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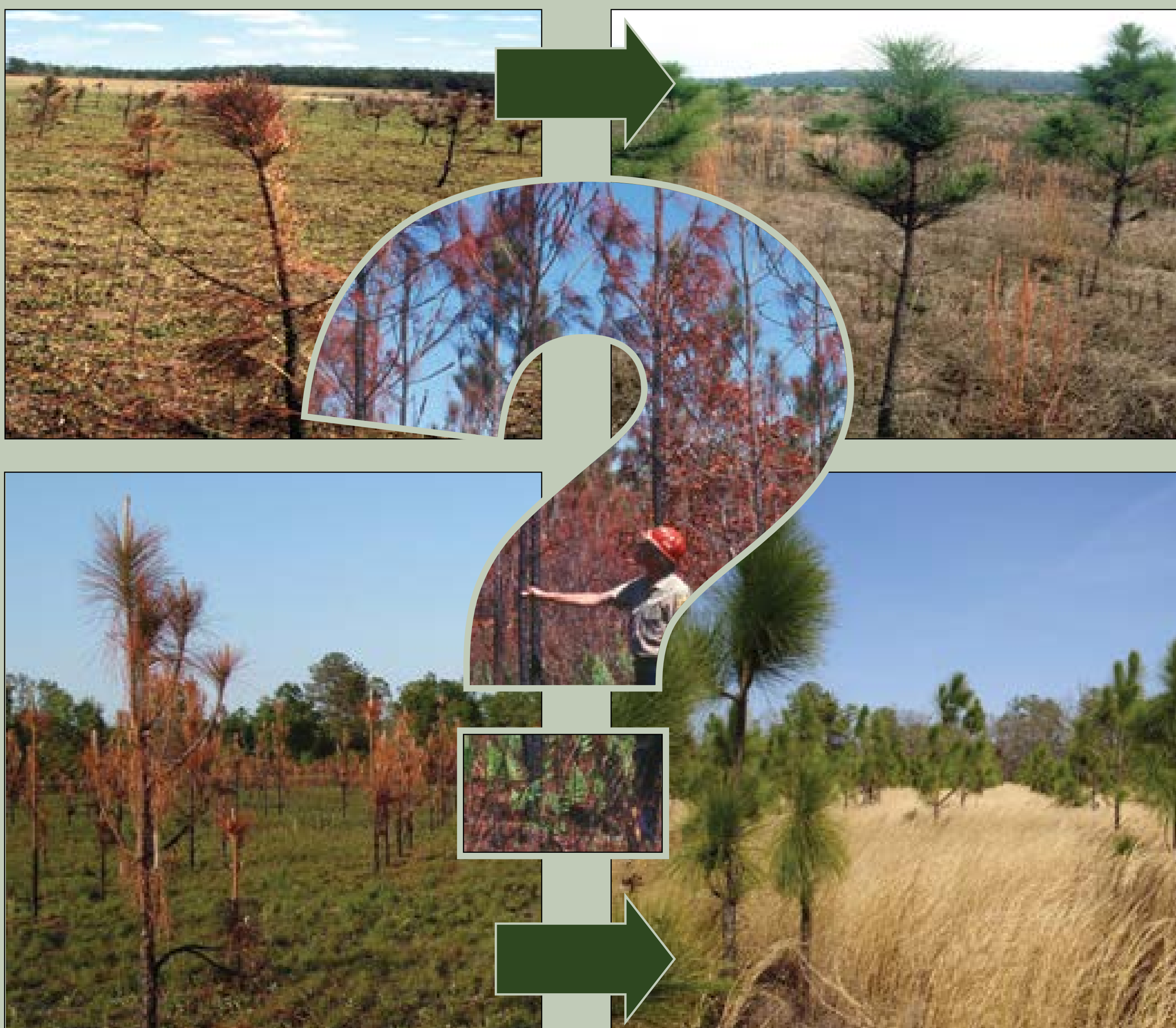
Defoliation Effects on Growth and Mortality of Three Young Southern Pine Species

David R. Weise, Dale D. Wade, Ragnar W. Johansen, Haiganoush K. Preisler, David C. Combs, and Edward E. Ach



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Cover photos: Young slash (*Pinus elliottii Engelm.*) (top), loblolly (*P. taeda L.*) (middle), and longleaf (*P. palustris Mill.*) (bottom) pines can experience substantial crown scorch from wild and prescribed fires and recover successfully. Top row photos: David J. Moorhead, University of Georgia, Bugwood.org; Middle row photo: USDA Forest Service, Southeastern Forest Experiment Station, C. Wayne Adkins; Bottom row photos: Johnny Stowe, South Carolina Department of Natural Resources.

Abstract

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Foliage from loblolly (*Pinus taeda* L.), slash (*P. elliottii* Engelm.), and longleaf (*P. palustris* Mill.) pines was hand plucked to isolate the effects of level and timing of foliage removal on growth and mortality. Slash and loblolly pine received one of five defoliation treatments during one of four months: January, April, July, or October. Longleaf pine received one of three defoliation treatments during one of five 2-week periods from September to December. Growth and mortality were measured for each species for several years after treatment. Increased defoliation resulted in increased growth loss. Only total October defoliation caused significant mortality in loblolly and longleaf pine and moderate mortality in slash pine. Estimated difference in volume between control and defoliated trees after 5 or 6 years ranged from 0 to 2.3 ft^3 (about 30 percent) per tree depending on species, defoliation season, and amount of defoliation. Trees receiving 95 percent or greater defoliation were generally smaller than the control trees after 13 or 19 years posttreatment.

Keywords: Defoliation, growth, mortality, d.b.h., height, fire damage, crown scorch, *Pinus taeda, Pinus elliottii, Pinus palustris.*

Summary

In the mid-1980s, the causes of mortality in young southern pines were unknown although there were several mechanisms that had been postulated. The effects of crown scorch (CS), the heat-caused killing of foliage by a fire, on survival and growth were strongly debated and study results were often contradictory. We established a study to separate the effects of foliage removal from the combined effects of damage caused by a fire. In 1986, a study using 1,200 loblolly (*Pinus taeda* L.) and slash (*P. elliotii* Engelm.) pines grown in four separate plantations was established, and the trees were treated with one of several levels of manual defoliation. Survival and growth were measured for 5 years. In 1993, a similar study using 450 longleaf pines (*P. palustris* Mill.) was established at two locations and used a subset of the defoliation treatments. Survival and growth were measured for 6 years. Final measurements were made 13 and 19 years after treatment for the loblolly/slash study and the longleaf study, respectively. Increased defoliation resulted in increased growth loss. Only total October defoliation caused significant mortality in loblolly and longleaf pine and moderate mortality in slash pine. Estimated difference in volume between control and defoliated trees after 5 or 6 years ranged from 0 to 2.3 ft^3 (about 30 percent) per tree depending on species, defoliation season, and amount of defoliation. Trees receiving 95 percent or greater defoliation were generally smaller than the control trees after 13 or 19 years posttreatment.

Contents

Introduction

Southern yellow pines evolved with frequent fire and developed traits that allow them to survive fires that kill most tree species, including other pines (Agee 2000). Southern yellow pine ecosystems benefit from frequent fire, which has been extensively used throughout the Southern United States to manage loblolly (*Pinus taeda* L.), slash (*P. elliottii* Engelm.), and especially longleaf (*P. palustris* Mill.) pine ecosystems for well over three centuries (Demmon 1935, Long et al. 2004, Melvin 2012, Van Doren 1928). Prescribed burns conducted within commonly accepted guidelines (e.g., Waldrop and Goodrick 2012) are unlikely to damage bole cambium once loblolly and slash pine exceed 2.5 inches basal diameter (Wade 1987) or when longleaf root-collar diameter exceeds 0.5 inches diameter (Brockway et al. 2006).

If, however, a humus layer is present and consumed, basal stem and root damage will occur, typically resulting in substantial mortality irrespective of tree size (Ferguson et al. 1960; Varner et al. 2005, 2007; Wade and Johansen 1986). Regardless of tree size, care should always be exercised when burning to prevent thermal bud damage, which means keeping fireline intensity below about 500 Btu/sec/ft (~150 Btu/sec/ft for trees under 10 ft in height) and not burning even under mature trees when most are in candle (buds elongating without protective needles) nor under no-wind conditions when ambient temperatures are above roughly 80° F. Crown scorch (CS), "**browning** [not blackening] of needles or leaves in the crown of a tree or shrub caused by heating to lethal temperature during a fire" (National Wildfire Coordinating Group 2014), is a precursor to bud and branch damage. Bud damage has significantly more deleterious consequences on survival (Storey and Merkel 1960, Wade 1985) than CS. Southern pines are, however, commonly subjected to severe CS with virtually no associated bud or cambial damage. Many natural resource managers have indicated that understanding the effects of CS alone is a high-priority knowledge gap in southern pine management.

When fiber production is a management objective, knowledge of the type and magnitude of crown damage and likely duration of recovery is requisite to a meaningful decision to either remove the existing stand and replant, or to retain the plantation and accept any thermal thinning and reduced growth (Caulfield 1987, Caulfield and Teeter 1988, Prestemon and Holmes 2008). Studies that link the physical processes of fire to resulting physiological processes are also needed (Chatziefstratiou et al. 2013).

Planted southern pines, particularly loblolly and slash pine, reach merchantable size in less than 15 years so managers interested in maximizing fiber production need to act quickly to minimize length of time the site is unproductive, and, if trees are merchantable, to prevent the fairly rapid deterioration of wood quality from various pathogens. However, replacing a stand based on just its postfire appearance without inspecting tree crowns for bud damage can be a mistake from an economic standpoint. If bud damage is minimal, the financial return on one's investment will be greater if the survivors are retained in spite of reduced volume at harvest (Wade and Ward 1975). When assessing crown damage, CS should be separated from needle blackening and consumption because the latter conditions signal more serious meristematic damage to branches and buds (Wade 1985, Wade and Johansen 1986). When there are no blackened or consumed needles, that portion of the crown probably did not suffer bud or branch cambial damage, which is an excellent field indicator of probable southern pine survival.

This study is confined to the effects of defoliation and does not address cambial damage to buds, lower stem, or roots. Prior to this study, neither the probability nor magnitude of mortality from defoliation of young healthy southern pine, nor the length of the recovery period of survivors had been quantified. A large body of published reports of postfire tree responses exists. Although the results are generally accurately reported, virtually all lack crucial information necessary to quantify their results.

Growth is closely linked to amount of live foliage (Albaugh et al. 1998, Colbert et al. 1990). Numerous studies have shown defoliation caused by insects and disease or fire results in either death or a temporary reduction in growth because of the loss of photosynthetic surface area (Chambers et al. 1986, Duryea et al. 2007, Kulman 1971). The effects of defoliation differ widely depending on season of defoliation, species, and tree size and vigor. Quantifying the effects of fire, however, is problematic. Fire is a dynamic force that cannot be truly replicated because spatial and temporal changes in weather, topography, and fuels continually modify fire behavior and intensity, which determine thermal damage; all of these factors confound the effects of CS and preclude partitioning the individual effects of thermal injury. Season of burn is also confounded with fire intensity in most fire studies (Knapp et al. 2009).

Reported results from crown scorch range from growth loss to growth gain.

Published results cover the full range of possibilities from significant growth losses with near-total CS in southern pines (Cain 1985, Lilieholm and Hu 1987, Storey and Merkel 1960) to significant growth gains with near-total CS (Jemison 1943, Johansen 1975, Waldrop and Van Lear 1984). A few studies documented a slight increase in growth when CS was less than 33 percent, sometimes statistically significant (Villarrubia and Chambers 1978) and sometimes not (Gruschow 1952, Weise et al. 1987). The theory behind this ancillary prescribed fire benefit is that the lower crown receives little sunlight and thus foliage there requires more carbohydrates for maintenance than produced, resulting in a decrease in available energy for overall tree growth. We are aware of managers who purposely subject young longleaf to high fireline intensities to fire prune lower branches thereby enhancing the value of the butt log.

To avoid problems associated with the confounding effects of fire, we designed a study to determine the effects of CS on young southern pine by hand plucking needles. We quantified the effects of season and amount of CS on survival and growth of planted, sapling-size loblolly and slash. Based on preliminary results for these species, we adjusted both treatment variables to better evaluate the effects in the followup longleaf pine study. Our objective was to determine the effects of various levels of crown defoliation and the physiological season in which they occurred on survival and growth. We did not attempt to mimic or explain the full array of responses to thermal defoliation, which could conceivably produce other heat-induced physiological changes. Our purpose is to provide guidelines for resource managers along with the data and analyses used to formulate those recommendations. Although we did not couple any actual fires with this study, the results presented herein agree with our combined 100+ years of field observations of the effects of fire on southern pine.

Methods

Study Sites and Design

We established the loblolly and slash pine study in 4-year-old plantations (two locations each) in January 1986 and the longleaf pine study (two locations) in August 1993 (fig. 1). Trees selected for this study were young dominant/codominant saplings large enough (basal diameter >2.5 in and height >8 ft to withstand low-intensity fire (Wade 1987). Soils at the loblolly pine sites on International Paper land in Bainbridge, Georgia (BAIN), and Westvaco land in Branchville, South Carolina (BRAN), were Wagram, a loamy, kaolinitic, thermic arenic Kandiudult and Alpin, a thermic coated lamellic Quartzipsamment, respectively. Soils at the slash pine sites on Union Camp land in Palatka, Florida (PLKA), and Georgia Forestry Commission (GFC) Dixon Memorial Forest near Waycross, Georgia (WAYC), were Leon, a sandy, siliceous, thermic aeric Alaquod and Blanton, a loamy, siliceous, semiactive, thermic grossarenic Paleudult. Soils at the longleaf sites on the Savannah River Forest Station (SRFS) near Aiken, South Carolina, and the GFC Dixon Memorial Forest near Waycross, Georgia (LWYC), were Lakeland, a thermic, coated typic Quartzipsamment and a mixture of Leon and Blanton, respectively (Soil Survey Staff 1999, n.d.). Mean annual precipitation at the six sites ranged from 48 to 55 in, ambient temperature ranged from 64 to 81 °F, and elevation ranged from 15 to 130 ft above mean seal level (MSL). A lightning fire that went out on its

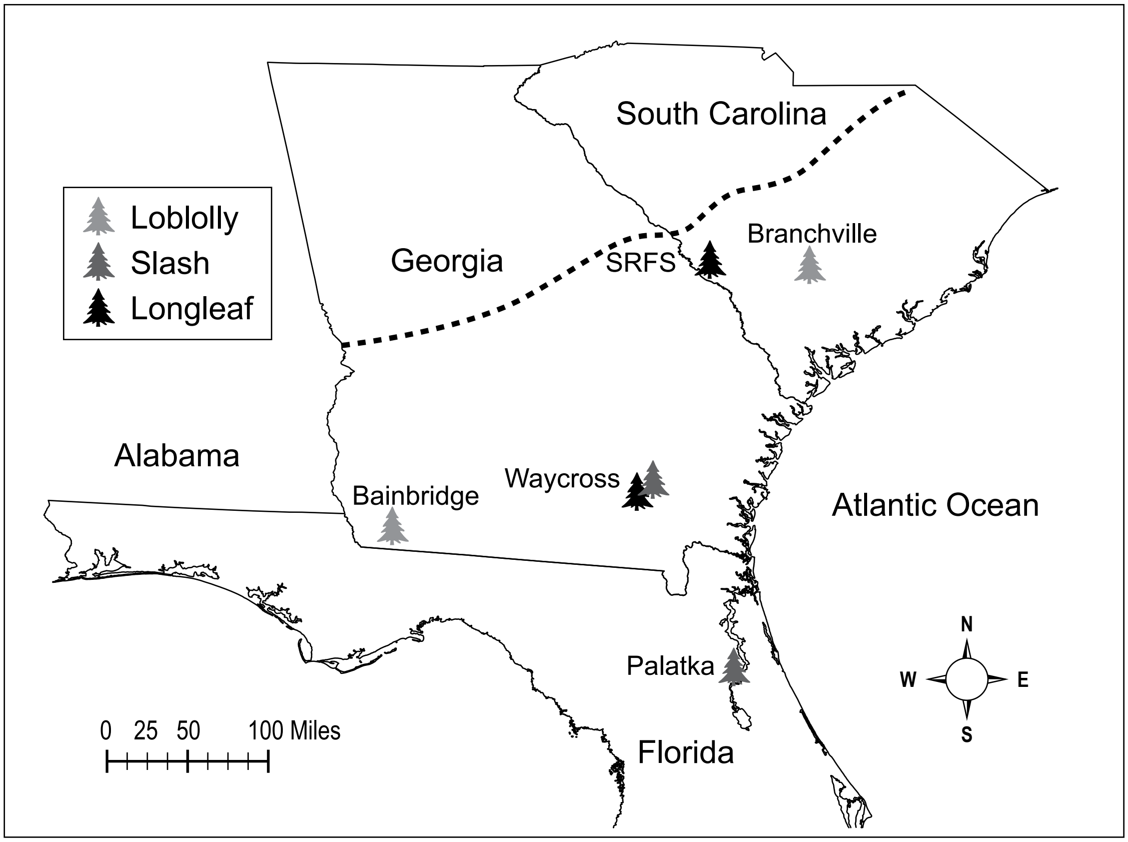

Figure 1—Location of southern pine defoliation sites in the southeastern United States coastal plain. Dashed line represents the location of the Fall Line—the boundary between the coastal plain and the piedmont. SRFS = Savannah River Forest Station.

own burned a portion of the Branchville, South Carolina, site sometime in February or early March 1988; trees within the burn perimeter were dropped from the study.

At all six locations, a full factorial treatment design was replicated 15 times using a randomized complete block design. Slash and loblolly pines randomly received one of five defoliation levels (0, 33, 66, 95, or 100 percent) during one of four seasons (April, July, October 1986, or January 1987). The initial results of the loblolly and slash pine study showed mortality only after October 100 percent defoliation (Weise et al. 1989). Based on those results, longleaf pines randomly received one of three defoliation levels (0, 95, or 100 percent) during one of five late-summer to early winter defoliation times (nominally August 18, September 15, October 13, November 10, or December 8), 1993. A plantation row comprised a replication/block. Study trees were healthy with good form at the time of selection and similar in size. We manually removed foliage beginning at the crown base and progressed upward through the crown as a fire would (fig. 2).

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Figure 2—Manual foliage removal started at the base of the tree simulated the effects of fire-caused crown scorch. The treatments left to right are 66 percent, 95 percent, and 100 percent of foliage volume removed. Control (0 percent) and 33 percent not pictured.

Measurements

Slash and loblolly pine diameter at breast height (d.b.h.) and total height measurement began in early 1986 prior to bud elongation. Annual measurement took place in January from 1987 through 1991 and in the fall of 1999. Terminal bud condition determined survival status. Lost tags (all sites), a wildfire (WAYC), and thinning (BRAN, WAYC) between 1991 and 1999 prevented relocating some of the study trees in 1999. About one-third of the trees were found (92, 105, 104, and 91 at BAIN, BRAN, PLKA, and WAYC, respectively). All treatments except for October 100 percent at BAIN and BRAN[1] were represented. Because the thinning was performed by removing rows of trees and a row comprised an experimental block, the effect of the thinning on the experimental design simply reduced the number of blocks. We recorded the number of annual growth flushes only at BRAN and PLKA for the 1986, 1987, and 1990 growing seasons.

We treated 1650 young southern pines tovarious defoliation treatments.

Longleaf pine d.b.h. and total height measurement began in August 1993 during the first defoliation treatment. Subsequent measurements took place January through February 1995, November 1995, August 1999, and April 2012. The 2012 remeasurement located 60 and 124 longleaf pine at LWYC[2] and SRFS, respectively. All longleaf treatments except for 100 percent defoliation on November 10 (LWYC only) were represented.

[1] These two replications were on pulp and paper company lands, and stunted trees were likely removed after the study ended in 1991.

[2] The stand was thinned in 2009 by removing every third row.

During the 2012 measurement, one control tree and two 95 percent defoliated trees were tallied with dead terminal leaders, and one November 95 percent defoliated tree was classed as suppressed; long-term survival of these four trees is questionable. Over the course of both studies, several trees developed double leaders irrespective of treatment. The tallest leader was measured in such cases.

Analysis

The study initially contained 600 loblolly, 600 slash, and 450 longleaf pines (Weise et al. 2014). Removing loblolly pines within the wildfire burn area from BRAN reduced that count to 544. Because of site differences, we analyzed each location separately. While all of the techniques used permit calculation of the probability values associated with the statistics, we use the term "significant" to indicate probability values < 0.05 and do not specify exact probabilities. The R[3] code (R Core Team 2013) used to perform the various tests that follow can be found in appendix 1.

Mortality—

We estimated mortality rate $(\hat{p})$ for each defoliation level for the fall defoliated trees by location and species using $\hat{p} = n_d / n$ where n_d = number of dead trees and n = number of trees treated for location/species. The 95 percent confidence interval for mortality probability was estimated using (eq. 1) where u and l are the upper and lower confidence bounds. When no trees died in a defoliation class, a 97.5 percent upper confidence bound for mortality probability, p_o, was produced by $\hat{p}_0 = 1\text{-}(0.025)^{l/n_0}$, where n_o is the number of trees in the defoliation class.

$$
\begin{aligned}
&\hat{\theta} = -\log\left(\hat{p}/\left(1-\hat{p}\right)\right) \\
&\hat{\sigma}_{\mathrm{p}} = \sqrt{\hat{p}\left(1-\hat{p}\right)/n} \\
&\hat{\sigma}_{\theta} = \hat{\sigma}_{p}\left|\left(1+\hat{p}\left(1-\hat{p}\right)\right)/\left(-\mathrm{e}^{\hat{\theta}}\left(1-\hat{p}\right)\right)\right| \\
&\mathrm{u} = -\mathrm{e}^{-\hat{\theta}+2\hat{\sigma}_{\theta}}/\left(1+\mathrm{e}^{-\hat{\theta}+2\hat{\sigma}_{\theta}}\right) \\
&l = -\mathrm{e}^{-\hat{\theta}+2\hat{\sigma}_{\theta}}/\left(1+\mathrm{e}^{-\hat{\theta}+2\hat{\sigma}_{\theta}}\right)
\end{aligned}
\tag{1}
$$

Growth—

Linear mixed-effects models were used to analyze d.b.h. and total height-growth response to defoliation (Meredith and Stehman 1991, Pinheiro and Bates 2000, Uzoh and Oliver 2008). The fixed effects were defoliation season (S) and defoliation level (D); time (T) since defoliation application was expressed as fractional years.

[3] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Two random effects were included—the effect resulting from experimental block (plantation row) and the effect resulting from the individual tree (repeated measure). An autoregressive covariance structure of order 1 modeled the repeated measure random effect, which described the serial correlation between successive growth measurements. Tree size generally increased linearly with time; however, we included a quadratic time term for curvature in the growth curves (Meredith and Stehman 1991). Defoliation level was treated as a continuous effect, and interaction with defoliation season was included:

	Degrees of freedom	
Source	**Loblolly, slash**	**Longleaf**
Season of defoliation (S)	3	4
Defoliation level (D)	1	1
D^2	1	
S × D interaction	3	4
$S \times D^2$	3	
Time since treatment (T)	1	1
T^2	1	1
S × T	3	4
$S \times T^2$	3	4

The degrees of freedom for the mean squared error term used in the tests of the fixed effects (season of defoliation and defoliation level) was 274 for BAIN, PLKA, and WAYC; 219 for BRAN; and 201 for each longleaf site. The mean squared error term used in the tests of the random effects (repeated measurement of d.b.h. and height) had more than 1,200 degrees of freedom. The *lme* routine in R was used to estimate the various terms using reduced maximum likelihood for each location separately. The season/time interaction tested the equality of the d.b.h. or height response over time between seasons. Owing to the smaller number of treatments and convergence issues in estimation for the longleaf data, all terms involving D^2 were dropped so only the linear growth response owing to defoliation level was tested for longleaf pine. The ratio of the measured size of the treated trees to the untreated controls was calculated to determine relative growth response. The standard error of the ratio was estimated using the delta method (Oehlert 1992) and the standard errors estimated from the fitted growth models. Ninety-five percent confidence intervals (± 2.5 percent) were constructed to determine when the ratios were significantly different from 1. These calculations were performed for d.b.h. and height.

To view the combined effects of the treatments, tree volumes were estimated using published equations. Kush et al. (2006) recommended the form-class segmented-profile equations developed by Clark et al. (1991) for plantation-grown longleaf pine; for consistency, we used coefficients for loblolly and slash pine from the same reference (eq. 2). Diameter outside bark at 17.3 ft was calculated using species-specific coefficients (table 4 in Clark et al. 1991), and volume at total height was calculated using the species coefficients for the Gulf and Atlantic Coastal Plain subregion (table 12 in Clark et al. 1991) as all six sites are located below the Fall Line—the division between the Piedmont and Coastal Plain (dashed line in fig. 1; Fenneman 1928). Although other equations could be used to estimate volume, these equations suffice to enable comparison.

$$V = 0.005454 \left(\begin{array}{l} I_1 d^2 \left\{ [1 - GW][U_1 - L_1] + W[(1 - L_1/h)^T (h - L_1) - (1 - U_1/h)^T (h - U_1)]/[r + 1] \right\} \\ + I_2 I_3 \left\{ T\,[U_2 - L_2] + Z[(1 - L_2/h)^F (h - L_2) - (1 - U_2/h)^F (h - U_2)]/[p + 1] \right\} \\ + I_4 F_2 \left\{ \begin{array}{l} b[U3 - L3] - b\left[(U3 - 17.3)^2 - (L_3 - 17.3)^2\right]/[h - 17.3] \\ [b / 3]\left[(U - 17.3)^3 - (L_3 - 17.3)^3\right]/[h - 17.3]^2 \\ + I_5 / 3\left[(1 - b)/a2\right]\left[a(h - 17.3) - (L_3 - 17.3)\right]^3/[h - 17.3]^{\,2} \\ - I_5 / 3\left[(1 - b)/a2\right]\left[a(h - 17.3) - (L_3 - 17.3)\right]^3/[h - 17.3]^{\,2} \end{array} \right\} \end{array} \right) \qquad (2)$$

D.b.h, height, and volume growth were studied.

Where V is volume (ft^3), I_1 to I_6 are indicator variables, d is d.b.h. (inches), F is diameter at 17.3 ft, G, T, W, and Z are combined variables involving d.b.h., height and F, L, and U are lower and upper heights of interest, and a, b, p, and r are regression coefficients tabulated in Clark et al. (1991). In addition to the growth-response modeling described above in which defoliation was treated as a continuous variable, we performed an additional analysis to determine if the defoliated trees were smaller than the control trees at the 5- or 6-year measurement. Dunnett's test, which is a multiple comparison test that compares the treatment values with the control value, was performed using the *multcomp* procedure (Bretz et al. 2011, p. 101). Analysis of variance was first performed; specific contrasts comparing growth for each defoliation percentage (33, 66, 95, and 100) with the control (0) were then tested simultaneously to maintain an overall 0.05 probability level.

Loblolly, slash, and longleaf pine do not have fully preformed buds meaning that after initial spring shoot elongation, additional elongations (flushes) can, and typically do, occur through late summer (Lanner 1976). The effects of defoliation season, level, and time since treatment on the number of growth flushes (a discrete variable) were estimated using generalized linear models (R routine *glm*) (Agresti 2013) assuming the Poisson distribution. Preliminary analysis revealed that overdispersion (variance greater than would be expected for a Poisson distribution) was not an issue for these data. While we initially analyzed the number of flushes at all four sites (Weise et al. 1987), 3 years of measurement (before and after defoliation) were only available for the BRAN and PLKA locations so these are the only two sites analyzed herein.

Results

Mortality

Loblolly and slash pine mortality occurred only after 100 percent defoliation in October (25 of 30 loblolly and 6 of 30 slash). Nearly all mortality occurred the first growing season following defoliation (all loblolly, five of the six slash pines). Mortality in longleaf occurred almost exclusively in the October and November 100 percent treatments at both locations (34 of 60 trees); one tree each in September 100 percent and December 100 percent treatments, and one tree receiving 95 percent defoliation in September also died. Nonoverlapping confidence intervals support the visually obvious difference between mortality after 100 percent foliage removal and all other levels for all three species (fig. 3). As would be expected given that treatments were randomly assigned to each tree at all locations, t-tests comparing initial d.b.h. and height of dead and living trees did not detect size differences.

Only 100 percent October defoliation caused mortality in loblolly and slash pines.

Growth–All Species

Before discussing the effects of treatments on growth, the d.b.h., height, and estimated volume of the control trees are presented as a reference point (table 1) for each location. When averaged by species, loblolly pine size increased the most followed by slash and longleaf. Diameter at breast height increased by 4.2, 2.5, and 1.9 in, and height increased by 22.1, 17.4, and 15.3 ft for loblolly, slash, and longleaf pine, respectively, over the 5- or 6-year period of the original studies (table 1). After 13 years, the remaining loblolly pines continued to outgrow the remaining slash pines over the same time period with d.b.h. growth of 7.2 versus 4.7 in and height growth of 52 versus 43.1 ft. Diameter at breast height of the longleaf pine 19 years posttreatment (5.7 in) was similar to loblolly pine at 5 years (5.9 in) and slash pine at 13 years (6.8 in). Longleaf was the shortest of the three species as indicated by the final measurements. The difference in growth between species was particularly apparent in the final measurements. At 13 years posttreatment, mean loblolly volume was nearly double the volume of slash pine. At 19 years posttreatment, the longleaf pines were less than one-third the size of the loblolly at 13 years:

	Volume (ft^3)		
Species	**Initial**	**Study end**	**Final**
Loblolly	0.0	3.1	14.1
Slash	0.0	1.7	7.5
Longleaf	0.0	1.1	4.4

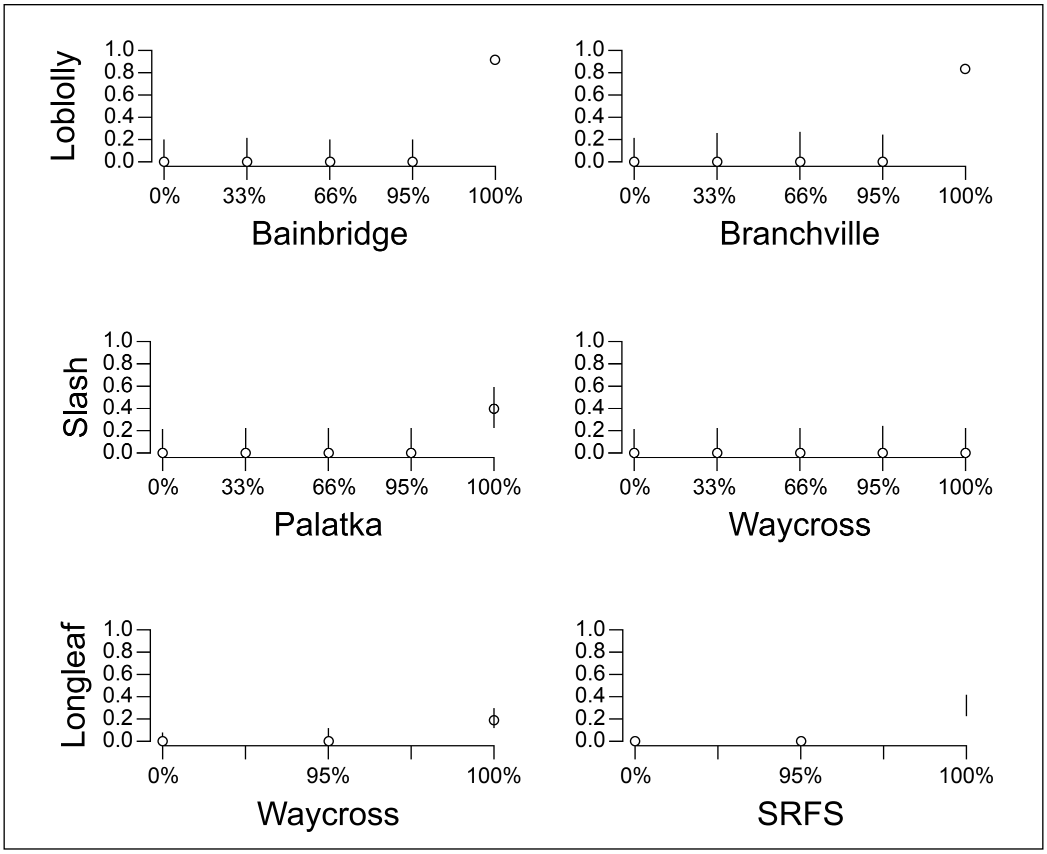

Figure 3—Estimated mortality probabilities and two-sided 95 percent confidence bounds for different levels of fall defoliation of loblolly, longleaf, and slash pine. When mortality = 0, one-sided 97.5 percent confidence bound displayed. SRFS = Savannah River Forest Station.

Table 1—Mean (standard deviation) growth of control (undefoliated) young southern pines

		Diameter at breast height			Height		
Species	Location	Initial	Study end	Final	Initial	Study end	Final
		Inches			*Feet*		
Loblolly	Bainbridge, Georgia	1.6 (0.4)	5.3 (0.6)	8.7 (1.0)	11.0 (1.7)	32.9 (2.2)	64.3 (3.1)
	Branchville, South Carolina	1.8 (0.6)	6.7 (0.8)	9.1 (1.6)	10.7 (2.0)	33.1 (2.2)	63.4 (5.9)
	Average	1.7	5.9	8.9	10.9	33.0	63.9
Slash	Palatka, Florida	2.1 (0.4)	4.5 (0.6)	6.6 (1.0)	12.1 (2.1)	30.1 (2.0)	53.2 (5.7)
	Waycross, Georgia	2.1 (0.4)	4.7 (0.6)	7.2 (0.8)	12.0 (1.8)	28.7 (2.5)	57.7 (3.5)
	Average	2.1	4.6	6.8	12.0	29.4	55.1
Longleaf	Aiken, South Carolina	1.7 (0.2)	3.3 (0.4)	5.0 (0.8)	10.0 (1.2)	23.9 (2.1)	40.6 (3.8)
	Waycross, Georgia	1.8 (0.3)	4.2 (0.6)	7.0 (0.9)	10.2 (1.1)	27.0 (2.6)	45.5 (4.1)
	Average	1.8	3.7	5.7	10.1	25.4	42.3

Note: Study end measurements performed 5 years after treatment for loblolly and slash pine and 6 years for longleaf pine. Final measurements performed at 13 years for loblolly and slash pine and at 19 years for longleaf pine.

As would be expected, mean size of all trees that survived the defoliation treatments increased over time (tables 4 to 7 in app. 2). The coefficient of variation (CV) for d.b.h. ranged from 0 to 37 percent and from 0 to 32 percent for height (table 8 in app. 2). The variability of d.b.h. was slightly higher than the variability of the height data (mean CV was 14 percent and 9 percent for d.b.h. and height, respectively). Analysis of variance of the fitted growth curves revealed some common trends between the species. Season of defoliation (month for longleaf) significantly affected d.b.h. and height growth at five of the six locations (not significant for longleaf at LWYC). The percentage of defoliation affected d.b.h. and height at all six locations. Interaction between season and time significantly affected d.b.h. of slash and loblolly and height for all three species indicating different growth response curves between seasons (months) (app. 4, figs. 8, 9).

The growth trend in d.b.h. and height was predominantly linear over time with some curvature for all three species at all locations; however, the curves fit to the first 5 or 6 years of data did not fit the longer term 13- and 19-year growth data (fig. 4) well. The full set of curves can be found in appendix 4 (figs. 8 and 9). The short-term model consistently overestimated d.b.h. for all longleaf (fall) and for spring, fall, and winter defoliation at one loblolly and for summer, fall, and winter at one slash site. At BAIN, observed d.b.h. for the 100 percent October defoliation did not fall on the fitted curve (circled data points) at all. A growth curve for the 5 years of d.b.h. data at PLKA is not shown because the algorithm did not converge; however, the algorithm was able to fit a growth curve for the 13 years of d.b.h. data. The short-term height growth curves also tended to overestimate the long-term height data for all three species except loblolly at BRAN with all levels of summer defoliation.

The results of Dunnett's test to determine if the 5- or 6-year treatment means were greater than or equal to the control mean are displayed in table 2. For the 100 percent defoliation, we rejected the null hypothesis that the d.b.h. of all three species at all six sites, and heights at one loblolly and all slash and longleaf sites were greater than or equal to the control trees. Similarly, we rejected the null hypothesis for 95 percent defoliation at all loblolly and slash and one longleaf site for d.b.h. as well as height at both slash and one loblolly and one longleaf site. This indicated that mean d.b.h. and height of the trees, which received 95 and 100 percent defoliation were significantly smaller than the controls for all three species at the end of the original study in most cases.

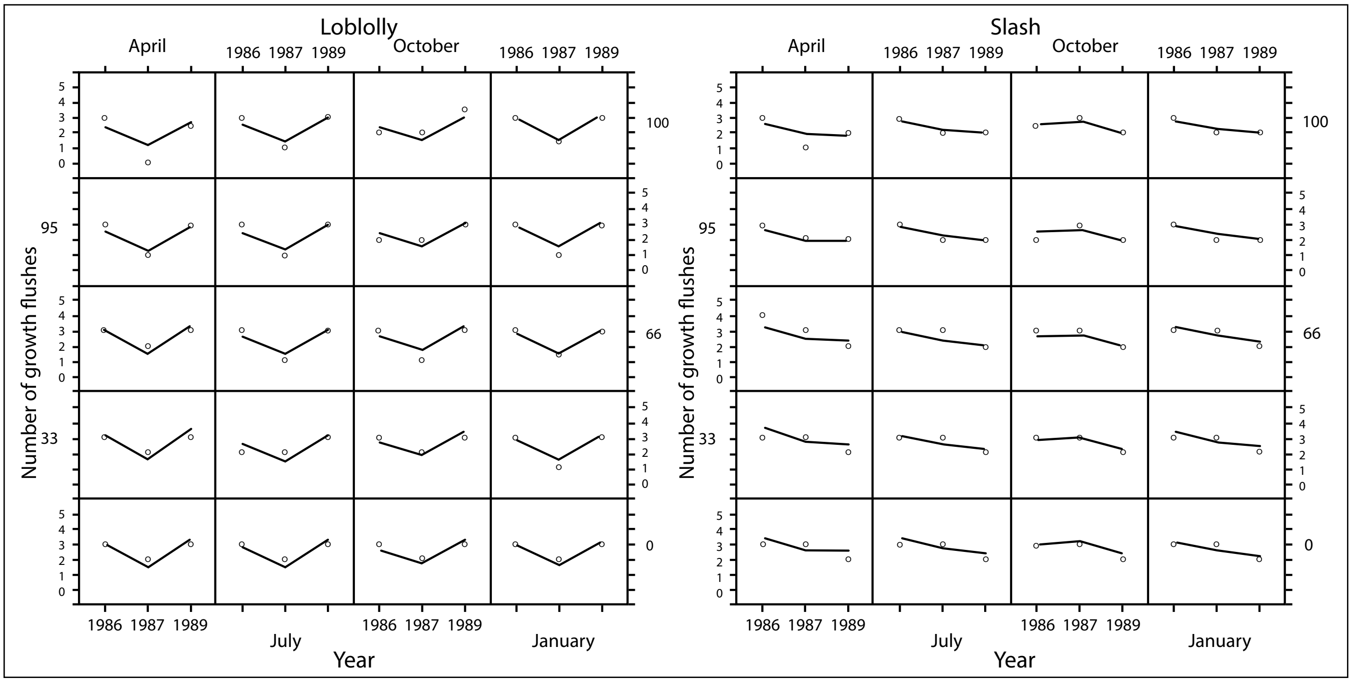

Figure 4—Estimated means (line) and observed medians (○) for number of height growth flushes produced annually by young loblolly (BRAN) and slash (PLKA) pines for various levels of seasonal defoliation.

Table 2—Summary of Dunnett's test to determine if diameter at breast height (d.b.h.) and height of defoliated southern pines are greater than or equal to d.b.h. and height of controls

		D.b.h.				Height			
Species	**Location**	**33**	**66**	**95**	**100**	**33**	**66**	**95**	**100**
Loblolly	Bainbridge, Georgia	*	**	***	***			*	**
	Branchville, South Carolina			*	*				
Slash	Palatka, Florida			*	***			**	*
	Waycross, Georgia			**	**			*	***
Longleaf	Aiken, South Carolina				**				*
	Waycross, Georgia			**	***			*	***

Note: * indicates probability of a greater t-value is less than 0.05, ** indicates probability of a greater t-value is less than 0.01, *** indicates probability of a greater t-value is less than 0.001. The 33 and 66 percent treatments were not applied to longleaf pine.

The ratio of observed d.b.h., height, and calculated volume of the treated trees to the control trees is another measure to determine similarity, and these ratios are located in appendix 5 (figs. 7, 8, and 9). The estimated confidence intervals around one used to determine if the ratios were equal to one are also shown in the figures. Summarized test results (by species across seasonal treatments) determining if the observed ratios were less than, equal to, or greater than one suggest that d.b.h. and height of all three species experiencing 95 or 100 percent defoliation did not regain the lost growth increment even though the fitted growth rates recovered:

	Measurement time	
Species	**Study end**	**Final**
Loblolly	D.b.h. and height of 95 and 100 percent less than controls; d.b.h. of many 66 percent defoliation less than controls	D.b.h. and height of 95 and 100 percent less than controls; d.b.h. and height of many 33 percent greater than controls
Slash	D.b.h. and height of all 66, 95, and 100 percent less than controls	D.b.h. and height of most 66, 95, and 100 percent less than controls
Longleaf	D.b.h. and height of nearly all 95 and 100 percent less than controls; none greater than controls	D.b.h. and height of nearly all 95 and 100 percent greater controls; none greater than controls

The combined effects of the treatments on d.b.h. and height were evident in the plots of the volume ratio (fig. 9). In most cases, the ratio of the volume of trees that lost 66 percent or more of their foliage and the control trees was significantly less than one for all three species at the original study end (5- or 6-year) measurements. Many of the slash and longleaf pines, in particular, had less volume at the final measurement as well. The 33 percent defoliation treatment often resulted in loblolly pines larger than the controls.

Defoliated trees were often still smaller than controls after 13 or 19 years

Volume difference between the defoliated and control trees for all three species ranged from -2.3 to -0.1 ft^3 at the study end measurements 5 or 6 years after treatment (table 3) indicating that the defoliated trees were smaller than the control trees at this time. The range of longer term differences in volume growth was -3.8 to 2.1, -5.4 to -0.2, and -2.3 to -0.5 ft^3 for loblolly, slash, and longleaf pines, respectively. Note that loblolly pine showed greater volume growth than the control trees for some of the defoliation treatments.

One might expect January defoliation to have the smallest impact as the trees are without full foliage for the least amount of time with this treatment month; but that was not the case for slash pine where neither October 33 percent nor July 33 percent and 66 percent had a negative effect on volume increment. The gap between volume of the controls and defoliated slash pines was still increasing at last measurement for all January levels and for October 95 and 100 percent. Defoliation had little effect on longleaf volume growth, particularly after defoliation in November. The maximum gap was less than 0.5 ft^3 after all treatment dates. Although longleaf had the longest time interval between initial and study-end measurement, at the study-end measurement, it still only had a mean estimated volume of 2.8 ft^3 compared to 5.7 for slash and 15.9 for loblolly.

Growth Flushes—Loblolly and Slash Only

The trees at BRAN (loblolly) and PLKA (slash) reacted differently to defoliation treatments (fig. 4). At BRAN, the mean number of growth flushes decreased in 1987, the year following defoliation, and returned to the pretreatment number by

Table 3—Range of mean difference between estimated volume of defoliated and control trees[a]

		Study end		Final	
Species	**Defoliation time**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
		Cubic feet			
Loblolly	April	-0.9	-0.4	-3.8	0.8
	July	-1.0	-0.1	-3.7	2.1
	October	-2.3	-0.2	-2.2	1.5
	January	-0.9	-0.3	-2.4	0.6
Slash	April	-0.5	-0.2	-3.0	-0.9
	July	-0.7	-0.1	-3.8	-0.2
	October	-1.0	-0.1	-4.6	-0.6
	January	-0.9	-0.4	-5.4	-0.5
Longleaf	August	-0.4	-0.3	-1.1	-0.8
	September	-0.3	-0.3	-1.6	-1.5
	October	-0.6	-0.4	-2.3	-1.6
	November	-0.4	-0.2	-1.9	-0.5
	December	-0.6	-0.4	-0.8	-0.7

Note: Study end measurements performed 5 years after treatment for loblolly and slash pine and 6 years for longleaf pine. Final measurements performed at 13 years for loblolly and slash pine and at 19 years for longleaf pine. Positive value indicates volume of defoliated tree was larger than undefoliated control.

[a] Mean value initially calculated for each level of defoliation (33, 66, 95, 100 percent) at each location and then minimum and maximum value of mean determined for each treatment time by species.

the end of the 1989 growing season. In contrast, the number of slash pine flushes at PLKA decreased the year following treatment and continued to decline through 1989, the last year flushes were tallied. Season and defoliation level did not affect the number of flushes for loblolly; defoliation level did affect the number of flushes in slash pine. The response over time was quadratic in loblolly and linear in slash. Our limited data set did not allow us to determine if this behavior occurred at the other two sites. For comparison purposes, the observed medians are included in figure 4.

Discussion

All 600 loblolly and 600 slash (including 120 control trees for each species) survived all treatment combinations except complete foliage removal in October; that one treatment combination resulted in high mortality for loblolly pine (25 of 30 trees) and moderate mortality for slash pine (6 of 15 trees) at one of the two slash pine study locations. For unknown reasons, no slash pine died at WAYC. We do not know why all slash pine completely defoliated in October at Waycross survived while 40 percent of the same treatment died at Palatka, but we note the exceptional growth recovery of scorched trees reported by Johansen (1975) occurred within a few miles of this study area. The trees that died at Palatka were similar in size to surviving trees. There is obviously still much to learn regarding factors that determine recovery/mortality after severe defoliation. Genetically "improved" planting stock was used at each site, so differences in survival could be physiological rather than physiographical.

Of the 450 longleaf (including 150 control trees), mortality was confined to the 100 percent defoliation treatment except for a single tree that died after 95 percent foliage removal in August. Thirty-two of the 60 longleaf subjected to complete foliage removal in October or November died along with one each after September and December defoliation.

Most surviving trees of all three species, however, suffered significant growth retardation compared to the controls. Although rate of growth recovered and the gap in tree volume between treated trees and controls was, in many cases, decreasing at last measurement, size differences were still visually obvious in many cases. There was no statistical difference in tree size when study trees were selected. Similar results have been reported in other studies. For example, Tew et al. (1989) reported that scorch greater than 80 percent from a November burn in a 14-year-old loblolly plantation killed 12 percent of the trees (all during the first postburn year), reduced d.b.h. growth by 97 percent the first year, and by 60 percent over the first 4 postburn years when compared to trees with no scorch. Increased foliage removal increased depression of growth, although height growth was less affected than radial growth. In that study, differences in diameter growth disappeared in the fourth postburn growing season. Similarly, Johansen and Wade (1987) reported CS exceeding 95 percent following a January burn reduced 2-year d.b.h. growth by 60 percent in a 25-year-old slash pine plantation.

Not accounting for missing tree rings can cause spurious results.

Determination of growth responses to severe crown injury should include the possibility of missing tree rings. Their presence can be determined by using the pith or a wide reference ring to establish proper dating. Failure to determine their presence can result in invalid conclusions, which in turn could deleteriously affect future prescribed burn planning decisions.

The life-threatening consequences of complete fall defoliation on southern pine are apparently due to the lack of photosynthate. Southern pines produce photosynthate year round; the amount produced dependent upon the amount of live foliage. This ability to produce photosynthate year-round means these species do not have to store large reserves of carbohydrate (starch) (Kozlowski 1992). But that doesn't mean belowground reserves are not crucial for foliage production and maintenance. During the growing season, young southern pines use more starch than they produce to put on root, stem, and crown growth, nearly exhausting their starch reserves (e.g., Gholz and Cropper 1991, Kuehler et al. 1999, Ludovici et al. 2002). The photosynthate produced between the last flush of summer and budbreak the following spring is used to fulfill maintenance respiration requirements and to rebuild reserves. Gholz and Cropper (1991) showed that slash pine in Florida gained 19 percent of its annual carbon during the winter. Onset of height and radial growth in spring requires substantial resources so if a lack of foliage prevents replenishment of these supplies, we hypothesize there may not be enough for spring budbreak. There is also a pulse of fine-root production in spring and early summer, which also requires considerable photosynthate (Sayer and Haywood 2006).

Foliage removal interrupts the production of photosynthate thereby limiting the amount available for maintenance and growth. In this study as well as others (e.g., Haywood et al. 2004, Tew et al. 1989), defoliation affected radial growth more than height growth. In fact, removal of 66 percent of the foliage in our study had only minor effects on height growth of all three species. Photosynthetic tissues have a higher priority than diameter growth or storage tissues (Sword and Haywood 1999, Waring and Schlesinger 1995). Thus after crown damage, available starch will be redirected to refoliation, and there may not be enough remaining for radial growth, hence a missing ring. This would explain why height growth was not as severely impacted as diameter growth in our study, but leaves us in a quandary regarding work by Wahlenberg (1939) and McCulley (1950) who reported height growth was more depressed than radial growth. Further discussion of carbohydrate dynamics can be found in Kozlowski (1992) and Little and Pharis (1995).

As southern pines become biologically mature, the amount of photosynthate required to maintain respiration approaches the amount produced so when trees reach this stage in their life cycle, even minor damage can result in mortality; that said, the base of the live crown of such trees is typically high enough that the lethal thermal threshold is not reached, particularly during dormant season burns. On the other hand, burning under inappropriate weather conditions such as when winds are calm and ambient temperature is above 90 °F can result in severe crown damage and death of even large mature longleaf (e.g., Boyer 1990).

Martin and Mitchell (1980, p.142) lamented that fire-insect interactions had received little attention and that "increased knowledge of interactions can lead to greatly improved and ecologically sound forest and range management." Secondary pests often infest trees after defoliation (Craighead and St. George 1928, Storey and Merkel 1960) and can be either assassins or undertakers (Menges and Deyrup 2001). But there are also many cases where insect infestations have not followed severe fires (e.g., Ferguson et al. 1960, Hanula et al. 2003). The literature pertaining to bark beetle infestation after fire raises more questions than answers regarding conditions that favor attack, (e.g., Fischer 1980, Hanula et al. 2003, Santoro et al. 2001). Many postfire reports (Dixon et al. 1984, Hanula et al. 2003, Storey and Merkel 1960, Sullivan et al. 2003) do not support the old adage that exploding bark beetle populations follow severe fire. In fact, Hanula et al. (2003) found lower populations of *Ips* spp. and *Dendroctonus* spp. (the assassins) in burned areas than in the controls; they also recorded increases in *Temnochila virescens,* a bark beetle predator, in burned areas and in ambrosia beetles (*Xyleborus* spp. and *Monarthrum mali*), which eat dead wood (the undertakers). Of a more serious nature, they found more than 75 percent of surviving trees were infected with *Leptographium* and/or *Graphium* spp. compared to none in unburned areas; they speculate that trees weakened by this root disease may succumb in the future.

Considerable genetic work has been conducted on these three species to increase growth rates, and all six locations were planted using genetically improved seedlings. The effect of these genetic alterations on photosynthate storage and allocation and thus recovery from severe defoliation is beyond the scope of this paper but a topic we think worthy of pursuing. It would also be of interest to track changes in root, stem, and branch carbohydrates after treatments such as those applied in this study. It has been suggested that other physiological changes such as the formation of resin ducts, and differences in and between early and late wood with respect to defoliation severity and timing are currently open questions that are worthy of future study.

Management Considerations

Although southern pine will survive complete CS during most seasons, it typically reduces both radial and height growth, is unsightly, and fosters negative images of prescribed fire in the minds of the public who will ultimately determine the future of intentional fire. When planning and executing prescribed fires to minimize CS and thermal bud damage (which is considerably more serious), the following should be considered:

Plan prescribed burns to minimize crown scorch and thermal bud damage.

Pay attention to forecast minimum windspeed; very low windspeeds mean heat energy produced may not be cooled below the lethal temperature threshold before reaching tree crowns. With light and variable winds, lulls in the wind will occur resulting in vertical flames, thereby reducing the distance between flame tips and the base of the crown.

Pay attention to forecast maximum windspeed and any mention of wind gusts; increased windspeed will dissipate the heat energy produced more quickly, but depending upon firing technique, can also increase flame length and fireline intensity.

If the forecast wind direction contains the word “variable,” changes in wind direction are likely, which will influence rate of fire spread and thus flame length and fireline intensity.

Do not use ignition patterns that will allow lines of fire to merge together all at once; substantial increases in flame height invariably occur along the juncture line.

Before you ignite a fire when offsetting increased ambient temperature against increased windspeed, be reasonably sure that the balance can be operationally achieved while keeping fireline intensity within planned limits.

Pay attention to the forecast time period the weather will accommodate your burn prescription; calculate the number of hours it will take to execute the burn using the planned firing technique(s) to make sure the burn will be completed within the forecast prescription window.

Vary season, burning conditions and technique on an area over time, and be very careful when conducting fall burns because of the specter of mortality after severe crown scorch at this time of year.

Consider postponing a burn in sapling-size southern pine when a majority of the trees are in candle because of the potential lethal consequences of bud kill.

Conclusions

Results of this study show postfire mortality of young planted loblolly, slash, and longleaf pines with less than complete CS is rarely due to foliage loss alone. Even with total loss of foliage, mortality is very unlikely unless defoliation occurs during October or November. Based on the results herein, we conclude prescribed fires can be scheduled and safely conducted throughout the year to achieve many resource objectives while avoiding southern pine mortality and minimizing growth loss owing to CS.

Further work is needed to better quantify postfire mortality from root and bud damage in southern pine and should be extended to include shortleaf (*Pinus echinata* Mill.) pine. We also suggest trees in this study be relocated at some point in the future to again compare the volume of treated trees with that of the controls.

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Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	2.54	Centimeters
Feet (ft)	.305	Meters
Miles (mi)	1.609	Kilometers
Cubic feet (ft^3)	.0283	Cubic meters
Degrees Fahrenheit	.56(°F - 32)	Degrees Celcius
British thermal units (Btu)	1,050	Joules

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Appendix 1: R Language Commands for Analyses

The majority of the analyses were performed using the statistical package R version 3.1. In general, the same code was used for each location to perform the analyses with only minor changes to address slight changes in format. Because the longleaf pine study design involved fewer and different treatments than the loblolly and slash pine study, the model statements differed. The code statements that follow outline the general analyses that were performed. The data are archived in the Forest Service Research Data Archive (Weise et al. 2014), and the details of inputting the data into R data structures are not included. The data set names for the locations were BAIN, BRAN, PLKA, WAYC, SRFS, and LWYC for Bainbridge, Branchville, Palatka, Waycross, Savannah River, and Waycross longleaf, respectively.

Calculation of Summary Statistics in Appendix 2

```
bain$def<-factor(bain$def)
# select data for 13, 5, and initial measurement, md is measurement date, td is treatment date
yr13<-subset(bain,md=="08/15/99")
yr5<-subset(bain,md=="01/15/91")
yr0<-subset(bain,(md=="04/15/86"|md=="07/15/86"|md=="10/15/86"|
(td=="01/15/87" & md=="01/15/87")))
# calculate mean, standard deviation, and coefficient of variation for each
season and defoliation combination for diameter at breast height (d.b.h.) and
height by location
bainmd<-tapply(yr0$dbh,list(yr0$seas,yr0$def),mean)
bainsd<-tapply(yr0$dbh,list(yr0$seas,yr0$def),sd)
baincd<-bainsd/bainmd
```

Simultaneous Comparison of Defoliation Treatment Means With Control

```
library(multcomp)
bain$def<-factor(bain$def)
bainaov_d<-aov(dbh ~ seas + def + seas*def, data=yr5)
summary(bainaov_d)
# perform a one-sided test with alternative hypothesis that treatment mean is less than control
bain_mcd<- glht(bainaov_d,linfct = mcp(def="Dunnett"), alternative = "less")
summary(bain_mcd,test = adjusted(type = "single-step"))
```

Effects of Treatments on Growth-Response Curves

The effects of treatments on the growth-response curves for d.b.h. and height were estimated using the code below. In this code, defoliation level was treated as a continuous variable (covariate with 1 degree of freedom) in contrast to being treated as a factor as in the Dunnett test above.

```
library(nlme);library(chron);library(lattice);library(latticeExtra);library(grid)
# formula for fitted linear model, seas = defoliation season, def = defoliation level,
trtdays = elapsed time since treatment applied
fmlad <- as.formula(ht ~ seas + def + I(def^2) + seas:def + seas:I(def^2) + trtdays
+ I(trtdays^2) + seas:trtdays + seas:I(trtdays^2))
lobsla<-read.table("c:\\Users\\dweise\\Documents\\defol\\data\\defol99mix.
dat",header=TRUE)
lobsla$seas<-factor(lobsla$seas,levels=c('SP','SM','FL','WN'))
# elapsed days converted to years
lobsla$trtdays<-(as.numeric(dates(as.character(lobsla$md))-dates(as.
character(lobsla$td))))/365.25
bain<-subset(lobsla,lobsla$loc=="BAIN" & !is.na(lobsla$ht))
# define correlation structure for repeated measurements
cr2<-corAR1(0.5,form = ~ 1 | rownum/tree)
# Separate models fit for 1st 5 (or 6) years of measurement and for all 13 (or 19) years
bainh.fit3<-lme(fmlad, data=bain, random = ~1 | rownum/tree, correlation=cr2)
bainh.fit4<-lme(fmlad, data=bain[bain$trtdays<10,],random = ~1 | rownum/tree,
correlation=cr2)
```

As indicated previously, the experimental setup for the longleaf study differed from the loblolly and slash pine setup. The linear mixed-effects model statements for the longleaf pine data follow.

```
lfmlad <- as.formula(ht ~ trt + def + trt:def+ trtdays + I(trtdays^2) + trt:trtdays +
trt:I(trtdays^2))
lnglef<-read.table("c:\\Users\\dweise\\Documents\\defol\\data\\lldefolmix.
dat",header=TRUE)
# treatment colors: RED – Aug, ORG – Sep, YEL – Oct, WHT – Nov, BLU - Dec
lnglef$trt<-factor(lnglef$trt,levels=c("RED","ORG","YEL","WHT","BLU"))
lnglef$trtdays<-(as.numeric(dates(as.character(lnglef$md))-dates(as.
character(lnglef$td))))/365.25
srfs<-subset(lnglef,lnglef$loc=="SRFS" & !is.na(lnglef$ht))
cr2<-corAR1(0.2,form = ~ 1 | rownum/tree)
srfsh.fit3<-lme(lfmlad, data=srfs, random = ~1 | rownum/tree, correlation=cr2)
srfsh.fit4<-lme(lfmlad, data=srfs[srfs$trtdays<10,], random = ~1 | rownum/tree,
correlation=cr2)
```

Ratio of Growth of Treated Trees to Controls

To determine if the defoliated trees had recovered lost growth or exceeded the growth of the control trees, the ratios of d.b.h., height, and estimated volume of the treated trees to the control trees were calculated at each measurement time. Using the fitted linear mixed-effects model to estimate the variance, a 95 percent confidence interval (2.5 percent above and below) around 1 was determined for each season of defoliation by location. The variance at the end of the study was assumed to be greatest, which we used. Ratios that fell within the confidence interval indicated that the size of the treated tree was not different from the size of the untreated controls.

```
fits<-update(bainh.fit3,method="ML")

beta<-fixef(fits)

varcov1=fits$varFix

kx=max(fits$data$trtdays) #SE around line is highest at max day

x0<-c(1,1,0,0,0,0,kx,kx^2,0,0,0,0,0,0,kx,0,0,kx^2,0,0) # season – SM, def = 0

x2<-c(1,1,0,0,33,33^2,kx,kx^2,33,0,0,33^2,0,0,kx,0,0,kx^2,0,0) # def = 33

x3<-c(1,1,0,0,66,66^2,kx,kx^2,66,0,0,66^2,0,0,kx,0,0,kx^2,0,0)

x4<-c(1,1,0,0,95,95^2,kx,kx^2,95,0,0,95^2,0,0,kx,0,0,kx^2,0,0)

x5<-c(1,1,0,0,100,100^2,kx,kx^2,100,0,0,100^2,0,0,kx,0,0,kx^2,0,0) # def=100

var1<-t(x0)%*%varcov1%*%x0

th1<-t(x0)%*%beta

var2<-t(x2)%*%varcov1%*%x2;th2<-t(x2)%*%beta;mu2<-th2/th1;vart2<-var2/
   (th1^2)+var1*(mu2/th1)^2

var3<-t(x3)%*%varcov1%*%x3;th3<-t(x3)%*%beta;mu3<-th3/th1;vart3<-var3/
   (th1^2)+var1*(mu3/th1)^2

var4<-t(x4)%*%varcov1%*%x4;th4<-t(x4)%*%beta;mu4<-th4/th1;vart4<-var4/
   (th1^2)+var1*(mu4/th1)^2

var5<-t(x5)%*%varcov1%*%x5;th5<-t(x5)%*%beta;mu5<-th5/th1;vart5<-var5/
   (th1^2)+var1*(mu5/th1)^2

vartSM<-max(vart2,vart3,vart4,vart5)

x0<-c(1,0,1,0,0,0,kx,kx^2,0,0,0,0,0,0,kx,0,0,kx^2,0) #  season FL

x2<-c(1,0,1,0,33,33^2,kx,kx^2,0,33,0,0,33^2,0,0,kx,0,0,kx^2,0)
```

```
x3<-c(1,0,1,0,66,66^2,kx,kx^2,0,66,0,0,66^2,0,0,kx,0,0,kx^2,0)

x4<-c(1,0,1,0,95,95^2,kx,kx^2,0,95,0,0,95^2,0,0,kx,0,0,kx^2,0)

x5<-c(1,0,1,0,100,100^2,kx,kx^2,0,100,0,0,100^2,0,0,kx,0,0,kx^2,0)

var1<-t(x0)%*%varcov1%*%x0

th1<-t(x0)%*%beta

var2<-t(x2)%*%varcov1%*%x2;th2<-t(x2)%*%beta;mu2<-th2/th1;vart2<-var2/
   (th1^2)+var1*(mu2/th1)^2

var3<-t(x3)%*%varcov1%*%x3;th3<-t(x3)%*%beta;mu3<-th3/th1;vart3<-var3/
   (th1^2)+var1*(mu3/th1)^2

var4<-t(x4)%*%varcov1%*%x4;th4<-t(x4)%*%beta;mu4<-th4/th1;vart4<-var4/
   (th1^2)+var1*(mu4/th1)^2

var5<-t(x5)%*%varcov1%*%x5;th5<-t(x5)%*%beta;mu5<-th5/th1;vart5<-var5/
   (th1^2)+var1*(mu5/th1)^2

vartFL<-max(vart2,vart3,vart4,vart5)

x0<-c(1,0,0,1,0,0,kx,kx^2,0,0,0,0,0,0,0,0,kx,0,0,kx^2) #season WN

x2<-c(1,0,0,1,33,33^2,kx,kx^2,0,0,33,0,0,33^2,0,0,kx,0,0,kx^2)

x3<-c(1,0,0,1,66,66^2,kx,kx^2,0,0,66,0,0,66^2,0,0,kx,0,0,kx^2)

x4<-c(1,0,0,1,95,95^2,kx,kx^2,0,0,95,0,0,95^2,0,0,kx,0,0,kx^2)

x5<-c(1,0,0,1,100,100^2,kx,kx^2,0,0,100,0,0,100^2,0,0,kx,0,0,kx^2)

var1<-t(x0)%*%varcov1%*%x0

th1<-t(x0)%*%beta

var2<-t(x2)%*%varcov1%*%x2;th2<-t(x2)%*%beta;mu2<-th2/th1;vart2<-var2/
   (th1^2)+var1*(mu2/th1)^2

var3<-t(x3)%*%varcov1%*%x3;th3<-t(x3)%*%beta;mu3<-th3/th1;vart3<-var3/
   (th1^2)+var1*(mu3/th1)^2

var4<-t(x4)%*%varcov1%*%x4;th4<-t(x4)%*%beta;mu4<-th4/th1;vart4<-var4/
   (th1^2)+var1*(mu4/th1)^2

var5<-t(x5)%*%varcov1%*%x5;th5<-t(x5)%*%beta;mu5<-th5/th1;vart5<-var5/
   (th1^2)+var1*(mu5/th1)^2

vartWN<-max(vart2,vart3,vart4,vart5)
```

```
x0<-c(1,0,0,0,  0 ,   0,kx,kx^2,0,0,0,0,0,0,0,0,0,0,0,0) # season SP
x2<-c(1,0,0,0, 33, 33^2,kx,kx^2,0,0,0,0,0,0,0,0,0,0,0,0)
x3<-c(1,0,0,0, 66, 66^2,kx,kx^2,0,0,0,0,0,0,0,0,0,0,0,0)
x4<-c(1,0,0,0, 95, 95^2,kx,kx^2,0,0,0,0,0,0,0,0,0,0,0,0)
x5<-c(1,0,0,0,100,100^2,kx,kx^2,0,0,0,0,0,0,0,0,0,0,0,0)
var1<-t(x0)%*%varcov1%*%x0
th1<-t(x0)%*%beta
var2<-t(x2)%*%varcov1%*%x2;th2<-t(x2)%*%beta;mu2<-th2/th1;vart2<-var2/
   (th1^2)+var1*(mu2/th1)^2
var3<-t(x3)%*%varcov1%*%x3;th3<-t(x3)%*%beta;mu3<-th3/th1;vart3<-var3/
   (th1^2)+var1*(mu3/th1)^2
var4<-t(x4)%*%varcov1%*%x4;th4<-t(x4)%*%beta;mu4<-th4/th1;vart4<-var4/
   (th1^2)+var1*(mu4/th1)^2
var5<-t(x5)%*%varcov1%*%x5;th5<-t(x5)%*%beta;mu5<-th5/th1;vart5<-var5/
   (th1^2)+var1*(mu5/th1)^2
vartSP<-max(vart2,vart3,vart4,vart5)
vartm<-c(vartSP,vartSM,vartFL,vartWN) # variance estimates for each season
xyplot(hrat~ trtdays | trt ,group=def,
   data=aggregate(hrat~def+trt+trtdays,rat[rat$loc=="BAIN" &
   rat$def!=0,],mean),
   type="p",outer=TRUE,layout=c(1,4),
   lty=c(1,5,2,3),lwd=1,pch=c(1,3,8,19),col="black",
   xlab="Time since defoliation (years)",ylab="Height ratio",ylim=c(0.7,1.3),
   strip=function(..., bg,style) strip.default(...,bg="gray", style = 1),
   panel = function(x, y, ...){
   panel.superpose(x,y,...)
   panel.xyplot(x, y, ...)
   } )
for (i in 1:4) {
   trellis.focus("panel", 1, i, highlight=FALSE)
   panel.abline(h=1+sqrt(vartm[i])*qnorm(.975,0,1),lwd=1,lty=3,col="black")
   panel.abline(h=1-sqrt(vartm[i])*qnorm(.975,0,1),lwd=1,lty=3,col="black")
   }
```

```
trellis.unfocus()

grid.text("Loblolly (BAIN)",
   gp=gpar(fontface="bold"),x=unit(c(0.5),"npc"),
   y=unit(c(0.98),"npc"),draw=TRUE)

grid.text(c("33","66","95","100"), gp=gpar(fontface="bold"),
   x=unit(c(0.5,0.6,0.7,0.8),"npc"),
   y=unit(c(0.74,0.74,0.74,0.74),"npc"),draw=TRUE)

grid.points(x=unit(c(0.53,0.63,0.73,0.83),"npc"),
   y=unit(c(0.74,0.74,0.74,0.74),"npc"),pch= c(1,3,8,19),
   size=unit(0.55,"char"))

grid.text("100 percent defoliation < 0.6",x=unit(c(0.7),"npc"),
   y=unit(c(0.55),"npc"),draw=TRUE)
```

Effects of Treatments on Number of Height Growth Flushes

Growth flush data were analyzed using a similar general linear model and specifying the Poisson distribution for discrete count data. These analyses were only performed on the Branchville, South Carolina, and Palatka, Florida, data. At this time, the *lme4* routine in R cannot perform Poisson regression so the *glm* routine was used.

```
flushes<-read.table("c:\\users\\dweise\\documents\\defol\\data\\defolflush.
   dat",header=TRUE)

flushes$seas<-factor(flushes$seas)

flushes$trtdays<-(as.numeric(dates(as.character(flushes$md))-dates(as.character(fl
   ushes$td))))/365.25    # elapsed days converted to yearsflushes$year<-factor(flush
   es$year,label=c('1986','1987','1990'))

flushes$md<-factor(flushes$md,label=c("1986","1987","1989"))

flushes$treeid<-(flushes$row-1)*20+flushes$tree

flbran<-subset(flushes,flushes$loc=="BRAN" & !is.na(flushes$gflush))

flbran.fit1<-glm(fmlad,data=flbran, family=poisson)

anova(flbran.fit1,test="Chisq")
```

Appendix 2: Diameter at Breast Height (d.b.h.) and Height Measurements

Table 4—Mean d.b.h. (standard deviation) of loblolly and slash pines 5 (study end) and 13 (final) years after being manually defoliated to simulate crown scorch[a] (continued)

Location	Defoliation		Diameter at breast height		
	Level	Season	Initial	Study end	Final
	Percent		*Inches*		
Bainbridge, Georgia	0	SP	1.28 (0.27)	5.43 (0.49)	8.49 (1.12)
		SM	1.22 (0.25)	5.29 (0.69)	8.85 (1.59)
		FL	1.81 (0.18)	4.96 (0.43)	8.30 (0.78)
		WN	2.02 (0.33)	5.32 (0.71)	8.84 (0.59)
	33	SP	1.08 (0.23)	4.92 (0.45)	8.22 (0.88)
		SM	1.26 (0.23)	5.32 (0.49)	9.58 (0.60)
		FL	1.89 (0.23)	5.17 (0.61)	8.63 (0.91)
		WN	2.03 (0.22)	5.12 (0.40)	8.02 (0.96)
	66	SP	1.08 (0.21)	4.81 (0.48)	7.90 (0.80)
		SM	1.15 (0.27)	4.88 (0.69)	7.35 (0.66)
		FL	1.86 (0.28)	4.73 (0.34)	7.80 (1.68)
		WN	2.14 (0.31)	5.09 (0.53)	8.25 (0.54)
	95	SP	1.11 (0.19)	4.66 (0.52)	7.10 (1.25)
		SM	1.16 (0.24)	4.64 (0.50)	6.40
		FL	1.89 (0.28)	4.18 (0.57)	7.32 (0.87)
		WN	2.06 (0.38)	4.50 (0.60)	7.67 (0.88)
	100	SP	1.21 (0.23)	4.46 (0.61)	7.78 (0.68)
		SM	1.10 (0.18)	4.49 (0.49)	7.76 (1.02)
		FL	2.02 (0.19)	2.41	
		WN	2.16 (0.19)	4.59 (0.35)	7.77 (0.38)
Branchville, South Carolina	0	SP	1.49 (0.26)	6.79 (0.55)	9.10 (1.80)
		SM	1.46 (0.26)	6.84 (1.13)	9.42 (2.38)
		FL	2.51 (0.38)	6.50 (0.94)	8.98 (1.48)
		WN	2.49 (0.36)	6.56 (0.51)	9.03 (1.00)
	33	SP	1.41 (0.23)	6.30 (0.96)	8.68 (0.93)
		SM	1.37 (0.24)	6.61 (0.61)	10.08 (1.97)
		FL	2.33 (0.30)	6.14 (0.46)	9.27 (1.55)
		WN	2.45 (0.32)	6.48 (0.80)	9.64 (1.17)
	66	SP	1.35 (0.34)	6.18 (0.46)	9.78 (2.05)
		SM	1.44 (0.23)	6.26 (0.81)	9.20 (0.56)
		FL	2.53 (0.28)	6.07 (0.70)	8.95 (1.48)
		WN	2.54 (0.28)	6.03 (0.69)	8.70 (1.01)
	95	SP	1.39 (0.32)	5.95 (0.81)	8.13 (0.46)
		SM	1.32 (0.28)	6.07 (0.94)	8.68 (2.22)
		FL	2.32 (0.29)	5.88 (0.80)	8.40 (1.89)
		WN	2.66 (0.35)	6.33 (0.72)	9.89 (1.25)
	100	SP	1.37 (0.38)	5.90 (0.81)	9.63 (1.80)
		SM	1.46 (0.34)	5.86 (1.04)	8.90 (0.93)
		FL	2.47 (0.21)	4.29 (0.25)	
		WN	2.54 (0.37)	5.54 (1.00)	8.38 (2.37)

Table 4—Mean d.b.h. (standard deviation) of loblolly and slash pines 5 (study end) and 13 (final) years after being manually defoliated to simulate crown scorch[a] (continued)

	Defoliation		Diameter at breast height		
Location	**Level**	**Season**	**Initial**	**Study end**	**Final**
	Percent		- - - - - - - - - - - - - *Inches* - - - - - - - - - - - - -		
Palatka, Florida	0	SP	1.86 (0.28)	4.52 (0.62)	6.41 (0.64)
		SM	2.00 (0.26)	4.31 (0.56)	5.80 (0.64)
		FL	2.46 (0.29)	4.54 (0.56)	6.60 (1.09)
		WN	2.54 (0.36)	4.66 (0.64)	7.25 (1.17)
	33	SP	1.81 (0.36)	4.25 (0.52)	5.87 (0.63)
		SM	2.23 (0.26)	4.51 (0.42)	6.75 (1.06)
		FL	2.40 (0.31)	4.48 (0.41)	6.03 (1.02)
		WN	2.32 (0.22)	4.09 (0.53)	5.86 (0.91)
	66	SP	1.92 (0.28)	4.12 (0.56)	5.10 (1.12)
		SM	2.21 (0.24)	4.13 (0.48)	4.30
		FL	2.47 (0.24)	4.15 (0.52)	5.83 (0.76)
		WN	2.42 (0.22)	3.94 (0.48)	5.87 (0.85)
	95	SP	1.84 (0.18)	4.02 (0.48)	4.98 (1.33)
		SM	2.24 (0.29)	3.87 (0.69)	5.00 (1.45)
		FL	2.37 (0.18)	3.50 (0.31)	4.50 (1.04)
		WN	2.28 (0.25)	3.42 (0.45)	4.73 (0.25)
	100	SP	1.93 (0.36)	3.83 (0.68)	5.31 (1.38)
		SM	2.16 (0.33)	3.48 (0.48)	4.71 (1.04)
		FL	2.28 (0.43)	2.93 (0.42)	3.63 (1.36)
		WN	2.34 (0.29)	3.48 (0.52)	4.31 (0.91)
Waycross, Georgia	0	SP	1.83 (0.24)	4.63 (0.58)	7.34 (0.84)
		SM	2.17 (0.28)	4.73 (0.58)	7.60 (0.80)
		FL	2.32 (0.16)	4.63 (0.55)	6.83 (0.88)
		WN	2.45 (0.29)	4.73 (0.59)	6.93 (0.51)
	33	SP	1.78 (0.27)	4.52 (0.44)	7.06 (1.36)
		SM	2.09 (0.28)	4.46 (0.45)	6.75 (1.41)
		FL	2.26 (0.17)	4.44 (0.60)	6.80 (0.56)
		WN	2.34 (0.28)	4.38 (0.39)	8.00 (0.52)
	66	SP	1.86 (0.41)	4.34 (0.40)	6.58 (0.58)
		SM	2.01 (0.27)	3.96 (0.53)	5.93 (1.23)
		FL	2.34 (0.28)	4.01 (0.57)	6.38 (0.15)
		WN	2.43 (0.24)	4.35 (0.52)	6.20 (0.85)
	95	SP	1.82 (0.32)	4.00 (0.52)	5.95 (1.34)
		SM	2.25 (0.24)	4.07 (0.43)	7.05 (1.35)
		FL	2.31 (0.26)	3.59 (0.39)	5.16 (1.03)
		WN	2.45 (0.42)	3.85 (0.63)	6.90 (1.09)
	100	SP	1.88 (0.44)	4.04 (0.63)	5.07 (0.80)
		SM	2.11 (0.19)	3.71 (0.36)	6.08 (0.87)
		FL	2.34 (0.36)	3.49 (0.45)	4.88 (0.82)
		WN	2.24 (0.31)	3.53 (0.55)	5.30 (0.99)

Note: Defoliation season: SP = spring (April), SM = summer (July), FL = fall (October), WN = winter (January).
[a] Initial diameter at breast height (d.b.h.) generally measured at the time of treatment application.

Table 5—Mean d.b.h. (standard deviation) of longleaf pines 6 (study end) and 19 (final) years after being manually defoliated to simulate crown scorch[a]

Location	Defoliation Level	Defoliation Month	Diameter at breast height Initial	Diameter at breast height Study end	Diameter at breast height Final
	Percent		*Inches*		
Aiken, South Carolina (Savannah River Forest Station)	0	Aug	1.64 (0.21)	3.10 (0.42)	4.76 (0.76)
		Sep	1.79 (0.14)	3.39 (0.40)	5.23 (0.99)
		Oct	1.83 (0.22)	3.43 (0.33)	5.27 (0.61)
		Nov	1.63 (0.22)	3.09 (0.35)	4.83 (0.77)
		Dec	1.73 (0.18)	3.27 (0.36)	4.97 (0.82)
	95	Aug	1.66 (0.27)	2.96 (0.46)	4.30 (1.13)
		Sep	1.71 (0.20)	2.88 (0.39)	4.32 (0.81)
		Oct	1.75 (0.28)	2.91 (0.42)	4.31 (0.84)
		Nov	1.79 (0.29)	2.89 (0.33)	4.08 (0.73)
		Dec	1.78 (0.21)	2.96 (0.29)	4.42 (0.71)
	100	Aug	1.70 (0.20)	2.75 (0.29)	4.29 (0.47)
		Sep	1.81 (0.23)	2.87 (0.39)	4.47 (0.88)
		Oct	1.70 (0.15)	2.73 (0.26)	3.93 (0.66)
		Nov	1.72 (0.27)	2.68 (0.24)	4.17 (0.61)
		Dec	1.68 (0.24)	2.86 (0.38)	4.55 (0.75)
Waycross, Georgia	0	Aug	1.80 (0.29)	4.26 (0.52)	6.93 (1.00)
		Sep	1.69 (0.23)	4.12 (0.58)	7.14 (0.80)
		Oct	1.88 (0.27)	4.34 (0.68)	7.10 (1.21)
		Nov	1.71 (0.18)	4.04 (0.42)	6.98 (1.11)
		Dec	1.85 (0.21)	4.36 (0.67)	6.50
	95	Aug	1.71 (0.20)	3.67 (0.50)	6.27 (1.10)
		Sep	1.80 (0.29)	3.80 (0.79)	6.27 (1.55)
		Oct	1.72 (0.28)	3.60 (0.53)	5.25 (0.78)
		Nov	1.76 (0.22)	3.78 (0.46)	7.23 (0.72)
		Dec	1.79 (0.29)	3.79 (0.48)	6.41 (0.76)
	100	Aug	1.74 (0.19)	3.41 (0.45)	5.47 (1.29)
		Sep	1.79 (0.30)	3.57 (0.58)	3.30
		Oct	1.74 (0.32)	3.61 (0.42)	5.60 (0.14)
		Nov	1.76 (0.30)	3.51 (0.58)	5.96 (0.74)
		Dec	1.70 (0.25)	3.21 (0.56)	5.75 (0.07)

[a] Initial diameter at breast height (d.b.h.) generally measured at the time of treatment application.

Table 6—Mean height (standard deviation) of loblolly and slash pines 5 (study end) and 13 (final) years after being manually defoliated to simulate crown scorch[a] (continued)

	Defoliation		Diameter at breast height		
Location	**Level**	**Season**	**Initial**	**Study end**	**Final**
	Percent		- - - - - -	*Feet*	- - - - - -
Bainbridge, Georgia	0	SP	9.54 (0.78)	32.99 (1.83)	64.29 (3.57)
		SM	9.63 (0.79)	33.56 (2.87)	65.50 (4.30)
		FL	12.49 (1.07)	32.23 (2.26)	62.33 (1.26)
		WN	12.30 (1.08)	32.63 (1.88)	64.60 (2.39)
	33	SP	9.34 (0.72)	32.49 (1.93)	64.33 (2.82)
		SM	9.68 (0.63)	33.33 (1.80)	66.80 (2.66)
		FL	12.79 (1.03)	32.40 (1.67)	64.92 (4.71)
		WN	12.61 (1.29)	32.51 (2.17)	65.30 (2.33)
	66	SP	9.00 (0.49)	31.66 (1.81)	60.00 (6.24)
		SM	9.40 (0.97)	32.62 (1.96)	62.58 (2.82)
		FL	12.69 (0.98)	32.30 (2.12)	62.00 (5.00)
		WN	13.21 (1.04)	33.05 (1.81)	64.88 (3.35)
	95	SP	9.21 (0.83)	31.08 (1.66)	59.67 (2.52)
		SM	9.47 (0.93)	32.02 (1.84)	61.00
		FL	12.39 (1.30)	29.98 (1.89)	62.40 (3.47)
		WN	12.23 (1.16)	30.70 (2.57)	62.92 (3.56)
	100	SP	9.44 (0.76)	30.72 (1.75)	62.50 (2.27)
		SM	9.42 (0.79)	31.63 (1.64)	64.90 (3.75)
		FL	12.95 (0.93)	19.55	
		WN	12.79 (1.07)	31.38 (2.16)	62.00 (1.55)
Branchville, South Carolina	0	SP	9.49 (0.97)	32.64 (2.43)	62.33 (10.30)
		SM	9.52 (0.83)	32.95 (2.35)	64.70 (4.52)
		FL	13.23 (1.02)	33.27 (1.61)	63.75 (3.70)
		WN	13.10 (1.42)	33.65 (2.61)	63.08 (3.87)
	33	SP	9.40 (0.66)	33.07 (1.75)	66.60 (1.43)
		SM	9.44 (0.59)	33.35 (1.16)	65.00 (3.42)
		FL	12.68 (0.75)	31.85 (3.05)	65.40 (4.52)
		WN	12.60 (0.92)	31.75 (2.41)	65.26 (1.55)
	66	SP	9.10 (0.92)	31.05 (1.88)	66.90 (2.04)
		SM	9.15 (0.65)	31.27 (1.83)	62.60 (2.41)
		FL	13.33 (0.82)	33.03 (1.74)	64.25 (4.35)
		WN	12.82 (0.78)	32.66 (1.94)	63.60 (2.79)
	95	SP	9.22 (0.77)	31.27 (1.65)	64.25 (0.29)
		SM	9.31 (0.88)	31.86 (1.87)	64.10 (3.15)
		FL	12.80 (1.04)	31.40 (2.25)	60.42 (7.19)
		WN	13.28 (0.74)	32.40 (1.98)	66.75 (3.87)
	100	SP	9.29 (0.94)	31.52 (2.76)	63.00 (3.12)
		SM	9.37 (0.67)	30.85 (2.50)	62.63 (4.03)
		FL	12.93 (1.11)	23.31 (1.56)	
		WN	13.43 (1.57)	31.21 (2.67)	62.10 (6.23)
Palatka, Florida	0	SP	9.64 (0.87)	29.98 (1.98)	51.71 (3.41)
		SM	12.69 (0.75)	29.39 (2.28)	51.00 (6.36)
		FL	14.16 (1.05)	30.99 (2.14)	53.81 (7.01)
		WN	14.04 (1.28)	29.96 (1.55)	55.83 (5.65)

Table 6—Mean height (standard deviation) of loblolly and slash pines 5 (study end) and 13 (final) years after being manually defoliated to simulate crown scorch[a] (continued)

	Defoliation		Diameter at breast height		
Location	**Level**	**Season**	**Initial**	**Study end**	**Final**
	Percent		- - - - - -	*Feet*	- - - - - -
	33	SP	9.81 (0.91)	29.92 (1.66)	52.79 (3.57)
		SM	13.45 (0.92)	28.96 (2.86)	53.50 (5.67)
		FL	13.99 (1.33)	30.57 (2.51)	54.00 (5.63)
		WN	13.64 (1.10)	29.70 (1.81)	51.70 (4.64)
	66	SP	9.92 (0.73)	29.54 (2.23)	44.25 (6.28)
		SM	13.52 (0.84)	29.73 (1.79)	45.00
		FL	13.86 (1.08)	29.23 (2.00)	51.71 (3.59)
		WN	13.56 (1.45)	28.82 (2.16)	55.17 (5.06)
	95	SP	9.52 (0.68)	27.55 (2.00)	41.83 (7.63)
		SM	13.40 (0.92)	28.04 (2.76)	44.17 (11.27)
		FL	13.91 (0.86)	26.85 (1.43)	43.17 (7.80)
		WN	13.25 (1.39)	25.90 (3.03)	48.33 2.84
	100	SP	10.03 (0.97)	28.01 (1.76)	48.56 (6.03)
		SM	12.85 (1.00)	26.11 (2.48)	44.79 (4.41)
		FL	13.71 (1.08)	24.06 (1.69)	38.33 (12.17)
		WN	13.86 (1.51)	26.71 (1.27)	44.75 (8.48)
Waycross, Georgia	0	SP	10.17 (0.93)	28.46 (3.00)	57.60 (3.76)
		SM	12.39 (1.50)	28.61 (2.63)	59.42 (3.31)
		FL	12.56 (1.01)	28.38 (2.42)	56.63 (4.31)
		WN	13.44 (1.26)	29.24 (2.25)	56.50 (2.80)
	33	SP	9.66 (0.97)	26.85 (2.61)	52.43 (12.24)
		SM	12.47 (1.21)	27.72 (2.36)	52.00 (8.97)
		FL	12.21 (0.93)	27.12 (2.43)	55.70 (2.61)
		WN	12.86 (1.09)	27.76 (1.91)	60.25 (2.22)
	66	SP	10.19 (1.29)	27.47 (2.31)	53.10 (6.21)
		SM	12.42 (0.99)	26.04 (2.33)	53.43 (6.88)
		FL	13.11 (1.10)	26.51 (3.22)	54.88 (5.85)
		WN	12.89 (0.91)	27.35 (1.69)	52.70 (6.12)
	95	SP	9.78 (1.13)	26.30 (2.49)	52.00 (3.54)
		SM	12.89 (1.10)	25.99 (1.66)	56.63 (3.47)
		FL	12.51 (1.30)	23.68 (1.55)	50.00 (8.04)
		WN	12.90 (1.14)	25.19 (2.34)	54.00 (3.34)
	100	SP	9.75 (0.96)	25.27 (2.50)	46.83 (5.35)
		SM	12.55 (0.89)	24.44 (1.86)	55.67 (3.54)
		FL	12.61 (1.18)	22.03 (1.44)	46.00 (3.06)
		WN	12.16 (0.97)	23.32 (2.04)	50.75 (4.60)

Note: Defoliation season: spring (SP) = spring (April), SM = summer (July), FL = fall (October), WN = winter (January).
[a] Initial height generally measured at the time of treatment application.

Table 7—Mean height (standard deviation) of longleaf pines 6 (study end) and 19 (final) years after being manually defoliated to simulate crown scorch

	Defoliation		Diameter at breast height		
Location	**Level**	**Month**	**Initial**	**Study end**	**Final**
	Percent			*Feet*	
Aiken, South Carolina (Savannah River Forest Station)	0	Aug	9.99 (1.25)	23.50 (2.33)	40.67 (3.59)
		Sep	10.28 (0.99)	24.73 (2.07)	40.55 (7.02)
		Oct	10.23 (1.26)	24.00 (2.27)	41.45 (2.43)
		Nov	9.43 (1.30)	22.97 (2.27)	39.67 (4.68)
		Dec	10.29 (0.95)	24.33 (1.25)	40.59 (2.84)
	95	Aug	9.67 (1.20)	22.11 (2.36)	36.78 (8.43)
		Sep	10.27 (1.09)	22.33 (2.11)	37.54 (6.29)
		Oct	10.19 (1.32)	22.97 (2.09)	38.24 (2.76)
		Nov	10.41 (1.24)	22.33 (2.14)	37.10 (6.60)
		Dec	10.08 (0.92)	22.10 (1.74)	36.66 (6.11)
	100	Aug	10.34 (1.16)	21.60 (2.09)	38.64 (3.10)
		Sep	10.37 (1.02)	22.33 (1.73)	40.11 (4.12)
		Oct	10.05 (1.20)	21.88 (1.11)	36.70 (1.73)
		Nov	10.51 (1.34)	20.00 (1.32)	37.30 (1.13)
		Dec	10.27 (1.57)	22.50 (2.04)	41.34 (3.21)
Waycross, Georgia	0	Aug	10.17 (1.22)	26.61 (2.24)	43.30 (3.79)
		Sep	9.83 (1.07)	27.09 (2.28)	46.05 (3.56)
		Oct	10.54 (1.20)	26.75 (3.08)	45.20 (5.55)
		Nov	10.08 (1.02)	27.21 (2.44)	46.52 (3.75)
		Dec	10.38 (0.99)	28.00 (3.24)	49.50
	95	Aug	9.87 (0.97)	24.35 (1.82)	40.60 (3.96)
		Sep	10.02 (1.04)	25.12 (2.21)	39.35 (5.32)
		Oct	10.09 (1.23)	24.50 (2.73)	42.75 (3.46)
		Nov	9.97 (1.21)	25.13 (2.43)	44.70 (4.91)
		Dec	10.26 (1.12)	26.14 (2.16)	41.97 (3.13)
	100	Aug	10.04 (1.12)	23.23 (1.33)	37.80 (3.47)
		Sep	10.12 (1.16)	24.05 (2.92)	32.70
		Oct	9.87 (0.94)	23.44 (1.84)	36.00 (4.67)
		Nov	10.01 (1.24)	24.08 (1.99)	39.28 (3.49)
		Dec	9.96 (1.25)	22.31 (2.51)	42.80 (4.81)

Table 8—Range of variability (expressed as coefficient of variation) in size of young southern pines subjected to manual defoliation to simulate crown scorch

			Initial		Study end		Final	
Variable	**Species**	**Location**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
d.b.h.	Loblolly	Bainbridge, Georgia	0.09	0.23	0.07	0.14	0.05	0.22
		Branchville, S. Carolina	0.09	0.28	0.06	0.18	0.06	0.28
	Slash	Palatka, Florida	0.07	0.20	0.09	0.18	0.05	0.37
		Waycross, Georgia	0.07	0.23	0.09	0.16	0.02	0.23
	Longleaf	Aiken, S. Carolina	0.08	0.16	0.09	0.16	0.11	0.26
		Waycross, Georgia	0.11	0.19	0.10	0.21	0.01	0.25
Height	Loblolly	Bainbridge, Gerogia	0.05	0.11	0.05	0.09	0.02	0.10
		Branchville, S. Carolina	0.06	0.12	0.03	0.10	0.00	0.17
	Slash	Palatka, Florida	0.06	0.11	0.05	0.12	0.06	0.32
		Waycross, Georgia	0.07	0.13	0.06	0.12	0.04	0.23
	Longleaf	Aiken, S. Carolina	0.09	0.15	0.05	0.11	0.03	0.23
		Waycross, Georgia	0.09	0.13	0.06	0.12	0.07	0.14

Note: Study end measurements performed 5 years after treatment for loblolly and slash pine and 6 years for longleaf pine. Final measurements performed at 13 years for loblolly and slash pine and at 19 years for longleaf pine. D.b.h. = diameter at breast height.

Appendix 3: Linear Mixed-Effects Model Results

These tables summarize the results of fitting the linear mixed-effects model to the diameter at breast height (d.b.h.) and height data for the six locations.

Bainbridge, Georgia—loblolly pine

Diameter at breast height—all measurements

Model summary

	DF[a]			
Source	**num**	**den**	**F-value**	**p-value**
Intercept	1	1,736	11407	<1E-04
Season	3	274	30	<1E-04
Defoliation	1	274	129	<1E-04
Defoliation^2	1	274	13	4E-04
Trtdays	1	1,736	27845	<1E-04
Trtdays^2	1	1,736	2659	<1E-04
Season:Defoliation	3	274	0.92	0.433
Season:Defoliation^2	3	274	1.17	0.323
Season:Trtdays	3	1,736	32	<1E-04
Season:Trtdays^2	3	1,736	12	<1E-04

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures.

The AIC is the Akaike Information Criterion, BIC is the Bayesian Information Criterion, LRML is the log of the restricted maximum likelihood, σ_B is the standard deviation of the random effect for row (block effect), σ_r is the standard deviation of the random repeated measure effect, $\hat{\sigma}$ is the standard deviation of the residual, and ϕ is the autoregressive correlation estimate.

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
634	775	-296	0.083	7E-05	0.507	0.883

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	1.536	0.114	1736	13	<1E-04
seasSM	-0.025	0.158	274	-0.16	0.876
seasFL	0.456	0.158	274	2.88	0.004
seasWN	0.712	0.160	274	4.46	<1E-04
def	-0.011	0.005	274	-2.11	0.036
def^2	6E-05	5E-05	274	1.14	0.255
trtdays	0.928	0.017	1736	54	<1E-04
$trtdays^2$	-0.032	0.001	1736	-30	<1E-04
seasSM:def	0.011	0.007	274	1.48	0.139
seasFL:def	0.013	0.007	274	1.78	0.077
seasWN:def	0.011	0.007	274	1.47	0.144
seasSM:def^2	-1E-04	7E-05	274	-1.62	0.107
seasFL:def^2	-1E-04	7E-05	274	-1.62	0.106
seasWN:def^2	-1E-04	7E-05	274	-1.36	0.174
seasSM:trtdays	0.052	0.025	1736	2.12	0.034
seasFL:trtdays	-0.146	0.026	1736	-5.52	<1E-04
seasWN:trtdays	-0.087	0.025	1736	-3.45	6E-04
seasSM:$trtdays^2$	-0.003	0.002	1736	-1.73	0.083
seasFL:$trtdays^2$	0.007	0.002	1736	4.34	<1E-04
seasWN:$trtdays^2$	0.003	0.002	1736	1.60	0.110

[a] DF = degrees of freedom.

Diameter at breast height—1986–1991

Model summary

	DF[a]			
Source	num	den	F-value	p-value
Intercept	1	1,644	13678	<1E-04
Season	3	274	25	<1E-04
Defoliation	1	274	97	<1E-04
$Defoliation^2$	1	274	9.92	0.002
Trtdays	1	1,644	20260	<1E-04
$Trtdays^2$	1	1,644	253	<1E-04
Season:Defoliation	3	274	1.06	0.369
Season:$Defoliation^2$	3	274	1.52	0.211
Season:Trtdays	3	1,644	36	<1E-04
Season:$Trtdays^2$	3	1,644	24	<1E-04

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
-319	-185	183	0.059	5E-05	0.431	0.904

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	1.505	0.099	1644	15	<1E-04
seasSM	-0.077	0.138	274	-0.56	0.576
seasFL	0.467	0.138	274	3.38	0.001
seasWN	0.711	0.139	274	5.10	<1E-04
def	-0.011	0.005	274	-2.36	0.019
def^2	6E-05	4E-05	274	1.36	0.174
trtdays	0.966	0.023	1644	41	<1E-04
$trtdays^2$	-0.040	0.004	1644	-9.59	<1E-04
seasSM:def	0.011	0.006	274	1.77	0.079
seasFL:def	0.013	0.006	274	2.06	0.040
seasWN:def	0.012	0.007	274	1.82	0.069
seasSM:def^2	-1E-04	6E-05	274	-1.90	0.059
seasFL:def^2	-1E-04	6E-05	274	-1.89	0.060
seasWN:def^2	-1E-04	6E-05	274	-1.71	0.088
seasSM:trtdays	0.199	0.035	1644	5.69	<1E-04
seasFL:trtdays	-0.210	0.038	1644	-5.50	<1E-04
seasWN:trtdays	-0.145	0.036	1644	-4.07	<1E-04
seasSM:$trtdays^2$	-0.034	0.006	1644	-5.43	<1E-04
seasFL:$trtdays^2$	0.022	0.007	1644	3.01	0.003
seasWN:$trtdays^2$	0.016	0.007	1644	2.25	0.025

[a] DF = degrees of freedom.

Height—all measurements

Model summary

	DF[a]			
Source	num	den	F-value	p-value
Intercept	1	1736	30036	<1E-04
Season	3	274	75	<1E-04
Defoliation	1	274	209	<1E-04
$Defoliation^2$	1	274	51	<1E-04
Trtdays	1	1736	80058	<1E-04
$Trtdays^2$	1	1736	801	<1E-04
Season:Defoliation	3	274	0.91	0.437
Season:$Defoliation^2$	3	274	2.49	0.061
Season:Trtdays	3	1736	9.15	<1E-04
Season:$Trtdays^2$	3	1736	9.59	<1E-04

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
7519	7654	-3736	0.418	0.452	1.839	0.664

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	9.795	0.373	1736	26	<1E-04
seasSM	0.304	0.504	274	0.60	0.547
seasFL	2.345	0.503	274	4.66	<1E-04
seasWN	2.445	0.511	274	4.79	<1E-04
def	-0.025	0.016	274	-1.57	0.117
def^2	7E-05	1E-04	274	0.49	0.624
trtdays	5.087	0.084	1736	61	<1E-04
trtdays^2	-0.082	0.005	1736	-15	<1E-04
seasSM:def	0.019	0.022	274	0.85	0.399
seasFL:def	0.048	0.022	274	2.11	0.035
seasWN:def	0.063	0.023	274	2.78	0.006
seasSM:def^2	-1E-04	2E-04	274	-0.70	0.483
seasFL:def^2	-4E-04	2E-04	274	-1.86	0.064
seasWN:def^2	-6E-04	2E-04	274	-2.59	0.010
seasSM:trtdays	0.484	0.120	1736	4.02	1E-04
seasFL:trtdays	-0.365	0.127	1736	-2.86	0.004
seasWN:trtdays	0.147	0.125	1736	1.18	0.239
seasSM:trtdays^2	-0.024	0.008	1736	-2.98	0.003
seasFL:trtdays^2	0.022	0.009	1736	2.59	0.010
seasWN:trtdays^2	-0.010	0.008	1736	-1.17	0.244

[a] DF = degrees of freedom.

Height—1986–1991

Model summary

	DF[a]			
Source	num	den	F-value	p-value
Intercept	1	1,644	34415	<1E-04
Season	3	274	35	<1E-04
Defoliation	1	274	117	<1E-04
Defoliation^2	1	274	36	<1E-04
Trtdays	1	1,644	42266	<1E-04
Trtdays^2	1	1,644	270	<1E-04
Season:Defoliation	3	274	0.74	0.527
Season:Defoliation^2	3	274	2.43	0.065
Season:Trtdays	3	1,644	25	<1E-04
Season:Trtdays^2	3	1,644	15	<1E-04

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
6371	6505	-3162	0.298	0.965	1.318	0.581

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	10.390	0.347	1644	30	<1E-04
seasSM	0.109	0.478	274	0.23	0.820
seasFL	2.365	0.477	274	4.95	<1E-04
seasWN	2.330	0.482	274	4.83	<1E-04
def	-0.021	0.015	274	-1.38	0.170
def^2	4E-05	1E-04	274	0.28	0.782
trtdays	3.471	0.128	1644	27	<1E-04
trtdays^2	0.265	0.025	1644	11	<1E-04
seasSM:def	0.018	0.022	274	0.85	0.395
seasFL:def	0.044	0.022	274	2.01	0.046
seasWN:def	0.061	0.022	274	2.78	0.006
seasSM:def^2	-2E-04	2E-04	274	-0.75	0.454
seasFL:def^2	-4E-04	2E-04	274	-1.83	0.068
seasWN:def^2	-5E-04	2E-04	274	-2.59	0.010
seasSM:trtdays	1.183	0.190	1644	6.22	<1E-04
seasFL:trtdays	-0.526	0.207	1644	-2.55	0.011
seasWN:trtdays	0.124	0.200	1644	0.62	0.535
seasSM:trtdays^2	-0.171	0.037	1644	-4.59	<1E-04
seasFL:trtdays^2	0.097	0.043	1644	2.28	0.023
seasWN:trtdays^2	0.054	0.043	1644	1.27	0.205

[a] DF = degrees of freedom.

Branchville, South Carolina—loblolly pine

Diameter at breast height—all measurements

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	1,355	5598	<1E-04
Season	3	219	11	<1E-04
Defoliation	1	219	37	<1E-04
Defoliation^2	1	219	7.35	0.007
Trtdays	1	1,355	11420	<1E-04
Trtdays^2	1	1,355	2573	<1E-04
Season:Defoliation	3	219	0.41	0.746
Season:Defoliation^2	3	219	0.17	0.920
Season:Trtdays	3	1,355	20	<1E-04
Season:Trtdays^2	3	1,355	6.41	3E-04

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
2038	2167	-995	0.166	1E-04	0.743	0.857

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	1.691	0.178	1355	9.52	<1E-04
seasSM	0.112	0.244	219	0.46	0.648
seasFL	0.663	0.245	219	2.70	0.007
seasWN	0.895	0.248	219	3.60	4E-04
def	-0.006	0.008	219	-0.76	0.445
def^2	1E-05	7E-05	219	0.17	0.867
trtdays	1.279	0.029	1355	44	<1E-04
trtdays^2	-0.053	0.002	1355	-29	<1E-04
seasSM:def	0.003	0.011	219	0.30	0.767
seasFL:def	0.003	0.012	219	0.23	0.821
seasWN:def	0.008	0.012	219	0.71	0.478
seasSM:def^2	-5E-05	1E-04	219	-0.49	0.656
seasFL:def^2	-2E-05	1E-04	219	-0.21	0.837
seasWN:def^2	-6E-05	1E-04	219	-0.56	0.580
seasSM:trtdays	0.085	0.043	1355	1.96	0.050
seasFL:trtdays	-0.128	0.047	1355	-2.75	0.006
seasWN:trtdays	-0.162	0.045	1355	-3.62	3E-04
seasSM:trtdays^2	-0.005	0.003	1355	-2.06	0.041
seasFL:trtdays^2	0.004	0.003	1355	1.50	0.135
seasWN:trtdays^2	0.006	0.003	1355	2.24	0.025

[a] DF = degrees of freedom.

Diameter at breast height—1986–1991

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	1,256	8632	<1E-04
Season	3	219	8.34	<1E-04
Defoliation	1	219	40	<1E-04
Defoliation^2	1	219	5.87	0.016
Trtdays	1	1,256	11967	<1E-04
Trtdays^2	1	1,256	379	<1E-04
Season:Defoliation	3	219	0.46	0.710
Season:Defoliation^2	3	219	0.30	0.827
Season:Trtdays	3	1,256	25	<1E-04
Season:Trtdays^2	3	1,256	9.87	<1E-04

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
1114	1241	-533	0.111	1E-04	0.569	0.858

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	1.727	0.137	1256	13	<1E-04
seasSM	-0.039	0.189	219	-0.21	0.837
seasFL	0.548	0.191	219	2.87	0.005
seasWN	0.868	0.192	219	4.51	<1E-04
def	-0.009	0.006	219	-1.42	0.157
def^2	3E-05	6E-05	219	0.56	0.573
trtdays	1.380	0.040	1256	34	<1E-04
trtdays^2	-0.074	0.007	1256	-10	<1E-04
seasSM:def	0.004	0.009	219	0.50	0.620
seasFL:def	0.003	0.009	219	0.29	0.770
seasWN:def	0.009	0.009	219	1.02	0.307
seasSM:def^2	-4E-05	9E-05	219	-0.50	0.617
seasFL:def^2	-1E-05	8E-05	219	-0.11	0.910
seasWN:def^2	-7E-05	8E-05	219	-0.81	0.420
seasSM:trtdays	0.306	0.061	1256	5.04	<1E-04
seasFL:trtdays	-0.022	0.069	1256	-0.32	0.751
seasWN:trtdays	-0.171	0.064	1256	-2.69	0.007
seasSM:trtdays^2	-0.055	0.011	1256	-4.86	<1E-04
seasFL:trtdays^2	-0.020	0.013	1256	-1.48	0.140
seasWN:trtdays^2	0.007	0.013	1256	0.53	0.599

[a] DF = degrees of freedom.

Height—all measurements

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	1,355	23829	<1E-04
Season	3	219	54	<1E-04
Defoliation	1	219	77	<1E-04
Defoliation^2	1	219	29	<1E-04
Trtdays	1	1,355	68138	<1E-04
Trtdays^2	1	1,355	555	<1E-04
Season:Defoliation	3	219	0.72	0.543
Season:Defoliation^2	3	219	0.20	0.897
Season:Trtdays	3	1,355	8.15	<1E-04
Season:Trtdays^2	3	1,355	4.60	0.003

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
6204	6333	-3078	0.471	0.352	2.108	0.712

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	9.561	0.460	1355	21	<1E-04
seasSM	0.554	0.628	219	0.88	0.379
seasFL	2.683	0.639	219	4.20	<1E-04
seasWN	3.456	0.644	219	5.37	<1E-04
def	0.003	0.020	219	0.13	0.895
def^2	-1E-04	2E-04	219	-0.74	0.460
trtdays	5.116	0.102	1355	50	<1E-04
trtdays^2	-0.070	0.006	1355	-11	<1E-04
seasSM:def	-0.008	0.028	219	-0.29	0.776
seasFL:def	0.007	0.029	219	0.25	0.801
seasWN:def	-0.005	0.029	219	-0.17	0.867
seasSM:def^2	5E-05	3E-04	219	0.21	0.831
seasFL:def^2	-1E-04	3E-04	219	-0.50	0.620
seasWN:def^2	1E-04	3E-04	219	0.38	0.706
seasSM:trtdays	0.417	0.149	1355	2.81	0.005
seasFL:trtdays	0.044	0.162	1355	0.27	0.786
seasWN:trtdays	0.098	0.157	1355	0.63	0.532
seasSM:trtdays^2	-0.035	0.010	1355	-3.71	2E-04
seasFL:trtdays^2	-0.017	0.011	1355	-1.61	0.109
seasWN:trtdays^2	-0.017	0.010	1355	-1.66	0.097

[a] DF = degrees of freedom.

Height—1986–1991

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	1,256	27277	<1E-04
Season	3	219	19	<1E-04
Defoliation	1	219	46	<1E-04
Defoliation^2	1	219	20	<1E-04
Trtdays	1	1,256	27870	<1E-04
Trtdays^2	1	1,256	1.05	0.306
Season:Defoliation	3	219	0.45	0.717
Season:Defoliation^2	3	219	0.23	0.878
Season:Trtdays	3	1,256	3.24	0.021
Season:Trtdays^2	3	1,256	4.69	0.003

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
5179	5306	-2565	0.331	0.958	1.443	0.597

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	10.125	0.393	1256	27	<1E-04
seasSM	0.035	0.543	219	0.06	0.948
seasFL	2.303	0.553	219	4.16	<1E-04
seasWN	3.227	0.552	219	5.85	<1E-04
def	-0.018	0.017	219	-1.06	0.291
def^2	3E-05	2E-04	219	0.18	0.855
trtdays	4.629	0.152	1256	30	<1E-04
trtdays^2	0.036	0.029	1256	1.24	0.217
seasSM:def	0.012	0.025	219	0.49	0.628
seasFL:def	0.019	0.025	219	0.74	0.458
seasWN:def	0.007	0.025	219	0.28	0.781
seasSM:def^2	-1E-04	2E-04	219	-0.45	0.656
seasFL:def^2	-2E-04	2E-04	219	-0.80	0.427
seasWN:def^2	-3E-06	2E-04	219	-0.01	0.989
seasSM:trtdays	0.960	0.228	1256	4.22	<1E-04
seasFL:trtdays	0.160	0.267	1256	0.60	0.551
seasWN:trtdays	0.147	0.245	1256	0.60	0.549
seasSM:trtdays^2	-0.159	0.045	1256	-3.55	4E-04
seasFL:trtdays^2	-0.037	0.054	1256	-0.70	0.487
seasWN:trtdays^2	-0.009	0.053	1256	-0.18	0.860

[a] DF = degrees of freedom.

Growth Flushes—1986–1990

Model summary—analysis of deviance table

Source	DF	Deviance	Residual DF	Residual Deviance
Null			707	349.53
Season	3	0.864	704	348.67
Defoliation	1	1.908	703	346.76
Defoliation^2	1	1.365	702	345.39
Trtdays	1	24.34	701	321.05
Trtdays^2	1	78.136	700	242.92
Season:Defoliation	3	2.073	697	240.85
Season:Defoliation^2	3	1.877	694	238.97
Season:Trtdays	3	43.42	691	195.55
Season:Trtdays^2	3	2.226	688	193.32

[a] DF = degrees of freedom.

Fixed-effects estimates

Coefficient	Value	Std. error	z-value	p-value
Intercept	1.380	0.139	9.97	<1E-04
seasSM	0.178	0.235	0.76	0.448
seasFL	0.207	0.274	0.76	0.451
seasWN	-0.317	0.182	-1.74	0.082
def	0.004	0.005	0.88	0.378
def^2	-6E-05	5E-05	-1.35	0.176
trtdays	-1.240	0.219	-5.66	<1E-04
trtdays^2	0.365	0.060	6.04	<1E-04
seasSM:def	-0.005	0.007	-0.76	0.446
seasFL:def	-0.001	0.007	-0.21	0.837
seasWN:def	-0.005	0.007	-0.78	0.434
seasSM:def^2	6E-05	7E-05	1.01	0.315
seasFL:def^2	3E-05	6E-05	0.41	0.682
seasWN:def^2	8E-05	7E-05	1.14	0.256
seasSM:trtdays	-0.002	0.334	-0.01	0.994
seasFL:trtdays	0.215	0.341	0.63	0.528
seasWN:trtdays	0.342	0.288	1.19	0.235
seasSM:trtdays^2	-0.042	0.086	-0.49	0.622
seasFL:trtdays^2	-0.120	0.082	-1.46	0.144
seasWN:trtdays^2	-0.053	0.085	-0.63	0.531

Palatka, Florida—slash pine

Diameter at breast height—all measurements

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	1,718	12226	<1E-04
Season	3	274	0.99	0.399
Defoliation	1	274	79	<1E-04
Defoliation^2	1	274	0.65	0.420
Trtdays	1	1,718	8707	<1E-04
Trtdays^2	1	1,718	1373	<1E-04
Season:Defoliation	3	274	3.13	0.026
Season:Defoliation^2	3	274	1.80	0.148
Season:Trtdays	3	1,718	9.42	<1E-04
Season:Trtdays^2	3	1,718	6.78	2E-04

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
402	536	-177	8e-07	8e-05	0.575	0.925

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	2.124	0.129	1718	16	<1E-04
seasSM	0.094	0.185	274	0.51	0.612
seasFL	0.500	0.187	274	2.68	0.008
seasWN	0.795	0.186	274	4.27	<1E-04
def	-0.006	0.006	274	-0.93	0.355
def^2	2E-05	6E-05	274	0.29	0.776
trtdays	0.594	0.016	1718	37	<1E-04
trtdays^2	-0.023	0.001	1718	-24	<1E-04
seasSM:def	0.015	0.009	274	1.74	0.084
seasFL:def	0.009	0.009	274	0.97	0.331
seasWN:def	-0.005	0.009	274	-0.59	0.554
seasSM:def^2	-2E-04	8E-05	274	-1.81	0.071
seasFL:def^2	-1E-04	8E-05	274	-1.53	0.127
seasWN:def^2	-2E-06	8E-05	274	-0.02	0.982
seasSM:trtdays	-0.073	0.023	1718	-3.10	0.002
seasFL:trtdays	-0.104	0.025	1718	-4.22	<1E-04
seasWN:trtdays	-0.126	0.024	1718	-5.33	<1E-04
seasSM:trtdays^2	0.004	0.001	1718	2.54	0.011
seasFL:trtdays^2	0.005	0.002	1718	3.48	5E-04
seasWN:trtdays^2	0.006	0.001	1718	4.05	1E-04

[a] DF = degrees of freedom.

Diameter at breast height—1986–1991

The model did not converge so no estimates or hypothesis tests are presented.

Height—all measurements

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	1,718	34,680	<1E-04
Season	3	274	11	<1E-04
Defoliation	1	274	116	<1E-04
Defoliation^2	1	274	0.29	0.594
Trtdays	1	1,718	25,262	<1E-04
Trtdays^2	1	1,718	700	<1E-04
Season:Defoliation	3	274	2.95	0.033
Season:Defoliation^2	3	274	0.50	0.685
Season:Trtdays	3	1,718	1.64	0.179
Season:Trtdays^2	3	1,718	10	<1E-04

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
8299	8434	4126	0.151	8E-04	2.625	0.768

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	10.726	0.511	1718	21	<1E-04
seasSM	2.339	0.730	274	3.20	0.002
seasFL	3.858	0.748	274	5.16	<1E-04
seasWN	4.339	0.741	274	5.86	<1E-04
def	0.005	0.023	274	0.22	0.829
def^2	-3E-04	2E-04	274	-1.18	0.238
trtdays	4.658	0.110	1718	42	<1E-04
trtdays^2	-0.131	0.007	1718	-19	<1E-04
seasSM:def	0.037	0.033	274	1.11	0.266
seasFL:def	0.009	0.034	274	0.28	0.783
seasWN:def	8E-04	0.034	274	0.02	0.981
seasSM:def^2	-3E-04	3E-04	274	-1.07	0.286
seasFL:def^2	-3E-04	3E-04	274	-0.91	0.362
seasWN:def^2	-1E-04	3E-04	274	-0.35	0.726
seasSM:trtdays	-0.860	0.159	1718	-5.40	<1E-04
seasFL:trtdays	-0.548	0.169	1718	-3.24	0.001
seasWN:trtdays	-0.679	0.163	1718	-4.15	<1E-04
seasSM:trtdays^2	0.051	0.010	1718	5.04	<1E-04
seasFL:trtdays^2	0.032	0.011	1718	2.92	0.004
seasWN:trtdays^2	0.045	0.011	1718	4.22	<1E-04

[a] DF = degrees of freedom.

Height—1986–1991

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	1,614	47,075	<1E-04
Season	3	274	17	<1E-04
Defoliation	1	274	114	<1E-04
Defoliation^2	1	274	31	<1E-04
Trtdays	1	1,614	20,155	<1E-04
Trtdays^2	1	1,614	16	1E-04
Season:Defoliation	3	274	3.80	0.011
Season:Defoliation^2	3	274	0.63	0.594
Season:Trtdays	3	1,614	18	<1E-04
Season:Trtdays^2	3	1,614	23	<1E-04

[a] DF = degrees of freedom, num=numerator, den=denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
5970	6104	-2961	0.174	0.001	1.739	0.817

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	10.320	0.359	1614	29	<1E-04
seasSM	2.912	0.510	274	5.71	<1E-04
seasFL	4.130	0.524	274	7.88	<1E-04
seasWN	4.491	0.516	274	8.70	<1E-04
def	0.013	0.016	274	0.83	0.411
def^2	-3E-04	2E-04	274	-1.71	0.089
trtdays	4.430	0.126	1614	35	<1E-04
trtdays^2	-0.081	0.023	1614	-3.52	4E-04
seasSM:def	0.028	0.023	274	1.18	0.239
seasFL:def	-0.003	0.024	274	-0.15	0.883
seasWN:def	-0.010	0.024	274	-0.42	0.672
seasSM:def^2	-3E-04	2E-04	274	-1.20	0.231
seasFL:def^2	-1E-04	2E-04	274	-0.58	0.562
seasWN:def^2	-4E-06	2E-04	274	-0.02	0.986
seasSM:trtdays	-1.916	0.188	1614	-10	<1E-04
seasFL:trtdays	-1.166	0.209	1614	-5.58	<1E-04
seasWN:trtdays	-0.931	0.193	1614	-4.82	<1E-04
seasSM:trtdays^2	0.284	0.035	1614	8.09	<1E-04
seasFL:trtdays^2	0.173	0.040	1614	4.32	<1E-04
seasWN:trtdays^2	0.116	0.039	1614	2.97	0.003

[a] DF = degrees of freedom.

Growth Flushes—1986–1990

Model summary–analysis of deviance table

			Residual	
Source	DF[a]	Deviance	DF	Deviance
Null			893	253.35
Season	3	0.283	890	253.07
Defoliation	1	13	889	240.16
Defoliation^2	1	1.17	888	238.99
Trtdays	1	36	887	202.78
Trtdays^2	1	1.08	886	201.70
Season:Defoliation	3	1.70	883	200.00
Season:Defoliation^2	3	2.33	880	197.68
Season:Trtdays	3	0.25	877	197.43
Season:Trtdays^2	3	7.54	874	189.89

[a] DF = degrees of freedom.

Fixed-effects estimates

Coefficient	Value	Std. error	z-value	p-value
Intercept	1.350	0.120	11.21	<1E-04
seasSM	0.017	0.195	0.09	0.932
seasFL	-0.400	0.230	-1.74	0.082
seasWN	-0.197	0.158	-1.25	0.213
def	0.003	0.004	0.77	0.442
def^2	-6E-05	4E-05	-1.56	0.120
trtdays	-0.414	0.165	-2.51	0.012
trtdays^2	0.087	0.045	1.92	0.056
seasSM:def	-0.006	0.006	-0.97	0.333
seasFL:def	-0.006	0.006	-0.97	0.331
seasWN:def	-6E-05	0.006	-0.01	0.991
seasSM:def^2	7E-05	6E-05	1.21	0.226
seasFL:def^2	7E-05	6E-05	1.22	0.221
seasWN:def^2	2E-05	6E-05	0.36	0.717
seasSM:trtdays	0.123	0.249	0.49	0.622
seasFL:trtdays	0.682	0.261	2.61	0.009
seasWN:trtdays	0.196	0.216	0.91	0.365
seasSM:trtdays^2	-0.043	0.064	-0.68	0.499
seasFL:trtdays^2	-0.164	0.063	-2.61	0.009
seasWN:trtdays^2	-0.052	0.063	-0.82	0.412

Waycross, Georgia—slash pine

Diameter at breast height—all measurements

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	1,721	15784	<1E-04
Season	3	274	1.84	0.141
Defoliation	1	274	74	<1E-04
Defoliation^2	1	274	2.33	0.128
Trtdays	1	1,721	14723	<1E-04
Trtdays^2	1	1,721	863	<1E-04
Season:Defoliation	3	274	0.99	0.398
Season:Defoliation^2	3	274	1.16	0.325
Season:Trtdays	3	1,721	25	<1E-04
Season:Trtdays^2	3	1,721	4.37	0.005

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
447	581	-199	2E-04	2E-05	0.534	0.908

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	2.017	0.121	1721	16	<1E-04
seasSM	0.442	0.171	274	2.58	0.010
seasFL	0.490	0.171	274	2.87	0.005
seasWN	0.643	0.175	274	3.67	3E-04
def	-1E-04	0.006	274	-0.02	0.982
def^2	-4E-05	5E-05	274	-0.67	0.505
trtdays	0.610	0.016	1721	37	<1E-04
trtdays^2	-0.019	0.001	1721	-19	<1E-04
seasSM:def	-0.012	0.008	274	-1.47	0.143
seasFL:def	-0.002	0.008	274	-0.25	0.806
seasWN:def	-5E-04	0.008	274	-0.06	0.953
seasSM:def^2	1E-04	8E-05	274	1.35	0.178
seasFL:def^2	-1E-05	8E-05	274	-0.16	0.872
seasWN:def^2	-2E-05	8E-05	274	-0.27	0.785
seasSM:trtdays	-0.074	0.024	1721	-3.09	0.002
seasFL:trtdays	-0.098	0.025	1721	-3.98	1E-04
seasWN:trtdays	-0.097	0.024	1721	-4.01	1E-04
seasSM:trtdays^2	0.004	0.001	1721	2.84	0.005
seasFL:trtdays^2	0.003	0.002	1721	1.76	0.079
seasWN:trtdays^2	0.005	0.002	1721	3.28	0.001

[a] DF = degrees of freedom.

Diameter at breast height—1986–1991

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	1,630	18,879	<1E-04
Season	3	274	3.19	0.024
Defoliation	1	274	64	<1E-04
Defoliation^2	1	274	0.64	0.423
Trtdays	1	1,630	9,444	<1E-04
Trtdays^2	1	1,630	1.64	0.201
Season:Defoliation	3	274	1.48	0.220
Season:Defoliation^2	3	274	0.75	0.525
Season:Trtdays	3	1,630	11	<1E-04
Season:Trtdays^2	3	1,630	9.17	<1E-04

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
-542	-408	295	9E-12	6E-05	0.438	0.920

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	1.974	0.101	1630	19	<1E-04
seasSM	0.440	0.143	274	3.08	0.002
seasFL	0.535	0.142	274	3.75	2E-04
seasWN	0.673	0.146	274	4.61	<1E-04
def	-1E-04	0.005	274	-0.02	0.983
def^2	-3E-05	4E-05	274	-0.61	0.543
trtdays	0.613	0.022	1630	28	<1E-04
trtdays^2	-0.020	0.004	1630	-5.09	<1E-04
seasSM:def	-0.008	0.007	274	-1.23	0.218
seasFL:def	-0.003	0.007	274	-0.37	0.708
seasWN:def	-5E-04	0.007	274	-0.07	0.943
seasSM:def^2	6E-05	6E-05	274	1.02	0.301
seasFL:def^2	-5E-06	6E-05	274	-0.08	0.933
seasWN:def^2	-3E-05	6E-05	274	-0.40	0.692
seasSM:trtdays	-0.162	0.033	1630	-4.96	<1E-04
seasFL:trtdays	-0.222	0.035	1630	-6.32	<1E-04
seasWN:trtdays	-0.157	0.033	1630	-4.73	<1E-04
seasSM:trtdays^2	0.023	0.006	1630	3.95	1E-04
seasFL:trtdays^2	0.030	0.007	1630	4.60	<1E-04
seasWN:trtdays^2	0.020	0.007	1630	3.05	0.002

[a] DF = degrees of freedom.

Height—all measurements

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	1,721	34,596	<1E-04
Season	3	274	11	<1E-04
Defoliation	1	274	119	<1E-04
Defoliation^2	1	274	11	0.001
Trtdays	1	1,721	40,219	<1E-04
Trtdays^2	1	1,721	13	3E-04
Season:Defoliation	3	274	2.85	0.038
Season:Defoliation^2	3	274	1.92	0.127
Season:Trtdays	3	1,721	5.83	6E-04
Season:Trtdays^2	3	1,721	11	<1E-04

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
7888	8023	-3920	0.153	5E-04	2.443	0.788

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	10.990	0.499	1721	22	<1E-04
seasSM	2.399	0.701	274	3.42	7E-04
seasFL	2.219	0.709	274	3.13	0.002
seasWN	3.548	0.722	274	4.92	<1E-04
def	-0.021	0.022	274	-0.95	0.342
def^2	3E-05	2E-04	274	0.13	0.898
trtdays	3.719	0.101	1721	37	<1E-04
trtdays^2	-0.039	0.006	1721	-6.01	<1E-04
seasSM:def	-0.015	0.032	274	-0.46	0.646
seasFL:def	0.034	0.032	274	1.07	0.284
seasWN:def	0.017	0.032	274	0.53	0.600
seasSM:def^2	2E-04	3E-04	274	0.51	0.607
seasFL:def^2	-5E-04	3E-04	274	-1.61	0.108
seasWN:def^2	-3E-04	3E-04	274	-1.05	0.295
seasSM:trtdays	-0.637	0.146	1721	-4.37	<1E-04
seasFL:trtdays	-0.467	0.152	1721	-3.07	0.002
seasWN:trtdays	-0.256	0.149	1721	-1.72	0.086
seasSM:trtdays^2	0.052	0.009	1721	5.62	<1E-04
seasFL:trtdays^2	0.031	0.010	1721	3.16	0.002
seasWN:trtdays^2	0.024	0.010	1721	2.45	0.015

[a] DF = degrees of freedom.

Height—1986–1991

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	1,630	32018	<1E-04
Season	3	274	10	<1E-04
Defoliation	1	274	99	<1E-04
Defoliation^2	1	274	5.02	0.026
Trtdays	1	1,630	16155	<1E-04
Trtdays^2	1	1,630	95	<1E-04
Season:Defoliation	3	274	3.57	0.015
$\text{Season:Defoliation}^2$	3	274	0.92	0.430
Season:Trtdays	3	1,630	9.65	<1E-04
Season:Trtdays^2	3	1,630	9.31	<1E-04

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
6026	6159	-2989	0.214	3E-04	1.859	0.845

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	10.780	0.405	1630	26	<1E-04
seasSM	2.691	0.566	274	4.75	<1E-04
seasFL	2.567	0.571	274	4.50	<1E-04
seasWN	3.667	0.581	274	6.31	<1E-04
def	-0.007	0.018	274	-0.40	0.687
def^2	-7E-05	2E-04	274	-0.39	0.694
trtdays	3.200	0.125	1630	25	<1E-04
trtdays^2	0.073	0.023	1630	3.22	0.001
seasSM:def	-0.005	0.026	274	-0.21	0.836
seasFL:def	0.016	0.026	274	0.626	0.532
seasWN:def	0.007	0.026	274	0.251	0.802
seasSM:def^2	2E-05	2E-04	274	0.099	0.921
seasFL:def^2	-3E-04	2E-04	274	-1.280	0.202
seasWN:def^2	-2E-04	2E-04	274	-0.939	0.348
seasSM:trtdays	-1.177	0.187	1630	-6.287	<1E-04
seasFL:trtdays	-0.584	0.203	1630	-2.869	0.004
seasWN:trtdays	-0.125	0.192	1630	-0.651	0.515
seasSM:trtdays^2	0.173	0.035	1630	4.976	<1E-04
seasFL:trtdays^2	0.061	0.039	1630	1.576	0.115
seasWN:trtdays^2	0.010	0.039	1630	0.271	0.787

[a] DF = degrees of freedom.

Aiken, South Carolina—longleaf pine

Diameter at breast height—all measurements

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	721	7263	<1E-04
Month	4	201	1.81	0.128
Defoliation	1	201	53	<1E-04
Trtdays	1	721	7036	<1E-04
Trtdays^2	1	721	326	<1E-04
Month:Defoliation	4	201	1.02	0.401
Month:Trtdays	4	721	0.87	0.480
Month:Trtdays^2	4	721	0.33	0.858

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
597	714	-275	0.076	4E-05	0.427	0.789

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	1.775	0.071	597	25	<1E-04
monthSEP	0.201	0.098	201	2.06	0.041
monthOCT	0.207	0.098	201	2.10	0.037
monthNOV	-0.014	0.098	201	-0.14	0.889
monthDEC	0.105	0.098	201	1.08	0.282
def	-0.001	8E-04	201	-1.50	0.134
trtdays	0.165	0.020	597	8.12	<1E-04
trtdays^2	0.007	0.003	597	2.35	0.019
monthSEP:def	-0.002	0.001	201	-1.33	0.184
monthOCT:def	-0.002	0.001	201	-1.64	0.102
monthNOV:def	6E-04	0.001	201	0.53	0.594
monthDEC:def	-9E-04	0.001	201	-0.73	0.468
monthSEP:trtdays	-0.010	0.029	597	-0.33	0.741
monthOCT:trtdays	0.042	0.032	597	1.30	0.194
monthNOV:trtdays	0.037	0.033	597	1.15	0.252
monthDEC:trtdays	0.040	0.031	597	1.28	0.201
monthSEP:trtdays^2	0.003	0.004	597	0.67	0.502
monthOCT:trtdays^2	-0.004	0.005	597	-0.81	0.418
monthNOV:trtdays^2	-0.005	0.005	597	-1.03	0.305
monthDEC:trtdays^2	-0.003	0.004	597	-0.72	0.473

[a] DF = degrees of freedom.

Diameter at breast height—1993–1999

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	597	8959	<1E-04
Month	4	201	2.88	0.024
Defoliation	1	201	57	<1E-04
Trtdays	1	597	5429	<1E-04
Trtdays^2	1	597	13	3E-04
Month:Defoliation	4	201	1.71	0.150
Month:Trtdays	4	597	1.40	0.233
Month:Trtdays^2	4	597	0.93	0.446

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
-131	-18	-90	0.065	3e-05	0.292	0.813

Fixed effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	1.775	0.071	597	25	<1E-04
monthSEP	0.201	0.098	201	2.06	0.041
monthOCT	0.207	0.098	201	2.10	0.037
monthNOV	-0.014	0.098	201	-0.14	0.889
monthDEC	0.105	0.098	201	1.08	0.282
def	-0.001	8E-04	201	-1.50	0.134
trtdays	0.165	0.020	597	8.11	<1E-04
trtdays^2	0.007	0.003	597	2.35	0.019
monthSEP:def	-0.002	0.001	201	-1.33	0.184
monthOCT:def	-0.002	0.001	201	-1.64	0.102
monthNOV:def	0.001	0.001	201	0.53	0.594
monthDEC:def	-0.001	0.001	201	-0.73	0.468
monthSEP:trtdays	-0.010	0.029	597	-0.33	0.741
monthOCT:trtdays	0.042	0.032	597	1.30	0.194
monthNOV:trtdays	0.037	0.033	597	1.15	0.252
monthDEC:trtdays	0.040	0.031	597	1.28	0.201
monthSEP:trtdays^2	0.003	0.004	597	0.67	0.502
monthOCT:trtdays^2	-0.004	0.005	597	-0.81	0.418
monthNOV:trtdays^2	-0.005	0.005	597	-1.03	0.305
monthDEC:trtdays^2	-0.003	0.004	597	-0.72	0.473

[a] DF = degrees of freedom.

Height–all measurements

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	721	10796	<1E-04
Month	4	201	3.29	0.012
Defoliation	1	201	42	<1E-04
Trtdays	1	721	13179	<1E-04
Trtdays^2	1	721	500	<1E-04
Month:Defoliation	4	201	0.82	0.517
Month:Trtdays	4	721	0.45	0.776
Month:Trtdays^2	4	721	0.72	0.577

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
4415	4531	-2184	0.508	3E-04	2.528	0.515

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	9.652	0.519	721	18	<1E-04
monthSEP	0.249	0.714	201	0.35	0.728
monthOCT	0.275	0.716	201	0.38	0.702
monthNOV	-0.281	0.715	201	-0.39	0.695
monthDEC	0.368	0.708	201	0.52	0.604
def	-0.012	0.006	201	-2.17	0.031
trtdays	2.514	0.110	721	23	<1E-04
trtdays^2	-0.050	0.005	721	-9.55	<1E-04
monthSEP:def	-8E-04	0.008	201	-0.11	0.916
monthOCT:def	0.003	0.008	201	0.42	0.676
monthNOV:def	0.010	0.008	201	1.29	0.197
monthDEC:def	-0.002	0.008	201	-0.20	0.840
monthSEP:trtdays	0.170	0.156	721	1.08	0.279
monthOCT:trtdays	0.184	0.166	721	1.11	0.268
monthNOV:trtdays	0.045	0.165	721	0.27	0.785
monthDEC:trtdays	0.257	0.159	721	1.61	0.107
monthSEP:trtdays^2	-0.007	0.007	721	-0.92	0.360
monthOCT:trtdays^2	-0.008	0.008	721	-1.07	0.284
monthNOV:trtdays^2	-0.003	0.008	721	-0.43	0.665
monthDEC:trtdays^2	-0.012	0.008	721	-1.58	0.115

[a] DF = degrees of freedom.

Height—1993–1999

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	597	18465	<1E-04
Month	4	201	7.13	<1E-04
Defoliation	1	201	62	<1E-04
Trtdays	1	597	18831	<1E-04
Trtdays^2	1	597	934	<1E-04
Month:Defoliation	4	201	1.16	0.328
Month:Trtdays	4	597	5.88	1E-04
Month:Trtdays^2	4	597	1.41	0.2287

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
2718	2831	-1335	0.247	2E-04	1.601	0.778

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	10.635	0.378	597	28	<1E-04
monthSEP	0.531	0.527	201	1.01	0.314
monthOCT	0.029	0.531	201	0.05	0.957
monthNOV	-0.439	0.531	201	-0.83	0.409
monthDEC	0.441	0.527	201	0.84	0.404
def	-0.009	0.004	201	-1.95	0.053
trtdays	0.492	0.121	597	4.08	1E-04
trtdays^2	0.267	0.017	597	16	<1E-04
monthSEP:def	-0.004	0.006	201	-0.58	0.565
monthOCT:def	0.002	0.006	201	0.28	0.781
monthNOV:def	0.008	0.006	201	1.26	0.208
monthDEC:def	-0.004	0.006	201	-0.57	0.567
monthSEP:trtdays	-0.030	0.174	597	-0.17	0.864
monthOCT:trtdays	0.415	0.190	597	2.18	0.029
monthNOV:trtdays	0.201	0.193	597	1.04	0.297
monthDEC:trtdays	0.226	0.186	597	1.22	0.225
monthSEP:trtdays^2	0.027	0.024	597	1.09	0.278
monthOCT:trtdays^2	-0.036	0.027	597	-1.32	0.186
monthNOV:trtdays^2	-0.016	0.028	597	-0.58	0.563
monthDEC:trtdays^2	0.003	0.027	597	0.12	0.905

[a] DF = degrees of freedom.

Waycross, Georgia—longleaf pine

Diameter at breast height—all measurements

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	664	7333	<1E-04
Month	4	201	1.88	0.116
Defoliation	1	201	83	<1E-04
Trtdays	1	664	7394	<1E-04
Trtdays^2	1	664	527	<1E-04
Month:Defoliation	4	201	0.77	0.548
Month:Trtdays	4	664	1.99	0.095
Month:Trtdays^2	4	664	1.60	0.172

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
960	1075	-456	0.077	5e-05	0.495	0.742

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	1.983	0.117	664	17	<1E-04
monthSEP	-0.101	0.155	201	-0.65	0.514
monthOCT	0.075	0.157	201	0.48	0.634
monthNOV	-0.138	0.158	201	-0.88	0.382
monthDEC	0.093	0.178	201	0.52	0.602
def	-0.004	0.001	201	-3.31	0.001
trtdays	0.403	0.018	664	23	<1E-04
trtdays^2	-0.009	9E-04	664	-10	<1E-04
monthSEP:def	0.001	0.002	201	0.68	0.496
monthOCT:def	-8E-04	0.002	201	-0.42	0.676
monthNOV:def	0.002	0.002	201	1.13	0.261
monthDEC:def	-1E-04	0.002	201	-0.05	0.959
monthSEP:trtdays	0.024	0.025	664	0.96	0.337
monthOCT:trtdays	0.040	0.026	664	1.54	0.124
monthNOV:trtdays	0.010	0.025	664	0.40	0.691
monthDEC:trtdays	-3E-04	0.026	664	-0.01	0.991
monthSEP:trtdays^2	-0.001	0.001	664	-0.83	0.406
monthOCT:trtdays^2	-0.002	0.001	664	-1.80	0.072
monthNOV:trtdays^2	5E-04	0.001	664	0.39	0.699
monthDEC:trtdays^2	4E-04	0.001	664	0.28	0.781

[a] DF = degrees of freedom.

Diameter at breast height—1993–1999

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	604	6529	<1E-04
Month	4	201	0.26	0.902
Defoliation	1	201	61	<1E-04
Trtdays	1	604	6691	<1E-04
Trtdays^2	1	604	28	<1E-04
Month:Defoliation	4	201	1.52	0.199
Month:Trtdays	4	604	1.14	0.336
Month:Trtdays^2	4	604	0.72	0.582

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
468	581	-210	0.089	1e-05	0.397	0.773

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	2.032	0.098	604	21	<1E-04
monthSEP	-0.168	0.129	201	-1.30	0.194
monthOCT	0.052	0.131	201	0.40	0.689
monthNOV	-0.150	0.132	201	-1.13	0.258
monthDEC	0.086	0.148	201	0.58	0.563
def	-0.004	0.001	201	-3.50	6E-04
trtdays	0.233	0.031	604	7.56	<1E-04
trtdays^2	0.018	0.004	604	4.08	1E-04
monthSEP:def	0.002	0.002	201	1.38	0.171
monthOCT:def	-7E-04	0.002	201	-0.45	0.650
monthNOV:def	0.002	0.002	201	1.18	0.238
monthDEC:def	-5E-04	0.002	201	-0.30	0.762
monthSEP:trtdays	0.068	0.045	604	1.52	0.129
monthOCT:trtdays	0.074	0.046	604	1.60	0.110
monthNOV:trtdays	0.074	0.046	604	1.60	0.109
monthDEC:trtdays	0.066	0.048	604	1.38	0.168
monthSEP:trtdays^2	-0.008	0.006	604	-1.22	0.223
monthOCT:trtdays^2	-0.007	0.007	604	-1.05	0.292
monthNOV:trtdays^2	-0.009	0.007	604	-1.38	0.169
monthDEC:trtdays^2	-0.009	0.007	604	-1.36	0.175

[a] DF = degrees of freedom.

Height—all measurements

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	664	23938	<1E-04
Month	4	201	5.17	6E-04
Defoliation	1	201	129	<1E-04
Trtdays	1	664	11467	<1E-04
Trtdays^2	1	664	946	<1E-04
Month:Defoliation	4	201	0.08	0.989
Month:Trtdays	4	664	1.59	0.176
Month:Trtdays^2	4	664	0.67	0.613

[a] DF = degrees of freedom, num = numerator, den = denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
4052	4167	-2002	1E-05	4E-04	2.389	0.514

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	9.950	0.496	664	20	<1E-04
monthSEP	-0.043	0.669	201	-0.06	0.949
monthOCT	0.479	0.679	201	0.71	0.482
monthNOV	0.259	0.681	201	0.38	0.705
monthDEC	0.678	0.760	201	0.89	0.374
def	-0.017	0.006	201	-3.06	0.003
trtdays	3.032	0.109	664	28	<1E-04
trtdays^2	-0.071	0.005	664	-13	<1E-04
monthSEP:def	-0.003	0.008	201	-0.37	0.712
monthOCT:def	-0.003	0.008	201	-0.44	0.662
monthNOV:def	-0.003	0.008	201	-0.33	0.743
monthDEC:def	-0.003	0.008	201	-0.39	0.694
monthSEP:trtdays	0.273	0.154	664	1.77	0.077
monthOCT:trtdays	0.104	0.159	664	0.65	0.515
monthNOV:trtdays	0.290	0.155	664	1.88	0.061
monthDEC:trtdays	0.249	0.157	664	1.59	0.113
monthSEP:trtdays^2	-0.011	0.008	664	-1.41	0.159
monthOCT:trtdays^2	-0.004	0.008	664	-0.51	0.611
monthNOV:trtdays^2	-0.010	0.008	664	-1.31	0.190
monthDEC:trtdays^2	-0.007	0.008	664	-0.91	0.362

[a] DF = degrees of freedom.

Height—1993–1999

Model summary

Source	DF[a] num	DF[a] den	F-value	p-value
Intercept	1	604	23454	<1E-04
Month	4	201	1.43	0.227
Defoliation	1	201	70	<1E-04
Trtdays	1	604	18898	<1E-04
$Trtdays^2$	1	604	649	<1E-04
Month:Defoliation	4	201	0.16	0.960
Month:Trtdays	4	604	5.39	3E-04
$Month:Trtdays^2$	4	604	0.82	0.513

[a] DF = degrees of freedom, num = numerator, den =denominator.

Likelihood ratio tests and other measures

AIC	BIC	LRML	σ_B	σ_r	$\hat{\sigma}$	ϕ
2982	3095	-1467	2E-05	2E-04	1.843	0.770

Fixed-effects estimates

Coefficient	Value	Std. error	DF[a]	t-value	p-value
Intercept	11.123	0.442	604	25	<1E-04
monthSEP	-0.351	0.594	201	-0.59	0.555
monthOCT	0.187	0.602	201	0.31	0.757
monthNOV	-0.054	0.608	201	-0.09	0.929
monthDEC	0.432	0.681	201	0.63	0.527
def	-0.015	0.005	201	-2.95	0.004
trtdays	0.810	0.144	604	5.62	<1E-04
$trtdays^2$	0.282	0.020	604	14	<1E-04
monthSEP:def	0.002	0.007	201	0.34	0.734
monthOCT:def	-0.002	0.007	201	-0.34	0.734
monthNOV:def	-2E-04	0.007	201	-0.03	0.979
monthDEC:def	-0.003	0.008	201	-0.32	0.746
monthSEP:trtdays	0.326	0.210	604	1.55	0.121
monthOCT:trtdays	0.373	0.216	604	1.73	0.085
monthNOV:trtdays	0.585	0.215	604	2.73	0.007
monthDEC:trtdays	0.394	0.222	604	1.77	0.077
$monthSEP:trtdays^2$	-0.020	0.030	604	-0.67	0.506
$monthOCT:trtdays^2$	-0.038	0.031	604	-1.22	0.222
$monthNOV:trtdays^2$	-0.052	0.031	604	-1.69	0.092
$monthDEC:trtdays^2$	-0.019	0.032	604	-0.60	0.550

[a] DF = degrees of freedom.

Appendix 4: Fitted Growth Response Curves

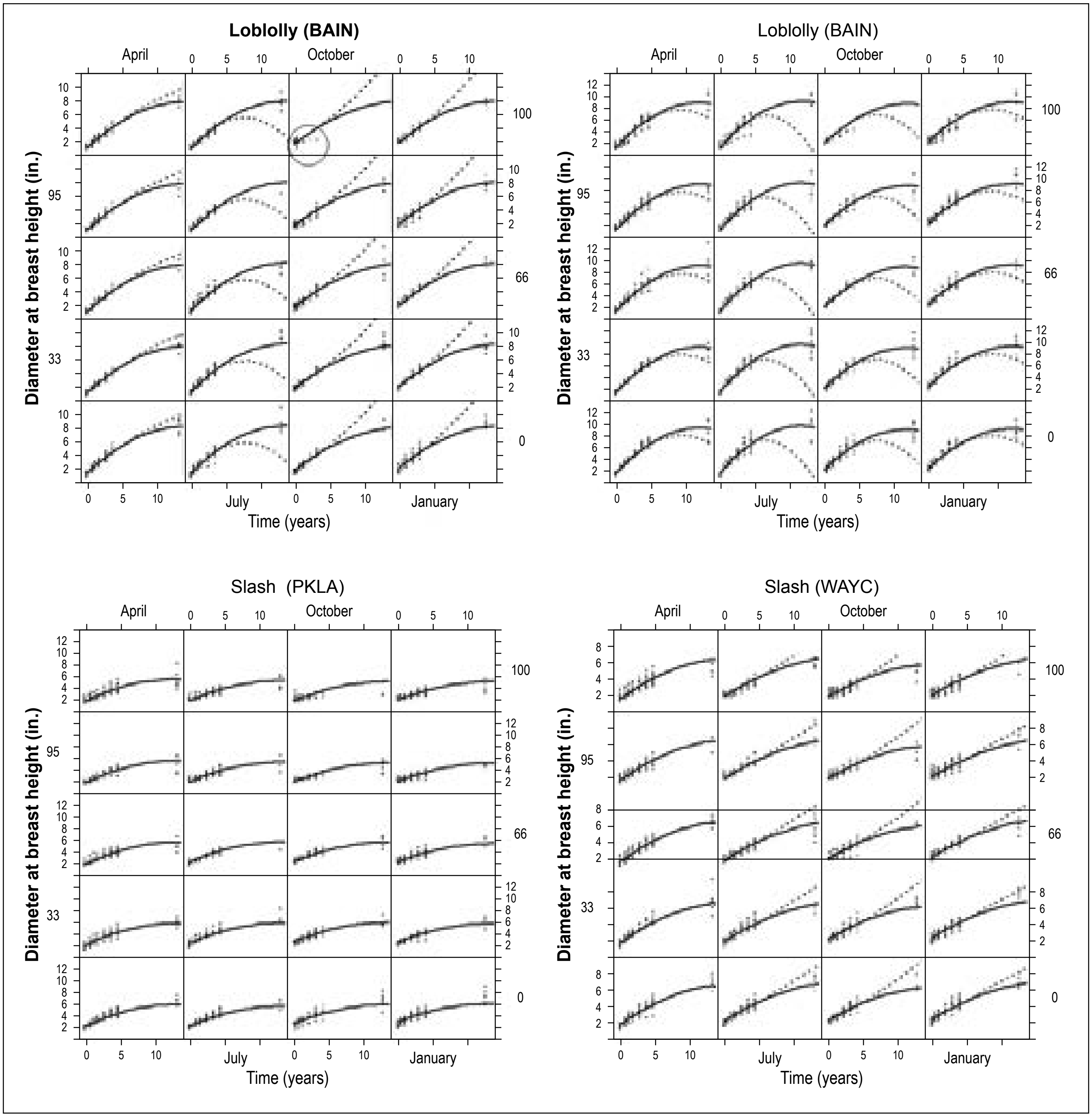

Figure 5—Observed diameter at breast height (d.b.h.) growth response and fitted growth curve of young southern pine subjected to various levels of defoliation. The solid line is growth response curve fit to 13 (loblolly, slash) or 19 (longleaf) years of data. The dotted line is fitted growth curve for 5 (loblolly, slash) or 6 (longleaf) years of data, points are observed data. Circled data points did not fall on the fitted curve. Sites: Bainbridge, Georgia (BAIN), Branchville, South Carolina (BRAN), Palatka, Florida (PLKA), Waycross, Georgia (WAYC), Savannah River Forest Station (SRFS), Waycross, Georgia (LWYC).

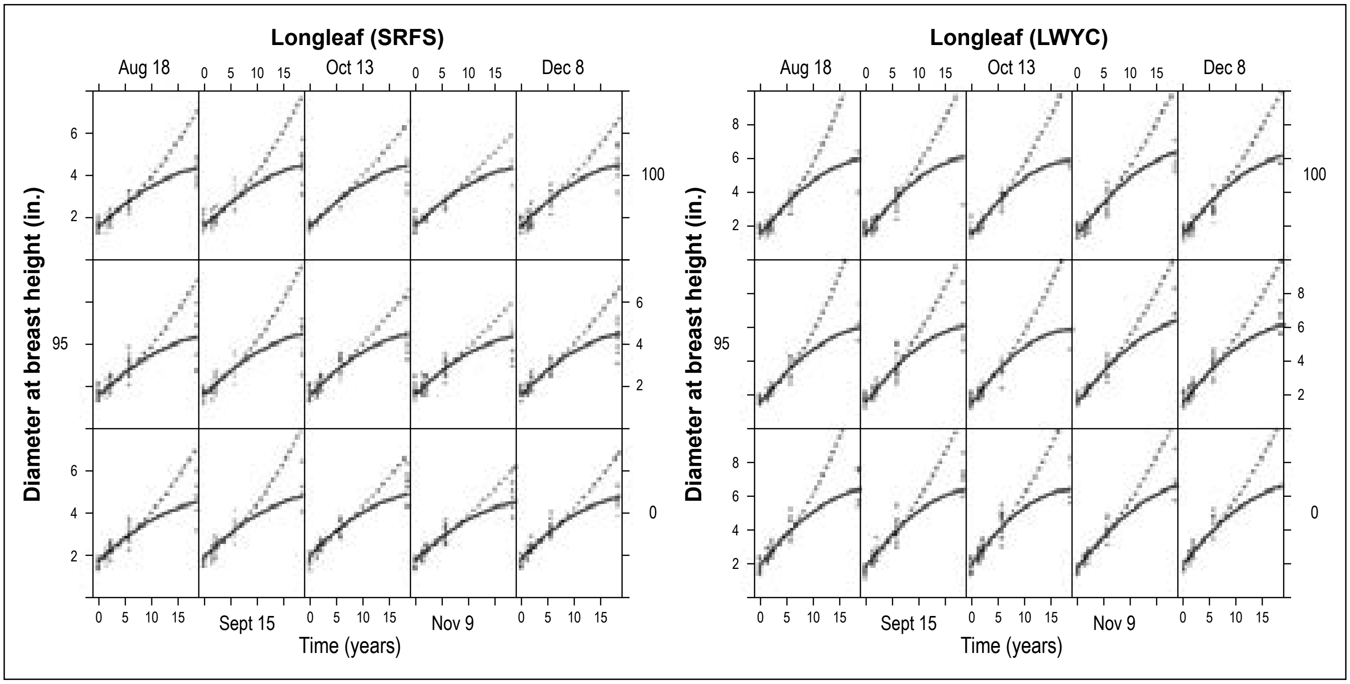

Figure 5—Continued.

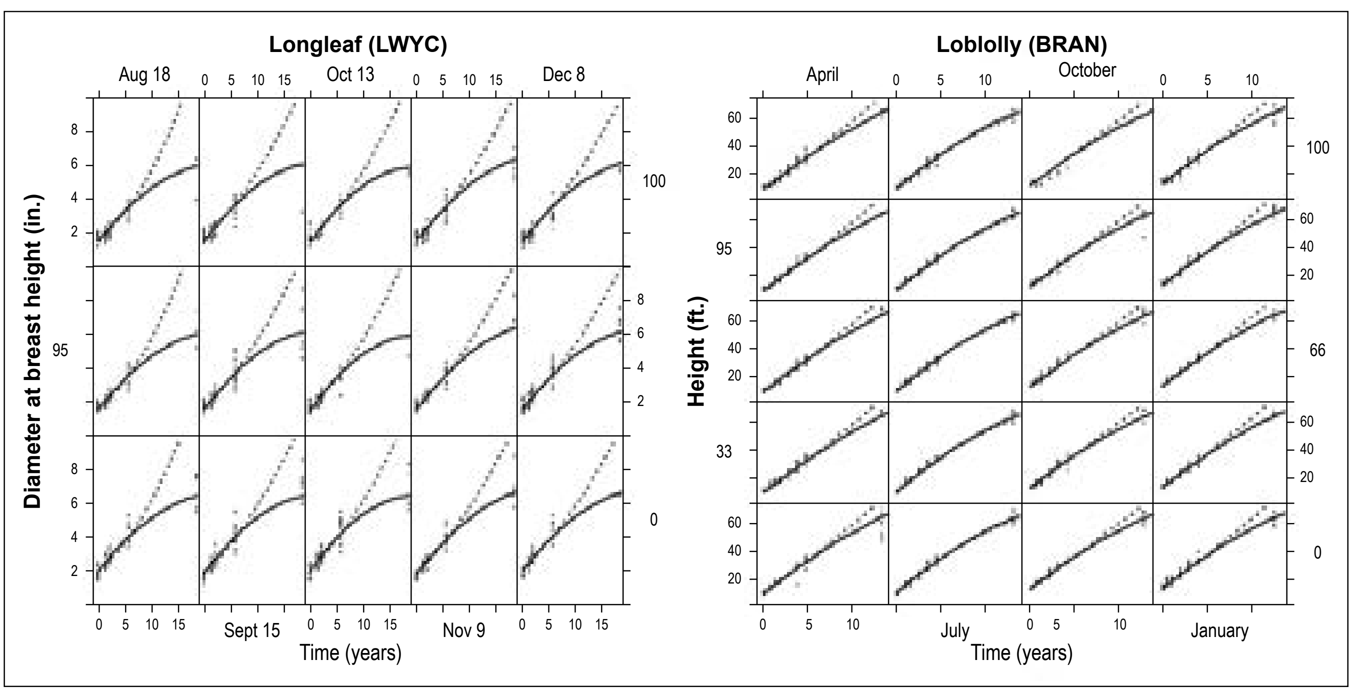

Figure 6—Observed height growth response and fitted growth curve of young southern pine subjected to various levels of defoliation. The solid line is growth response curve fit to 13 (loblolly, slash) or 19 (longleaf) years of data, dotted line is fitted growth curve for 5 (loblolly, slash) or 6 (longleaf) years of data, points are observed data. Sites: Bainbridge, Georgia (BAIN), Branchville, South Carolina (BRAN), Palatka, Florida (PLKA), Waycross, Georgia (WAYC), Savannah River Forest Station (SRFS), Waycross, Georgia (LWYC).

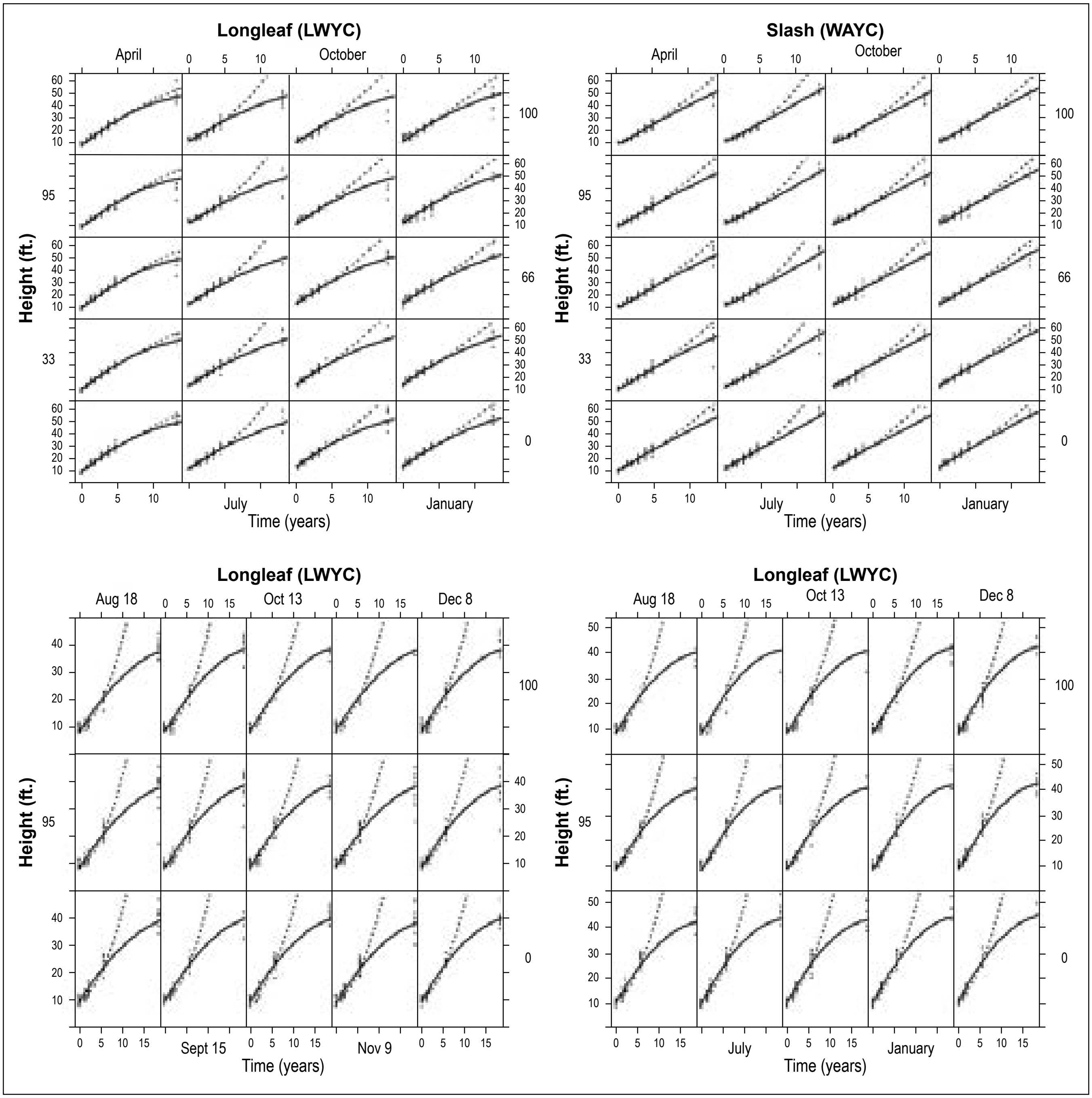

Figure 6—Continued

Appendix 5: Size of Treated Trees Relative to Untreated Trees

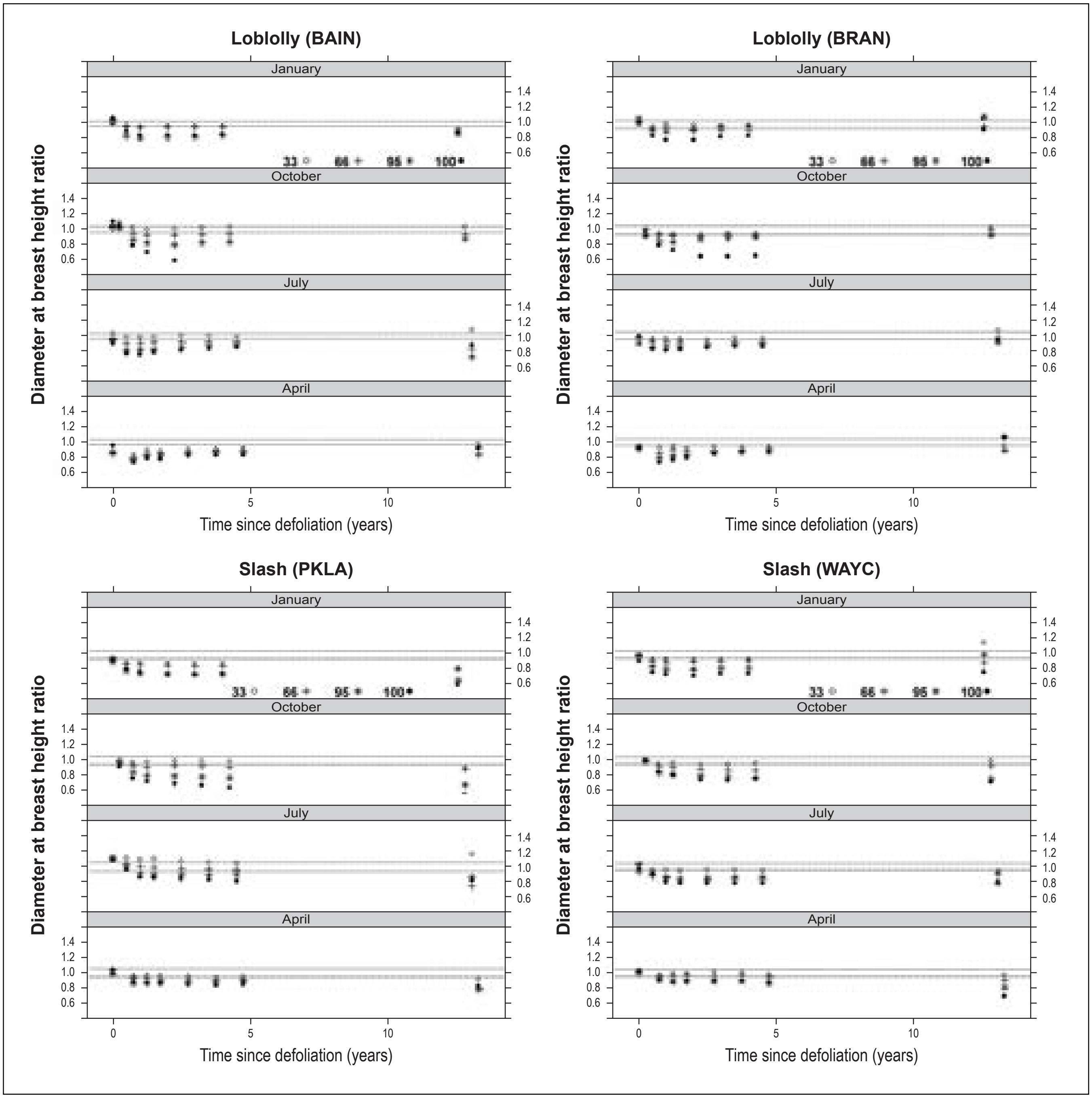

Figure 7—Ratio of observed diameter at breast height (d.b.h.) of young defoliated southern pine to control trees. Dashed line indicates the ±2.5 percent confidence interval around 1 used to determine if treated trees differed in size from control trees. Sites: Bainbridge, Georgia (BAIN), Branchville, South Carolina (BRAN), Palatka, Florida (PLKA), Waycross, Georgia (WAYC), Savannah River Forest Station (SRFS), Waycross, Georgia (LWYC).

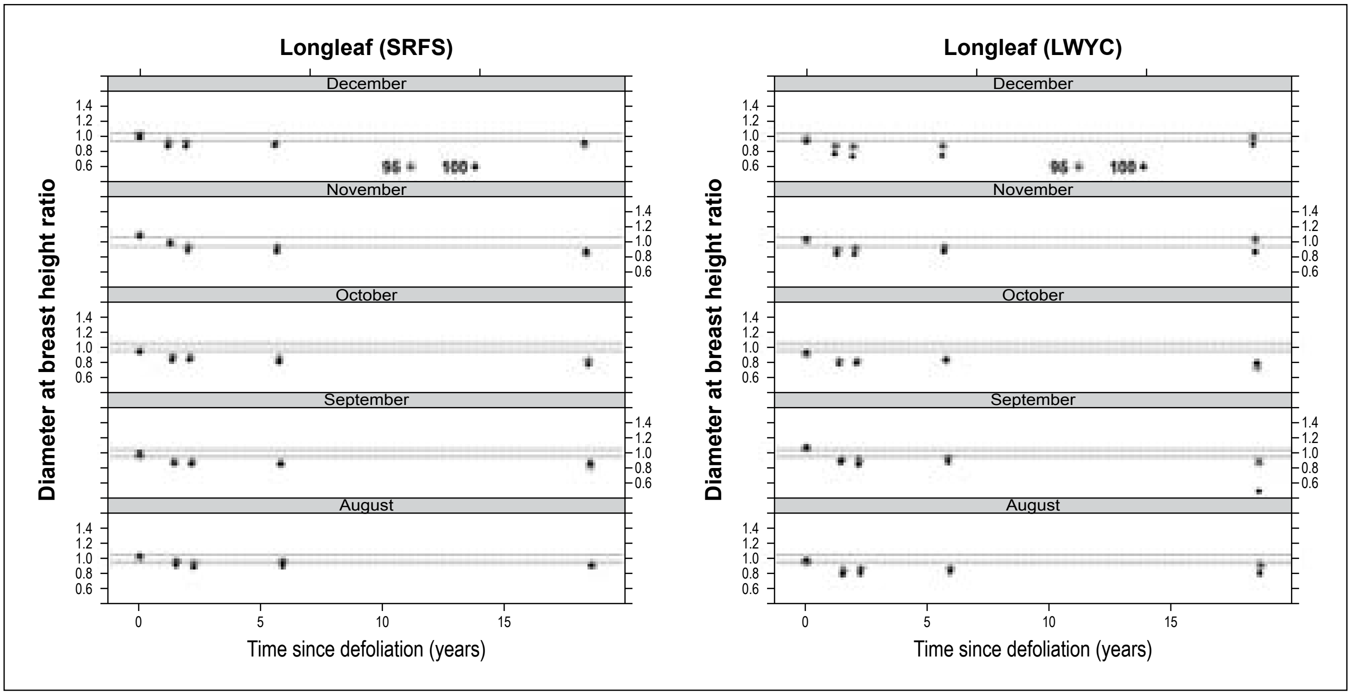

Figure 7—Continued

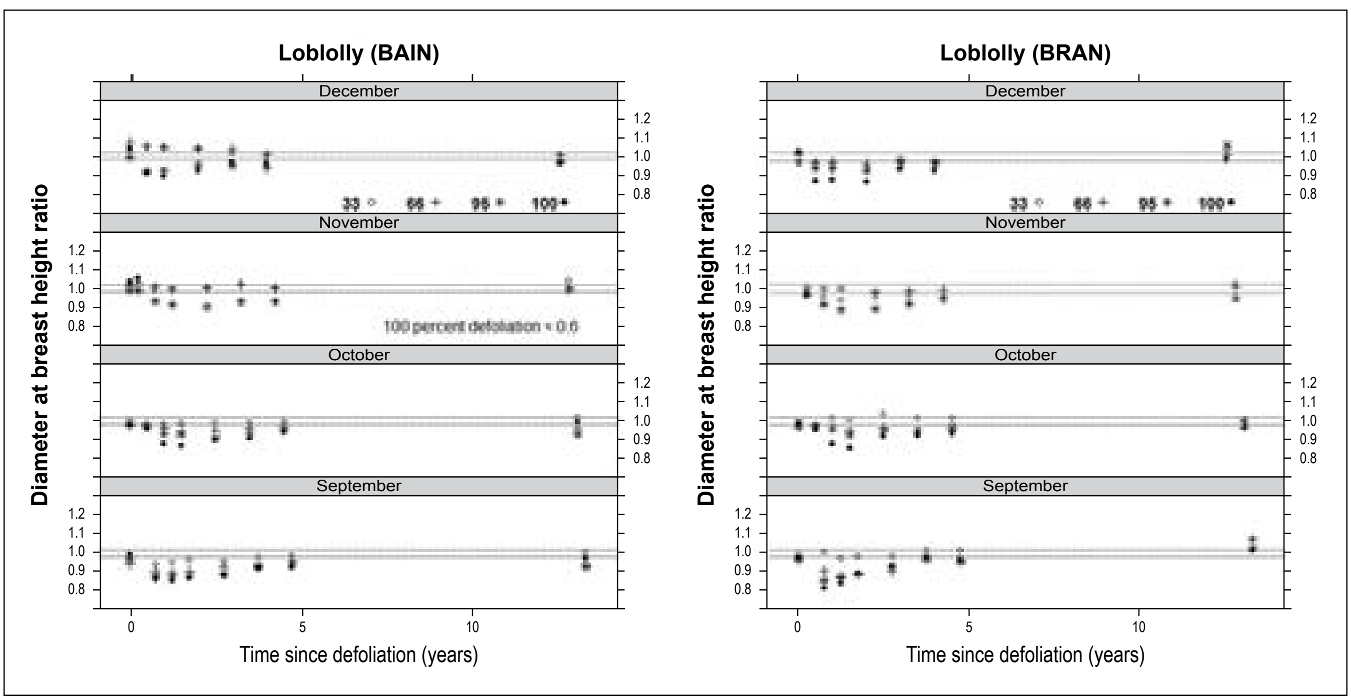

Figure 8—Ratio of observed height of young defoliated southern pine to control trees. The dashed line indicates the ±2.5 percent confidence interval around 1 used to determine if treated trees differed in size from control trees. Sites: Bainbridge, Georgia (BAIN), Branchville, South Carolina (BRAN), Palatka, Florida (PLKA), Waycross, Georgia (WAYC), Savannah River Forest Station (SRFS), Waycross, Georgia (LWYC).

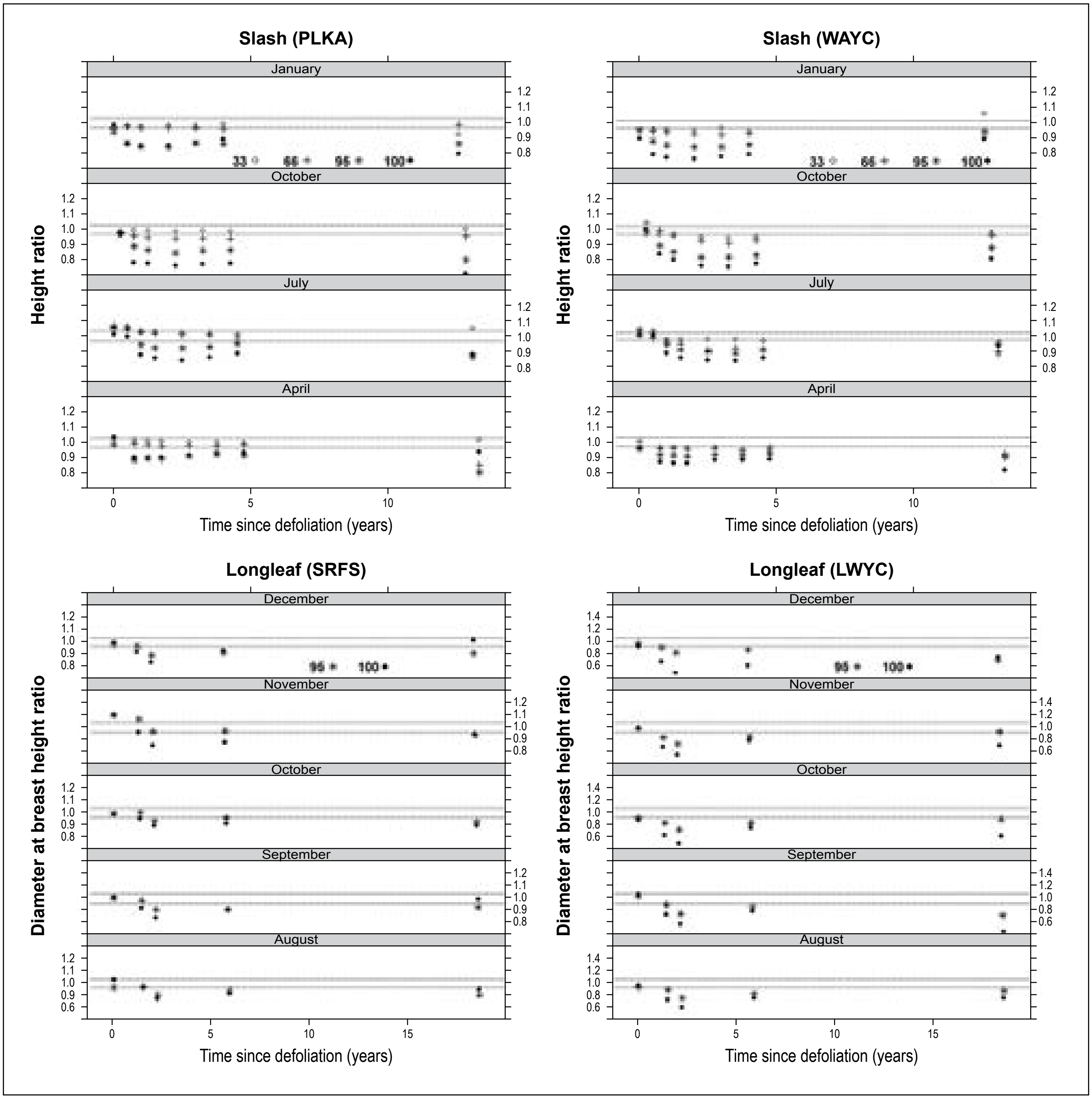

Figure 8—Continued.

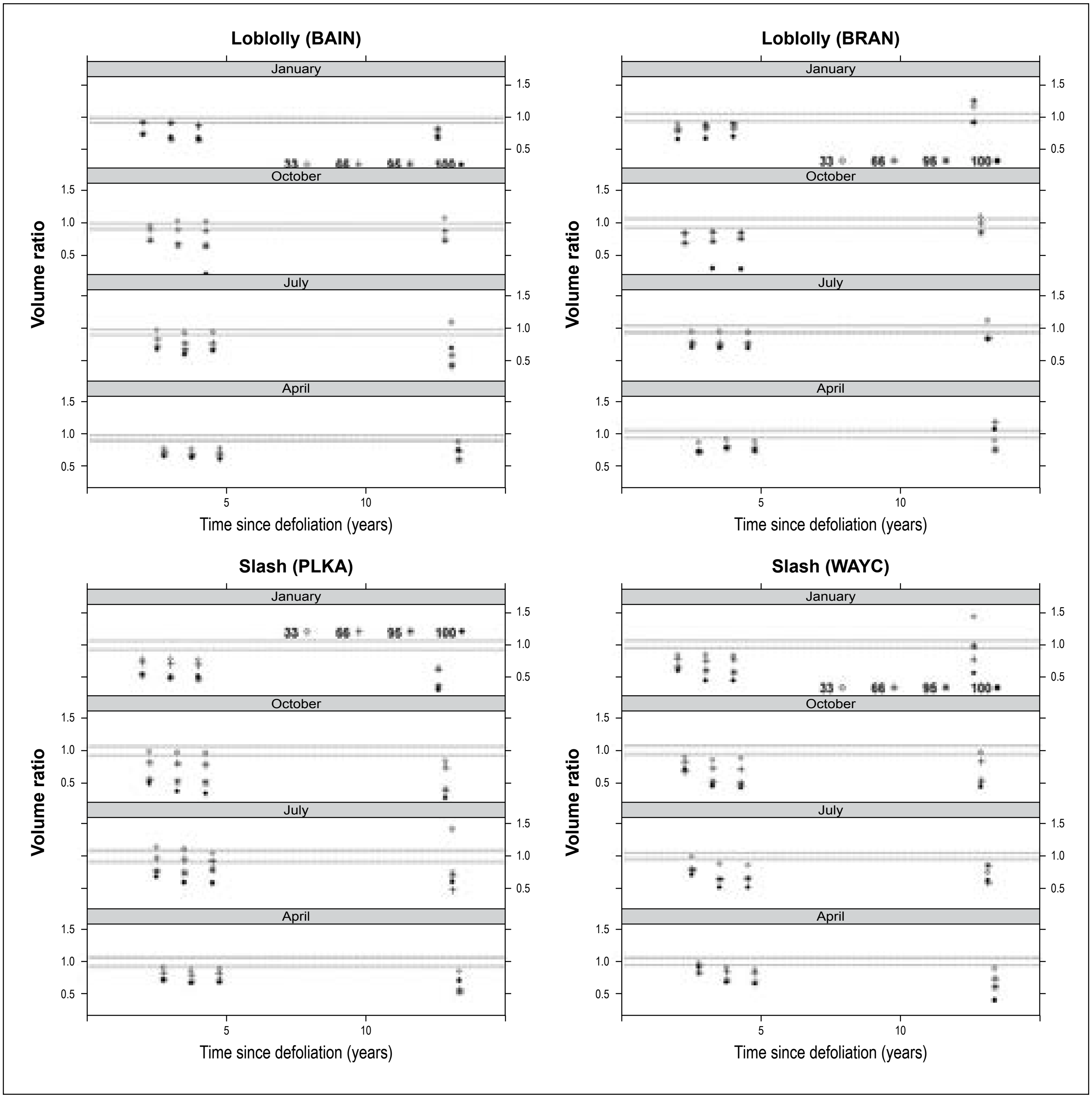

Figure 9—Ratio of estimated volume of young defoliated southern pine to control trees. Dashed line indicates the ±2.5 percent confidence interval around 1 used to determine if treated trees differed in size from control trees. Sites: Bainbridge, Georgia (BAIN), Branchville, South Carolina (BRAN), Palatka, Florida (PLKA), Waycross, Georgia (WAYC), Savannah River Forest Station (SRFS), Waycross, Georgia (LWYC).

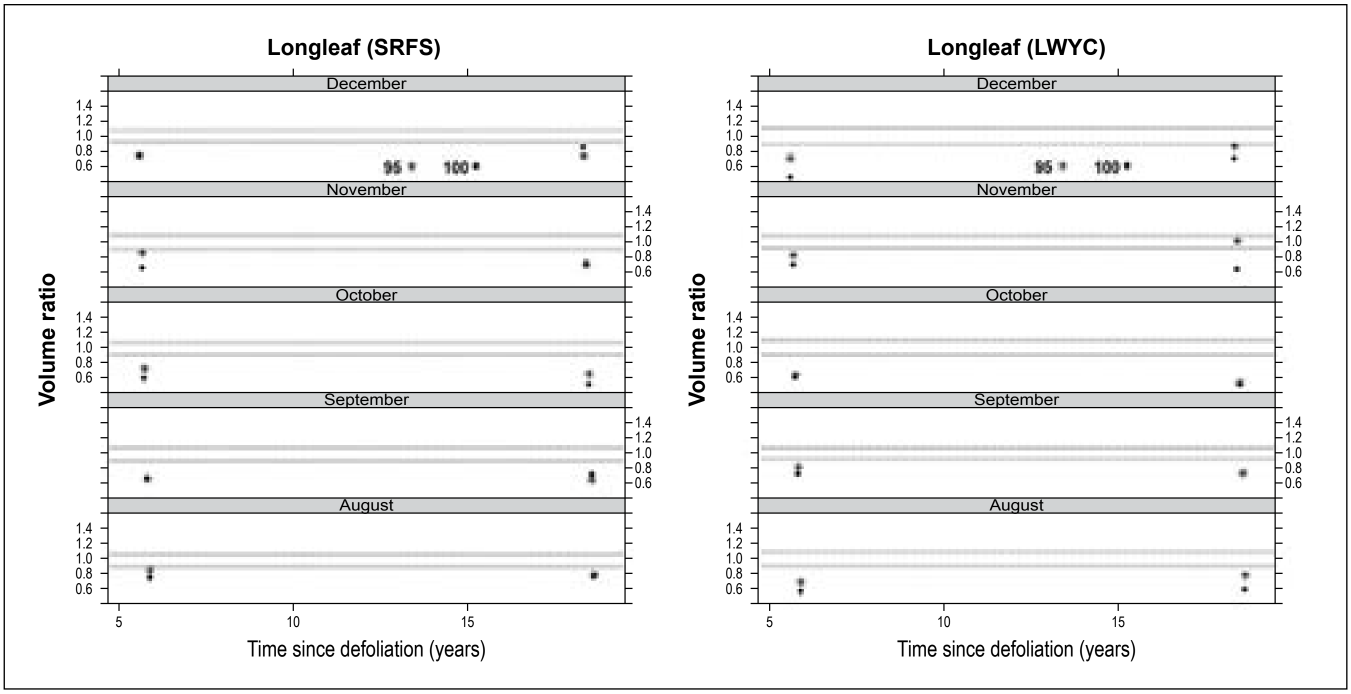

Figure 9—Continued