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Long-Term Responses to Competing Vegetation Management for *Pinus radiata*

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Abstract: Numerous studies have been carried out to quantify the response to competing vegetation control (CVC) in *P. radiata* plantations. Most of these publications have reported on the early response in tree growth; however, a knowledge gap exists regarding the growth responses throughout the rotation. In this study, we analyzed the long-term response of *P. radiata* plantations across a gradient of seven sites in central Chile. Treatments included a no-action control, two spot (circular) areas of competing vegetation control using herbicides around individual *P. radiata* seedlings (spot herbicide application of 0.75 and 1.5 m), and total competing vegetation control using herbicides. Additionally, three different timings for control regimes were included (0, 1, and 2 years after planting). Competing vegetation biomass abundance during the first growing season ranged from 0.6 to 5.7 Mg ha^{-1} across all sites. The total competing vegetation control treatment maintained for 2 years (TotalY$_{012}$) showed the largest gain in stem volume per hectare (VOL) in most of the sites. The sites included in this study showed contrasting values in productivity, having volume yields for the TotalY$_{012}$ treatment ranging from 238 m^3 ha^{-1} at the site with the lowest annual rainfall (age 12 years) to 471 m^3 ha^{-1} at the southern site (age 14 years). Across all sites, maximum gain in VOL ranged between 21 and 175 m^3 ha^{-1} at age 11 to 14 years and was linearly correlated to the amount of competing biomass controlled during the first year after planting. At the southern, wetter site, plots with only pre-planting spot herbicide application achieved 87% of VOL of plots with TotalY$_{012}$. Our results suggest that CVC improved the availability of resources at the site for *P. radiata* seedlings, increasing volume production by reducing environmental constraints to tree growth differentially at each site.

Keywords: radiata pine; competing vegetation management; intensive silviculture; timber production; weed control; forest herbicides

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1. Introduction

There are over four million hectares of *Pinus radiata* D. Don plantations around the world, mainly distributed in Australia, Chile, New Zealand, and Spain, making this species the most widely planted introduced conifer in the world [1]. By the end of 2019, more than 2.3 million hectares of commercial plantations were established in Chile, distributed in the south-central zone (36°3′ S and 40°7′ S), of which 56% were *P. radiata* [2]. Forest plantations can improve landscapes, water quality, erosion reduction, as well as carbon sequestration, biodiversity, and wood supply, producing a range of ecosystem services that contribute direct and indirect benefits [3,4]. Competing vegetation control (CVC) during plantation establishment is one of the most important silvicultural activities for improving the availability of resources at the site, increasing tree growth and, therefore, timber yield [5–9]. Previous studies have reported that the growth and survival of *P. radiata*, and several other conifers, can be strongly reduced due to competition with early seral vegetation for site resources such as water, nutrients, and light [6,10–15]. Many studies have reported that competing species composition (herbaceous and woody) affects the temporal availability of site resources throughout stand development. Herbaceous vegetation can severely reduce the availability of resources at the site during stand establishment, especially during the first year after planting. On the other hand, woody vegetation, which grows slowly in the early stages, can be a strong competitor for site resources after stand establishment, even after canopy closure [5,16]. Additionally, studies of different intensity of CVC have shown that at a lower intensity, there is a significant reduction in tree growth of *Pinus radiata* [15,17,18], *Pinus taeda* [19], and *Pseudotsuga menziesii* [13,14,18]. The growth response to CVC is driven by several factors, including site resource availability [6,20], the composition and abundance of competing vegetation [9,13,21,22], the intensity of CVC (defined as the area free from neighboring vegetation around each seedling), and the timing of CVC [13,23–25]. Over the past twenty years, most research efforts have been focused on quantifying the growth response associated with CVC in *P. radiata* [7,10,15]. Nevertheless, studies on the long-term (post-canopy closure to rotation end) growth responses to CVM are less common [6].

This study focused on determining the long-term growth responses to different intensities of CVC on *P. radiata* and the amount of vegetation biomass present during the first year after planting. We hypothesized that the response in stem volume production of *P. radiata* is proportional to the amount of competing vegetation biomass (intensity of competition) affecting site resource availability during the first year.

2. Materials and Methods

2.1. Site Description

The study of competing vegetation control on *P. radiata* was established by Bioforest S.A. in seven sites of Forestal Arauco S.A. located in south-central Chile (Table 1), considering a range of climates and competing vegetation compositions. The study sites experienced rainfall mainly during autumn and winter (75% of the annual total rainfall occurs between May and September) and a dry summer.

Table 1. Site location, including latitude, longitude and elevation, and average annual rainfall (rain, mm), potential evapotranspiration (PET, mm y^{-1}), water deficit (WD, mm y^{-1}), mean monthly maximum temperature (Tmax, °C), mean monthly minimum temperature (Tmin, °C), soil depth (SD, m), and clay content (clay, %), soil texture class, and soil organic matter (SOM, %) of the top 20 cm of soil depth for each site.

Site	Latitude (South)	Longitude (West)	Altitude (m)	Rain (mm y^{-1})	PET (mm y^{-1})	WD (mm y^{-1})	Tmax (°C)	Tmin (°C)	SD (m)	Clay (%)	Soil Texture	SOM (%)
SA	36°3′	71°7′	268	966	1380	−842	20.1	6.9	2.2	44.7	Clay	3.8
EB	37°7′	73°4′	255	1467	1002	−539	16.4	8.0	2.8	45.4	Clay	5.9
BL	38°1′	71°9′	753	2255	1157	−411	16.6	5.0	2.9	17.2	Loam	14.8
SL	38°1′	72°7′	197	991	1217	−716	18.9	6.9	2.9	41.1	Clay	3.2
HU	40°1′	73°0′	202	1739	1112	−374	17.0	6.1	2.4	25.1	Loam	14.2
EJ	40°3′	73°1′	93	1299	1131	−502	17.5	6.5	2.5	33.2	Clay loam	9.2
EM	40°7′	73°3′	52	1367	1047	−429	16.6	6.7	2.1	42.5	Clay loam	9.4

The Baltimore (BL) and Huequecura (HU) sites were second rotation, the harvest residues were mechanically arranged in windrows, and were planted in 2003. The El Mirador (EM) site was planted in 2003 and was a first-rotation plantation on land that was previously grassland (livestock production). The San Alberto (SA) and San Luis (SL) sites were second rotation, the harvest residues were mechanically arranged in windrows, and were planted in 2005. The El Blanco (EB) site was a second rotation, the harvest residues were shredded, and was planted in 2006. The El Japones (EJ) site was a first-rotation plantation on an agricultural land, and was planted in 2006. All sites were planted during winter.

2.2. Experimental Design and Treatments

At each site, a randomized complete block design with eight CVC treatments and five replicates (blocks) was used. All experimental sites included a competing vegetation-free treatment (Total) to estimate the maximum productivity of *P. radiata* in the absence of competing vegetation, and a no-action treatment (Control) without CVC to estimate the response of the plantation under conditions of maximum competition. Other treatments also included two spot (circular) herbicide treatments around each plant with spot diameters of 0.75 m ($Spot_{0.75}$) and 1.5 m ($Spot_{1.5}$). Additionally, three different timings of the control regimes were included, namely herbicide application during year 0 (Y_0), during years 0 and 1 (Y_{01}), and during years 0, 1, and 2 (Y_{012}) (Table 2). All herbicide applications during year 0 were made before planting during fall. All herbicide application during years 1 and 2 was carried out after planting during spring. Each experimental plot consisted of 90 seedlings (9 rows × 10 seedlings), with a central measurement plot of 30 seedlings (5 rows × 6 seedlings), surrounded by a buffer of 2 rows around each measurement plot. All sites were planted at 3.0 × 2.5 m (1333 trees ha^{-1}) using a mix of genetically improved *P. radiata* plants produced in container stock cuttings at Forestal Arauco's nurseries. Additionally, to quantify the abundance of competing vegetation biomass in each block, an extra plot with no herbicide application (similar to the Control plot) was established with 90 plants in total (9 rows × 10 plants).

Table 2. Description of the treatments.

Treatments	Spot Diameter (m)	Timing of Control (Years)	Area of Control (%)
Control	No herbicide	-	0
$Spot_{0.75}Y_0$	0.75	0	6
$Spot_{1.5}Y_0$	1.5	0	28
$Spot_{1.5}Y_{01}$	1.5	0 and 1	28
$Spot_{1.5}Y_{012}$	1.5	0, 1, and 2	28
$TotalY_0$	Weed-free	0	100
$TotalY_{01}$	Weed-free	0 and 1	100
$TotalY_{012}$	Weed-free	0, 1, and 2	100

All herbicide applications were carried out manually with backpack pumps using an average volume of 120 L ha^{-1}. At all sites, a mixture of glyphosate (2.0–2.5 kg commercial ingredient ha^{-1}), atrazine (3.0–4.0 kg commercial ingredient ha^{-1}), and an organosilicon adjuvant (100 mL ha^{-1}) was applied. The commercial herbicides used were Roundup Ultramax (74.7% glyphosate), Atrazine 90 WG (90% atrazine), and Silwet (adjuvant). For post-planting herbicide applications (Y_1 and Y_2), all *P. radiata* seedlings were protected from a potential drift of herbicides using a plastic shield. For spot application treatments, we used circular metal frames of 30 cm height and the corresponding spot diameter.

2.3. Competing Vegetation Biomass Measurements

In order to quantify competing vegetation abundance at each site, vegetation biomass was measured monthly during the first growing season. The evaluation was performed using 2 × 2 m clip-plots, randomly selected within each biomass plot (five plots per site each time). Samples of herbaceous and woody vegetation were extracted from each clip-plot and the fresh weight was registered in the field. A subsample consisting of approximately 10% of the fresh weight collected from each clip-plot was transported to the laboratory to determine moisture content and dry weight using a sample that was oven-dried at 90 °C for 48 h. In this study, we present the values of maximum biomass abundance recorded at each site.

2.4. Data Analysis

Measurements of tree growth and survival were taken every year during the fall and winter seasons. Trials have been measured up 11 to 14 years after planting. Measurements of the total tree height (H, m) and stem diameter at breast height at 1.3 m (DBH, cm) were used to calculate individual tree volume, using Cofre's taper function [26], assuming a top stem diameter limit of 8 cm. The effect of the CVC treatments was evaluated for all measurements, including mean DBH and H, as well as basal area (BA, $m^2\ ha^{-1}$), stem volume over-bark (VOL, $m^3\ ha^{-1}$), and survival (%), using an analysis of variance (ANOVA) including Tukey's multiple comparison test when differences were present. For the survival analysis, logit transformation was performed.

Simple and multiple linear regression analysis was performed to analyze the relationships between the climate and the soil characteristics of each site and mean annual increment in VOL (MAI, $m^3\ ha^{-1}\ y^{-1}$). Additionally, the relationship between competing vegetation biomass and VOL gain (VOL of treated plot minus VOL of control plot within each block and site) was tested for all study sites. When multiple linear regression was performed, the model with significant parameter estimates with the lowest AIC was finally selected. In order to detect multicollinearity among explanatory variables, the variance inflation factor (VIF) was monitored, discarding variables included in the model with VIF larger than 5. All statistical analyses and model fitting were carried out using the statistical software program R-Project (version 4.1.2).

3. Results

3.1. Competing Vegetation Biomass Production

All sites showed a larger proportion of herbaceous vegetation during the first year after planting (Figure 1). The greatest abundance of early seral competing vegetation biomass was observed at the EM site (5.7 Mg ha^{-1}) and the lowest abundance at the EJ site (0.6 Mg ha^{-1}). Regarding the proportion between herbaceous and woody, EB and EJ showed a large proportion of woody early seral vegetation (34% and 46% of the total biomass, respectively). At the SL and EM sites, no woody vegetation biomass was observed.

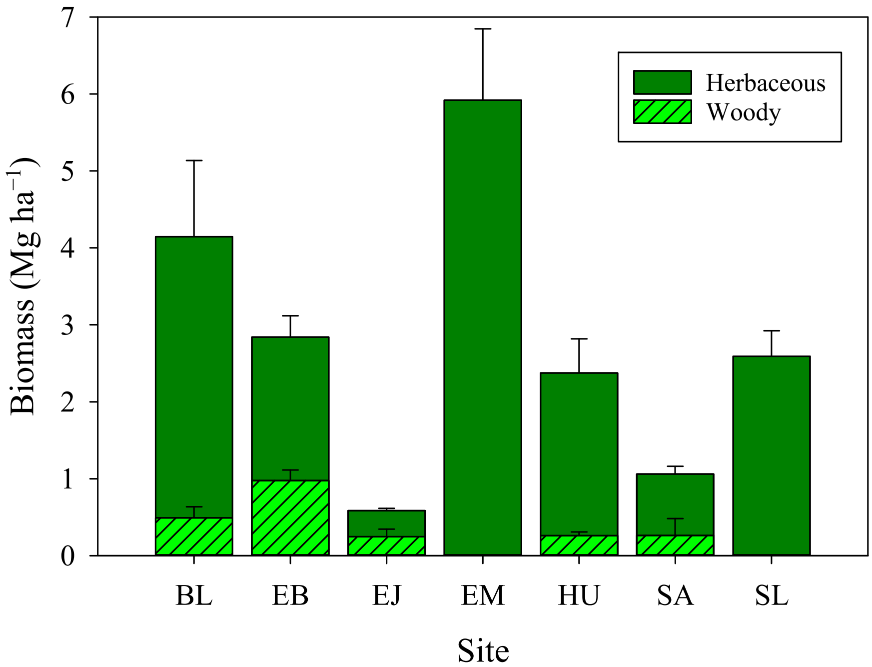

Figure 1. Early seral vegetation biomass abundance (Mg ha^{-1}) of herbaceous (dark green) and woody (light green) components during the first growing season at seven sites in south-central Chile.

3.2. Stand Yield

Table 3 presents a summary of mean BA (m^2 ha^{-1}), DBH (cm), H (m), VOL (m^3 ha^{-1}), and survival (%) for all CVC treatments at all tested sites on the last measurement date. A different letter within each site indicates a significant difference for α = 0.05.

Table 3. Summary average basal area (BA), stem diameter (DBH), height (H), stem volume over bark (VOL), and survival (%) for different sites and competing vegetation control treatments.

Site	Treatment	BA (m^2 ha^{-1})		DBH (cm)		H (m)		VOL (m^3 ha^{-1})		Survival (%)	
SA (12.0)	Control	29.6	a	17.7	a	16.5	a	167.8	a	86.7	a
	$Spot_{0.75}$ Y_0	34.7	a	19.5	ab	17.8	a	209.7	ab	85.0	a
	$Spot_{1.5}$ Y_0	35.0	a	19.5	ab	16.9	a	202.7	ab	85.9	a
	$Spot_{1.5}$ Y_{01}	35.3	a	19.2	ab	17.4	a	207.5	ab	89.2	a
	$Spot_{1.5}$ Y_{012}	35.5	a	19.7	b	17.5	a	210.1	ab	85.0	a
	Total Y_0	34.6	a	19.2	ab	17.2	a	202.2	ab	85.9	a
	Total Y_{01}	37.0	a	20.0	b	18.0	a	236.9	b	83.4	a
	Total Y_{012}	38.8	a	20.7	b	18.0	a	237.7	b	84.2	a
EB (11.2)	Control	36.3	a	18.9	a	18.1	a	226.1	a	94.0	a
	$Spot_{0.75}$ Y_0	35.8	a	18.8	a	18.1	a	226.5	a	92.5	a
	$Spot_{1.5}$ Y_0	34.4	ab	18.4	a	18.1	a	226.6	a	89.1	a
	$Spot_{1.5}$ Y_{01}	43.4	abc	20.6	ab	18.7	a	276.9	ab	93.3	a
	$Spot_{1.5}$ Y_{012}	42.0	abc	20.6	ab	18.9	a	273.0	ab	92.4	a
	Total Y_0	50.4	b	22.9	b	19.1	a	325.2	b	91.9	a
	Total Y_{01}	50.9	c	24.3	b	19.2	a	329.8	b	84.6	a
	Total Y_{012}	52.9	c	23.8	b	19.1	a	340.8	b	90.6	a
BL (14.3)	Control	42.1	a	22.7	a	22.3	a	324.0	a	74.7	a
	$Spot_{0.75}$ Y_0	45.4	ab	22.6	a	22.2	a	347.3	ab	82.0	a
	$Spot_{1.5}$ Y_0	51.5	b	23.9	ab	22.8	a	397.8	ab	84.0	a
	$Spot_{1.5}$ Y_{01}	48.9	a	24.2	ab	23.0	a	384.7	ab	77.4	a
	$Spot_{1.5}$ Y_{012}	48.8	a	23.6	ab	22.6	a	374.0	ab	80.7	a
	Total Y_0	51.3	b	24.9	b	23.3	a	408.5	bc	78.0	a
	Total Y_{01}	55.6	c	25.0	b	23.7	a	445.8	c	82.7	a
	Total Y_{012}	57.4	c	25.0	b	22.8	a	451.1	c	86.0	a
SL (12.1)	Control	33.0	a	19.9	a	16.7	a	186.7	a	77.5	a
	$Spot_{0.75}$ Y_0	40.3	ab	20.9	a	17.4	ab	236.4	a	86.7	a
	$Spot_{1.5}$ Y_0	41.2	ab	20.7	a	17.5	ab	243.6	a	90.0	a
	$Spot_{1.5}$ Y_{01}	40.4	ab	21.6	a	18.0	bc	245.2	a	82.5	a
	$Spot_{1.5}$ Y_{012}	40.4	ab	21.2	a	17.2	bc	235.0	a	85.0	a
	Total Y_0	38.3	ab	21.4	a	17.5	bc	226.1	a	80.0	a
	Total Y_{01}	40.3	bc	20.2	a	17.4	bc	235.5	a	92.5	a
	Total Y_{012}	42.6	bc	20.9	a	17.8	bc	256.8	b	90.9	a
HU (14.2)	Control	43.5	a	21.2	a	19.6	a	306.1	a	84.2	a
	$Spot_{0.75}$ Y_0	43.0	ab	22.8	ab	20.6	ab	311.6	ab	74.2	a
	$Spot_{1.5}$ Y_0	43.8	ab	21.3	ab	20.3	ab	318.0	ab	84.2	a
	$Spot_{1.5}$ Y_{01}	46.1	ab	23.5	ab	20.7	ab	334.6	ab	74.2	a
	$Spot_{1.5}$ Y_{012}	44.1	ab	22.1	ab	20.2	ab	315.4	ab	80.0	a
	Total Y_0	52.5	ab	24.2	ab	21.0	ab	384.3	ab	80.9	a
	Total Y_{01}	50.6	ab	23.3	ab	20.5	ab	365.5	ab	83.4	a
	Total Y_{012}	57.0	b	25.0	b	21.5	b	418.9	b	84.2	a
EJ (11.0)	Control	57.0	a	24.0	a	17.0	a	330.9	a	92.0	a
	$Spot_{0.75}$ Y_0	56.8	a	23.9	a	17.1	a	331.2	a	92.7	a
	$Spot_{1.5}$ Y_0	58.2	a	23.8	a	16.9	a	336.7	a	95.4	a
	$Spot_{1.5}$ Y_{01}	59.0	a	23.9	a	17.1	a	345.5	a	96.0	a
	$Spot_{1.5}$ Y_{012}	60.1	a	24.5	a	17.3	a	353.2	a	93.4	a
	Total Y_0	58.7	a	24.3	a	17.3	a	345.7	a	92.7	a
	Total Y_{01}	57.7	a	23.8	a	17.0	a	334.9	a	94.7	a
	Total Y_{012}	59.9	a	24.4	a	17.3	a	351.9	a	93.4	a

Table 3. *Cont.*

Site	Treatment	BA (m^2 ha^{-1})		DBH (cm)		H (m)		VOL (m^3 ha^{-1})		Survival (%)	
EM (14.2)	Control	42.1	a	21.2	a	19.3	a	296.6	a	78.9	a
	$Spot_{0.75}$ Y_0	55.5	b	23.7	ab	21.6	ab	413.2	b	90.0	a
	$Spot_{1.5}$ Y_0	55.0	b	22.8	ab	21.8	ab	425.1	b	94.5	a
	$Spot_{1.5}$ Y_{01}	59.3	b	23.2	ab	20.4	ab	439.5	b	97.8	a
	$Spot_{1.5}$ Y_{012}	60.2	b	24.6	ab	21.1	ab	454.9	b	91.1	a
	Total Y_0	55.8	b	23.7	ab	21.9	b	427.4	b	90.0	a
	Total Y_{01}	58.5	b	24.1	ab	22.0	b	450.3	b	91.1	a
	Total Y_{012}	62.9	b	25.1	b	22.6	b	471.4	c	93.4	a

Values in parenthesis below site name indicate stand age (years) at measurement time. Within a column and site, variables that share a letter are not significantly different at α = 0.05

At age 4 years, all sites showed significant differences in BA, DBH, H, and VOL due to the CVC treatments, with the exception of survival (Table 4). Similar results were observed at age 8 years, with the exception of the EJ site, where none of the variables showed significant differences (Table 4).

Table 4. Summary of analysis of variance (ANOVA) showing the *p*-values of the effects of competing vegetation control treatments on basal area (BA), stem diameter (DBH), height (H), stem volume per hectare (VOL), and survival at age 4 and 8 years.

Site	Age 4 Years					Age 8 Years				
	BA	DBH	H	VOL	Survival	BA	DBH	H	VOL	Survival
SA	0.012	0.005	0.053	0.035	0.720	0.015	0.032	0.234	0.013	0.720
EB	<0.001	<0.001	0.004	<0.001	0.417	<0.001	< 0.001	0.049	<0.001	0.573
BL	<0.001	<0.001	<0.001	<0.001	0.293	<0.001	<0.001	<0.001	< 0.001	0.338
SL	<0.001	<0.001	<0.001	<0.001	0.110	0.025	0.183	0.004	0.017	0.649
HU	<0.001	<0.001	<0.001	<0.001	0.482	<0.001	<0.001	<0.001	<0.001	0.546
EJ	0.044	0.041	0.037	0.048	0.731	0.196	0.145	0.425	0.243	0.972
EM	<0.001	<0.001	<0.001	0.012	0.130	0.004	0.002	0.001	0.004	0.102

At the last measurement (between age 11 and 14 years), most sites showed significant differences in VOL between the CVC and control treatments (Figure 2, Table 5). The exceptions were the SL (p = 0.089) and EJ (p = 0.914) sites. High variability in productivity was observed at all sites included in this study, having VOL yields for the most intensive treatment ($TotalY_{012}$), ranging from 238 m^3 ha^{-1} at the site with the lowest annual rainfall (SA site, age 12 years) to 471 m^3 ha^{-1} at the southern site (EM site, age 14 years). The VOL yields for the Control treatment ranged from 168 m^3 ha^{-1} at the SA site to 331 m^3 ha^{-1} at the site with the lowest amount of vegetation biomass (0.6 Mg ha^{-1}) (EJ site, age 11 years).

Table 5. Summary of analysis of variance (ANOVA) showing the *p*-values of the effects of competing vegetation control treatments on basal area (BA), stem diameter (DBH), height (H), stem volume per hectare (VOL), and survival at last measurement date.

Site	BA	DBH	H	VOL	Survival
SA	0.061	0.003	0.449	0.030	0.785
EB	0.001	<0.001	0.425	0.001	0.840
BL	0.001	0.003	0.057	<0.001	0.491
SL	0.078	0.604	0.410	0.089	0.356
HU	0.032	0.023	0.172	0.048	0.678
EJ	0.823	0.6020	0.946	0.914	0.497
EM	0.089	0.0244	0.011	0.042	0.106

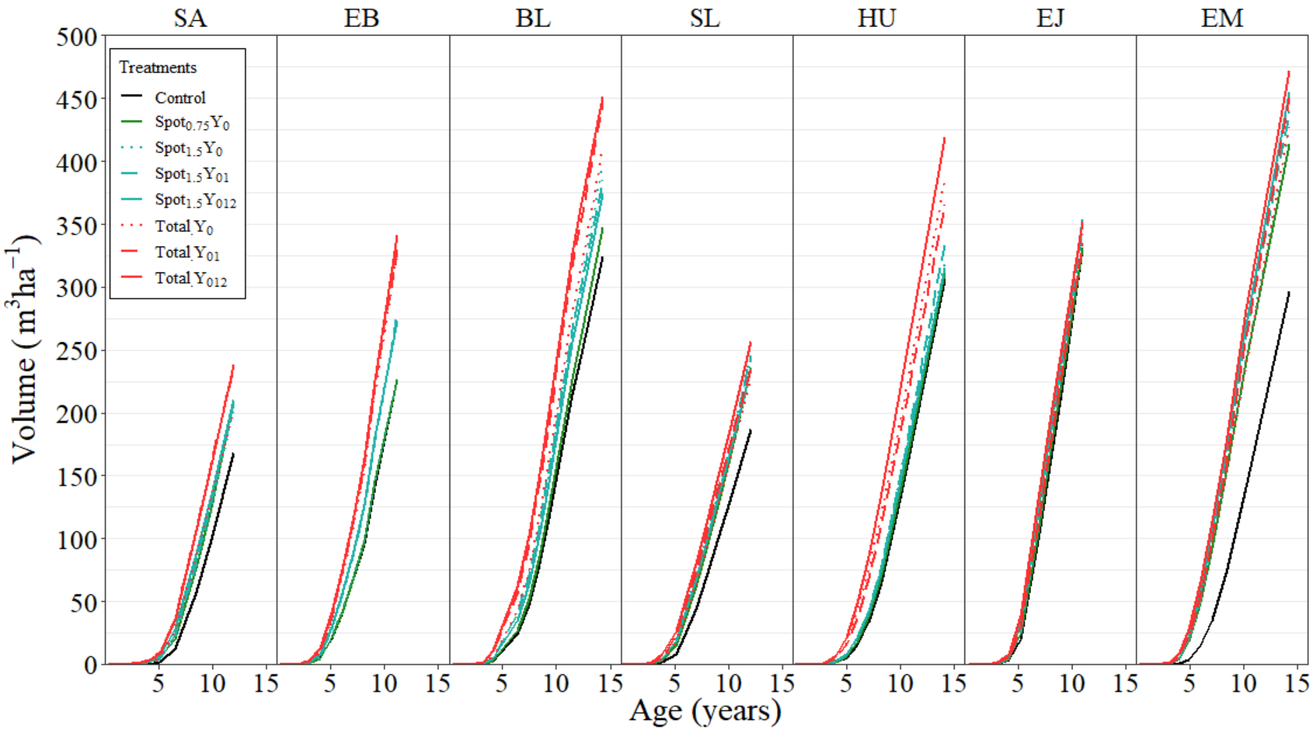

Figure 2. Time series of stem volume over bark per hectare (VOL, m^3 ha^{-1}) for *P. radiata* stands growing under different competing vegetation control treatments on seven sites in south-central Chile.

Even though there were no significant differences in the CVC treatments on survival, a general trend of increasing survival was observed as the intensity of competing vegetation control increased across the sites (Table 3). Most sites showed no significant differences in H between the CVC treatments, with the exception of the EM site (p = 0.011), which showed the largest competing vegetation biomass (5.7 Mg ha^{-1}). Significant differences were observed at most sites for DBH due to CVC treatments, with the exception of the SL site (p = 0.604, age 12 years) and the EJ site (p = 0.602, age 11 years). For BA, a significant effect of the CVC treatments was observed at the EB site (p = 0.001, age 11 years), BL site (p = 0.001, age 14 years), and HU site (p = 0.032, age 14 years). Figure 3 showed that at the last measurement most of the sites had a general trend of increasing VOL gain as the intensity and duration of CVC increased.

3.3. Tree Survival

At the last measurement, no sites showed differences in survival due to MCV treatments (Table 5, Figure 4). However, the increasing intensity of competing vegetation control tended to increase survival at most sites, except for the EJ site, where the lowest amount of vegetation biomass was observed (0.6 Mg ha^{-1}) (Figure 1). In contrast, at the EM site, where the largest amount of vegetation biomass was observed (5.7 Mg ha^{-1}), the largest mortality was observed on the Control plots (21%; p = 0.106). The HU site showed high mortality from the $Spot_{0.75}Y_0$ and $Spot_{0.75}Y_0$ treatment, probably explained by herbicide damage.

3.4. Effect of Area and Years of Control

The results shown in Table 3 are graphically depicted in Figure 5 (area of control) and Figure 6 (years of control). Treatments that included an herbicide application only during year 0 (Y_0) showed a significant gain in VOL with just 6% area of control. On the other hand, treatments that included an herbicide application during years 0, 1, and 2 (Y_{012}) showed an increased gain in VOL with 100% area of control, with the exception of the EJ site, where none of the treatments showed significant differences (Figure 5). At the EM site, a spot diameter of 0.75 m (6% area of control) applied during year 0 ($Spot_{0.75}Y_0$) achieved

68% of VOL gain of total CVC (TotalY_{012}), whereas a spot diameter of 1.5 m (28% area of control) applied during year 0 ($Spot_{1.5}Y_0$) achieved 74% of stem volume gain of total CVC (TotalY_{012}).

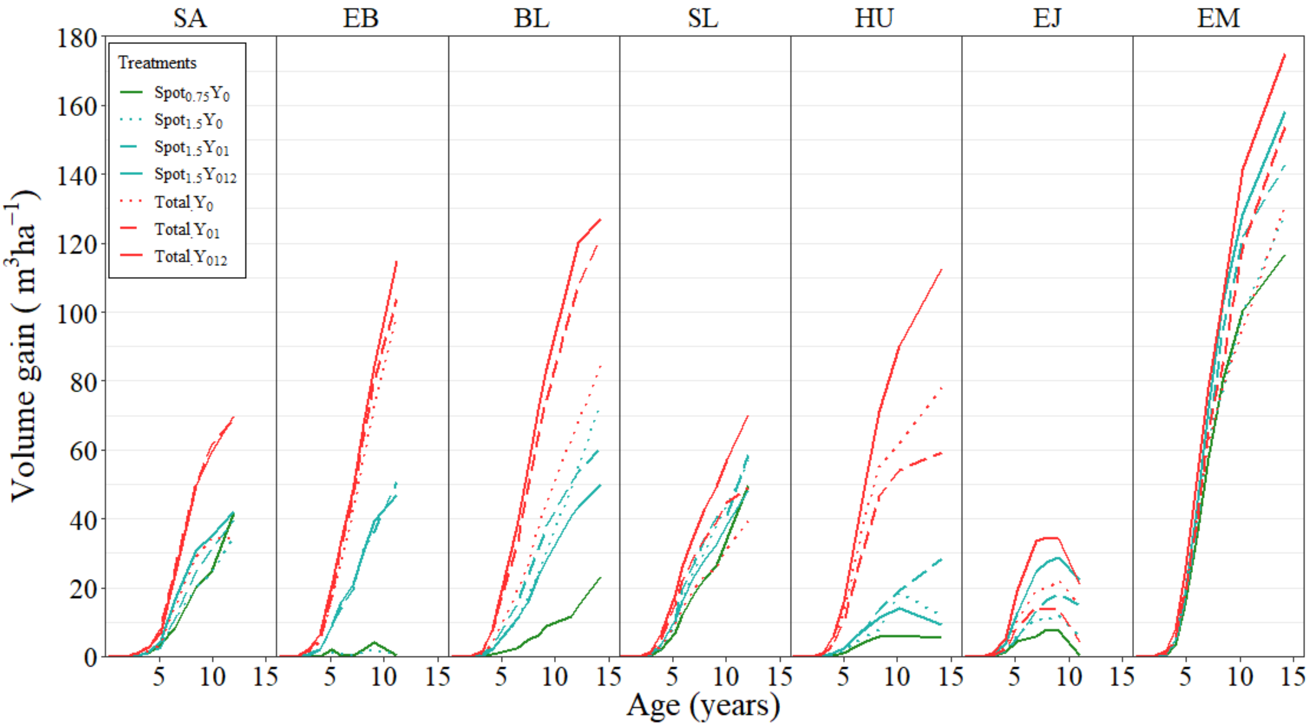

Figure 3. Time series of stem volume over bark per hectare gain ($m^3\ ha^{-1}$) for *P. radiata* stands growing under different competing vegetation control treatments on seven sites in south-central Chile.

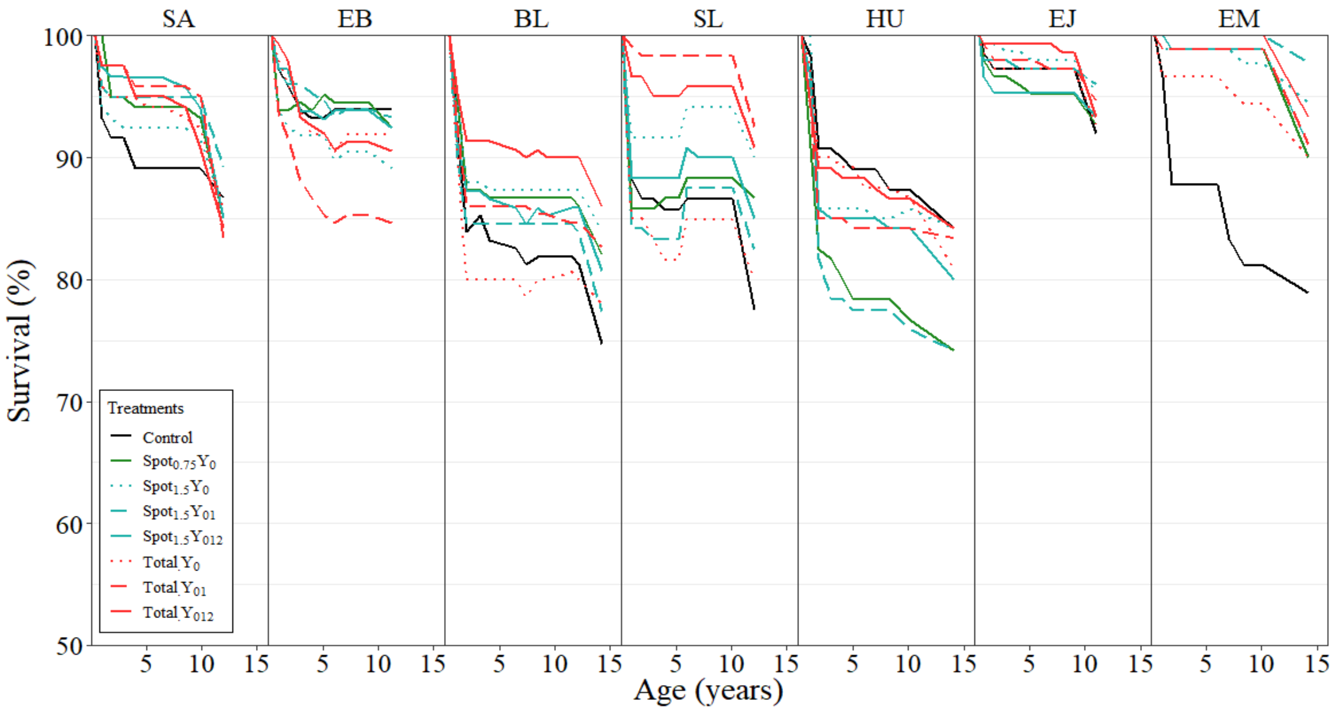

Figure 4. Time series of survival (%) for *P. radiata* stands growing under different competing vegetation control treatments on seven sites in south-central Chile.

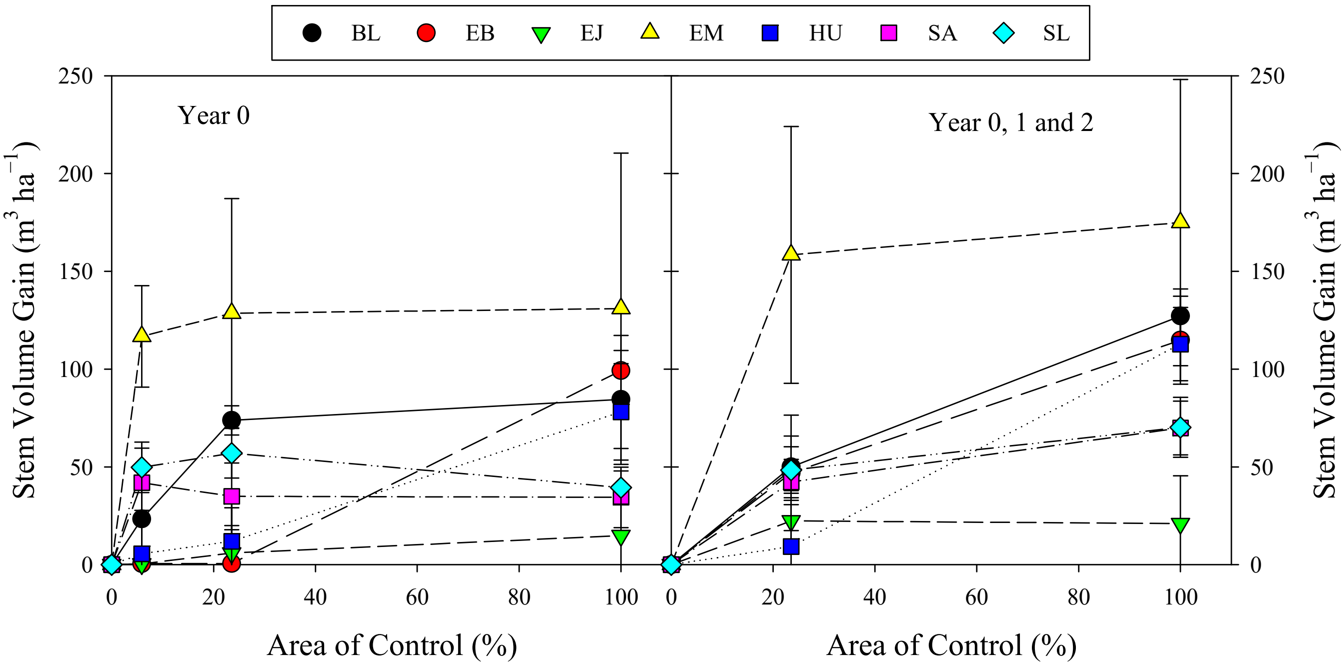

Figure 5. Stem volume over bark gain over control (m^3 ha^{-1}) for *P. radiata* stands growing under different treatments of area of competing vegetation control applied during planting year (Year 0, left panel) and during the first three years after planting (Years 0, 1, and 2, right panel) at seven sites in south-central Chile.

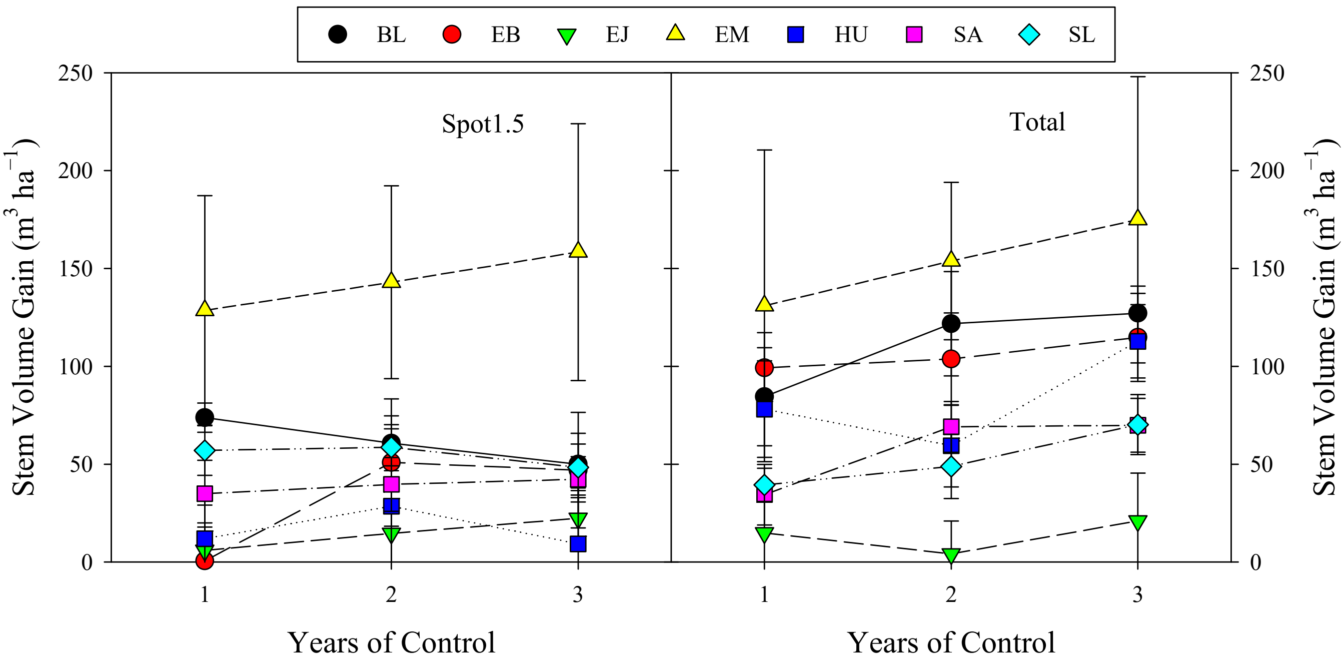

Figure 6. Stem volume over bark gain over control (m^3 ha^{-1}) for *P. radiata* stands growing under spot ($Spot_{1.5}$ treatment diameter 1.5 m; left panel) and total (right panel) competing vegetation control treatments applied over 1–3 years after planting on seven sites in south-central Chile.

Even though small differences in VOL gain were observed when comparing years of control for either 28% or 100% area of control, most of the sites showed a general trend of increasing stem volume gain as the area of control was 100% and 3 years of control (Figure 6).

3.5. Relationship between Environmental Conditions and Stand Productivity

Relationships between stem volume over bark mean annual increment (MAI, m^3 ha^{-1} y^{-1}) and environmental characteristics of tested sites are shown in Figure 7 (climate and soil data used in this analysis are shown in Table 1). Different relationships were obtained for stands growing under no-action treatment without CVC (control; filled symbol) and sustained total CVC during years 0, 1, and 2 (Total$Y_{0,1,2}$; open symbol). Overall, there was a negative relationship between WD (Figure 7a) and Tmax (Figure 7c) and MAI. On the other hand, there was a positive correlation between SOM and MAI until SOM reached a value of about 8%; after that, no gain in MAI was observed for increasing SOM (Figure 7b). For any environmental condition observed, sites growing under sustained total CVC showed larger MAI than stands growing under no-action treatment without CVC. Nevertheless, there was a trend of having reduced volume growth gain due to CVC in sites with high WD, low SOM, and high Tmax.

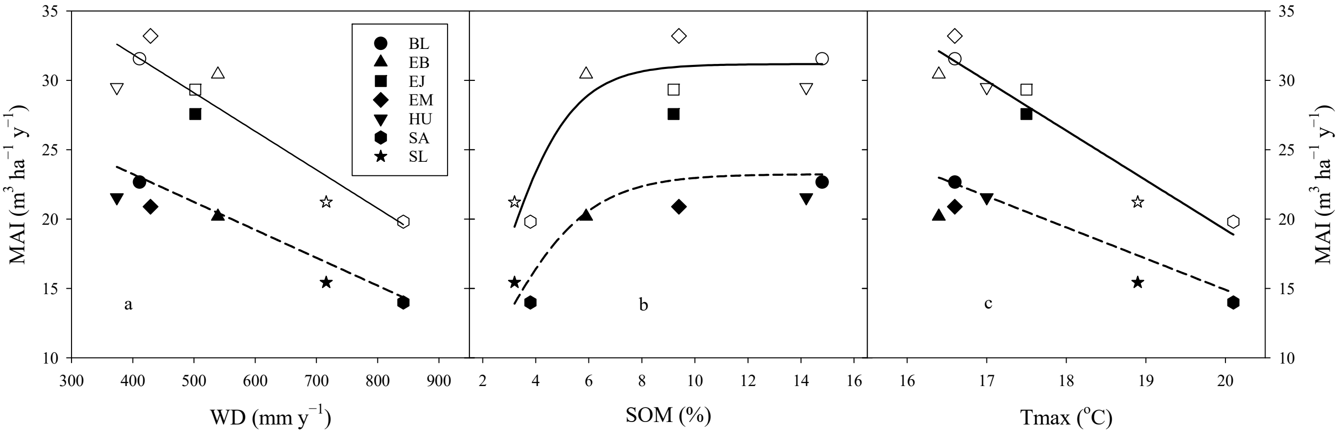

Figure 7. Relationships between stem volume mean annual increment (MAI, m^3 ha^{-1} y^{-1}) and (**a**) water deficit (WD, mm y^{-1}), (**b**) soil organic matter (SOM, %), and (**c**) mean monthly maximum temperature (Tmax, °C) for *P. radiata* stands growing under different competing vegetation control treatments (open symbol: Total $Y_{0,1,2}$; filled symbol: Control) at seven sites in south-central Chile. Solid and dashed lines represent model fit for total $Y_{0,1,2}$ and control treatments, respectively.

When multiple linear regression was tested, the MAI of Control plots was correlated with both WD and the biomass of early seral competing vegetation biomass during the first growing season (Bv, Mg ha^{-1}). On the other hand, the MAI of plots with sustained total CVC were correlated only with the Tmax of the site (Figure 7). Parameter estimates and fit statistics are shown in Table 6.

Table 6. Parameter estimates and fit statistics of models for the relationships between stem volume over bark mean annual increment (MAI, m^3 ha^{-1} y^{-1}) and to estimate soil organic matter (SOM), water deficit (WD), for 11–14-year-old *Pinus radiata* stands growing under different competing vegetation control treatments on seven sites in south-central Chile.

Treatment	Model	Parameter	Parameter Estimate	SE	Adj-R^2	RMSE	CV
Control	$MAI = a + b \cdot WD + c \cdot Bv$	a	40.8652	5.03535	0.831	2.97	11.27
		b	−0.0295	0.00668			
		c	−1.5747	0.65616			
Total $Y_{0,1,2}$	$MAI = a + b \cdot Tmax$	a	90.7169	8.06461	0.924	1.57	5.62
		b	−3.5742	0.45735			
Total $Y_{0,1,2}$	$VOL\ gain = a + b \cdot Bv$	a	32.0637	9.35898	0.880	12.37	12.19
		b	24.5400	2.86556			

Table 6. *Cont.*

Treatment	Model	Parameter	Parameter Estimate	SE	Adj-R^2	RMSE	CV
	$SOM = a + b \cdot e^{-c \cdot WD}$	*a*	2.5186	1.3437	0.884	1.56	18.04
		b	136.3	40.873			
		c	0.0064	0.00189			
	$WD = a + b \cdot Tmax$	*a*	−1444.3916	396.3589	0.835	77.05	14.14
		b	113.1091	22.47778			

MAI is stem volume mean annual increment (m^3); WD is annual water deficit (mm y^{-1}); Bv is competing vegetation biomass during the first growing season (Mg ha^{-1}); Tmax is mean monthly maximum temperature (Tmax, °C); SOM is soil organic matter (%); SE is the standard error; Adj-R^2 is adjusted coefficient of determination; RMSE is root mean square error; CV is coefficient of variation (%). All parameter estimates were significant at α = 005.

The lack of significance of other environmental variables such as SOM or WD is explained by the strong correlation between those variables, as SOM was negatively correlated with WD (Figure 8a), and WD was positively correlated with Tmax (Figure 8b). On average, sites with a WD of 400 mm y^{-1} had a SOM of 13% and a Tmax of 16.3 °C, while sites with a WD of 800 mm y^{-1} had a SOM of 3.3% and a Tmax of 19.9 °C. The parameter estimates and fit statistics are shown in Table 6.

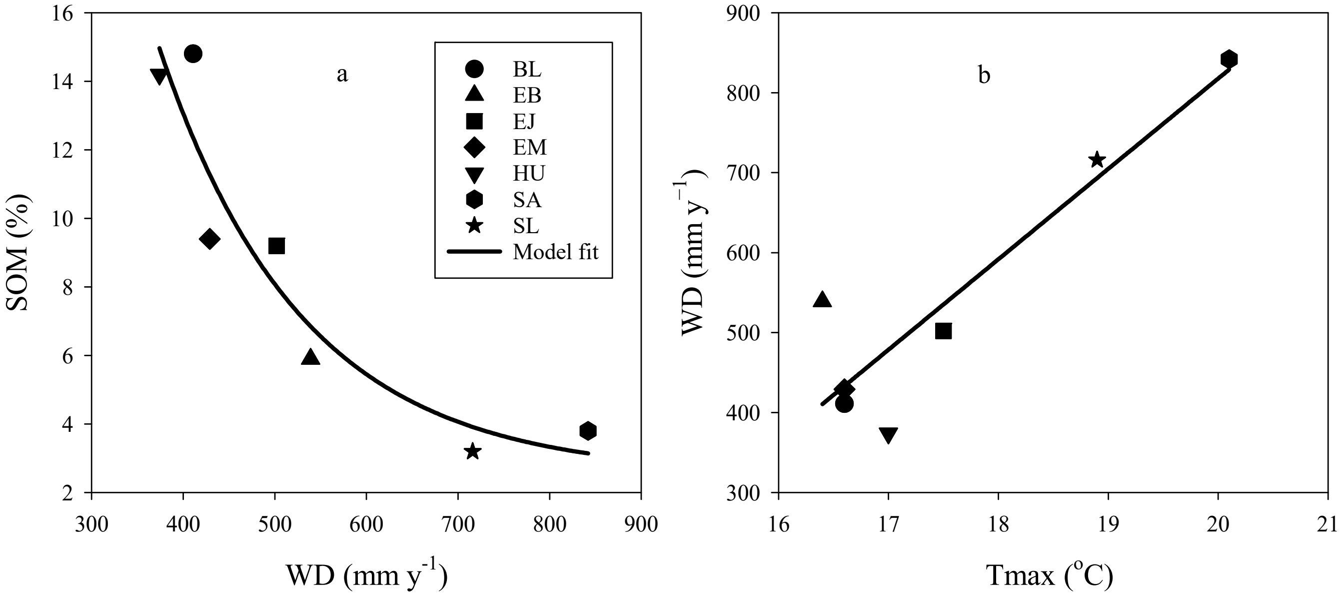

Figure 8. Relationships between environmental conditions for the seven sites used in this study: (**a**) water deficit (WD, mm y^{-1}) and soil organic matter (SOM, %); (**b**) mean monthly maximum temperature (Tmax, °C) and water deficit (WD, mm y^{-1}).

3.6. Relationship between Volume Response and Competing Vegetation Biomass

A strong correlation was observed between VOL gain of the $TotalY_{012}$ treatment and the amount of early seral competing vegetation biomass controlled during the first year (Figure 9). Several models were tested, and the linear model shown in Table 6 was selected. On average, there was a volume gain of about 60.2 m^3 ha^{-1} and 175.7 m^3 ha^{-1} for sites that had about 1 Mg ha^{-1} and 6 Mg ha^{-1} of competing vegetation abundance during the first growing season, respectively.

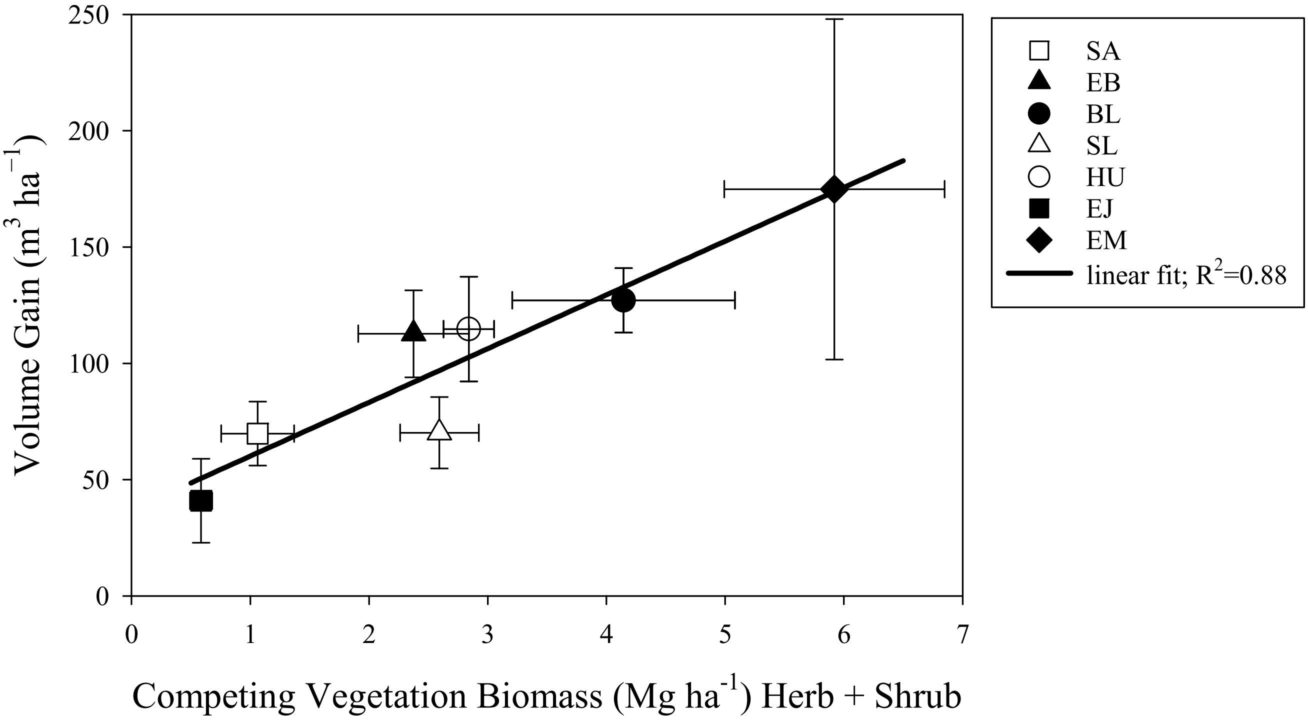

Figure 9. Relationship between VOL gain at age 11–14 years and competing vegetation biomass (Mg ha^{-1}) during first growing season after planting *P. radiata* stands at seven sites in south-central Chile.

4. Discussion

In this study, all sites showed a larger proportion of herbaceous vegetation during the first year (Figure 1). Treatment that included CVC only during year 0 and spot diameter of 0.75 m ($Spot_{0.75}Y_0$) showed a significant gain in VOL with just 6% area of control at the EM site (Figure 5). Similar results were reported by [27], who confirmed that even a small area free from neighboring vegetation around each seedling may increase survival and growth. One advantage of spot herbicide treatment is that it applies substantially fewer chemicals than broadcast herbicide treatment. The surrounding vegetation not controlled by the spot herbicide treatment may release nutrients due to plant senescence and tissue turnover, allowing for increased nutrient availability for planted crop trees [15]. Most of the sites showed a trend of increasing VOL yield as the intensity of CVC increased. Studies that evaluated different levels of intensity of CVC in *P. menziesii* plants in Oregon [13] and *P. radiata* in New Zealand [15] showed similar results. At the EM site, spot applications of 0.75 or 1.5 m diameter applied during year 0 achieved 88% and 90%, respectively, of stand volume yield of broadcast herbicide treatment applied during years 0, 1, and 2. These results suggest that surrounding competing vegetation can be a strong competitor for site resources, but a diameter of 35–40 cm around each seedling may provide enough resources for *P. radiata* seedlings, allowing them to capture resources needed for early growth. At sites with contrasting competing vegetation abundance (the EJ site, 0.6 Mg ha^{-1} and the EM site, 5.7 Mg ha^{-1}), high mortality was observed on treatment without CVC at the EM site in comparison with the EJ site. This may be explained by strong competition for water, nutrients, and light between competing vegetation and *P. radiata* seedlings. Similar results were observed in previous studies where different CVC treatments demonstrated high competition for water as it reflected contrasting xylem water potential [28]. A decrease in soil water availability is associated with reductions in xylem water potential, which may lead to decreasing stomatal conductance and, therefore, a reduction in carbon fixation [29]. Additionally, at the southern site (EM), which had high annual rainfall, low evaporative demand, and the highest abundance of vegetation biomass of all sites, the observed results suggest a high competition for light among early seral vegetation and *P. radiata* seedlings. Similar results were reported by [5,10], where increased survival of *P. radiata* seedlings was related to the increment in available light, in addition to soil water due to competing vegetation control. Although all sites included in this study were in areas with a dry summer, at higher latitudes, there was a trend of increased soil water availability during the growing season (Table 1) [30].

When comparing contrasting sites in relation to annual rainfall (BL site had 133% greater rainfall than SA site), stand volume yield on the last measurement of TotalY_{012} plots was 90% larger at the BL site. Across all sites, the largest stand volume yield on TotalY_{012} plots was observed at the EM, BL, and HU sites (471, 451, and 419 m^3 ha^{-1} at age 14 years, respectively). This high productivity may be related to higher SOM (Figure 7b). We observed a trend of reduced MAI on sites with low SOM (Figure 7b). Conversely, the TotalY_{012} plots showed the lowest volume yield at the SA and SL sites (238 and 257 m^3 ha^{-1}, respectively). This response may be attributed to lower water availability and longer dry summer periods at these sites, which had a total annual rainfall of 966 and 991 mm, respectively, which occurred mainly during autumn and winter. A strong relationship was observed between WD and SOM (Figure 8a; Adj-R^2 = 0.884) and between Tmax and WD (Figure 8b; Adj-R^2 = 0.835). Those relationships were obtained by incorporating sites with contrasting environmental conditions. In our study, there was a negative relationship between MAI and WD (Figure 7a) and Tmax (Figure 7c). Similar results were reported by [30], who confirmed that sites with large productivity were associated with low annual water deficit and reduced maximum growing season temperature. Water availability is the factor most limiting the productivity of *P. radiata* in central Chile [30].

Our results demonstrated that site productivity was affected by site conditions (WD, Tmax, and SOM), but also by the presence of competing vegetation; a larger MAI was observed in treated plots across the gradients of WD, Tmax, and SOM (Figure 7) [31]. Competing vegetation abundance and composition affect the temporal availability of site resources throughout stand development. At the beginning of stand establishment, herbaceous vegetation competes strongly for site resources, while woody vegetation growth is slower during the first years after planting but could be an important competitor for site resources even after stand canopy closure [5]. Initially, roots of competing vegetation and *P. radiata* seedlings occupy the same soil horizons [32,33]. Vertical stratification of root systems is an eventual pattern observed in many habitats, with shallow-rooted herbaceous vegetation utilizing shallower resources and deep-rooted woody species acquiring separate resources from deeper soil horizons [28,34]. In addition, once the stand is established, trees may be able to exploit deeper water in soil layers than most annual herbaceous vegetation [35].

Although rainfall was similar at both southern sites (EM and EJ), the EM site showed, for TotalY_{012} treatment, a volume gain eight times larger than the EJ site. These results can be explained by the difference in competing vegetation abundance at those sites (5.7 and 0.6 Mg ha^{-1}, respectively). Larger volume gain was observed at plots that had the highest abundance of competing vegetation during the first growing season. In contrast, the EJ site, which had the lowest abundance of competing vegetation, showed a smaller volume gain. These results suggest that increasing abundance of early seral competing vegetation is reflected in higher levels of competition for site resources. Similar results were reported by [36], where seedling growth response to CVC was correlated to competing vegetation biomass abundance present at the site. CVC not only increases gains in stem volume per hectare but may also have other impacts such as reducing the risk of fire, reducing seed bank abundance, and facilitating access for silvicultural operations, among others [24]. Our results suggest that competing vegetation probably decreased soil water availability during early stand development stage at all sites [37–40].

A strong correlation was found between the stem volume gain of the TotalY_{012} treatment at age 11–14 years and the amount of competing biomass controlled during the first growing season (Table 6 and Figure 9; Adj-R^2 = 0.88). On average, there was a stem volume gain of about 57 m^3 ha^{-1} for sites that had about 1 Mg ha^{-1} of competing vegetation abundance during the first growing season. The volume gain increased to about 179 m^3 ha^{-1} at sites that had about 6 Mg ha^{-1} of vegetation abundance during the first growing season. Similar relationships have been found for other species in a variety of environments [21,41–44]. In this study, a common relationship across sites was observed, suggesting that the stand volume response of *P. radiata* was linearly correlated to the amount of competing biomass during the first year. Since the cost of CVC is an important component of stand establishment budgets, such costs need to be considered according to the potential long-term response in volume yield, in order to determine the optimum economic scenario.

5. Conclusions

An increase in stem volume production at age 11–14 years was observed on *P. radiata* stands as the area free of competing vegetation around individual seedlings and the amount of competing vegetation biomass controlled during the first growing season increased. Additionally, total CVC treatment maintained for 2 years after planting showed the largest gain in stem volume per hectare at most of the sites.

Our current understanding of the physiological mechanisms that affect survival and plant growth associated with competition vegetation control across sites is limited. However, developing appropriate lines of research to better understand the interactions between early-seral vegetation (abundance and composition), crop trees (including different species and genotypes), and availability of resources on the site is an important challenge in order to develop sustainable forest management regimes.

Even though this study focused on determining the long-term responses to CVC intensity for *P. radiata* stem volume productivity, we recognize that in future studies, it will be important to assess the potential impacts of CVC on ecosystem services, such as water quantity and quality, seed bank abundance, native vegetation abundance and diversity, and soil nutrient bioavailability, as well as the effects on wildlife habitat and native pollinators. Ongoing research in some of these areas is being carried out by the authors in their respective research institutions.

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