JOURNAL OF FOREST SCIENCE, *62*, 2016 (4): 153–162

doi: 10.17221/106/2015-JFS

Mid-rotation response to fertilizer by *Pinus radiata* D. Don at three contrasting sites

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ABSTRACT: Mid-rotation responses to fertilization of *Pinus radiata* D. Don plantations after the first or second thinning have been observed in research experiments in many regions where the species is grown. The practice is not however common in commercial plantations. This is probably because the effects of soil-site conditions on the magnitude and duration of tree and stand growth responses are not well understood. The effects of nitrogen (150 and 300 kg N·ha^{-1}) and phosphorus (0, 20 and 40 kg P·ha^{-1}) including common base fertilization of boron (8 kg B·ha^{-1}) and potassium (65 kg K·ha^{-1}) were evaluated in three mid-rotation *P. radiata* plantations after thinning. The plantations were located on sites with contrasting nutrient and water availability, sandy, granitic and red-clay sites, in south-central Chile. The magnitude and duration of growth response was site specific. After 8 years, the growth response to the highest dose of fertilization relative to the control was 57 m^3·ha^{-1} (16%) at the granitic and 24 m^3·ha^{-1} (14%) at the sandy site. No response to either nitrogen or phosphorus fertilizer was observed at the red-clay site. Nitrogen and phosphorus were limiting at both granitic and sandy sites, and high fertilization doses considering 300 kg N·ha^{-1} plus 40 kg P·ha^{-1} would ameliorate nutrient resource limitations and yield a cost-effective increment in stand volume.

Keywords: forest fertilization; sustained response; volume increment; stand growth; foliar nitrogen

The local and international demand for timber is increasing. This has resulted in the need to increase wood supply for plantations and a favourable environment for investment (Cubbage et al. 2007). An important intervention for improving productivity from planted forests is to optimize tree nutrition at various stages throughout a rotation by management (Albaugh et al. 2004). The application of fertilizer at mid-rotation to fast-growing pine plantations has been reported for *P. radiata* D. Don in Australia (Carlyle 1995; Hopmans et al. 2008), New Zealand (Rivaie, Tillman 2009), and has become a more common practice in the southeastern United States for loblolly pine (Fox et al. 2007; Albaugh et al. 2012). However, these practices have been rarely reported in South

Supported by the Universidad de Concepción, by the Bioforest S.A. (Forestal Arauco S.A.), and by the Forestal Mininco, Project No. FPC-RW13, and by the National Commission for Scientific and Technological Research – Chile (CONICYT), and by the Chilean International Cooperation Agency (AGCI), Project No. 2013-63130285.

America where extensive areas of pine plantations have been established. Commercial plantations of *P. radiata* are the main basis for forest industry in Chile (Álvarez et al. 2013), and by 2013 more than 1.5 million ha had been established across a range of soil and climate conditions (Infor 2015), resulting in different growth. The large range in current productivity suggests that some plantations may respond to mid-rotation application of fertilizer but uncertainty remains about site specific factors affecting the response.

Forest productivity is driven by the availability of water and nutrient resources (Turner, Lambert 1986; Snowdon, Benson 1992; Albaugh et al. 2004; Landsberg, Sands 2010). It is also known that demand for nitrogen increases in fast-growing plantations when canopy closure has occurred (Allen et al. 1990). On most sites this demand is sustained after canopy closure while by mid-rotation the availability of N in the soil decreases due to continuous uptake by the stand, competition for resources, weeds and forest floor immobilization (Richter et al. 2000). The net effect of these mechanisms and mismatch in the timing of supply and demand are a reduction in growth rates (Albaugh et al. 2004). The addition of fertilizers at this stage of stand development in order to match soil nutrient availability with demand and improve stand productivity has gained considerable attention by forest industry (Fox et al. 2006). Positive growth responses to mid-rotation application of N and P have been documented across a variety of sites and stand conditions in loblolly pine (*Pinus taeda* Linnaeus) (Fisher, Garbett 1980; Rojas 2005). Site-specific opportunities exist to have a positive growth response to mid-rotation fertilization with N and P (Carlyle 1995; Fox et al. 2007; Albaugh et al. 2012) due to the increase in short-term availability of nutrients that promotes leaf area and foliage production (Fox et al. 2007; Rubilar et al. 2013).

Quantifying the magnitude and duration of growth responses to silvicultural treatments (weed control, fertilization) is essential to understand how silviculture affects site resource availability (Albaugh et al. 2004). The growth response of plantations to mid-rotation application of fertilizer may follow four patterns (type A, B, C, and D) relative to an untreated control. A treatment response is considered type A if growth increments increase throughout the rotation and result in an increased carrying capacity (Snowdon, Waring 1984; Snowdon 2002; Nilsson, Allen 2003; Albaugh et al. 2015). Response to P fertilization at planting on P limited sites, but also treatments that reduce or eliminate hardwood competition (e.g., soil tillage, herbicide application) may result in a type A response (Zutter, Miller 1998; Nilsson, Allen 2003). A response is considered type B if growth increases in response to treatment relative to an untreated control occur for a short time after treatment, then the initial available resources are exhausted or are no longer available, and treated trees then stop responding (Albaugh et al. 2015). Generally, mid-rotation nutrient applications on nutrient-limited sites result in a type B response (Miller 1981; Fox et al. 2007). Type C is similar to type B, where there is a positive response shortly after treatment; although the response will be partially or completely lost over time. Type D is observed as a negative growth response relative to an untreated control from the time of treatment initiation (Albaugh et al. 2015).

Type B responses to N fertilization have been observed to last for 3 to 5 years when N is applied to *P. radiata* at mid-rotation thinning (Miller 1981), but the best growth responses to fertilization have been reported when N and P were applied together (Rojas 2005). Blevins et al. (2006) found that *Tsuga heterophylla* (Rafinesque) Sargent stands that received N alone increased individual tree growth approximately fourfold during the first 4 years after application. Although growth response to the first application of P alone was not as large as to N alone, P fertilization seems to have induced a longer duration of response by 10–15 years (a type A response).

The magnitude and duration of the response to mid-rotation application of fertilizer in *P. radiata* have not been widely reported. This makes it difficult for forest managers to justify mid-rotation application of fertilizer as a tool to increase stand growth (Gent et al. 1986) and improve economic returns. Moreover, limited information exists to identify sites and stands which may provide an economic response to fertilization to develop site-specific management prescriptions (Carlyle 1998). The objective of our study was to evaluate the magnitude and duration of the response of *P. radiata* to mid-rotation application of N and P at three sites with contrasting fertility and water availability in order to understand how resource availability affects duration and response type across sites. This study also represents the first report exploration of growth responses to mid-rotation application of fertilizer for *P. radiata* in south-central Chile.

MATERIAL AND METHODS

Study area. The study sites were located in the Bío-Bío Region (Region VIII) in south-central Chile. Three *P. radiata* stands that were

Table 1. Site and stand characteristics for granitic, sandy and red-clay sites in the Bio-Bio region of Chile

Site	Granitic	Sandy	Red-clay
Latitude and longitude	36°39'0.72''S 72°44'52.08''W	37°9'47.88''S 72°14'17.53''W	37°48'46.80''S 72°19'30.00''W
Annual mean temperature (°C)	13.6 (6 yr)	13.6 (15 yr)	13 (35 yr)
Annual mean precipitation (mm)	860 (35 yr)	1,319 (35 yr)	1,254 (35 yr)
Geology	granite	volcanic sands	ancient volcanic ash
Soil taxonomy	Ultic Palexeralfs	Typic Xeropsamments	Xeric Paleumults
Texture	clay-loam	sandy	clay
pH	5.6	6	5.3
Organic matter (%)	7	3	14
Total N (%)	0.1	0.06	0.22
Drainage	moderately drained	well drained	well to moderately drained
Planting year	1991	1991	1991
Date of fertilization	May 2003	June 2004	June 2007
Age in the year of fertilization (yr)	12	13	15
Diameter before fertilization (cm)	25	21	24
Height before fertilization (m)	19	16	22
Basal area before fertilization ($m^2\cdot ha^{-1}$)	20	16	19
Volume before fertilization ($m^3\cdot ha^{-1}$)	124	87	143

thinned at mid-rotation to an average stocking of 400 trees per hectare were chosen for the study. These plantations were on granitic, sandy and red-clay sites that represented contrasting soil textures and parent materials (Table 1). The climate at the three study sites is characterized by warm-dry summers, and cool winter. The rainfall mainly 65–70% of the annual total precipitation occurs during the winter (June–August) and most other rainfalls during autumn (March–May) and spring (September–November).

Experimental design. At each site a factorial experimental design with 4 blocks was used. The plots were 0.36 ha (60 × 60 m) with internal measurement plots of 0.09 ha centred within the treatment plots. Plots having similar pretreatment stand vegetation characteristics (height, basal area, stand density) were assigned to a single block to minimize within-block variation. Treatments included a control (no fertilization), and a factorial combination of 2 levels of N (150 and 300 kg $N\cdot ha^{-1}$) and 3 levels of P (0, 20 and 40 kg $P\cdot ha^{-1}$), plus a basal application of 8 kg $B\cdot ha^{-1}$ + 65 kg $K\cdot ha^{-1}$ (Table 2). The fertilizer sources included urea (46% N), triple superphosphate (20% P), boronatrocalcite (10% B) and potassium chloride (61.5% K). Fertilizer was applied by hand broadcast in autumn, and herbicides were applied before fertilization to the stands at the granitic and red clay sites, while application was not necessary at the sandy site.

Table 2. Description of treatments used to examine the effect of N and P fertilization in *Pinus radiata* D. Don at mid-rotation on stand growth

Treatment	Element ($kg\cdot ha^{-1}$)			
	N	P	B	K
T-000	0	0	0	0
T-101	150	0	8	65
T-111	150	20	8	65
T-121	150	40	8	65
T-201	300	0	8	65
T-211	300	20	8	65
T-221	300	40	8	65

T-000 – control

Foliage sampling and analysis. Five dominant trees in each measurement plot were selected and identified, and 20 fascicles were collected from the current years of growth to obtain a composite sample of 100 fascicles by plot. Foliage was collected before addition of fertilizer at each site, and 1–3 years after application of fertilizer. Needles were collected from the first flush foliage on a primary lateral branch in the upper one-third of the live crown. At the sandy site the samples were collected until year 2 only. Foliage samples were dried to a constant weight at 65–70°C and then analysed for N using an NC 2100 CHN auto-analyser (CE Instruments Ltd., Hindley Green, UK). In the case of P a nitric acid wet digestion was applied using the method described by Jones and Case (1990) and concentrations were determined using an ICP-AES spectrophotometer (SPECTRO Analytical Instruments GmbH, Kleve, Germany).

Stand productivity. Plots were installed in homogenous site and stand conditions. Diameter (diameter at breast height) and total height were taken of all trees in measurement plots, and basal area and stand volume were estimated before fertilization to have a baseline (Table 1).

After treatment, stand measurements were done and repeated annually in all treatments to calculate the stand growth over time.

Data analysis. The effect of treatments on foliar N and P concentration was calculated annually (1st–3rd year since treatment), and diameter, height, basal area and volume growth were plotted over time to determine the expected long-term response for each site up to age 21. Statistical analysis of mean treatment differences with respect to the control was done using the JMP 8 statistical software (SAS Institute, Cary, USA; SAS 2009a).

A longitudinal repeated measures analysis (Littell et al. 2006) was conducted to evaluate the effects of fertilization (F) over time (T) on current annual volume increment (CAI) for each site, using the following statistical model (Eq. 1):

$$Y_{ijk} = \mu + \alpha_i + \gamma_k + (\alpha\gamma)_{ik} + e_{ijk} \qquad (1)$$

where:

Y_{ijk} – current annual volume increment ($kg \cdot ha^{-1} \cdot yr^{-1}$)
M – mean for treatment i at time k
α_i – effect for treatment
γ_k – effect for time
$(\alpha\gamma)_{ik}$ – effect for treatment × time interaction
e_{ijk} – random error associated with the measurement at time k on the j^{th} subject that is assigned to treatment i

The longitudinal analysis was developed by using a mixed model that considered several variance-covariance structures for each variable, including compound symmetry and first order autoregression. The Bayesian information criterion was used to select the best fit to the data (SAS 2009b). All statistical analyses were evaluated using a P-value of < 0.05 as a significance level, and were specific to a site. There were no statistical comparisons between sites.

RESULTS

Foliar nitrogen and phosphorus

Three years after the application of fertilizer, the foliar N concentrations for treatments with 300 kg $N \cdot ha^{-1}$ plus P (20, 40 kg $P \cdot ha^{-1}$) (T-211, T-221) were significantly higher than in the control at the granitic site (Fig. 1a, Table 3).

One year after treatment foliar N concentration increased significantly for all treatments with N application (T-201, T-211, T-221) at the sandy site (Fig. 1b, Table 3). At the red-clay site foliar N concentration was significantly higher in all fertilized treatments one and two years after application of fertilizer (Fig. 1c, Table 3). The greatest relative increase in foliar N concentration occurred for treatments where 300 kg $N \cdot ha^{-1}$ were applied, and the increments ranged between 14 to 38% (Table 3).

The effect of fertilization on foliar N concentration decreased after application for sandy and red-clay sites (Figs 1b, c). The fertilization did not increase foliar P concentration at any site (Figs 1d–f).

Growth response

Growth of each stand was vigorous and there were no differences in mortality between treatments. Seven to eight years (granitic, sandy), and four years (red-

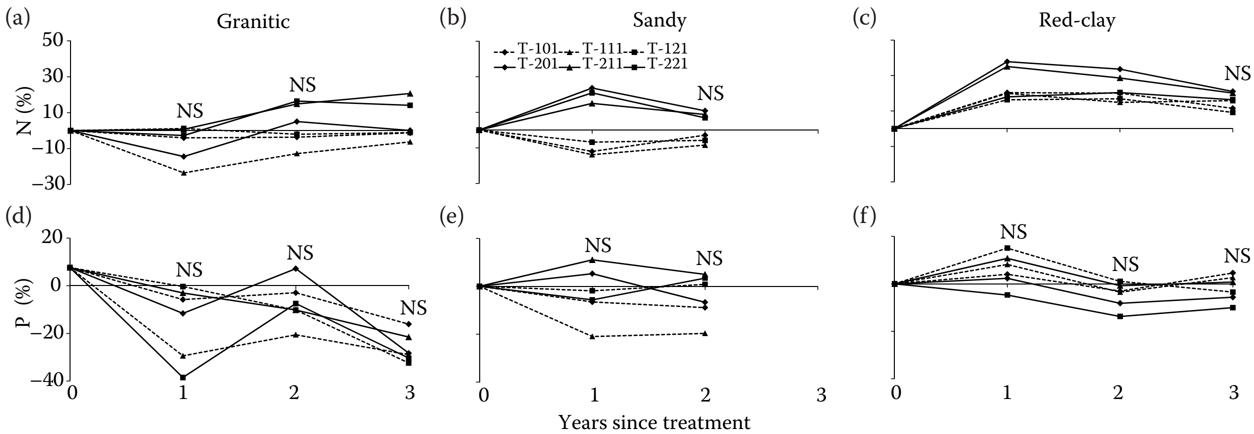

Fig. 1. Changes in response to foliar N and P concentration for granitic (a, d), sandy (b, e) and red-clay site (c, f)
NS – no significant differences

Table 3. Increment response (treatment means), percentage of response and summary of statistical significance (*P*-value) of main effects of fertilization in *Pinus radiata* D. Don at mid-rotation (N and P) relative to the control treatment (T-000), for foliar N and P concentration within 1–3 years from the treatment application at the granitic, red-clay, and sandy sites

Site	Treatments	Year 1		Year 2		Year 3	
		(%)	*P*	(%)	*P*	(%)	*P*
Granitic	T-000/T-211	–	–	–	–	21	0.001
	T-000/T-221	–	–	–	–	14	0.043
Sandy	T-000/T-201	24	0.002	–	–		
	T-000/T-211	15	0.022	–	–		
	T-000/T-221	21	0.004	–	–		
Red-clay	T-000/T-101	20	0.004	20	0.005	–	–
	T-000/T-111	20	0.004	15	0.033	–	–
	T-000/T-121	16	0.013	17	0.013	–	–
	T-000/T-201	38	< 0.001	34	< 0.001	–	–
	T-000/T-211	35	< 0.001	29	< 0.001	–	–
	T-000/T-221	18	0.008	20	0.004	–	–

clay) after treatment, fertilizer significantly increased diameter growth for T-121, T-201, T-211, T-221 treatments at the sandy site (11.8–18.7% response) (Fig. 2b, Table 4), and for T-211 at the red clay site (Fig. 2c, Table 4). Addition of fertilizer increased basal area at granitic (T-221) and sandy site (T-121, T-201, T-211 and T-221) (5.9–18.1%) (Figs 2g, h, Table 4), and had no significant effect on height at any site (Table 4).

A type B response was observed for diameter and basal area at the sandy site (all treatments with positive response), whereas a type A response was observed for diameter at the red-clay site (T-211), and for basal area at the granitic site (T-221).

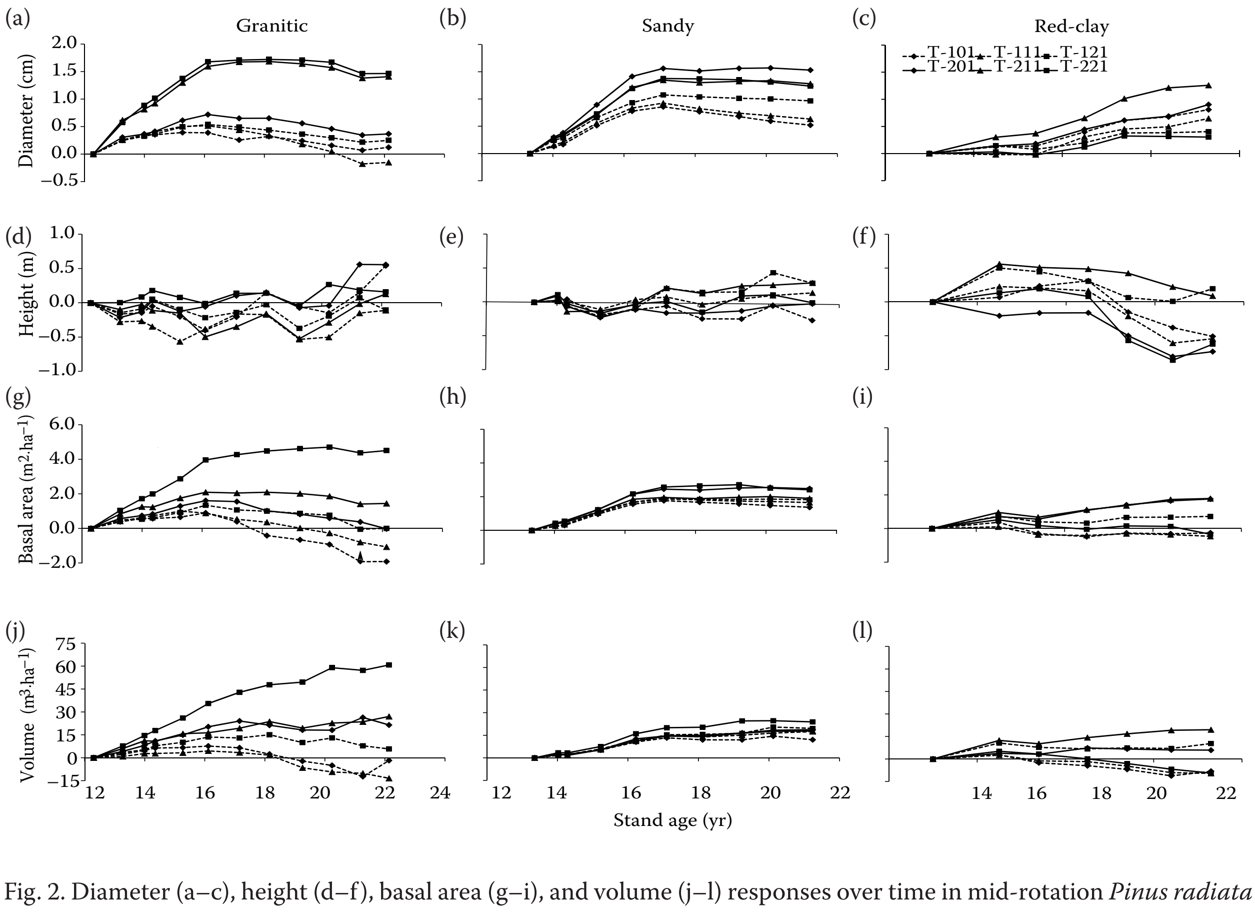

Fig. 2. Diameter (a–c), height (d–f), basal area (g–i), and volume (j–l) responses over time in mid-rotation *Pinus radiata* D. Don stand fertilized with N and P at granitic (d, e, g, j), sandy (b, e, h, k) and red-clay (c, f, i, l) sites

Table 4. Diameter, height, basal area, and volume response (treatment means), percentage of response and summary of statistical significance (*P*-value) of mid-rotation fertilizer application (N and P) relative to the control (T-000) for *Pinus radiata* D. Don at 21 years of age at the granitic, sandy and red-clay sites

	Diameter			Height			Basal area			Volume		
Treatments	(cm)	(%)	*P*	(m)	(%)	*P*	($m^2\cdot ha^{-1}$)	(%)	*P*	($m^3\cdot ha^{-1}$)	(%)	*P*
Granitic												
T-000/T-101	0.07	0.54	0.927	0.15	1.07	0.685	–1.93	–8.00	0.340	–12.31	–3.41	0.637
T-000/T-111	–0.18	–1.41	0.819	–0.15	–1.05	0.688	–0.79	–3.30	0.691	–10.18	–2.82	0.696
T-000/T-121	0.22	1.71	0.780	0.07	0.49	0.849	–0.04	–0.19	0.983	7.80	2.16	0.764
T-000/T-201	0.34	2.72	0.658	0.56	3.94	0.145	0.38	1.55	0.850	26.39	7.32	0.316
T-000/T-211	1.38	10.98	0.085	–0.02	–0.10	0.967	1.42	5.87	0.480	23.57	6.53	0.369
T-000/T-221	1.46	11.63	0.070	0.19	1.31	0.617	4.38	**18.14**	**0.038**	57.23	**15.87**	**0.037**
Sandy												
T-000/T-101	0.52	6.37	0.136	–0.24	–2.67	0.538	1.37	9.11	0.131	12.01	7.03	0.258
T-000/T-111	0.63	7.72	0.074	0.17	1.88	0.660	1.65	10.97	0.072	17.43	10.20	0.106
T-000/T-121	0.97	**11.80**	**0.009**	0.31	3.51	0.421	1.82	**12.12**	**0.049**	19.53	11.43	0.726
T-000/T-201	1.53	**18.66**	**0.000**	0.01	0.11	0.986	2.48	**16.49**	**0.010**	18.73	10.96	0.084
T-000/T-211	1.28	**15.61**	**0.001**	0.32	3.57	0.413	1.90	**12.62**	**0.041**	17.83	10.43	0.099
T-000/T-221	1.24	**15.10**	**0.001**	0.02	0.25	0.953	2.41	**16.03**	**0.012**	23.90	**13.98**	**0.031**
Red-clay												
T-000/T-101	0.81	11.09	0.189	–0.51	–7.45	0.479	–0.27	–1.93	0.844	–8.23	–4.49	0.633
T-000/T-111	0.65	8.90	0.290	–0.54	–7.93	0.450	–0.47	–3.38	0.729	–9.58	–5.23	0.579
T-000/T-121	0.41	5.54	0.506	0.20	2.85	0.787	0.72	5.22	0.594	10.31	5.63	0.550
T-000/T-201	0.91	12.39	0.145	–0.73	–10.74	0.311	1.76	12.81	0.199	5.89	3.22	0.732
T-000/T-211	1.26	**17.25**	**0.047**	0.09	1.28	0.903	1.79	12.99	0.193	19.46	10.63	0.264
T-000/T-221	0.31	4.18	0.615	–0.62	–9.10	0.387	–0.34	–2.49	0.799	–9.40	–5.13	0.586

in bold – significant at $P < 0.05$

At the sandy site and a give rate of P application, the increase in diameter was greater for 300 kg N·ha^{-1} than for the 150 kg N·ha^{-1} treatment (Table 4). A type C volume response was found at the granitic site for treatments with 150 kg N·ha^{-1} (T-101, T-111 and T-121 with 0, 20 and 40 kg P·ha^{-1}, respectively). The 300 kg N·ha^{-1} and 40 kg P·ha^{-1} treatment (T-221) had a sustained response and significantly increased the stand volume at the granitic site of 57.2 m^3·ha^{-1} (15.87%) (Fig. 2j) relative to T-000 at 21 years of age (22 years are considered as the normal harvesting age), with a mean annual increment (MAI) of 6.4 m^3·ha^{-1}·yr^{-1} over 9 years. The same treatment significantly increased the stand volume at the sandy site with a volume increment of 23.9 m^3·ha^{-1} (13.98%) (Fig. 2k) at 21 years of age, with a MAI of 3.0 m^3·ha^{-1}·yr^{-1} over 8 years. Fertilization had no effect on volume at red-clay site at 21 years of age (Fig. 2l, Table 4).

There was a significant fertilizer application by time interaction (F × T) on CAI at the granitic and sandy sites (Table 5) that was maintained for 10 and 7 years after fertilizer application, respectively (Table 5, Fig. 3a, b). The F × T was not evident at the red-clay site (Table 5, Fig. 3c). Generally, treatments that included 300 kg N ha^{-1} had higher CAI for volume compared with the lower dose of 150 kg N·ha^{-1}. This difference was largest when P was applied (Table 6). Specifically, 300 kg N·ha^{-1} plus 40 kg P·ha^{-1} treatment (T-221) showed the highest CAI and the duration of response was longer than 5 years (Table 4, Fig 3a, b).

Table 5. Repeated measures analysis of fertilization (F) and sampling date (T) effects on mid-rotation *Pinus radiata* D. Don stand and current annual volume increment responses at the granitic, sandy and red-clay sites

	Type 3 tests of fixed effects				
Soil	Effect	Num DF	den DF	*F*	*P*
Granitic	F	6	21	1.25	0.32
	T	11	231	293.06	**< 0.0001**
	F × T	66	231	1.44	**0.03**
Sandy	F	6	21	0.73	0.63
	T	9	189	735.18	**< 0.0001**
	F × T	54	189	1.38	**0.05**
Red-clay	F	6	21	0.63	0.70
	T	6	126	241.83	**< 0.0001**
	F × T	36	126	0.94	0.56

in bold – significant at $P < 0.05$, Num DF – degree of the numerator, den DF – degree of the denominator

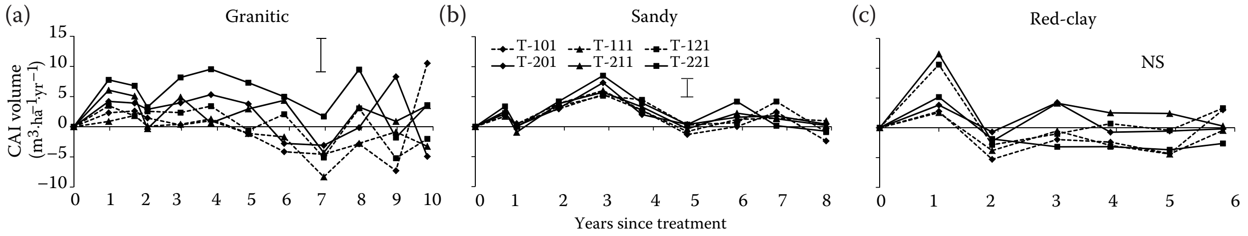

Fig. 3. Current annual increment (CAI) volume response to N and P application at mid-rotation *Pinus radiata* D. Don stands above the control (T-000) at granitic, sandy and red-clay sites. Error bars are the standard error of longitudinal analysis

NS – no significant differences

Higher CAI volume responses were observed for T-221 treatment, compared with other treatments at the granitic and sandy site (Fig. 3). The CAI volume response of T-221 above the control treatment (T-000) was 24.1 and 19.8% for 4 and 8 years after fertilizer application, respectively, at the granitic site, and reached increments of 19.4%, 27.9 and 18.6 at 2, 4 and 6 years after fertilizer application, respectively, at the sandy site (Table 6). These temporal patterns of CAI responses suggest a type A volume response of T-221 at granitic and sandy sites (Fig. 3a, b, Table 6).

Table 6. Repeated measures longitudinal analysis of contrasts, evaluating fertilizer application against control treatment by sampling date on current annual volume increment response for mid-rotation in *Pinus radiata* D. Don at the granitic, sandy and red-clay sites

Years from treatment	Treatment	*P*	Response (%)
Granitic			
4	**T-000/T-221**	**0.023**	**24.1**
7	T-000/T-111	0.047	–21.3
8	**T-000/T-221**	**0.024**	**19.8**
9	T-000/T-201	0.048	18.1
10	T-000/T-101	0.013	26.2
Sandy			
2	T-000/T-111	0.041	17.8
2	T-000/T-211	0.042	17.7
2	**T-000/T-221**	**0.026**	**19.4**
3	T-000/T-101	0.005	19.9
3	T-000/T-111	0.002	22.3
3	T-000/T-121	0.007	19.2
3	T-000/T-201	0.000	27.2
3	T-000/T-211	0.003	21.3
4	T-000/T-121	0.018	31.6
4	**T-000/T-221**	**0.036**	**27.9**
6	**T-000/T-221**	**0.027**	**18.6**
7	T-000/T-121	0.027	17.3

only comparisons that had a significant statistical level lower than 5% are shown ($P < 0.05$), values highlighted in bold indicate comparison between the control (T-000) and T-221 means showing the highest responses at the end of the study

DISCUSSION

Similar to our study, Will et al. (2006) found that the concentration of N in foliage increased by 32% in a 13-year-old loblolly pine stand fertilized annually with 72 kg N·ha^{-1} for 12 years and with 59 kg P·ha^{-1} at age one and two, and 36 kg P·ha^{-1} at years 11 and 12. The foliar concentration of P was not affected by fertilization. Increases in the foliar concentration of N have been reported within the first year of fertilizer application in stands of *Pinus pinaster* Aiton (Keay et al. 1968) and Corsican pine (Miller, Cooper 1973). Fife and Nambiar (1997) indicated that the amount of foliar N translocated within the tree increased with increasing rate of N application and contributed to the growth response of trees for five years after fertilizer application. The same authors suggested that most of, if not all, applied N had been taken up by the trees or leached below the rooting zone within 1 year after application. Similarly, Smethurst and Nambiar (1990) and Woods et al. (1992) reported potentially high leaching losses of mineral soil N in plantations on sandy soils. Despite being a poor site, in our study responses in basal area (ranging from 1.8 to 2.48 m^2·ha^{-1}) and volume (3 m^3·ha^{-1}·yr^{-1}) at the sandy site were not expected. In a N and P fertilization study developed by Hunter et al. (1986) in New Zealand, basal area response averaged 1.35 m^2·ha^{-1} (it ranged from 1.1 to 5.0 m^2·ha^{-1}), and the largest responses occurred in stands that had received fertilizer at an early age and were on soils poor in N availability such as sandy soils.

The responses observed in our study at the red-clay site are less nutrient limited compared with granitic and sandy sites, and this could have influenced the lack of response. Similarly, Vose and Allen (1988) reported for an N deficient site the highest volume production for the highest application of N fertilizer (336 kg·ha^{-1}). Similar treatments applied onto another site which was not N deficient showed no response to fertilizer application. Similarly, current annual increment responses observed at our sandy site showed a similar magnitude of response to N and P like that reported for a series of fertilizer application trials, across a variety of site and stand conditions in the southeastern United States for loblolly pine. These sites exhibited fertilizer application responses of 3.8 m^3·ha^{-1}·yr^{-1} (Rojas 2005; Fox et al. 2007) and 3.2 m^3·ha^{-1}·yr^{-1} (Albaugh et al. 2012) for the highest doses of N and P. However, CAI responses reached at our granitic site were nearly twice higher than those in the cited studies.

Major changes in cumulative growth response at the granitic and sandy sites were due to fertilizer effects when N was applied at the highest dose (300 kg N·ha^{-1}). In an experiment in which four levels of N were used (0, 150, 300 and 600 kg·ha^{-1}), Fife and Nambiar (1995) also reported similar responses for 600 kg N·ha^{-1} treatment showing a long-term response in 6-year-old *P. radiata* stand.

The observed growth response at mid-rotation of *P. radiata* stands after thinning for our sites supports the synergistic effect of N and P fertilization described by Turner et al. (1996). They reported a 21% volume increment in a study with 21 trials of fertilizer application after thinning in *P. radiata* stands on sites with contrasting soil-site characteristics in New South Wales, Australia. The highest responses for both basal area and volume increment across sites were observed also for the highest level of nutrient addition considering 400 kg N·ha^{-1} in conjunction with P application. However, there was no significant response to N or P alone in these trials.

Blevins et al. (2006) reported long-term growth responses (15 years) related with the effects of including P in the fertilizer on western red cedar and western hemlock regenerating on cedar-hemlock sites. Their results indicated that western hemlock did not respond to a second application of N unless P had been applied at least once. Opposite to this, Carlyle (1998) reported that basal area increment increased in response to the rate of N fertilizer applied, but there was neither response to P alone nor any N and P interaction.

The combined effect of N and P application is consistent with the suggestion that P may be responsible for the long-term improvements in nutrient supply and microbial activity in the forest floor, N mineralization rates, and site quality reported after 13 years of N + P fertilizer addition to cedar-hemlock sites (Bradley et al. 2000; Bennett et al. 2003). Some authors have suggested that the inclusion of P in the fertilizer may stimulate N cycling (Bennett et al. 2003) and increase rates of N mineralization (Côté et al. 2000; White, Reddy 2000; Carlyle, Nambiar 2001). Our study showed that both N and P were necessary for the volume response observed at granitic and sandy sites. Our results suggest that part of the observed growth response at the granitic and sandy sites was related to changes in N cycling and improving N availability over time considering the duration and magnitude of response observed for the highest N dose applied (300 kg N·ha^{-1}) compared to the 150 kg N·ha^{-1} dose.

However, the red-clay site showed no response to the same treatments. In addition to nutrients, this could be attributed to differences in soil and climate conditions between the sites. Climate factors such as rainfall amount and distribution should be taken into account due to their effect on tree growth (Gower et al. 1994) and because stemwood production for *P. radiata* plantations is controlled by incoming solar radiation, soil water, nutrient content and temperatures (Álvarez et al. 2012). Similarly, Linder et al. (1987) and Snowdon and Benson (1992) examining tree growth response in a water and nutrient manipulation study, identified both elements as the most important factors limiting the growth of *P. radiata* near Canberra, Australia (Benson et al. 1992). Despite the importance of *P. radiata* plantations in Chile, few systematic analyses have been developed to explain the observed variability in productivity (Álvarez et al. 2012) that may explain responses to nutrient additions. However, our study suggests that there exist large opportunities to increase *P. radiata* productivity across sites in Chile and limitations in soil N and also in soil P seem to be more critical in the range of productivity sites rather than water resource availability in the observed range of sites. For future studies, climate and periodical soil assessments may provide a better understanding of the processes related with stand growth responses over time and differences between sites.

CONCLUSIONS

Fertilization increased the foliar N concentration within 1–3 years after fertilization. N limited pine growth at granitic and sandy sites, and fertilization at mid-rotation ameliorated these nutrient limitations. Type A volume responses occurred when N was applied at higher doses in combination with

P (300 kg N·ha^{-1} + 40 kg P·ha^{-1}). Fertilization increased the stand volume at the granitic site by 57.23 m^3·ha^{-1} (15.87%), and at the sandy site with an increment volume of 23.9 m^3·ha^{-1} (13.98%) at 21 years of age. The addition of both nutrients, N and P, promoted a much larger and long-term response at these sites and may provide opportunities for large increases in productivity, and to obtain a type A response. Conversely, red-clay sites apparently with higher soil nutrient availability at mid-rotation showed no growth responses to fertilizer application.

Acknowledgement

We thank the Soil, Nutrition and Forest Productivity Laboratory at Universidad de Concepción for providing lab equipment and space for analyses.

References

Albaugh T., Alvarez J., Rubilar R., Fox T., Allen H., Stape J., Mardones O. (2015): Long-term *Pinus radiata* productivity gains from tillage, vegetation control, and fertilization. Forest Science, 61: 800–808.

Albaugh T., Rubilar R., Alvarez J., Allen H. (2004): Radiata pine response to tillage, fertilization and weed control in Chile. Bosque, 25: 5–15.

Albaugh T., Stape J., Fox T., Rubilar R., Allen H. (2012): Midrotation vegetation control and fertilization response in *Pinus taeda* and *Pinus elliottii* across the southeastern United States. Southern Journal of Applied Forestry, 36: 44–53.

Álvarez J., Allen H., Albaugh T., Stape J., Bullock B., Song C. (2013): Factors influencing the growth of radiata pine plantations in Chile. Forestry, 86: 13–26.

Allen H., Dougherty P., Campbell R. (1990). Manipulation of water and nutrients; practice and opportunity in southern US pine forests. Forest Ecology and Management, 30: 437–453.

Bennett J., Blevins L., Barker J., Blevins D., Prescott C. (2003). Increases in tree growth and nutrient supply still apparent 10 to 13 years following fertilization and vegetation control of salal-dominated cedar hemlock stands on Vancouver Island. Canadian Journal of Forest Research, 33: 1516–1524.

Benson M., Myers B., Raison R. (1992): Dynamics of stem growth of *Pinus radiata* as affected by water and nitrogen supply. Forest Ecology and Management, 52: 117–137.

Blevins L., Prescott C., Van Niejenhuis A. (2006): The roles of nitrogen and phosphorus in increasing productivity of western hemlock and western redcedar plantations on northern Vancouver Island. Forest Ecology and Management, 234: 116–122.

Bradley R., Titus B., Preston C., Bennett J. (2000): Improvement of nutritional site quality 13 years after single application of fertiliser N and P on regenerating cedar-hemlock cutovers on northern Vancouver Island, BC. Plant and Soil, 223: 197–208.

Carlyle J. (1995): Nutrient management in a *Pinus radiata* plantation after thinning: The effect of nitrogen fertilizer on soil nitrogen fluxes and tree growth. Canadian Journal of Forest Research, 25: 1673–1683.

Carlyle J. (1998): Relationships between nitrogen uptake, leaf area, water status and growth in an 11-year-old *Pinus radiata* plantation in response to thinning, thinning residue, and nitrogen fertiliser. Forest Ecology and Management, 108: 41–55.

Carlyle J., Nambiar E. (2001): Relationships between net nitrogen mineralization, properties of the forest floor and mineral soil, and wood production in *Pinus radiata* plantations. Canadian Journal of Forest Research, 31: 889–898.

Côté L., Brown S., Paré D., Fyles J., Bauhus J. (2000): Dynamics of carbon and nitrogen mineralization in relation to stand type, stand age and soil texture in the boreal mixedwood. Soil Biology and Biochemistry, 32: 1079–1090.

Cubbage F., Mac Donagh P., Júnior J., Rubilar R., Donoso P., Ferreira A., Hoeflich V., Olmos V., Ferreira G., Balmelli G. (2007): Timber investment returns for selected plantations and native forests in South America and the Southern United States. New Forests, 33: 237–255.

Fife D.N., Nambiar E.K.S. (1995): Effect of nitrogen on growth and water relations of radiata pine families. Plant and Soil, 168–169: 279–285.

Fife D.N., Nambiar E.K.S. (1997): Changes in the canopy and growth of *Pinus radiata* in response to nitrogen supply. Forest Ecology and Management, 93: 137–152.

Fisher R., Garbett W. (1980): Response of semimature slash and loblolly pine plantations to fertilization with nitrogen and phosphorus. Soil Science Society of America Journal, 44: 850–854.

Fox T., Allen H., Albaugh T., Rubilar R., Carlson C. (2006): Forest fertilization in southern pine plantations. Better Crops, 90: 12–15.

Fox T., Allen H., Albaugh T., Rubilar R., Carlson C. (2007): Tree nutrition and forest fertilization of pine plantations in the southern United States. Southern Journal of Applied Forestry, 31: 5–11.

Gent J., Allen H., Campbell R., Wells C. (1986): Magnitude, duration, and economic analysis of loblolly pine growth response following bedding and phosphorus fertilization. Southern Journal of Applied Forestry, 10: 124–128.

Gower S.T., Gholz H.L., Nakane K., Baldwin V.C. (1994): Production and carbon allocation patterns of pine forests. In: Gholz H.L., Linder S., McMurtrie R.E. (eds): Environmental Constraints on The Structure and Productivity of Pine Forest Ecosystems: A Comparative Analysis. Ecological Bulletins, No. 43. Lund, Oikos Editorial Office: 115–135.

Hopmans P., Collett N.C., Smith I.W., Elms S.R. (2008): Growth and nutrition of *Pinus radiata* in response to ferti-

lizer applied after thinning and interaction with defoliation associated with *Essigella californica*. Forest Ecology and Management, 255: 2118–2128.
Hunter I., Graham J., Prince J., Nicholson G. (1986): What site factors determine the 4-year basal area response of *Pinus radiata* to nitrogen fertilizer. New Zealand Journal of Forestry Science, 16: 30–40.
Infor (2015): Chilean Statistical Yearbook of Forestry 2015. Santiago de Chile, Ministerio de Agricultura, Gobierno de Chile: 161.
Jones J.B., Case V.W. (1990). Sampling, handling and analyzing plant tissue samples. In: Westerman R.L. (ed.): Soil Testing and Plant Analysis. 3rd Ed. Madison, Soil Science Society of America, Inc.: 389–428.
Keay J., Turton A., Campbell N. (1968): Some effects of nitrogen and phosphorus fertilization of *Pinus pinaster* in Western Australia. Forest Science, 14: 408–417.
Landsberg J., Sands P. (2010): Physiological Ecology of Forest Production: Principles, Processes and Models. San Diego,, Academic Press: 304.
Linder S., Benson M., Myers B., Raison R. (1987): Canopy dynamics and growth of *Pinus radiata*.: I. Effects of irrigation and fertilization during a drought. Canadian Journal of Forest Research, 17: 1157–1165.
Littell R.C., Milliken G.A., Stroup W.W., Wolfinger R.D., Schabenberger O. (2006): SAS for Mixed Models. 2nd Ed. Cary, SAS Institute Inc.: 814.
Miller H. (1981): Forest fertilization: some guiding concepts. Forestry, 54: 157–167.
Miller H., Cooper J. (1973): Changes in amount and distribution of stem growth in pole-stage corsican pine following application of nitrogen fertilizer. Forestry, 46: 157–190.
Nilsson U., Allen H. (2003): Short-and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. Forest Ecology and Management, 175: 367–377.
Richter D., Markewitz D., Heine P., Jin V., Raikes J., Tian K., Wells C. (2000): Legacies of agriculture and forest regrowth in the nitrogen of old-field soils. Forest Ecology and Management, 138: 233–248.
Rivaie A.A., Tillman R.W. (2009): Growth response of second-rotation *Pinus radiata* on an orthic allophanic soil to P fertilizer and weed control. Taiwan Journal of Forest Science, 24: 11–24.
Rojas J. (2005): Factors influencing responses of loblolly pine stands to fertilization. [Ph.D. Thesis.] Raleigh, North Carolina State University: 147.
Rubilar R., Albaugh T., Allen H., Alvarez J., Fox T., Stape J. (2013): Foliage development and leaf area duration in *Pinus radiata*. Forest Ecology and Management, 304: 455–463.
SAS (2009a): JMP® 8 User Guide. 2nd Ed. Cary, SAS Institute Inc.: 513.
SAS (2009b): SAS/STAT® 9.2. User's Guide. 2nd Ed. Cary, SAS Institute Inc.: 7869.
Smethurst P., Nambiar E. (1990): Distribution of carbon and nutrients and fluxes of mineral nitrogen after clear-felling a *Pinus radiata* plantation. Canadian Journal of Forest Research, 20: 1490–1497.
Snowdon P. (2002): Modeling Type 1 and Type 2 growth responses in plantations after application of fertilizer or other silvicultural treatments. Forest Ecology and Management, 163: 229–244.
Snowdon P., Benson M. (1992): Effects of combinations of irrigation and fertilisation on the growth and above-ground biomass production of *Pinus radiata*. Forest Ecology and Management, 52: 87–116.
Snowdon P., Waring H.D. (1984): Long-term nature of growth responses obtained to fertilizer and weed control applied at planting and their consequences for forest management. In: Grey D.C., Schonau A.P.G., Schutz C.J. (eds): Proceedings of the IUFRO Symposium on Site and Productivity of Fast Growing Plantations, Pretoria, Pietermaritzburg, Apr 30–May 11, 1984: 701–711.
Turner J., Knott J.H., Lambert M. (1996): Fertilization of *Pinus radiata* plantations after thinning. I Productivity gains. Australian Forestry, 59: 7–21.
Turner J., Lambert M.J. (1986): Nutrition and nutritional relationships of *Pinus radiata*. Annual Review of Ecology and Systematics, 17: 325–350.
Vose J., Allen H. (1988): Leaf area, stemwood growth, and nutrition relationships in loblolly pine. Forest Science, 34: 547–563.
White J., Reddy K. (2000). Influence of phosphorus loading on organic nitrogen mineralization of Everglades soils. Soil Science Society of America Journal, 64: 1525–1534.
Will R., Markewitz D., Hendrick R., Meason D., Crocker T., Borders B. (2006): Nitrogen and phosphorus dynamics for 13-year-old loblolly pine stands receiving complete competition control and annual N fertilizer. Forest Ecology and Management, 227: 155–168.
Woods P., Nambiar E., Smethurst P., (1992): Effect of annual weeds on water and nitrogen availability to *Pinus radiata* trees in a young plantation. Forest Ecology and Management, 48: 145–163.
Zutter B., Miller J. (1998): Eleventh-year response of loblolly pine and competing vegetation to woody and herbaceous plant control on a Georgia flatwoods site. Southern Journal of Applied Forestry, 22: 88–95.

Received for publication November 21, 2015
Accepted after corrections February 18, 2016

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