For. Sci. 61(4):800–808
http://dx.doi.org/10.5849/forsci.14-207

Long-Term *Pinus radiata* Productivity Gains from Tillage, Vegetation Control, and Fertilization

Timothy J. Albaugh, Jose Alvarez, Rafael A. Rubilar, Thomas R. Fox, H. Lee Allen, Jose L. Stape, and Oscar Mardones

The effects of tillage, vegetation control, and fertilizer treatments applied at stand establishment of *Pinus radiata* D. Don. at three sites (Sand, Clay, and Ash) in Chile were examined 10 years after planting. Selected sites were typical of sites that routinely received tillage as a normal part of site preparation operations in Chile. At each site, we used four blocks of a split plot design with whole plots testing tillage effects (none or subsoiling + bedding) and subplots testing a factorial combination of vegetation control (none or 2-year banded) and fertilization (boron at establishment or nitrogen, phosphorus, and boron at establishment + nitrogen, phosphorus, potassium, and boron after 2 years). We estimated the main effect growth responses, determined response types (Type A, B, C, D), and calculated main effect volume growth age shifts for each site. Vegetation control increased volume growth 7–99% through 10 years (Type A, B, or C responses), which resulted in volume age shifts of 3.4, 1.3, and 1.0 years for the Sand, Clay, and Ash sites, respectively. Fertilization increased volume growth at the Clay site (14%, Type A) and decreased volume growth at the Ash site (6%, Type D), with volume age shifts of 1.0 and 1.0 years for the Sand and Clay sites, respectively. Tillage increased survival at the Sand site and decreased height growth at the Ash site (4%, Type D) with volume age shifts of 0.9 and 0.1 years for the Sand and Ash sites, respectively. Vegetation control likely ameliorated water (Sand and Clay sites) and light (Ash site) limitations that were critical for improved growth. Fertilization addressed secondary nutrient limitations, especially on the Clay site. Tillage provided little benefit, likely because the sites were well drained and soil bulk density was not at a level where limitations to root growth would be found. When determining which treatments to apply, managers should have an understanding of what resources may be limiting and select the appropriate treatment to ameliorate those limitations in the most cost-effective manner. For sites similar to those in this study, vegetation control would likely ameliorate resource limitations in a cost-effective manner.

Keywords: age shift, response type

Forest productivity is driven by the availability of resources to crop trees (Cannell 1989, Landsberg and Sands 2011). One of the best opportunities to improve crop tree resource availability is during stand establishment when it is possible to ameliorate soil limitations through tillage (Morris and Lowery 1988, Carlson et al. 2006), the control of competing vegetation (Miller et al. 1991, Will et al. 2006), and addition of limiting nutrients (Pritchett and Comerford 1982, Gent et al. 1986a, Will et al. 2006). Treatments that improve resource availability at planting may increase overall growth and permit crop trees to rapidly capture the site. These treatments may also improve stand homogeneity (less variation in height and diameter among trees). Increased stand uniformity facilitates ease of planning for pruning and thinning operations and may increase light-use efficiency (Binkley et al. 2010). To quantify early silvicultural treatment response and to plan management activities, including thinning, fertilization, and harvests, forest managers project

---

Manuscript received October 31, 2014; accepted January 26, 2015; published online March 26, 2015.

Affiliations: *Timothy J. Albaugh (tim_albaugh@vt.edu), Virginia Polytechnic Institute and State University, Blacksburg, VA. Jose Alvarez (Jose.Alvarez-Munoz@Weyerhaeuser.com), Weyerhaeuser Company. Rafael A. Rubilar (rafaelrubilar@udec.cl), Fac. Cs. Forestales, Universidad de Concepción. Thomas R. Fox (trfox@vt.edu), Virginia Polytechnic Institute and State University. H. Lee Allen (allen.profor@gmail.com), Profor Consulting. Jose L. Stape (jlstape@ncsu.edu), North Carolina State University. Oscar Mardones (Oscar.mardones@forestal.cmpc.cl), Forestal Mininco.*

Acknowledgments: *We appreciate support from Forest Productivity Cooperative members and especially Forestal Mininco for their role in the establishment and management of the trials central to this publication. We gratefully acknowledge the support provided by the Department of Forest Resources and Environmental Conservation at Virginia Polytechnic Institute and State University, the Departamento de Silvicultura, Facultad de Ciencias Forestales, Universidad de Concepción, and the Department of Forestry and Environmental Resources at North Carolina State University. Funding for this work was provided in part by the Virginia Agricultural Experiment Station and the Program McIntire Stennis of the National Institute of Food and Agriculture, US Department of Agriculture. The use of trade names in this paper does not imply endorsement by the associated agencies of the products named, nor criticism of similar ones not mentioned.*

This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; cubic meters (m^3): 1 m^3 = 35.3 ft^3; millimeters (mm): 1 mm = 0.039 in.; hectares (ha): 1 ha = 2.47 ac; kilograms (kg): 1 kg = 2.2 lb; grams (g) 1 g = 0.035 oz.

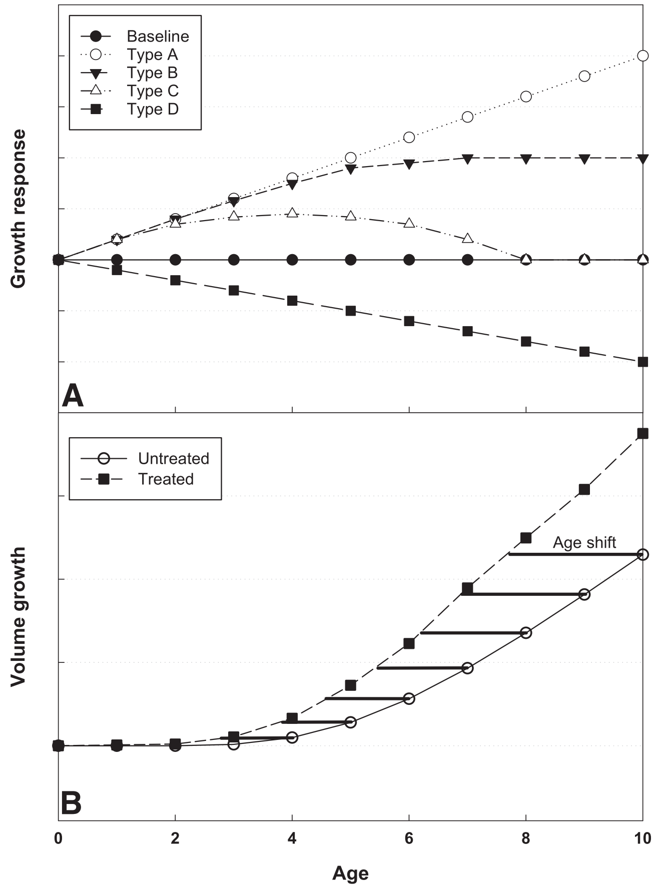

Figure 1. Hypothetical examples of Type A, B, C, and D treatment responses (A) where the A response continues to increase over the baseline with time, the B response increases for a certain time period and is then maintained, the C response increases for a certain time period and then returns to the baseline, and the D response is consistently lower than the baseline. A graphical representation of the age-shift calculation (B), where the solid horizontal lines indicate the age-shift for each year.

current growth to rotation age (Gent et al. 1986b). However, response to improved resource availability at stand establishment does not guarantee that early rotation gains will be evident at a specific point during the rotation or at harvest (Nilsson and Allen 2003).

Four growth patterns (Type A, B, C, and D) in response to improved resource availability relative to an untreated control may occur when observing growth over a rotation (Snowdon and Waring 1984, Morris and Lowery 1988, Snowdon 2002, Nilsson and Allen 2003). Types are distinguished by the way resources (light, water, and nutrients) become available to and are used by trees and response duration, which is related to longevity of resource availability. A treatment response is considered Type A if growth gains increase throughout the rotation and result in increased carrying capacity (Figure 1A). Response to phosphorus fertilization at planting on phosphorus limited sites and treatments (e.g., soil tillage, herbicide application) that reduce or eliminate hardwood competition may result in a Type A response (Ballard 1972, Pritchett and Comerford 1982, Schmidtling 1984, Gent et al. 1986a, Glover and Zutter 1993, Zutter and Miller 1998, Nilsson and Allen 2003). For a Type A response, resources are made available throughout the rotation for treated trees, and untreated trees never have access to these resources. For Type B, growth increases in response to treatment relative to an untreated control occur for a short time after treatment; treated trees then stop responding and the response is maintained. Early rotation herbaceous weed control and midrotation nutrient applications on nutrient-limited sites may result in a Type B response (Miller et al. 1991, Mason and Milne 1999, Snowdon 2002, Nilsson and Allen 2003, Fox et al. 2007). For a Type B response, treated trees use additionally available resources for a short time but then those resources are exhausted or are no longer available, and the resources are never available to untreated trees. Type C is similar to Type B where there is a positive response shortly after treatment; however, the response will be partially or completely lost over time. Soil tillage may generate a Type C response if soil nutrients are moved off site; similarly, herbicide application (especially on sandy soils) may create a Type C response if it results in a loss of nutrients (Fox et al. 1989, Smethurst and Nambiar 1989, Vitousek et al. 1992, Richardson 1993). Resources are initially available to treated trees in a Type C response, but treatment results in a situation where treated trees suffer from a lack of resources that are available to untreated trees in the long term, and therefore, untreated trees are eventually able to outgrow treated trees. The final response pattern, Type D, has a negative growth response relative to an untreated control from the time of treatment initiation. A fertilizer application without management of competing vegetation early in the rotation may lead to a type D response (Albaugh et al. 2004). In this case, treatment results in a situation where treated trees are unable to use applied nutrients because the applied nutrients stimulate competing vegetation, which then outcompetes the trees for nutrients and light.

There may be tradeoffs when applying silvicultural treatments because treatments may affect the same or different resources and may have short- or long-term effects. For example, soil tillage, fertilization, and vegetation control may all influence nutrient and water resource availability and do so for different lengths of time. Tillage may eliminate hardwood competing vegetation, which will allow crop vegetation access to nutrients and water that competing vegetation would use if it had not been controlled (Nilsson and Allen 2003). This response would likely persist for the length of the rotation. Fertilization is the direct application of limited nutrients and may act to improve water availability through improved water use efficiency (Ewers et al. 1999, Fox et al. 2007). Fertilization may have a relatively short response time for midrotation applications, which average an 8-year response period (Fox et al. 2007) or longer response times for applications at establishment where severe phosphorus deficiencies are ameliorated throughout the rotation (Everett and Palm-Leis 2009). Vegetation control directly eliminates competing vegetation, which will allow crop vegetation indirect access to additional native site nutrients and water (Hanna 2000). Vegetation control may increase crop tree resource availability in the short term when herbaceous plants are controlled or over a long-term period when woody brush is controlled (Zutter and Miller 1998).

Forest managers typically prefer the most cost-effective treatment to allocate resources to their stands (Gent et al. 1986b). Given that resources may be affected by a variety of silvicultural treatments, managers need tools to evaluate their available options and determine the best silvicultural methods to apply. One such tool is an age-shift analysis, which compares growth between treatments by calculating the difference in years (age-shift) between treated and untreated trees when they achieve the same growth (Mason et al. 1997, South et al. 2006, Carlson et al. 2008). The age-shift method avoids problems associated with the relationship between tree size

Table 1. Site and stand characteristics for the three sites in the central valley of Chile that were used in this study.

Site name	Sand	Clay	Ash
Latitude	37° 10' 40" S	37° 50' 43" S	39° 4' 40" S
Longitude	72° 15' 47" W	72° 20' 5" W	72° 24' 23" W
Elevation (masl)	170	261	225
Geology	Volcanic sands	Red clay - old volcanic ash	Recent volcanic ash
Soil taxonomic name	Fragmental, thermic dystric xerorthents	Very fine, mixed, thermic typic rhodoxeralfs	Medial, mesic typic haploxerands
Soil series	Arenales	Collipulli	Santa Barbara
Drainage	Somewhat excessively well	Well	Well
Family Genotype	IF24	MP31	MP31
Initial stocking (trees ha^{-1})	1,250	1,000	1,250
Mean annual temperature	13.7	13.3	10.7
Mean annual rainfall (mm yr^{-1})	1,160	1,100	2,180
Site index (height at 20 yr)	14.9	24.4	this is first rotation
Productivity (age 24 in m^3 ha^{-1} yr^{-1})	7.8	15.5	this is first rotation

and growth rate by comparing treatments on the basis of tree age at a fixed stand volume (or other growth variable) rather than comparing different stand volumes at a fixed age. The age-shift may be estimated graphically by determining the time difference in *x*-coordinates of treated and nontreated stands for a given volume or calculated using height-age curves assuming treatment does not alter the curve shape but simply shifts the curve along the *x*-axis (Lauer et al. 1993, Kimberley et al. 2004, South et al. 2006, Carlson et al. 2008) (Figure 1B). Additionally, the age-shift estimates a reduction in rotation age (Carlson et al. 2008).

Determining rotation length response to silvicultural treatments applied at the time of planting and the use of the age-shift to describe treatment responses has been well documented for *Pinus taeda* L. grown in the southeast United States (Huang and Teeter 1990, Lauer et al. 1993, Miller et al. 1995, Nilsson and Allen 2003, South et al. 2006, Carlson et al. 2008). For *P. radiata* D. Don., data are available in the literature on early responses to silvicultural treatments applied at the time of planting, including tillage, fertilization, and vegetation control (Alvarez et al. 1999, Alvarez et al. 2004, Albaugh et al. 2004, Alvarez et al. 2013). However, long-term responses to these treatments and calculation of associated age-shifts in *P. radiata* have not been reported. Our interest then was to examine long-term (10 years) growth effects of tillage, fertilization, and vegetation control applied at establishment on the volume growth of *P. radiata* and to estimate associated age-shifts. Our hypotheses were that after 10 years of growth at each site: (1) tillage will not affect volume growth; (2) fertilization will not affect volume growth; and (3) vegetation control will not affect volume growth.

Methods

Experimental Design

We installed a 2 × 2 × 2 factorial design with tillage, fertilization, and vegetation control as factors at three sites in the central valley of Chile where other work has been completed (Albaugh et al. 2004, Rubilar et al. 2013a, Rubilar et al. 2013b). The sites were established on three soil types, i.e., andesitic-basaltic dry sands (Sand), old volcanic ash red clay soils (Clay), and recent volcanic ash loamy soils (Ash), covering a broad range of mean annual temperatures (10.7–13.7° C) and rainfall (1,100–2,180 mm yr^{-1}) (Table 1). All sites had the same experimental design and treatment applications. Tillage was applied before plot establishment due to operational logistical issues. The tillage main effect plots were randomly applied at each site, and we did not observe differences between tilled and nontilled areas; consequently, the analysis was completed as a split-plot design with whole plots testing tillage effects (S0 = none, S1 = 80-cm deep subsoiling plus bedding [20-cm bed height]). At the time of study installation, selected sites were typical of sites that routinely received tillage, similar to the S1 treatment, as a normal part of site preparation operations in Chile. There were four replications of whole plots and a factorial combination of vegetation control (W0 = none, W1 = 2-year banded postplanting) and fertilization (F0 = boron at establishment, F1 = nitrogen, phosphorus, and boron at establishment + nitrogen, phosphorus, potassium, and boron after 2 years) was installed in each block as subplots. The Ash site was a pasture conversion; a broadcast preplant vegetation control treatment was applied to the entire site to eliminate pasture grasses before any other installation work was completed. Treatment and internal measurement plots were 0.4 ha and 0.09–0.12 ha, respectively; the surface area with buffers at each site was approximately 15 ha. Each measurement plot contained 100 trees.

Tillage was completed in February and March 2000 using a Savannah plow. Vegetation control was applied in September and October of 2000 and 2001 as a 2-m band centered on the planting row. Glyphosate at 2 kg ha^{-1} plus 3 kg ha^{-1} atrazine and 1 ml l^{-1} Galactic surfactant were used for both applications. Chemicals were applied using backpack sprayers, and planted pines were protected from the herbicide spray. Glyphosate was Roundup Max with 48.7% glyphosate (N-(phosphonomethyl) glycine), obtained from Moviagro S.A. in Chile. Atrazine was Atrazine 90 WG with 90% p/p dispersed granules of atrazine (2-chloro-4 ethylamino-6-isopropylamino-s-triazine), obtained from ANASAC in Chile. Galactic is a blend of organosilicone and nonionic surfactants designed to improve herbicide performance. All trees received 1.5 g $plant^{-1}$ of elemental boron in September 2000. In the F1 plots, trees received 29.5, 32.4, and 1.5 g $plant^{-1}$ of elemental nitrogen, phosphorus, and boron, respectively, applied in September 2000. A second fertilizer application of 29.5, 32.4, 25.0, and 3.0 g $plant^{-1}$ of elemental nitrogen, phosphorus, potassium, and boron, respectively, was completed in September 2002 on the F1 plots. In September 2000, fertilizer was applied superficially around each tree; in September 2002, fertilizer was applied on the planting row. Nutrient additions on a per tree basis were the same at all sites. However, due to different stocking levels, area-based fertilizer amounts were higher at the Sand and Ash sites. The total nutrient additions on the Clay site for the F1 treatments were 59.0, 64.8, 25.0, and 4.5 kg ha^{-1} for nitrogen, phosphorus, potassium, and boron, respectively. Nutrient additions at the Sand and Ash sites for the F1 treatments were 73.7, 81.0, 31.3, and 5.6 kg ha^{-1} for nitrogen, phosphorus, potassium, and boron, respectively. In subsequent text, we refer to fertilizer treatments at all sites as F0 and F1; the reader should be aware that the F1 treatments differ between sites, where the Clay site received less fertilizer in the F1 plots on an area basis than the Sand and Ash sites.

Full-sib *Pinus radiata* bareroot 1–0 cuttings were planted using a shovel at each site (Table 1) in June and July 2000. The Sand and Ash sites were planted at 1,250 trees ha^{-1} (4.0 × 2.0 m spacing), and the Clay site was planted at 1,000 trees ha^{-1} (2.0 × 5.0 m).

Planted pines were measured immediately after planting and annually in the dormant season (June to August) for 10 years. Tree height was measured in all years and dbh (1.4 m) was measured beginning in year three when the trees achieved breast height. Volume was estimated using

$$V = (-0.00214+0.0000295{*}D^2 + 0.001349{*}H + 0.00002486{*}D^2{*}H) \quad (1)$$

where V is volume in m^3 tree^{-1}, D is dbh, and H is height (Mininco 1995).

All significance levels were $P < 0.05$. PROC MIXED (SAS Institute, Inc. 2002) was used to evaluate the analysis of variance (ANOVA) for diameter, height, basal area, volume, survival, and the coefficient of variation for height after 10 years of growth. Analyses were specific to a site and there were no statistical comparisons between sites.

Response Type Determination

Main effect treatment response for height, diameter, and volume was calculated each year and plotted over time to determine the expected long-term response type (A, B, C, or D) for each site. We considered main effect responses different from the untreated treatment if the standard error of the main effect volume mean did not overlap the zero response line (the untreated mean).

Age-Shift Gain Projection

We projected treatment age-shift gain at each site using site mean responses following methods presented by South et al. (2006) (their second method) and Carlson et al. (2008). For each year, we estimated the volume age-shift using a nonlinear regression for the untreated treatment (the mean of treatments not receiving a given main effect treatment) at each site (e.g., when examining the vegetation control main effect, the untreated plots were all those with W0 vegetation control designation). Cumulative increment and years since treatment were dependent and independent variables, respectively. Main effect treatment data were substituted into the untreated treatment equation, and we calculated years since treatment required to achieve the same increment. The difference between the years since treatment to achieve a given level of cumulative growth for the untreated treatment and the main effect was the age-shift gain for that treatment. We assumed that the growth curve shape was the same for all treatments (South et al. 2006, Carlson et al. 2008). Models were fit using PROC REG (SAS Institute, Inc. 2002) and evaluated by examining the mean square error and r^2 (Carlson et al. 2008). Residual analysis indicated the models were unbiased.

Untreated treatment volume growth was calculated as

$$Y_t = e^{a+b/X} \quad (2)$$

where Y_t is volume at time t, X is the number of years after treatment application when volume was measured, and b_0 and b_1 are parameters to be estimated. The volume age-shift was determined as

$$A_t = \frac{(b_1)}{\log(V) - b_0} - t \quad (3)$$

where A_t is the age shift in years at year t, t is measurement year (3–10), V is volume response in m^3 ha^{-1}, and b_0 and b_1 are parameters from the untreated treatment (Equation 2). These calculations were conducted in each block at each site for each main effect treatment. Block data at each site were used to estimate the mean volume age shift and standard error. Age-shifts were considered significant if the mean age-shift plus or minus one standard error did not overlap zero.

Results

After 10 years, tillage significantly increased survival at the Sand site (13%) and decreased height (0.8 m, 4%) at the Ash site (Tables 2 and 3). Fertilizer significantly increased diameter at the Sand (0.5 cm, 4%) and Clay (1.0 cm, 6%) sites; increased height at the Sand (0.3 m, 4%) and Clay (0.6 m, 5%) sites and decreased height at the Ash site (0.4 m, 2%). Fertilizer increased basal area at the Clay site (2.5 m^2 ha^{-1}, 12%) and decreased it at the Ash site (2.5 m^2 ha^{-1}, 4%). Fertilizer increased volume at the Clay site (16 m^3 ha^{-1}, 14%) and decreased it at the Ash site (24 m^3 ha^{-1}, 6%). Fertilization reduced the height coefficient of variation by 12% at the Clay site (Table 2 and Figure 2B). At the Sand site, vegetation control significantly increased diameter (1.2 cm, 10%), height (1.5 m, 16%), basal area (5.3 m^2 ha^{-1}, 45%), volume (82 m^3 ha^{-1}, 99%), and survival (21%) but reduced the height coefficient of variation (32%) (Tables 2 and 3; Figure 2A). At the Clay site, vegetation control significantly increased diameter (1.2 cm, 7%), height (1.5 m, 11%), basal area (3.3 m^2 ha^{-1}, 15%), and volume (28 m^3 ha^{-1}, 25%). At the Ash site, vegetation control increased height (1.0 m, 6%) and volume (25 m^3 ha^{-1}, 7%). At the Sand site, a significant tillage by vegetation control interaction was observed for diameter and height such that for plots with a W0 code, there was less diameter and height growth in plots with tillage (S1) than in those that did not receive tillage (S0). In addition, there was a significant tillage by vegetation control interaction for survival such that for plots without vegetation control (W0), those that had no tillage (S0) had lower 10-year survival rates than those that received tillage (S1). At the Ash site, a significant tillage by vegetation control interaction was observed for diameter such that for plots without vegetation control (W0), there was less diameter growth in plots with tillage (S1) than in those that did not receive tillage (S0).

Type A, B, and C responses were observed for vegetation control. Type A volume responses of more than 25 m^3 ha^{-1} were observed at the Sand and Clay sites (Figure 3G and H, respectively). Type B responses were observed for height (more than 1 m increase) at all sites (Figure 3A, B, and C for the Sand, Clay, and Ash sites, respectively), and for volume (more than 25 m^3 ha^{-1}) at the Ash site (Figure 3I). Type C responses were observed for diameter at all sites (Figure 3D, E, and F for the Sand, Clay, and Ash sites, respectively).

Fertilization resulted in Type A, B, and D responses. Type A responses were observed for height at the Sand (0.3 m increase) and Clay (0.6 m increase) sites (Figure 3A and B, respectively), as well as

Table 2. Summary of statistical significance (prob > F) of main effects (soil tillage, fertilization, and weed control) and their interactions for dominant height, diameter, basal area, volume, survival, and the coefficient of variation for height for measurements at age 10 years at the three sites in the central valley of Chile.

Effect	Diameter	Dominant height	Basal area	Volume	Survival	Height coefficient of variation
Sand						
Soil tillage (S)	0.184	0.087	0.221	0.234	**0.012**	0.567
Fertilization (F)	**0.009**	**0.014**	0.165	0.082	0.098	0.060
Weed control (W)	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
S × F	0.938	0.570	0.440	0.414	0.161	0.583
S × W	**0.002**	**0.044**	0.387	0.701	**0.000**	0.548
F × W	0.841	0.208	0.399	0.191	0.137	0.220
S × F × W	0.703	0.955	0.794	0.865	0.382	0.175
Clay						
Soil tillage (S)	0.606	0.823	0.668	0.574	0.204	0.391
Fertilization (F)	**0.001**	**0.045**	**0.001**	**0.004**	0.865	**0.026**
Weed control (W)	**0.000**	**0.000**	**0.000**	**0.000**	0.137	0.114
S × F	0.197	0.511	0.137	0.130	0.242	0.175
S × W	0.207	0.064	0.174	0.290	0.610	0.709
F × W	0.255	0.093	0.336	0.480	0.399	0.767
S × F × W	0.907	0.390	0.780	0.572	0.610	0.601
Ash						
Soil tillage (S)	0.263	**0.035**	0.440	0.051	0.356	0.981
Fertilization (F)	0.373	**0.026**	**0.027**	**0.015**	0.055	0.876
Weed control (W)	0.880	**0.000**	0.351	**0.013**	0.593	0.607
S × F	0.973	0.819	0.699	0.860	0.805	0.844
S × W	**0.045**	0.238	0.222	0.491	0.051	0.832
F × W	0.398	0.482	0.255	0.345	0.742	0.888
S × F × W	0.594	0.535	0.557	0.489	0.391	0.941

Values in bold are < 0.05.

Table 3. Ten-year survival and growth measurements (treatment mean) and response and percent response relative to the S0F0W0 treatment for the three sites in the central valley of Chile.

	Diameter			Dominant height			Basal area			Volume			
Treatment	Growth cm	Response cm	Response %	Growth m	Response m	Response %	Growth m^2ha^{-1}	Response m^2ha^{-1}	Response %	Growth m^3ha^{-1}	Response m^3ha^{-1}	Response %	Survival %
Sand													
S0F0W0	12.1			9.1			11.3			48			75
S0F0W1	12.8	0.8	6	10.1	1.0	11	16.6	5.2	46	75	27	55	99
S0F1W0	12.6	0.6	5	9.2	0.1	1	11.2	−0.2	−2	47	−1	−2	68
S0F1W1	13.2	1.1	9	10.5	1.5	16	17.3	6.0	53	81	32	66	98
S1F0W0	11.1	−1.0	−8	8.5	−0.6	−6	12.0	0.6	5	50	1	3	93
S1F0W1	12.9	0.8	7	10.1	1.0	11	16.7	5.3	47	75	27	56	99
S1F1W0	11.5	−0.5	−5	8.8	−0.3	−4	12.6	1.3	11	53	5	9	92
S1F1W1	13.3	1.3	10	10.7	1.6	17	17.8	6.5	57	84	35	73	100
Clay													
S0F0W0	15.8			12.7			20.1			106			99
S0F0W1	17.7	1.9	12	14.5	1.8	15	25.2	5.0	25	146	40	38	99
S0F1W0	16.8	1.0	6	13.2	0.6	4	22.5	2.4	12	121	15	14	98
S0F1W1	18.0	2.2	14	14.5	1.8	15	25.9	5.7	28	148	42	40	99
S1F0W0	15.5	−0.3	−2	12.1	−0.5	−4	19.6	−0.5	−3	100	−6	−5	99
S1F0W1	16.7	0.9	5	13.5	0.9	7	22.5	2.3	11	124	18	17	100
S1F1W0	17.1	1.3	8	13.1	0.5	4	23.7	3.5	17	125	19	18	100
S1F1W1	17.7	1.9	12	14.5	1.8	14	25.6	5.4	27	147	41	39	100
Ash													
S0F0W0	27.4			18.5			56.6			381			75
S0F0W1	26.0	−1.4	−5	19.3	0.8	4	58.4	1.7	3	410	29	8	84
S0F1W0	27.2	−0.2	−1	18.0	−0.4	−2	53.9	−2.7	−5	356	−25	−7	71
S0F1W1	26.9	−0.5	−2	18.9	0.4	2	56.9	0.2	0	389	8	2	77
S1F0W0	25.4	−2.0	−7	17.5	−0.9	−5	58.2	1.6	3	376	−4	−1	89
S1F0W1	26.0	−1.4	−5	18.5	0.0	0	56.0	−0.6	−1	379	−1	0	80
S1F1W0	25.6	−1.8	−7	16.9	−1.5	−8	53.4	−3.3	−6	335	−46	−12	78
S1F1W1	26.5	−0.9	−3	18.4	−0.1	0	54.9	−1.7	−3	369	−12	−3	77

Treatment codes are site preparation = S where 0 = none, and 1 = subsoiling + bedding; fertilization = F where 0 = only B and 1 = N, P, K, and B; weed control = W where 0 = none and 1 = 2 years banded.

diameter (more than 1 cm increase) (Figure 3E) and volume (more than 15 m^3 ha^{-1}) (Figure 3H) at the Clay site. Type B responses were observed for diameter (up to 0.5 cm) and volume (up to 5 m^3 ha^{-1}) at the Sand site (Figure 3D and G, respectively). Type D responses were found for height (0.4 m decrease) and volume (18 m^3 ha^{-1} decrease) at the Ash site (Figure 3C and I, respectively).

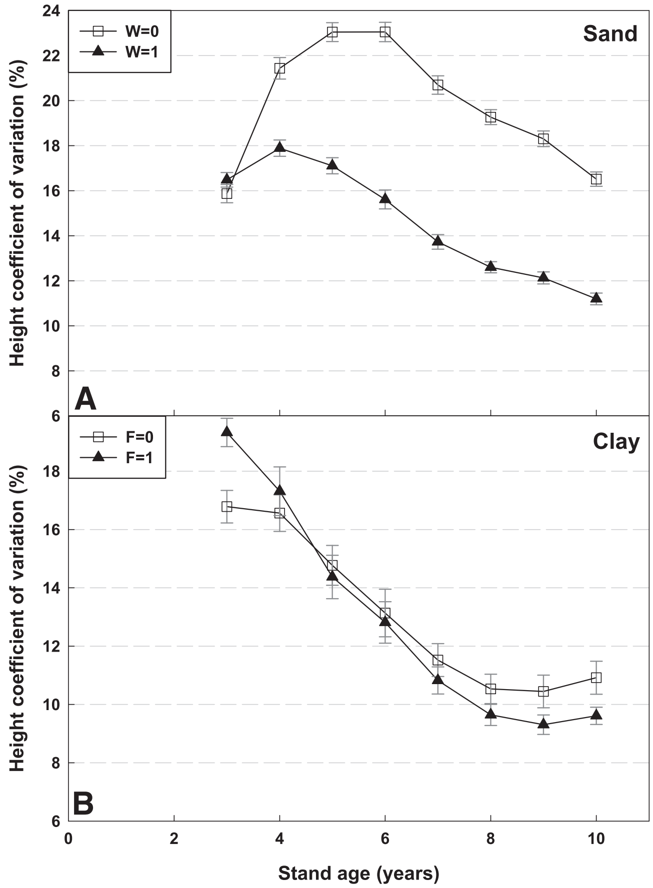

Figure 2. Height coefficient of variation at the Sand (A) and Clay (B) sites over time, where W0 is no vegetation control, W1 is 2-year banded vegetation control, F0 is boron at establishment and F1 is nitrogen, phosphorus, and boron applied at establishment plus nitrogen, phosphorus, potassium, and boron application after 2 years. Error bars are plus or minus one standard error.

Tillage resulted in Type B and D responses. A Type B response was observed for volume (4 m^3 ha^{-1} maximum increase) at the Sand site. Type D responses were found for height at the Ash (0.8 m decrease) site (Figure 3C), diameter for the Sand (0.5 cm decrease) and Ash (1.0 m decrease) sites (Figure 3D and F, respectively), and volume at the Ash site (18 m^3 ha^{-1} decrease).

Maximum volume age-shifts in response to vegetation control were 3.4, 1.3, and 1.0 years for the Sand, Clay, and Ash sites, respectively (Figure 4A, B, and C, respectively). At the Sand site, fertilization and tillage resulted in an age-shift of less than 1 year. Fertilization resulted in an age-shift of 1 year at the Clay site. For the Ash site, the tillage age shift was 0.2 years.

Discussion

We rejected our hypotheses for vegetation control at all sites and for fertilization at the Clay and Ash sites. We accepted our hypotheses for tillage at all sites and for fertilization at the Sand site. Vegetation control increased 10-year volume growth at all sites. Fertilization increased volume growth at the Clay site, decreased it at the Ash site, and had no effect at the Sand site. Tillage had no effect on 10-year volume growth at any site.

Vegetation control clearly improved tree growth at all sites. The Sand and Clay sites experience extended dry periods during the growing season when available soil water is less than 3 and 7%, respectively (Rubilar et al. 2013a). Consequently, vegetation control likely alleviates crop tree water limitations at these sites. Water constraints were less of a concern at the Ash site where there was more than 20% available soil water (Rubilar et al. 2013a). However, this site was a pasture conversion, and vegetation control likely reduced light competition from extant pasture species (mostly grass species). With vegetation control, water and light would be available only to treated trees and only for a limited time because eventually untreated trees would become established and shade out competing vegetation and acquire the resources the competing vegetation was using. Consequently, we would expect a Type B response if trees in vegetation control plots were accessing more available water and light. We observed a Type B response for height at all sites. Diameter displayed a Type C response; however, this may be related to stocking (Table 3) where vegetation control plots experienced greater intraspecific competition earlier because stand development advanced more rapidly with treatment.

Fertilization improved tree growth on the Sand and Clay sites, although it did not improve growth as much as vegetation control. At the Ash site, fertilization had little effect or reduced growth. Some combination of the applied nutrients (nitrogen, phosphorus, and potassium) appeared to be secondarily limiting at the Sand and Clay sites. The Clay site exhibited a Type A response for height, diameter, and volume, following a similar pattern to that observed for phosphorus limited sites (Gent et al. 1986a, Nilsson and Allen 2003). The Clay site received less fertilizer on an area basis than the other sites but still exhibited a Type A response, highlighting the severity of the apparent nutrient limitation at this site. The Sand site exhibited both Type A and B responses, indicating that some limiting nutrients may have been depleted (similar to nitrogen in midrotation fertilizer applications (Fox et al. 2007), while others continued to be available over time (similar to phosphorus applications). Reduced growth with fertilization at the Ash site initially suggested that fertilizer may have stimulated competing vegetation growth. However, the 10-year data did not indicate a fertilizer by vegetation control interaction at this site.

Tillage did not affect growth at the Sand and Clay sites, but it decreased height growth at the Ash site. Height growth at the Ash site exhibited a Type D response where treated trees had less height growth than untreated trees throughout the study. Tillage reduces root growth restrictions in high-strength soils (well-drained clays) and improves soil aeration in poorly drained soils and may also reduce woody competing vegetation (Daddow and Warrington 1983, Morris and Lowery 1988, Carlson et al. 2006). However, these conditions did not exist at our sites. Drainage was good, and bulk density at all sites was at a level indicating no need for tillage and that there were likely no restrictions to root growth based on soil strength limitations (Rubilar et al. 2013b). Our data support results from previous work where pine grown on upland sites generally did not respond to tillage (subsoiling) because root development readily occurred in well-structured soil and through old root channels (Carlson et al. 2006). Even in highly compacted soils, *P. radiata* has the ability to grow to and through weaker areas (old roots, fractures in the soil) to access deeper soil depths and available resources contained there (Nambiar and Sands 1992). Given that information regarding drainage and soil strength was already available at the time of study installation, it is interesting that sites similar to our study sites were routinely being tilled in a manner similar to the S1 treatment. An additional argument for tillage is that survival and stand uniformity will be improved. Tillage did improve survival at the

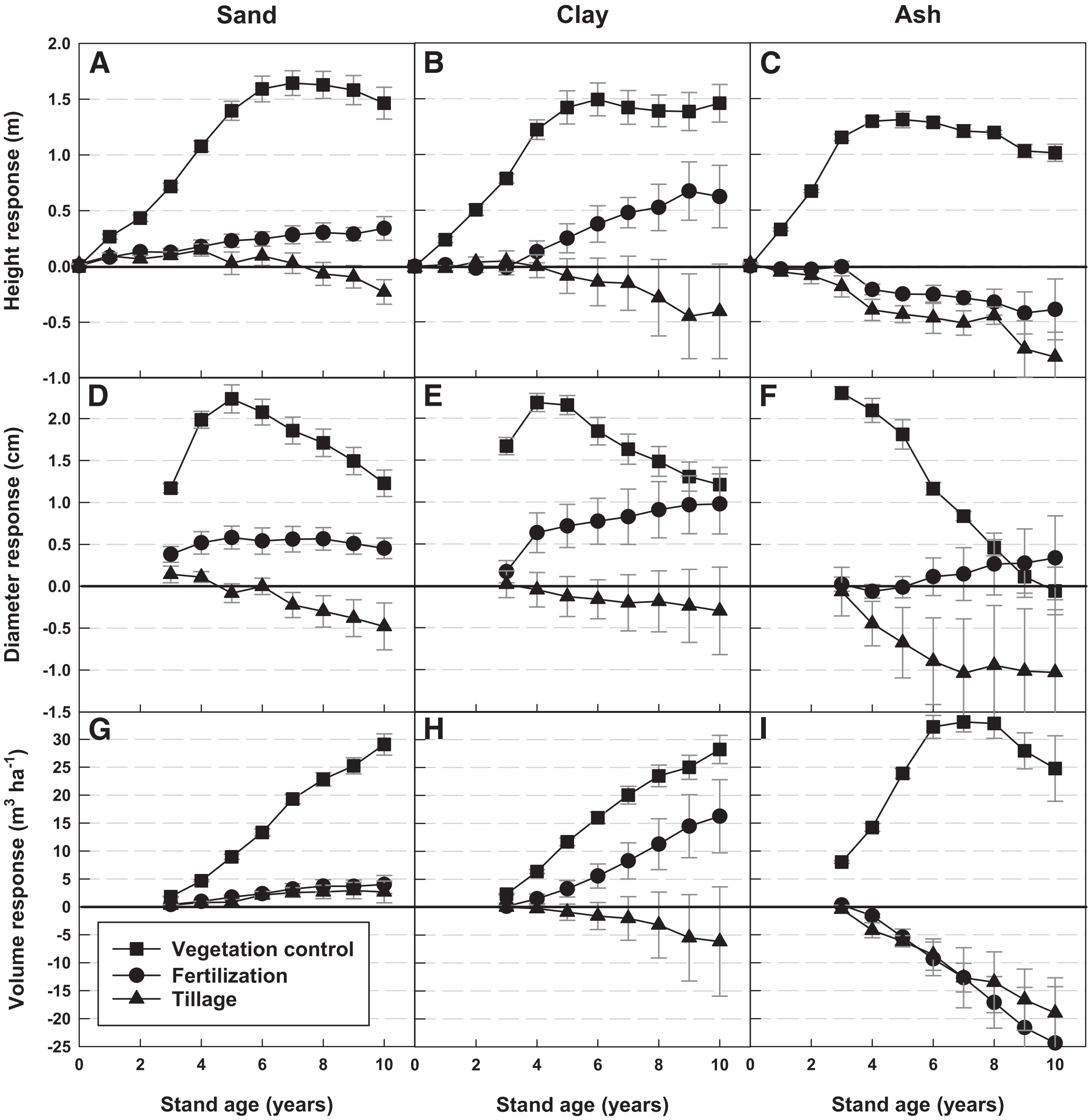

Figure 3. Main effect (vegetation control, fertilization, and tillage) treatment responses for height, (A, B, and C) diameter (D, E, and F), and volume (G, H, and I) over time for the Sand (A, D, and G), Clay (B, E, and H) and Ash (C, F, and I) sites. Error bars are plus or minus one standard error.

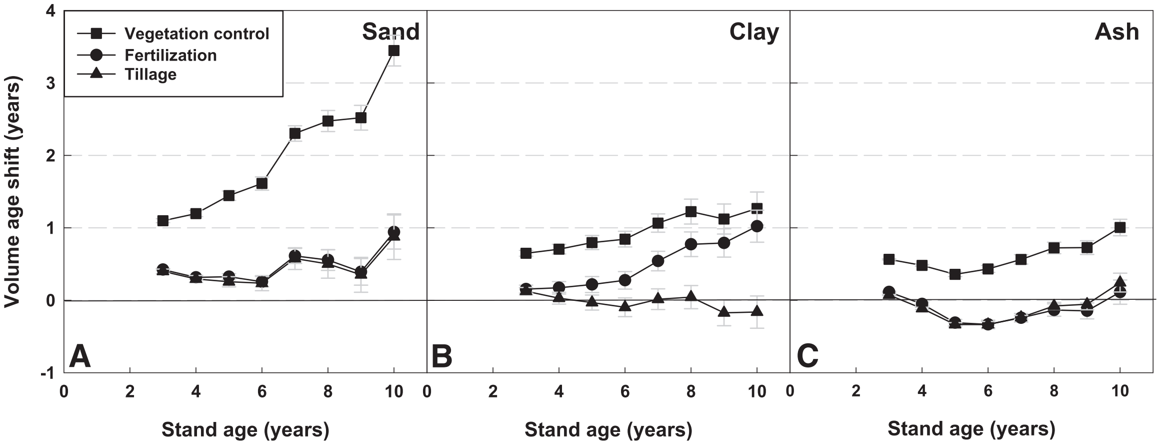

Figure 4. Volume age shift (in years) over time for the main effects (vegetation control, fertilization, and tillage) for the Sand (A), Clay (B), and Ash (C) sites. Error bars are plus or minus one standard error.

Sand site but did not affect uniformity (the height coefficient of variation). However, when comparing treatments at the Sand site, vegetation control performed better than tillage because it increased survival and growth and improved stand uniformity (reduced the height coefficient of variation). In another study at these sites, Rubilar et al. (2013a) found that tillage reduced Ash site fascicle length and foliage display, suggesting that tillage resulted in a reduction in nutrient or water availability for foliage development. They hypothesized that, in this case, tillage increased below ground allocation (more root production at greater depths) and thus diverted resources away from aboveground growth. Somerville (1979) found that ripping (similar to the 80-cm subsoiling completed in our study) shifted the root distribution to greater depths but did not affect root mass. However, Somerville's (1979) analysis only measured roots to a depth of 1 m; therefore, additional work would be necessary to test this hypothesis.

Given soil conditions at our sites (good drainage and low soil strength), it was not surprising that tillage did not improve growth at these sites. This is in agreement with data from the literature for *P. radiata* (Mason et al. 1995, Mason and Milne 1999) and other species (Carlson et al. 2006, du Toit et al. 2010) where tillage did not improve growth at sites with similar soil conditions as those in this study. In contrast, Nilsson and Allen (2003) found that intensive site preparation that included tillage resulted in more uniform stands and greater growth later in the life of the stand. However, they concluded that the growth response to intensive site preparation was a function of better herbaceous weed control early in the rotation and control of competing hardwood vegetation later in the rotation. Du Toit et al. (2010) suggested that after accounting for vegetation control effects, there was little growth improvement with ripping or subsoiling if these treatments were carried out in addition to surface tillage. From a management perspective, unless there are conditions that clearly indicate a need for tillage, there appears to be little supporting information to recommend investing in this type of operation.

The age-shift estimated for vegetation control was greater than or equal to that of other treatments at all sites. South et al. (2006) estimated volume age-shifts of 2.2 and 3.1 years at ages 8 and 15, respectively, for herbaceous weed control on *P. taeda* sites without a hardwood component. These sites would be similar to ours where there was little woody competing vegetation and our volume age-shifts (1.0–3.4 years at 10 years old) were in the same range. Similarly, Lauer et al. (1993) projected volume growth gains of 3 years for time of planting herbaceous weed control measurements at 9 years of age. Carlson et al. (2008) estimated a volume age shift of 2.4 years for midrotation nitrogen and phosphorus applications 10 years after treatment. Their estimate was somewhat greater than our estimate of 1.0 year, likely because our nitrogen application rates (59–74 kg elemental nitrogen ha^{-1}) were smaller than theirs (up to 336 kg elemental nitrogen ha^{-1}) and growth response is linked to nitrogen application rate (Fox et al. 2007). No estimates of tillage age shift were found in the literature.

At the Sand and Clay sites, the volume response for vegetation control followed a Type A response, indicating that the growth gains should continue through the end of the rotation. However, given that height response at these sites exhibited a Type B response and diameter exhibited a Type C response, the volume gains may not be carried through rotation age. The treated stands will experience density-dependent mortality before the untreated stands, which would reduce treated stand volume growth. Density-dependent mortality was already observed at the Ash site where survival had decreased to approximately 80% across all treatments. However, midrotation silvicultural interventions such as thinning or fertilization may permit treated stands to continue to grow better than untreated stands throughout the rotation (Nilsson and Allen 2003).

For a manager making decisions about which treatments to apply (i.e., tillage, vegetation control, or fertilization) on similar site types, it is clear that vegetation control should be selected first. Vegetation control ameliorated the primary limiting factor at each site (water or light) and resulted in good survival, growth, and uniformity and would be inexpensive to apply. Fertilization would be the next treatment to consider at the Sand and Clay sites where it ameliorated secondary limiting nutrients. To date, however, fertilization does not appear to be needed at the Ash site. Tillage would be the last treatment to include, given that the only positive response to tillage was an increase in survival at the Sand site, which could be provided for by vegetation control. At the same time, it is likely that significant cost savings will result by avoiding tillage because it is the most expensive of the treatments to apply.

Literature Cited

ALBAUGH, T.J., R.A. RUBILAR, J. ALVAREZ, AND H.L. ALLEN. 2004. Radiata pine response to tillage, fertilization and weed control in Chile. *Bosque* 25(2):5–15.

ALVAREZ, J., H.L. ALLEN, T.J. ALBAUGH, J.L. STAPE, B.P. BULLOCK, AND C. SONG. 2013. Factors affecting the growth of radiata pine plantations in Chile. *Forestry* 86:13–36.

ALVAREZ, J., J. RODRIGUEZ, AND D. SUAREZ. 1999. Mejoramiento de la productividad de plantaciones de *Pinus radiata* D. Don, a través de un método racional de fertilización [Improving the productivity of Pinus radiata D. Don. plantations through a rational method of fertilization]. *Bosque* 20(1):23–36.

ALVAREZ, J., R. VENEGAS, AND C. PEREZ. 2004. Impacto de la duración y geometria del control de malezas en la productividad de plantaciones de *Pinus radiata* D. Don. en cinco ecosistemas del sur Chile [Impact of duration and geometry of weed control on the production of Pinus radiata D. Don. plantations in 5 ecosystems in southern Chile]. *Bosque* 25(2):57–67.

BALLARD, R. 1972. Influence of a heavy phosphate dressing and subsequent radiata pine response on the properties of a riverhead clay soil. *N. Z. J. For. Sci.* 2(2):202–216.

BINKLEY, D., J.L. STAPE, W.L. BAUERLE, AND M.G. RYAN. 2010. Explaining growth of individual trees: Light interception and efficiency of light use by *Eucalyptus* at four sites in Brazil. *For. Ecol. Manage.* 259: 1704–1713.

CANNELL, M.G.R. 1989. Physiological basis of wood production: A review. *Scand. J. For. Res.* 4:459–490.

CARLSON, C.A., T.R. FOX, H.L. ALLEN, AND T.J. ALBAUGH. 2008. Modeling mid-rotation fertilizer responses using the age-shift approach. *For. Ecol. Manage.* 256**:**256–262.

CARLSON, C.A., T.R. FOX, S.R. COLBERT, D.L. KELTING, H.L. ALLEN, AND T.J. ALBAUGH. 2006. Growth and survival of *Pinus taeda* in response to surface and subsurface tillage in the southeastern United States. *For. Ecol. Manage.* 234:209–217.

DADDOW, R.L., AND G.E. WARRINGTON. 1983. Growth-limiting soil bulk densities as influenced by soil texture. USDA For. Serv., Water Systems Development Group, Rep. No. WSD6-TN-00005, Fort Collins, CO. 17 p.

DU TOIT, B., C.W. SMITH, K.M. LITTLE, G. BOREHAM, AND R.N. PALLETT. 2010. Intensive, site-specific silviculture: Manipulating resource availability at establishment for improved stand productivity. A review of South African research. *For. Ecol. Manage.* 259:1836–1845.

Everett, C.J., and H. Palm-Leis. 2009. Availability of residual phosphorus for loblolly pine. *For. Ecol. Manage.* 258:2207–2213.

Ewers, B.E., R. Oren, T.J. Albaugh, and P.M. Dougherty. 1999. Carry-over effects of water and nutrient supply on water use of *Pinus ta*eda. *Ecol. Appl.* 9(2):513–525.

Fox, T.R., H.L. Allen, T.J. Albaugh, R.A. Rubilar, and C.A. Carlson. 2007. Tree nutrition and forest fertilization of pine plantations in the southern United States. *South. J. Appl. For.* 31(1):5–11.

Fox, T.R., L.A. Morris, and R.A. Maimone. 1989. The impact of windrowing on the productivity of a rotation age loblolly pine plantation. P. 133–140 in *Proceedings of the fifth biennial southern silvicultural research conference.* USDA For. Serv., New Orleans, LA.

Gent, J.A., H.L. Allen, and R.G. Campbell. 1986a. Phosphorus and nitrogen plus phosphorus fertilization in loblolly pine stands at establishment. *South. J. Appl. For.* 10(2):114–117.

Gent, J.A., H.L. Allen, R.G. Campbell, and C.G. Wells. 1986b. Magnitude, duration, and economic analysis of loblolly pine growth response following bedding and phosphorus fertilization. *South. J. Appl. For.* 10:124–128.

Glover, G.R., and B.R. Zutter. 1993. Loblolly-pine and mixed hardwood stand dynamics for 27 years following chemical, mechanical, and manual site preparation. *Can. J. For. Res.* 23(10):2126–2132.

Hanna, S.A. 2000. *Midrotation responses of loblolly pine to fertilization and vegetation control.* PhD dissertation, Auburn Univ., Auburn, AL. 209 p.

Huang, Y.S., and L. Teeter. 1990. An economic evaluation of research on herbaceous weed control in southern pine plantations. *For. Sci.* 36(2):313–329.

Kimberley, M.O., H. Wang, P.J. Wilks, C.R. Fisher, and G.N. Magesan. 2004. Economic analysis of growth response from a pine plantation forest applied with biosolids. *For. Ecol. Manage.* 189(1–3): 345–351.

Landsberg, J.J., and P.J. Sands. 2011. *Physiological ecology of forest production principles, processes and models.* Academic Press, London. 331 p.

Lauer, D.K., G.R. Glover, and D.H. Gjerstad. 1993. Comparison of duration and method of herbaceous weed control on loblolly pine response through midrotation. *Can. J. For. Res.* 23:2116–2125.

Mason, E.G., and P.G. Milne. 1999. Effects of weed control, fertilization, and soil cultivation on the growth of *Pinus radiata* at midrotation in Canterbury, New Zealand. *Can. J. For. Res.* 29(7):985–992.

Mason, E.G., D.B. South, and Z. Weizhong. 1995. Performance of *Pinus radiata* D. Don in response to seedling grade, weed control, and soil cultivation in the central north island of New Zealand. In *Popular summaries from 2nd international conference on forest vegetation management,* Gaskin, R.E., and J.A. Zabkeiwicz (eds.). Forest Research Institute, Bull. No. 192, Rotorua, New Zealand.

Mason, E.G., A.G.D. Whyte, R.C. Woollons, and B. Richardson. 1997. A model of the growth of juvenile radiata pine in the Central North Island of New Zealand: Links with older models and rotation-length analyses of the effects of site preparation. *For. Ecol. Manage.* 97(2):187–195.

Miller, J.H., R.L. Busby, B.R. Zutter, S.M. Zedaker, M.B. Edwards, and R.A. Newbold. 1995. Response of loblolly pine to complete woody and herbaceous control: Projected yields and economic outcomes—The COMProject. P. 81–89 in *Proceedings of the eighth biennial southern silvicultural research conference,* Edwards, M.B. (ed.). USDA For. Serv., Southern Research Station, Asheville, NC.

Miller, J.H., B.R. Zutter, S.M. Zedaker, M.B. Edwards, J.D. Haywood, and R.A. Newbold. 1991. A regional study on the influence of woody and herbaceous competition on early loblolly pine growth. *South. J. Appl. For.* 15:329–334.

Mininco, F. 1995. Compendio de funciones para especies de interés de Forestal Mininco S.A. [Compendium of functions for species of interest to Forestal Minin S.A., Publisher is Forestal Mininco]. Concepción, Chile.

Morris, L.A., and R.F. Lowery. 1988. Influence of site preparation on soil conditions affecting stand establishment and tree growth. *South. J. Appl. For.* 12:170–178.

Nambiar, E.K.S., and R. Sands. 1992. Effects of compaction and simulated root channels in the subsoil on root development, water-uptake and growth of radiata pine. *Tree Physiol.* 10(3):297–306.

Nilsson, U., and H.L. Allen. 2003. Short- and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. *For. Ecol. Manage.* 175:367–377.

Pritchett, W.L., and N.B. Comerford. 1982. Long-term response to phosphorus fertilization on selected southeastern Coastal-Plain soils. *Soil Sci. Soc. Am. J.* 46(3):640–644.

Richardson, B. 1993. Vegetation management practices in plantation forests of Australia and New Zealand. *Can. J. For. Res.* 23(10): 1989–2005.

Rubilar, R.A., T.J. Albaugh, H.L. Allen, J. Alvarez, T.R. Fox, and J.L. Stape. 2013a. Foliage development and leaf area duration in *Pinus radiata*. *For. Ecol. Manage.* 304:455–463.

Rubilar, R.A., T.J. Albaugh, H.L. Allen, J. Alvarez, T.R. Fox, and J.L. Stape. 2013b. Influences of silvicultural manipulations on above- and belowground biomass accumulations and leaf area in young *Pinus radiata* plantations, at three contrasting sites in Chile. *Forestry* 86(1): 27–38.

SAS Institute, Inc. 2002. *SAS version 9.1 TS.* SAS Institute, Inc., Cary, NC. 5136 p.

Schmidtling, R.C. 1984. Early intensive culture affects long-term growth of loblolly pine trees. *For. Sci.* 30(2):491–498.

Smethurst, P.J., and E.K.S. Nambiar. 1989. Role of weeds in the management of nitrogen in a young *Pinus radiata* plantation. *New Forests* 3(3):203–224.

Snowdon, P. 2002. Modeling Type 1 and Type 2 growth responses in plantations after application of fertilizer or other silvicultural treatments. *For. Ecol. Manage.* 163:229–244.

Snowdon, P., and H.D. Waring. 1984. Long-term nature of growth responses obtained to fertiliser and weed control applied at planting and their consequences for forest management. P. 701–711 in *Proceedings of the IUFRO symposium on site and site productivity of fast growing plantations,* Grey, D.C., A.P.G. Schonau, C.J. Schutz, and A. van Laar (eds.). South African Forest Research Institute (SAFRI) and Department of Environmental Affairs, Pretoria.

Somerville, A. 1979. Root anchorage and root morphology of *Pinus radiata* on a range of ripping treatments. *N. Z. J. For. Sci.* 9(3):294–315.

South, D.B., J.H. Miller, M.O. Kimberley, and C.L. Vander Schaaf. 2006. Determining productivity gains from herbaceous vegetation management with "age-shift" calculations. *Forestry* 79(1):43–56.

Vitousek, P.M., S.W. Andariese, P.A. Matson, L.A. Morris, and R.L. Sanford. 1992. Effects of harvest intensity, site preparation, and herbicide use on soil nitrogen transformations in a young loblolly pine plantation. *For. Ecol. Manage.* 49 (3–4): 277–292.

Will, R.E., D. Markewitz, R. Hendrick, D.F. Meason, T.R. Crocker, and B.E. Borders. 2006. Nitrogen and phosphorus dynamics for 13-year-old loblolly pine stands receiving complete competition control and annual N fertilizer. *For. Ecol. Manage.* 227(2006):155–168.

Zutter, B.R., and J.H. Miller. 1998. Eleventh-year response of loblolly pine and competing vegetation to woody and herbaceous plant control on a Georgia flatwoods site. *South. J. Appl. For.* 22(2):88–95.