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Mid-rotation response of *Pinus taeda* to early silvicultural treatments in subtropical Argentina

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A R T I C L E I N F O

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A B S T R A C T

Pinus taeda plantations in subtropical areas of South America are extremely productive and commonly established on well-drained red clay sites. In the past, land with more poorly-drained soil was avoided due to concern over the factors limiting site productivity. Establishment of intensively managed plantations on poorly-drained soils usually includes soil preparation by subsoiling and/or bedding, weed control, and fertilization. However, forest managers lack information about the efficacy of early silvicultural practices to ameliorate environmental limitations and if these intensive practices generate long-term improvements in productivity in this area. Consequently, we established studies in northeastern Argentina on two sites differing by drainage class and soil texture as a full factorial design with site preparation (S; disking and disking + subsoiling (red clay) or bedding (wet loam)), fertilization (F; none or 78 kg ha^{-1} elemental phosphorus at planting), and weed control (W; none or two-year banded). Seven years after planting, the red clay and wet loam sites were equally productive, with maximum treatment means of 218 m^3 ha^{-1} and 264 m^3 ha^{-1} respectively. At the red clay site, only weed control significantly increased volume. At the wet loam site, both weed control and site preparation significantly increased volume, mainly due to increased survival. The combination of weed control and bedding yielded a non-additive volume response as indicated by a significant W*S interaction. Our results do not support the common practice of subsoiling on red clay soils. In addition, fertilization with P alone appears counterproductive or unneeded at both sites.

1. Introduction

Loblolly pine (*Pinus taeda* L.) is native to the southeastern United States but is extremely productive in subtropical regions of South America. The estimated mean annual increment for loblolly pine plantations in South America (30 m^3 ha^{-1} yr^{-1}) is often more than twice than that found in loblolly pine's native range (12 m^3 ha^{-1} yr^{-1}) (Cubbage et al., 2007). Loblolly pine is, consequently, an important plantation species in northeastern Argentina, southern Brazil, and northern Uruguay (Geary, 2001; IBÁ, 2016; Martiarena et al., 2011). In Argentina, loblolly pine plantations cover more area than any other plantation species, and they are concentrated in the subtropical provinces of Misiones and Corrientes (FAO, 2004). In Brazil, loblolly pine occupies 1.6 million hectares and is concentrated in the states of Paraná (42%) and Santa Catarina (34%) (IBÁ, 2016). In Uruguay, loblolly pine covers 74,100 ha and 62,160 ha in the departments of Rivera and Tacuarenbó, respectively (DIEA, 2019). Despite loblolly pine's extensive use as a plantation species in South America, many questions regarding its proper management in the region remain.

Typically, pine plantations are established on sites unsuitable for agriculture, like red soils (Martiarena et al., 2011). Red soils (red clay soils) or Ultisols (Nitossolos in Brazil) are common across Corrientes

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and Misiones, Argentina (Rubio et al., 2019), the southern states of Brazil (IBGE, 2019), and limited areas in Uruguay (DIEA, 2019). These red soils typically are clayey, acidic, and nutrient deficient with good structure for plant growth and good drainage (Baligar et al., 2004; Rubio et al., 2019). Another common soil in this region of Argentina, but less widely planted in pine plantations, are Inceptisols located in flat and poorly-drained areas (Rubio et al., 2019). In the past, land with poor drainage was usually avoided for plantations due to concern of the factors limiting site productivity and operability.

These two soil groups differ from each other in structure and drainage and thus require different management. Establishment of intensively managed plantations at these sites usually includes intensive site preparation by burning, disking, subsoiling and/or bedding, weed control, and fertilization. However, there is a lack of understanding regarding resource limitations, how the site resources can be effectively manipulated by early silvicultural treatments, and if these intensive practices may truly generate long-term improvements in productivity. This study aims to inform the management of site-specific resource availability for these soils. A better understanding of the factors limiting growth is key to the sustainable management of pine plantation productivity.

Observations of early growth response to treatments can help managers better project growth responses to the end of the rotation (Snowdon, 2002). To describe growth responses, they can be grouped in four general patterns: Type A, B, C, D (Hughes et al., 1979; Morris and Lowery, 1988). Type A responses occur when treated stand growth shows continual divergence from the untreated control over time. P-fertilization at planting can show a Type A response, on P-deficient sites (Ballard, 1978; Gentle et al., 1986). Type B responses occur when temporary growth gains are made early in the rotation and reduce the rotation length (Snowdon, 2002). Weed control or N-fertilization (Neilsen et al., 1992) can show a Type B response or a boost in treated stand growth followed by parallel growth to the untreated control. Type B response treatments can be repeatedly added to yield a Type A response, such as multiple N-fertilizations in one rotation. Type C responses occur when treatments result in growth gains that eventually dissipate and converge back to the untreated stand growth over time. Type C responses can occur when N is available earlier in the rotation due to site preparation, then becomes limiting sooner in the treated stand than it does for the untreated stand (Morris and Lowery, 1988). Type D responses are negative relative to the untreated stand growth. An example of a negative response is fertilization at establishment without weed control on a nutrient-rich site, resulting in increased mortality due to weeds out-competing the crop trees for the added nutrients (Albaugh et al., 2015; Allen and Lein, 1998). Identifying site-specific growth responses to silvicultural treatments facilitates their cost-effective deployment.

In this study, we evaluated growth and survival effects at mid-rotation of site preparation, weed control, and fertilization applied at stand establishment on loblolly pine growth for two contrasting sites in subtropical Argentina.

2. Methods

2.1. Site description

This study was established in northern Argentina at two sites, identified hereafter by their soil textures: red clay and wet loam. The sites were 2 km apart in northeastern Corrientes Provence, 60 km southwest of Posadas, Misiones (−27.905, −56.156). The geology was basalt, "Grupo Serra Geral." The Köppen-Geiger climate classification is Csc (Kottek et al., 2006), with a warm temperate climate, mean annual temperature of 20 °C, and mean annual rainfall of 1814 mm yr^{-1}. At an elevation of 106 masl, the red clay site was classified as a Typic Kandihumult. The wet loam site, at 98 masl, was classified as a Humic Endoaquept. Both sites were previously cattle pasture.

Table 1
Soil nutrient concentrations from 32 samples at each site in subtropical Argentina. Mehlich-3 extractant was used in soil tests. Standard deviation is provided in parentheses.

		Red Clay		Wet Loam	
		Average	SD	Average	SD
pH		4.99	(0.30)	4.75	(0.10)
N	%	0.18	(0.01)	0.23	(0.05)
P	mg/kg	3.39	(0.69)	6.70	(1.85)
K	mg/kg	77.08	(15.31)	40.41	(10.51)
Ca	mg/kg	764.24	(72.23)	203.72	(40.26)
Mg	mg/kg	187.54	(20.59)	24.82	(7.92)
B	mg/kg	0.47	(0.07)	0.19	(0.07)
Mn	mg/kg	499.24	(47.22)	12.31	(9.61)
Zn	mg/kg	1.79	(0.26)	0.81	(0.23)
Cu	mg/kg	14.17	(1.38)	6.68	(0.58)

Table 2
Statistical summary (P values) for tree (diameter at breast height (DBH), height (Ht)) and stand scale (basal area (BA), stem volume (Volume) and survival) metrics after seven years of growth at red clay and wet loam sites in northern Argentina. Factors were weed control (W) as two-year banded, site preparation (S) as disking + subsoiling (red clay) or bedding (wet loam), and fertilization (F) as 78 kg ha^{-1} elemental phosphorus at planting). Sites were analyzed separately. Degrees of freedom is 21 for all metrics. Values in bold are P < 0.05.

Effect	DBH	Ht	BA	Volume	Survival
Red Clay					
W	0.11	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**
S	0.07	0.35	0.13	0.16	**0.02**
F	0.44	0.57	0.97	0.93	0.94
W*S	**0.04**	0.49	0.26	0.28	0.05
W*F	0.24	0.26	0.76	0.94	0.87
S*F	0.40	0.84	0.76	0.83	0.89
W*S*F	0.37	0.65	0.63	0.58	0.70
Wet Loam					
W	0.05	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**
S	**0.02**	**0.01**	**0.03**	**0.03**	**0.02**
F	**0.04**	0.45	0.25	0.26	0.13
W*S	0.18	**0.01**	**< 0.01**	**< 0.01**	**0.02**
W*F	0.07	0.39	0.26	0.25	0.16
S*F	0.19	0.61	0.13	0.30	0.24
W*S*F	0.16	0.51	0.10	0.12	0.10

2.2. Experimental design

At both sites, we established a 2 × 2 × 2 full factorial experiment in a randomized block split-plot design with four replications (blocks). Plots were blocked by field location. The factors evaluated were weed control (W), site preparation (S), and fertilization (F). Both sites received a prescribed burn before site preparation. Soil samples at a depth of 0–15 cm were taken in June 2003 and tested using Mehlich-3 extractant (Table 1). Site preparation was completed in July 2003 and was randomly assigned to the whole-plots within a block; S was applied as disking or disking + subsoiling at the red clay site and disking or bedding at the wet loam site. Disking consisted of two passes of tillage to a depth of 20–30 cm with a disk harrow. Subsoiling occurred to a depth of 50 cm. Bedding consisted of a single pass with a Savannah plow. Fertilizer and weed control were randomly assigned to the sub-plots within a whole-plot. Fertilizer (none, or 78 kg ha^{-1} elemental phosphorus) was applied to each seedling as 120 g $tree^{-1}$ triple super phosphate in September 2003 at the red clay site and in October 2003 at the wet loam site. Weed control (none, or two-year banded) was applied as glyphosate 3 L ha^{-1} with metsulfuron methyl 0.05 kg ha^{-1} and vegetable oil adjuvant 0.05 L ha^{-1}. Loblolly pine seedlings (Marion County, Florida origin) were planted in August 2003 at a 4 × 1.75 m spacing (1428 trees ha^{-1}). Measurement plots include 100 trees and 15 m buffers. Each treatment plot area was 0.17 ha including the

Table 3
Seven-year treatment mean and response (treatment minus control) summary at red clay and wet loam sites in northern Argentina. Treatments were combinations of weed control (W) as two-year banded, site preparation (S) as disking + subsoiling (red clay) or bedding (wet loam), and fertilization (F) as 78 kg ha^{-1} elemental phosphorus at planting).

	DBH			Height			Basal Area			Volume			Survival
	Mean	Response		Mean	Response		Mean	Response		Mean	Response		Mean
Treatment	cm	cm	%	m	m	%	m^2ha^{-1}	m^2ha^{-1}	%	m^3ha^{-1}	m^3ha^{-1}	%	%
Red Clay													
Control	17.7			12.5			29.1			177.7			80
W	18.0	0.3	2	12.9	0.4	3	33.8	4.7	16	211.8	34.1	19	91
S	17.4	−0.3	−2	12.6	0.1	1	30.8	1.7	6	190.1	12.4	7	89
F	18.3	0.6	3	12.4	−0.1	−1	28.7	−0.4	−1	174.3	−3.4	−2	76
W + S	18.0	0.3	2	13.0	0.5	4	34.6	5.5	19	218.2	40.5	23	92
W + F	17.9	0.2	1	13.1	0.6	5	33.7	4.6	16	213.7	36.0	20	92
S + F	17.4	−0.3	−2	12.6	0.1	1	31.7	2.6	9	195.2	17.5	10	91
W + S + F	18.0	0.3	2	13.1	0.6	5	34.2	5.1	18	216.4	38.7	22	92
Wet Loam													
Control	19.7			10.8			22.1			124.6			58
W	19.6	−0.1	−1	12.5	1.7	16	35.9	13.8	62	219.2	94.6	76	81
S	19.2	−0.5	−3	12.8	2.0	19	34.6	12.5	57	217.0	92.4	74	82
F	22.6	2.9	15	10.3	−0.5	−5	12.5	−9.6	−43	66.5	−58.1	−47	29
W + S	19.1	−0.6	−3	13.5	2.7	25	40.4	18.3	83	264.0	139.4	112	96
W + F	19.7	0.0	0	12.8	2.0	19	36.1	14.0	63	226.0	101.4	81	83
S + F	19.8	0.1	1	12.5	1.7	16	36.3	14.2	64	220.8	96.2	77	81
W + S + F	19.3	−0.4	−2	13.3	2.5	23	40.1	18.0	81	257.9	133.3	107	93

Table 4
Red clay site means for significant main effect, with (1) and without (0) weed control, at year seven. Letters denote significant differences using Tukey HSD.

	Height		Basal Area		Volume		Survival	
W	m		m^2ha^{-1}		m^3ha^{-1}		%	
1	13.0	A	34.1	A	215.1	A	74.3	A
0	12.5	B	30.1	B	184.3	B	65.3	B

0.07 ha measurement plot in the center. Tree diameter at breast height (DBH), total height, and survival were measured annually 2003–2010, except for 2008.

2.3. Data analysis

We estimated stem volume using

$$V = EXP(LN(D) * 1.943059 + LN(H) * 0.847355 - 9.627622) \quad (1)$$

where V is outside bark volume in m^3 $tree^{-1}$, D is DBH in cm, H is height in m (Bosques del Plata, company developed equation). Volume and basal area were summed per plot and scaled to an area basis. Response was calculated as the difference between each treatment and the control at each site. A generalized linear mixed model was used to examine main effects and interactions (PROC GLIMMIX) seven years after planting at each site. All significance levels were at an alpha level of 0.05. Sites were analyzed separately due to differences in soil type and site preparation methods. Block was a random effect and site preparation, weed control, and fertilization were fixed effects (Ott and

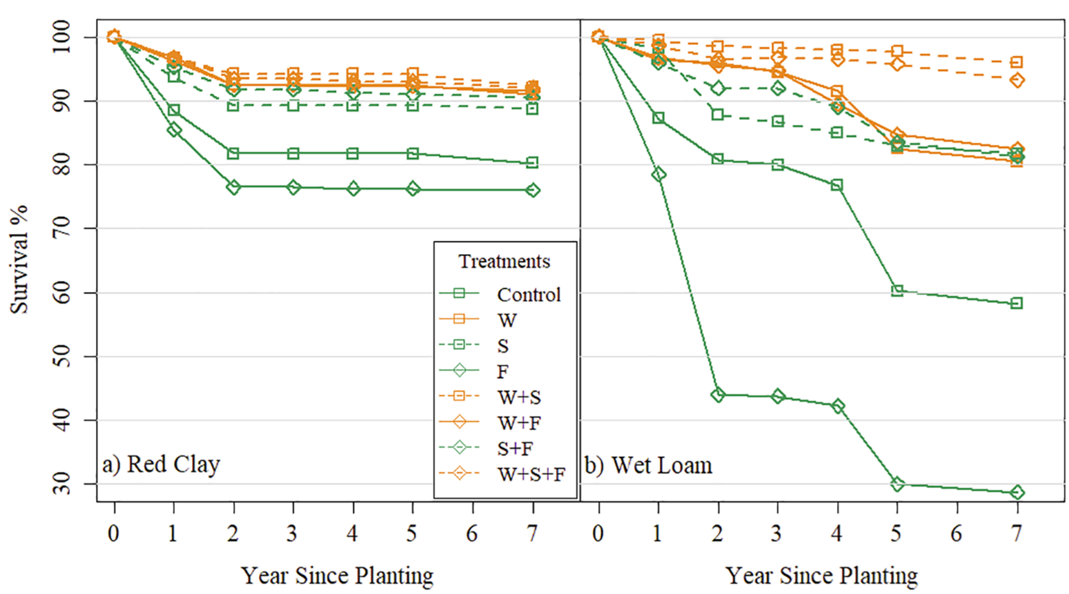

Fig. 1. Treatment mean survival over time for the a) red clay site and b) wet loam site in northern Argentina. Treatments were weed control (W) as two-year banded glyphosate, site preparation (S) as disking + subsoiling (red clay) or bedding (wet loam), and fertilization (F) as 78 kg ha^{-1} elemental phosphorus at planting). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

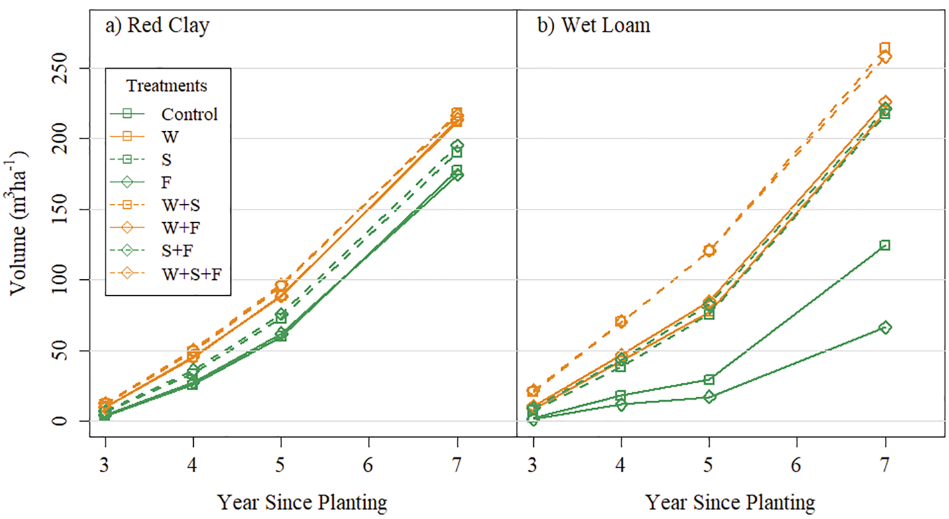

Fig. 2. Treatment mean cumulative volume over time for the a) red clay site and b) wet loam site in northern Argentina. Treatments were weed control (W) as two-year banded glyphosate, site preparation (S) as disking + subsoiling (red clay) or bedding (wet loam), and fertilization (F) as 78 kg ha^{-1} elemental phosphorus at planting). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Longnecker, 2015). A Shapiro-Wilk test (PROC UNIVARIATE) showed survival at the red clay site was non-normally distributed ($P < 0.05$). An arcsine transformation yielded a normal distribution for the red clay site survival. We used Tukey Honest Significant Difference (via LSMEANS statement) for means separation of significant main effects. We evaluated simple main effects (via SLICE statement) for means separation of significant two-way interactions. In this analysis, data were first divided (or sliced) into a first factor's levels. Then, within the first factor's levels, means separation was conducted between the levels of a second factor. Significant P values indicate that the second factor influenced the metric being evaluated in the presence (1) or absence (0) of the first factor.

To compare the two sites, a sub-set of analyses were performed. The control treatment means, the highest-volume treatment means, and maximum volume response means at year seven were tested with a paired *t*-test for site comparison. Maximum volume response was calculated as the difference between the W + S treatment volume and the control treatment volume for each site. All data analysis was completed using SAS software, Version 9.4 (SAS Institute Inc., 2019). Our presentation focused on volume and survival because they integrate DBH, height, and basal area.

3. Results

3.1. Red clay site

At the red clay site, the weed control main effect was significant for height, basal area, volume, and survival at year seven (Table 2). The site preparation main effect was only significant for survival (Table 2). Individual treatment means are shown for year seven in Table 3. The fertilization main effect was not significant for any metric (Table 2). Height, basal area, volume, and survival significantly increased with weed control (Table 4). Survival also significantly increased with site preparation from 66% to 73%.

Survival stabilized for all treatments after year two (Fig. 1a), ranging from 76 to 92% at year seven (Table 3). Cumulative volume ranged from 174 to 218 m^{3}ha^{-1} at year seven (Fig. 2a). Type B volume responses were observed for all factors (Fig. 3a).

The weed control by site preparation interaction was significant for DBH (Table 2). With weed control, site preparation had no effect on DBH (Table 5). Without weed control, site preparation decreased DBH (Table 5) by 0.6 cm (Table 6). With site preparation, weed control increased DBH (Table 5) by 0.6 cm (Table 6). Without site preparation, weed control had no effect on DBH (Table 5).

3.2. Wet loam site

At the wet loam site, site preparation and fertilization main effects were significant for DBH (Table 2). Site preparation decreased DBH by 1 cm. Fertilization increased DBH by 1 cm. Individual treatment means are shown for year seven in Table 3.

The weed control by site preparation interaction was significant for height, basal area, volume, and survival (Table 2). With weed control, site preparation had no effect on height, basal area, volume, and survival (Table 5). Without weed control, site preparation increased height, basal area, volume, and survival (Tables 5 and 6). With site preparation, weed control had no effect on height, basal area, and survival (Table 5). Without site preparation, weed control increased height, basal area, and survival (Tables 5 and 6). Weed control increased volume with and without site preparation (Tables 5 and 6).

Survival continued to decrease over time for all treatments (Fig. 1b), ranging from 29 to 96 % at year seven (Table 3). Cumulative volume ranged from 66–264 m^{3}ha^{-1} at year seven (Fig. 2b), with all treatments, except fertilization, having higher volume than the control (Table 3). Type A volume responses were observed for weed control, site preparation, and their interaction (Fig. 3b).

3.3. Site comparison

There was no significant difference ($P = 0.20$) between the control treatment mean volumes at the red clay and wet loam sites (178 and 125 m^3 ha^{-1}, respectively). The highest volume treatment at both sites was W + S, with means of 218 m^3 ha^{-1} at the red clay site and 264 m^{3}ha^{-1} at the wet loam site (Table 3). There was, however, no significant difference in W + S treatment means between sites ($P = 0.11$). The wet loam site maximum volume response was significantly higher ($P = 0.03$) than the red clay site, with response values of 139.4 and 40.5 m^{3}ha^{-1}, respectively.

4. Discussion

4.1. Red clay site

At the red clay site, weed control was the only factor to significantly increase volume at year seven (Table 4). The primary weed competition was from grasses (authors' personal observations), which is likely due to its past land use as pasture. In a similar study, Albaugh et al. (2015) also showed a positive response from weed control for a stand planted on a pasture site. We observed a Type B response (Fig. 3a), where weed control likely alleviated light competition from herbaceous weeds until the pine canopy closed and shaded the weeds out in non-treated plots

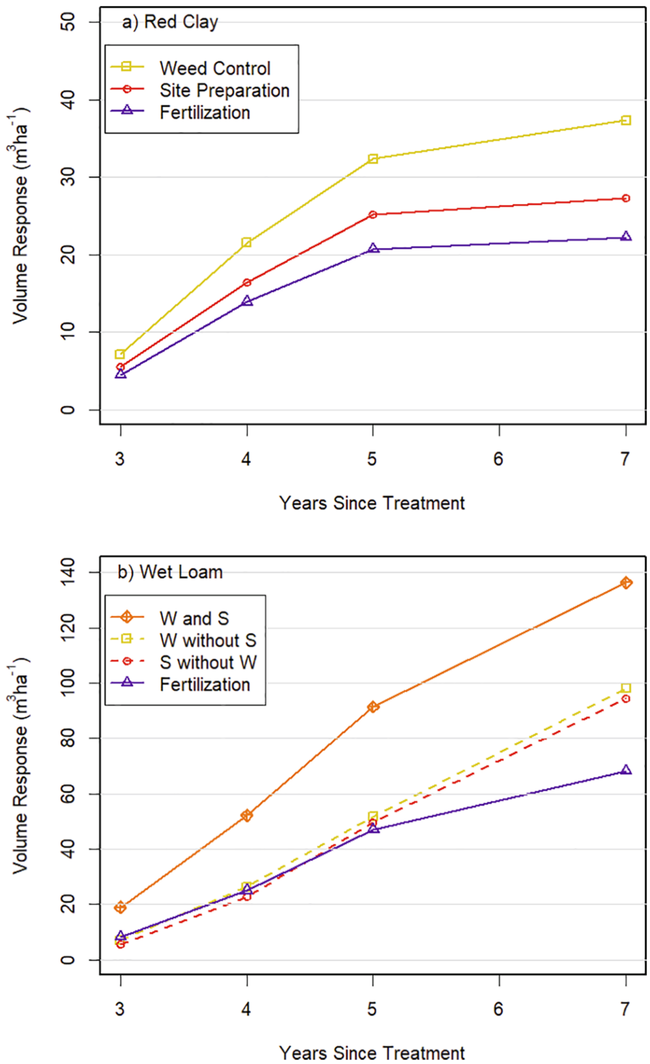

Fig. 3. Volume response of main effects compared to control of weed control, site preparation, and fertilization over time for the a) red clay and b) wet loam sites in northern Argentina. Factors were weed control (W) as two-year banded glyphosate, site preparation (S) as disking + subsoiling (red clay) or bedding (wet loam), and fertilization (F) as 78 kg ha^{-1} elemental phosphorus at planting). At the wet loam site, the interaction between W and S was significant at $P < 0.05$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Simple main effects (P values) for significant two-way weed control by site preparation interaction at year seven for red clay and wet loam sites. Simple main effects were evaluated using SLICE statement for both weed control (W) and site preparation (S). In this analysis, data were first divided (or sliced) into the factor levels specified in the "Factor Sliced By" column. Then, means separation was conducted between the levels of factors in the "Factor Tested" column. P values indicate if the factor tested had a significant effect on the metric being evaluated in the presence (1) or absence (0) of the slice factor. Values in bold are $P < 0.05$.

Factor Sliced By		Factor Tested	Red Clay	Wet Loam			
			DBH	Height	Basal Area	Volume	Survival
W	1	S	0.81	0.13	0.24	0.15	0.10
	0		**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**
S	1	W	**0.01**	**0.04**	0.06	**0.02**	0.08
	0		0.69	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**

Table 6
Means for significant two-way weed control by site preparation interaction at year seven for red clay and wet loam sites. The zeros (0) denote absence and ones (1) denote presence of weed control (W) and site preparation (S) in their respective columns.

		Red Clay	Wet Loam			
		DBH	Height	Basal Area	Volume	Survival
W	S	cm	m	m^{2}ha^{-1}	m^{3}ha^{-1}	%
1	1	18.0	13.4	40.2	261.0	94.6
1	0	17.9	12.6	36.0	222.6	81.5
0	1	17.4	12.6	35.4	218.9	81.5
0	0	18.0	10.5	17.3	95.5	43.5

(Albaugh et al., 2004). All treatments were burned and disked during site preparation, which also provided temporary mechanical weed control. This site was not responsive to fertilization and therefore is presumably not P-limited. The Mehlich-3 soil test P concentration of 3.39 mg kg^{-1} from this site (Table 1) fell just below a critical threshold reported from the southeastern US of 4.05 mg kg^{-1} (Wells, 1973). Wells (1973) found that sites below the threshold P concentration showed a range of growth responses, including no growth response, and that sites above the threshold consistently showed no growth response. Contrary to operational practices at the time, subsoiling had no significant effect on volume growth seven years after treatment (Table 2). Other studies have shown subsoiling did not increase growth in well-drained soils (Albaugh et al., 2015, 2004; Carlson et al., 2006; Wheeler et al., 2002). Rainfall is fairly evenly distributed throughout the year in this region, so soil strength was likely not prohibitive to root penetration (Greacen and Sands, 1980). Due to the lack of response to both subsoiling and fertilization, weed control and disking would be the only recommended practices on similar red clay sites.

4.2. Wet loam site

Weed control increased volume both with and without site preparation (Tables 5 and 6). The volume increase was primarily due to increased survival. The pattern in volume growth shown in Fig. 2, i.e., the order and magnitude of treatments diverging from the control over time, mirrored the pattern in survival (Fig. 1). The weed control by site preparation interaction for height, basal area, volume, and survival (Table 2) was significant due to the non-additive response of the main effects (Table 5). When weed control or site preparation was applied without the other, they significantly increased volume (Fig. 2, Table 6). Weed control and site preparation had similar volume responses (~75% increase); however, when combined, W + S increased volume growth response to 112% (Table 3).

The site preparation method at the wet loam site was bedding or disking. Bedding improves soil aeration for newly planted trees and can consequently improve survival (Allen and Lein, 1998; Amateis et al., 1997; Rahman and Messina, 2006). Weed control and disking likely reduced herbaceous vegetation considerably, also improving survival. Since the combination of weed control and bedding was non-additive, we can infer they manipulated some of the same resources. For example, bedding may have provided some mechanical weed control. Given that weed control would be less expensive to apply than bedding, weed control would be more economically attractive for forest managers working on similar sites (Albaugh et al., 2015; Carlson et al., 2006).

4.3. Site comparison

Volume growth at both sites was not responsive to fertilization (Table 2). Wells (1973) demonstrated in the southeastern US, that a growth response should not be expected at P concentrations above 3 mg kg^{-1} using Bray extractants (or 4.05 mg kg^{-1} using Mehlich-3).

Both sites had P concentration values near or above this critical value (Table 1), so the lack of response to fertilization was unsurprising. In addition, an N and P rate study nearby on these same soils also showed no growth response to fertilization (Albaugh et al., 2010). It appears that the sites had sufficient soil P in the rooting zone of the trees, such that additional P did not boost growth, possibly due to inherent fertility below 15 cm from basalt parent material.

Cumulative volume showed the wet loam site was more sensitive to treatments at year seven than the red clay site, where the maximum volume response (the difference between the W + S treatment and the control treatment) was greater at the wet loam site (112% increase) compared to the red clay site (23% increase). Apparently, silvicultural practices like weed control and bedding can successfully ameliorate potential concerns about using wet loamy sites for plantation production. Due to its operational scale, the metrics evaluated in this study do not allow us to separate the specific environmental drivers of overlapping Type A growth responses to weed control and bedding or lack of response from subsoiling and P fertilization. To further evaluate the mechanisms driving the observed growth responses, additional data, such as soil moisture and vegetation composition and biomass are needed. Long-term studies are critical to understanding the rotation-length responses to treatments and potential age-shifts of harvest. Additional post-thinning data from this study will further explain Type A and B volume responses over time.

5. Conclusions

Seven years after planting, the control treatments at the red clay and wet loam sites were similarly productive, but the wet loam site had a larger maximum volume response to weed control and site preparation than the red clay site. Weed control with disking is the only recommended practice on red clay soils. Our results do not support subsoiling on red clay soils. In addition, P fertilization was not necessary on either site. Weed control increased volume both with and without bedding at the wet loam site. The wet loam site demonstrates how effective silvicultural treatments can be at alleviating growth limitations and that similarly limited sites can be as productive as red clay sites. This work can inform pine plantation management on sites with similar soils in subtropical South America. Wet loam sites similar to the one in this study present some management challenges, like equipment access for operations, but they could be viably used for loblolly pine plantations more frequently than currently practiced in subtropical South America.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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