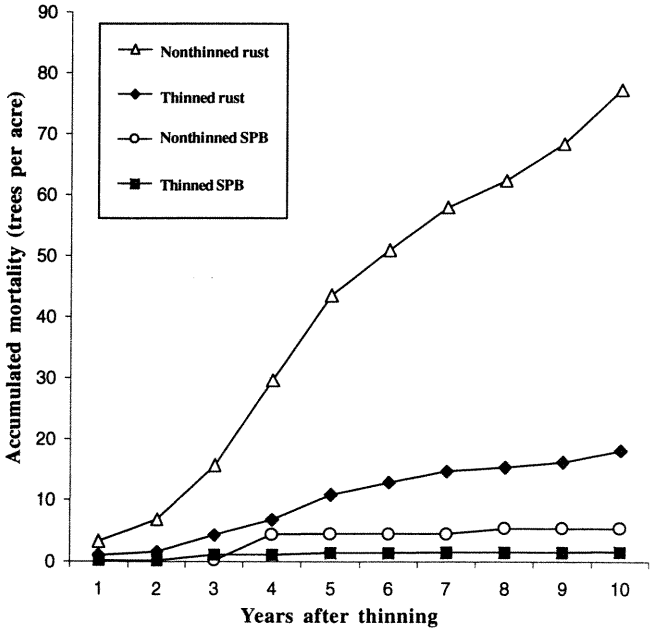


Figure 1—Accumulative tree mortality caused by fusiform rust and the southern pine beetle (SPB) in thinned and nonthinned portions of 10 slash pine plantations in the Coastal Plain of Georgia and South Carolina.

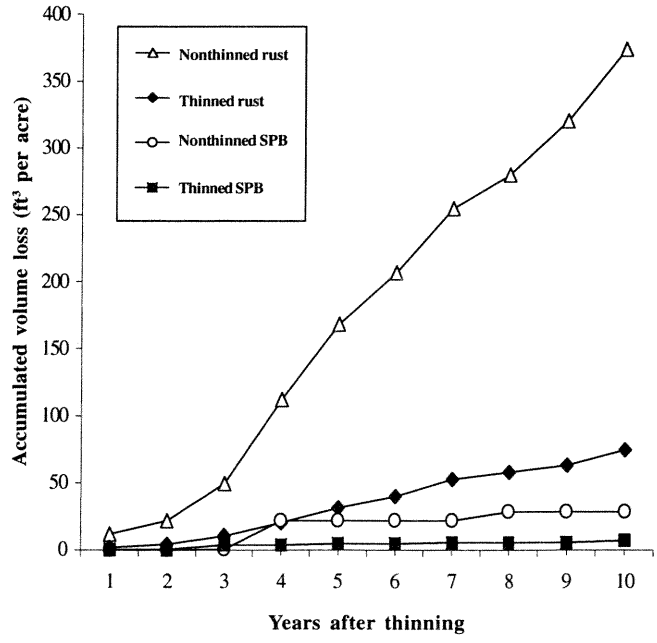


Figure 2—Accumulative volume loss caused by fusiform rust and the southern pine beetle (SPB) in thinned and nonthinned portions of 10 slash pine plantations in the Coastal Plain of Georgia and South Carolina.

Table 5—The incidence of roots with symptoms typical of *Heterobasidion annosum* in thinned and nonthinned portions of 10 slash pine plantations in the Coastal Plain of Georgia and South Carolina

Treatment	Sampled	Symptoms
Thinned	972	145 (14.9)[a]
Nonthinned	1,024	173 (17.9)
Total	1,996	318 (15.9)

[a] Percent of infected roots.

Table 6—The incidence of *Heterobasidion annosum* isolated from symptomatic roots sampled from thinned and nonthinned portions of 10 slash pine plantations in the Coastal Plain of Georgia and South Carolina

Treatment	Symptomatic roots sampled	Infected roots[a]
Thinned	91	1 (1.1)[b]
Nonthinned	120	0 (0.0)
Total	211	1 (0.5)

[a] Based on laboratory cultures from symptomatic roots.
[b] Percent of infected roots.

Periodic diameter growth—When the study was initiated, there were no significant differences in the average d.b.h. of residual dominant and codominant slash pine trees between thinned and nonthinned plots or between rust-free and rust-infected trees (table 7). Average diameter growth over the 10-year study period was also nonsignificant between thinned and nonthinned plots and between rust-infected and rust-free trees. Differences in periodic growth were significant, however, between risk classes. Diameter growth of trees with multiple galls and severe girdling was significantly less than moderate-risk, low-risk, or rust-free trees. Growth losses and related mortality associated with high-risk trees were significant during both 5-year measurement periods.

Periodic stand growth and total yield—Treatment, total mortality, and fusiform rust affected the average periodic growth and total yield of the slash pine plantations. After 10 years, average basal area, volume, and number of live trees per acre were greater in nonthinned plots than in thinned plots (table 8). However, periodic basal area growth and volume growth during the 10-year period were significantly

Table 7—Average diameter at breast height and periodic growth of dominant and codominant slash pine trees as affected by treatment, rust incidence, and risk class in 10 slash pine plantations in the Coastal Plain of Georgia and South Carolina

	Diameter at breast height			
Variable	Initial	5 years	10 years	Total difference
Treatment				
Thinned	7.0	8.1	9.2	2.2
Nonthinned	7.4	8.5	9.4	2.0
Rust occurrence				
Rust galls	7.3	8.3	9.3	2.0
Rust-free	7.2	8.2	9.3	2.1
Risk class				
Rust-free	7.2	8.2	9.3	2.1
Low	7.3	8.4	9.5	2.2
Moderate	7.6	8.6	9.6	2.0
High	7.0	7.7	8.4	1.4[a]

[a] Significantly different at 0.05 probability level.

greater in thinned plots than in nonthinned plots. Average total yield (thinned volume added to standing live volume) was also significantly greater for thinned plots (3,460 ft^3 per acre) than for nonthinned plots (3,193 ft^3 per acre). Mortality accounted for most of the differences in periodic growth. Losses in nonthinned plots were mostly rust associated and evenly distributed across diameter classes. Losses in thinned plots were mostly small trees damaged during logging operations. The selective cutting of high-risk trees reduced the potential for mortality in thinned plots.

At the end of the 10-year study period, the average number of sawtimber-sized trees per acre was marginally greater in nonthinned plots than thinned plots. However, 80 trees (75 percent) in the thinned plots were rust-free, 26 trees (24 percent) were in the low- or moderate-risk classes, and only 1 tree had severe stem girdling (table 8). By comparison, in the nonthinned plots, only 59 trees (48 percent) were rust-free, 55 trees (44 percent) were low- or moderate-risk trees, and 10 trees had severe stem girdling. Although rate of ingrowth was similar for both treatments, thinning improved the quality of high-value, sawtimber-sized trees significantly.

Table 8—Average periodic growth in thinned and nonthinned portions of 10 slash pine plantations after the selective thinning of rust-infected stems in the Coastal Plain of Georgia and South Carolina

Treatment	Stand structure			
	Basal area	Volume	Live trees	Sawtimber[a]
	Ft²/acre	*Ft³/acre*	*No./acre*	*No./acre*
Thinned				
Initial	67	1,672	296	21
5 years	84	2,241	270	54
10 years	104	2,729	252	107
Difference	37	1,057	-44	86
Nonthinned				
Initial	95	2,391	398	24
5 years	107	2,886	337	70
10 years	121	3,193	288	124
Difference	26	802	-110	100

[a] Trees ≥ 9.0 in. diameter at breast height.

Results—Loblolly Pine

Stand and rust characteristics—Average age of the nine loblolly pine plantations was 17 years when the study was established and ranged from 16 to 22 years. Average site quality at 25 years was 70 (Clutter and Lenhart 1968). Study plots contained an average of 462 trees per acre and a total volume (Bailey and Clutter 1970) of 2,856 ft³ per acre. Average d.b.h. was 6.8 inches. Approximately 16 percent of the stems were sawtimber-sized trees. Risk analysis ranked the potential for *H. annosum* infection as intermediate or low for seven of the plantation sites. The remaining two plantations were ranked as intermediate- to high-hazard sites.

The loblolly pine plots contained an average of 268 infected stems per acre. Incidence of stem galls averaged 58 percent and ranged from 46 to 74 percent. The average stem gall girdled 52 percent of the stem circumferences. Thirty-three percent of the infected stems were classified as high-risk trees.

Southern pine beetle populations were endemic in the Atlantic Gulf Coastal Plain when the study was initiated. There was no evidence of beetle-caused mortality in the loblolly pine study plantations before or immediately after thinning operations.

Immediate returns—materials salvaged—Extent of thinning in the nine loblolly pine plantations was generally classified as light to moderate (table 9). Average basal area was reduced from 126 to 97 ft² per acre. Residual stocking in the thinned stands averaged 333 live stems per acre. As with slash pine, thinning did not significantly change the average diameter, average tree height, or diameter distribution of loblolly pine.

Improvement in stand quality—Selective thinning reduced the number and severity of infected stems in the loblolly pine plantations (table 10). Incidence of stem infections was reduced from 59 to 47 percent with the total number of stem infections reduced by 49 percent. Thinning removed 71 percent of all high-risk trees. The average amount of stem circumference girdled was reduced from 51 to 42 percent.

Periodic responses—mortality—Total mortality in the nonthinned portions of the loblolly pine plantations was significantly higher than that recorded in thinned plantations during the 10-year measurement period (table 11). Rust-associated mortality accounted for 51 percent of the total volume loss. High-risk trees accounted for 65 percent of total RAM. Mortality classified as other and unknown accounted for only 11 percent of the total volume loss. Most of these losses were attributed to the gradual suppression of small trees (table 12).

Table 9—Average stand structure and individual tree characteristics after the selective thinning of fusiform rust-infected stems in nine loblolly pine plantations in the Coastal Plain of Alabama and Georgia

	Stand structure			Tree characteristics	
Treatment	Basal area	Volume	Live trees	D.b.h.	Height
	Ft^2/acre	*Ft^3/acre*	*No./acre*	*In.*	*Ft*
Thinned					
Initial	126	2,910	460	6.9	49.5
Removed	29	633	127	6.4	47.8
Residual	97	2,277	333	7.1	50.1
Nonthinned	122	2,803	464	6.7	49.2

D.b.h. = diameter at breast height.

Table 10—Average fusiform rust characteristics after the selective thinning of rust-infected stems in nine loblolly pine plantations in the Coastal Plain of Alabama and Georgia

	Stem infections				Gall characteristics	
Treatment	Infected stems	Incidence	Total stem galls	High risk trees	Circumference[a]	Max.[b]
	No./acre	*Percent*	*No./acre*		*Percent*	
Thinned						
Initial	272	59	496	86	51	60
Removed	114	90	243	61	62	76
Residual	158	47	253	25	42	49
Nonthinned	264	57	491	92	53	63

[a] Average percentage of stem circumference girdled.
[b] Percentage of stem circumference girdled by most severe gall.

Table 11—Average10-year tree mortality and volume losses caused by fusiform rust, southern pine beetle, and other factors in thinned and nonthinned portions of nine loblolly pine plantations in the Coastal Plain of Alabama and Georgia

	Thinned		Nonthinned	
Cause	Tree mortality	Volume loss	Tree mortality	Volume loss
	No./acre	*Ft^3/acre*	*No./acre*	*Ft^3/acre*
Fusiform rust	30.6	139.4	90.3	343.2
SPB	13.3	139.6	27.2	251.4
Other and unknown	22.0	85.2	28.7	74.1
Total	65.9	364.2	146.2	668.7

SPB = Southern pine beetle.

Table 12—Average diameter at breast height and total height of trees killed by fusiform rust, southern pine beetle, and other factors in thinned and nonthinned portions of nine loblolly pine plantations in the Coastal Plain of Alabama and Georgia

Cause	Thinned		Nonthinned	
	D.b.h.	Height	D.b.h.	Height
	In.	*Ft*	*In.*	*Ft*
Fusiform rust	5.7	46.6	5.5	45.7
SPB	8.5	46.6	8.0	55.2
Other and unknown	5.1	43.6	4.6	42.1

D.b.h. = diameter at breast height; SPB = southern pine beetle.

Net difference in total volume losses between thinned and nonthinned study plots averaged 305 ft per acre. Differences in rust-associated mortality between thinned and nonthinned plots accounted for 67 percent of the total volume salvaged by thinning. Tree mortality and volume losses caused by fusiform rust increased at a relatively constant rate in thinned and nonthinned study plots throughout the 10-year period (figs. 3, 4).

Southern pine beetle attack and spot spread were significant causes of mortality in both thinned and nonthinned plantations (figs. 3, 4). Southern pine beetle activity was low in the Gulf Coastal Plain during the early years of the study, increased during years 7 and 8, and became epidemic in years 9 and 10. Total volume loss caused by the SPB was 38 percent of all losses in nonthinned plots over the 10-year

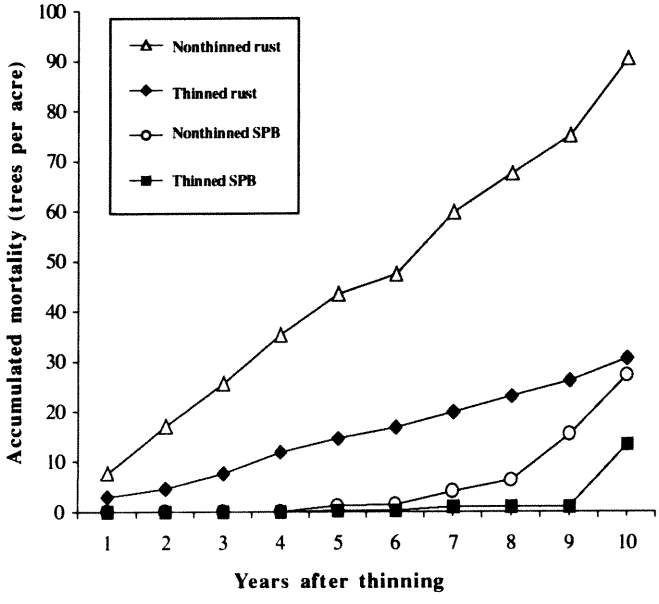


Figure 3—Accumulative tree mortality caused by fusiform rust and the southern pine beetle (SPB) in thinned and nonthinned portions of nine loblolly pine plantations in the Coastal Plain of Alabama and Georgia.

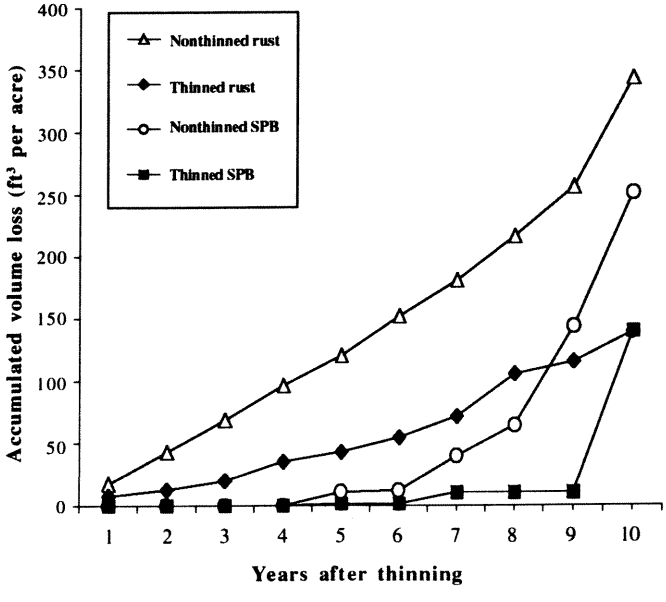


Figure 4—Accumulative volume loss caused by fusiform rust and the southern pine beetle (SPB) in thinned and nonthinned portions of nine loblolly pine plantations in the Coastal Plain of Alabama and Georgia.

period. Total tree mortality and volume losses caused by SPB activity were approximately twice as much in nonthinned plots as in thinned plots. Average d.b.h. and total height of trees killed by SPB were significantly greater than trees killed by fusiform rust or other causes (table 12). In thinned and nonthinned plots, losses of sawtimber volume caused by the SPB were more than three times greater than losses attributed to fusiform rust (fig. 5).

Like slash pine, the percentage of loblolly pine roots with symptoms typical of *H. annosum* did not differ significantly between thinned and nonthinned treatment areas (table 13). *Heterobasidion annosum* was isolated from 7.1 percent of symptomatic loblolly roots (table 14). No mortality in thinned or nonthinned plots was attributed to root diseases.

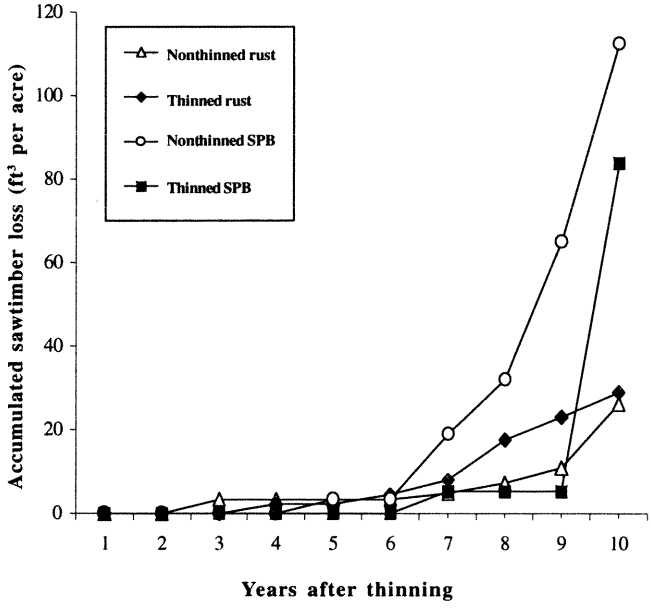


Figure 5—Accumulative sawtimber volume loss caused by fusiform rust and the southern pine beetle (SPB) in thinned and nonthinned portions of nine loblolly pine plantations in the Coastal Plain of Alabama and Georgia.

Table 13—The incidence of roots with symptoms typical of *Heterobasidion annosum* in thinned and nonthinned portions of nine loblolly pine plantations in the Coastal Plain of Alabama and Georgia

Treatment	Sampled	Symptoms
Thinned	913	158 (17.3)[a]
Nonthinned	923	147 (15.9)
Total	1,836	305 (16.6)

[a] Percent of infected roots.

Periodic diameter growth—When the study was initiated, there was no significant difference in the average d.b.h. of residual dominant and codominant loblolly pine trees between thinned and nonthinned plots (table 15). The average d.b.h. and diameter growth did not differ

Table 14—The incidence of *Heterobasidion annosum* from symptomatic roots sampled from thinned and nonthinned portions of nine loblolly pine plantations in the Coastal Plain of Alabama and Georgia

Treatment	Symptomatic roots sampled	Infected roots[a]
Thinned	140	10 (7.1)[b]
Nonthinned	115	8 (7.0)
Total	255	18 (7.1)

[a] Based on laboratory cultures from symptomatic roots.
[b] Percent of infected roots.

Table 15—Average diameter at breast height and periodic growth of dominant and codominant loblolly pine trees as affected by treatment, fusiform rust occurrence, and risk class in nine loblolly pine plantations in the Coastal Plain of Alabama and Georgia

	Diameter at breast height			
Variable	Initial	5 years	10 years	Total difference
Treatment				
Thinned	7.9	8.9	9.9	2.0
Nonthinned	7.7	8.7	9.4	1.7[a]
Rust occurrence				
Rust galls	7.7	8.7	9.5	1.8
Rust-free	7.8	8.8	9.7	1.9
Risk class				
Rust-free	7.8	8.8	9.7	1.9
Low	8.0	9.0	9.8	1.8
Moderate	7.6	8.7	9.4	1.8
High	7.4	8.3	8.9	1.5[a]

[a] Significantly different at 0.05 probability level.

significantly between trees in thinned and nonthinned plots during the 5-year period after treatment. Response to thinning did occur, however, during the 6- through 10-year growth period. Final measurements showed significantly greater d.b.h. growth for trees in thinned plots than in nonthinned plots.

Average diameter growth over the 10-year study period between rust-infected and rust-free trees was nonsignificant. Like slash pine, high-risk loblolly pines grew significantly less than those with no rust infections. There were no significant differences in average diameter growth between moderate-risk, low-risk, and rust-free trees. Growth losses were closely related to high mortality rate associated with high-risk trees. There were no significant correlations between the number of high-risk trees or growth losses and SPB incidence or amount of SPB-related mortality.

Periodic stand growth and total yield—After 10 years, the average stand basal area, total standing volume, and number of live trees per acre in the loblolly pine plantations were greater in the nonthinned plots than thinned plots (table 16). Periodic basal area increment and volume growth, however, were significantly greater in thinned plots than in nonthinned plots. Average total yield (thinned volume added to standing live volume) was also significantly greater in thinned plots (3,791 ft^3 per acre) than nonthinned plots (3,489 ft^3 per acre). Large amounts of rust-associated mortality and losses from SPB activity accounted for substantial volume reductions in the nonthinned plots.

Final stand structure showed the average number of sawtimber-sized trees was similar for thinned and nonthinned plots. The notable difference between treatments was in tree quality. In thinned plots, there was an average of 66 rust-free trees per acre, 75 low- or moderate-risk trees, and only 1 tree per acre with severe stem girdling caused by fusiform rust. By comparison, nonthinned plots had an average of 57 rust-free trees per acre, 83 low- or moderate-risk trees per acre, and 6 high-risk trees per acre. Reductions in diameter growth caused by severe stem girdling account in part for the low ingrowth of high-risk trees from pulpwood size to sawtimber.

Discussion

The primary purpose of this research was to evaluate strategies for management of merchantable-aged slash and loblolly pine plantations with moderate to high incidence of fusiform rust disease. Rust incidence in these plantations ranged from 30 to 70 percent. Thinning based on the removal

Table 16—Average periodic growth in thinned and nonthinned portions of nine loblolly pine plantations after the selective thinning of fusiform rust-infected stems in the Coastal Plain of Alabama and Georgia

Treatment	Stand structure			
	Basal area	Volume	Live trees	Sawtimber[a]
	Ft^2/acre	*Ft^3/acre*	*No./acre*	*No./acre*
Thinned				
Initial	97	2,277	333	46
5 years	117	2,732	305	103
10 years	127	3,158	266	142
Difference	30	881	-67	96
Nonthinned				
Initial	122	2,803	464	42
5 years	144	3,561	405	114
10 years	142	3,489	316	148
Difference	20	686	-148	106

[a] Trees ≥ 9.0 in. diameter at breast height.

of trees with severe to moderate fusiform rust galls on the main stem was the primary treatment imposed. In contrast with conventional silvicultural thinnings, little attention was given to establishing predetermined residual stand densities or fixed spacings. The selective removal of moderate- and high-risk trees provided an immediate return on trees that had a high probability of dying before final stand harvest. In addition, thinning provided improvements in stand quality and enhanced individual tree growth. Overall quality of the residual trees was excellent after thinning. In the slash and loblolly pine plantations, only 7 and 8 percent of the residual trees, respectively, had severe stem girdling galls.

Rust severity is an important consideration when developing management strategies to reduce losses from fusiform rust. Trees with severe stem girdling grew significantly less than rust-free trees or trees with small or moderate amounts of stem girdling. A large portion of the rust-associated mortality in the study appeared directly related to gradual reduction in tree growth caused by severe stem girdling. In addition, severe stem girdling equates to lower tree quality and value (Clark and McAllister 1998). Rust severity was more important in assessing the potential impact of rust than incidence alone. Although there was a direct and significant relationship between rust incidence and percentage of high-risk trees in the study plantations (Belanger and Zarnoch 1991), it is unknown whether these associations apply throughout the South.

Accumulative 10-year losses from fusiform rust in nonthinned plots were similar for both species. Loblolly pine sustained large additional losses from attack and spot spread by the SPB. Total tree mortality and volume loss caused by epidemic SPB activity were approximately twice as much in nonthinned study plots as in thinned plots. These findings are in agreement with survey results in Texas reported by Cameron and Billings (1988). The occurrence and severity of SPB activity are expected to increase as total volume, stand structure, and average age of loblolly pine plantations continue to increase throughout the South. Hedden (1983) indicated that reductions in stocking levels by thinning lowers the probability of SPB attack and subsequent spot spread. Results from this study confirm these predictions.

Losses from SPB attack were minimal in the slash pine plantations. Probable reasons are that (1) slash pine is highly resistant to successful SPB attack and spot spread, and (2) beetle populations were endemic in the slash pine study areas during the 10-year measurement period.

Field surveys and laboratory testing were conducted to assess levels of *H. annosum* in the plantations. Visual field examination of 3,832 secondary root systems showed that symptoms of *H. annosum* were present on 16 percent of the roots sampled. This low level was fairly consistent within slash and loblolly plantations and within thinned and nonthinned treatment areas. However, laboratory testing of a subsample of 466 symptomatic roots isolated positive *H. annosum* cultures from only 4 percent of the roots. Results from the laboratory testing agree with the low susceptibility rating for annosum root rot associated with soil type (Froelich and others 1966). No mortality was attributed to root rot fungi in slash or loblolly pine plantations.

Trends in periodic stand growth and total volume production were similar for slash pine and loblolly pine plantations. Standing volumes at the end of the 10-year study period were greater in nonthinned portions of the plantation. Periodic stand growth, however, was greater in thinned portions of the plantations. Total volume production (thinned volume added to standing volume) was also greater in thinned plots than nonthinned plots. Bennett and Jones (1983) noted that in free-to-grow stands, where mortality is not a factor, merchantable thinning will not increase total merchantable cubic volume yield. In this study, mortality was a significant factor. Rust-associated mortality reduced volume growth and production in the slash pine plantations. Losses from rust and the SPB had a severe impact on total production in the loblolly plantations.

In summary, silvicultural and pest management gains from the selective thinning of rust-infected trees include

- a significant improvement in the quality of trees in the residual stands;
- a reduction in growth losses caused by fusiform rust;
- the salvage of potential mortality;
- intermediate cash returns;
- a reduction in the potential for SPB attack and spot spread;
- an accelerated growth of the residual stands; and
- the ingrowth of quality sawtimber.

The major disadvantages of this specialized type of thinning include

- the costs of selective marking and harvesting; and
- lack of control over predetermined stand spacing or stocking levels.

Results, methodology, and practices developed during this study can be incorporated into conventional thinning programs used to regulate stand density, accelerate tree growth, and achieve specific management objectives. Trees with severe rust galls should be removed during all intermediate silvicultural practices. Guidelines have been developed for selecting trees for removal based on degree of stem girdling, number of galls, and location of galls (Belanger and others 1991). Removal of high-risk galled trees will improve the quality, growth, and general health of the residual stand.

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The primary objective of this study was to evaluate the selective thinning of trees with rust galls as a means of reducing losses to the fusiform rust (*Cronartium quercuum* (Berk.) Miyabe ex Shirai f. sp. *fusiforme*) disease in merchantable slash (*Pinus elliottii* Engelm. var. *elliottii*) and loblolly (*P. taeda* L.) pine plantations. Additional objectives were to assess the post-thinning occurrence and impacts of southern pine beetles (*Dendroctonus frontalis* Zimm.) and annosum root rot (*Heterobasidion annosum* Fr.). Nineteen rust-infected plantations were selected in Alabama, Georgia, and South Carolina to represent a wide range of stand and rust conditions. Thinnings were based primarily on the removal of trees with severe and moderate stem girdling caused by fusiform rust galls. Approximately 750 acres were thinned operationally to salvage potential mortality; 2,250 nonthinned acres served as controls. Study plots were surveyed annually for 10 years to determine the amount and causes of mortality. Stand growth and development were evaluated at the end of 5- and 10-year periods after treatment. Removal of rust-infected stems greatly improved the quality of trees in the residual stands. The periodic diameter growth of individual dominant and codominant slash and loblolly pine trees was affected by the extent of stem girdling. Trees with severe stem girdling (≥50 percent) grew significantly less than gall-free trees or trees with small or moderate stem girdling. Trends in periodic stand growth and total volume production were similar for slash and loblolly pine. Standing volume at the end of 10 years was greater in nonthinned portions of the plantations than in thinned portions. However, periodic stand growth and ingrowth of rust-free sawtimber (≥9 inches in diameter at breast height) were greater in thinned portions of the plantation. Rust-associated mortality was the primary factor that reduced volume growth and production in slash pine plantations. Losses from fusiform rust and the southern pine beetle had a severe impact on total production in the loblolly plantations. Thinning significantly reduced losses from both of these forest pests. Management implications can be incorporated into conventional thinning procedures for regulating stand density, increasing growth, and improving stand health.

Keywords: Annosum root rot, forest health, integrated pest management, *Pinus elliottii* Engelm. var. *elliottii*, *Pinus taeda* L. southern pine beetle, thinning.

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