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Long-term response to area of competition control in *Eucalyptus globulus* plantations

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Abstract Numerous studies have quantified the responses to vegetation management in *Eucalyptus* plantations but most publications have reported early responses in tree growth and a gap in knowledge exist about the magnitude and duration of growth responses throughout the whole rotation. We evaluated the long-term response (9 years-old) of *E. globulus* across a gradient of sites to different intensity levels of free area of competing vegetation around individual tree seedlings. Competing vegetation intensity levels considered free areas ranging between 0 (control) to 2.54 m^2 plus a treatment with total weed control. Competing vegetation biomass production during the first growing season was 2.9, 6.5, 2.2 and 12.9 Mg ha^{-1}, for sites ranging from low to high annual rainfall. Across sites, maximum response in stand volume ranged between 58 and 262 m^3 ha^{-1} at age 9 years and was proportional to the amount of competing biomass controlled during the first growing season. Total competing vegetation control showed the largest response in stand volume at sites with 2.9 and 12.9 Mg ha^{-1} of competing vegetation. However, the 2.54 m^2 vegetation control treatment showed the maximum response for sites with 2.2 and 6.5 Mg ha^{-1} of competing vegetation. The duration of response for vegetation control treatments ranged between 5 and 9 years. However, at the site with the largest accumulation of competing vegetation biomass the response to vegetation control showed a sustained and divergent response. Our results suggest that vegetation control improved site

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resources acquisition increasing long-term stand productivity by reducing environmental limitations to tree growth differentially at each site.

Keywords Weed control · Control intensity · Herbicide · Reforestation · Intensive silviculture · Forest management

Introduction

Planted *Eucalyptus* forests have been very successful worldwide because of their high growth rates and adaptability to a wide range of environmental conditions. Currently, there are more than 20 million hectares of *Eucalyptus* plantations around the world (FAO 2013), including more than 110 species of this genus that have been introduced in more than 90 countries (Booth 2013). Currently there are approximately 829,000 hectares ha of *Eucalyptus* plantations in Chile, located mainly in the south-central zone (between latitude − 35 and − 41), of which 69% consists of *E. globulus* (INFOR 2014).

Sustainable forest management requires an understanding of the interactions between tree growth response and site resource availability, and how those resources are modified throughout the rotation (Albaugh et al. 2004a; Powers and Reynolds 1999). Reducing competing vegetation biomass during stand establishment increases water, nutrient and light availability (Nambiar and Sands 1993; Kogan and Figueroa 1999; Balandier et al. 2006; Eyles et al. 2012) and, therefore, survival and tree growth (Adams et al. 2003; Rose et al. 2006; Wagner et al. 2006; Little et al. 2007; Haywood 2011).

Several studies have demonstrated that competing vegetation composition determines the temporal availability of site resources supporting crop tree occupancy throughout stand development. An example is the herbaceous vegetation, which is generally a strong competitor for resources at the beginning of rotation, while woody vegetation develops more slowly and may become a strong competitor for resources after crown closure (Zutter and Miller 1998; Balandier et al. 2006; Watt et al. 2015). In addition, studies that included different sizes of area free of competing vegetation around crop trees have shown that at a lower intensity of competing vegetation control there is a significant reduction in volume production of *Pinus taeda* (Dougherty and Lowery 1991), *Pinus radiata* (Richardson et al. 1996; Kogan et al. 2002), *Pseudotsuga menziesii* (Rose et al. 2006), and *Eucalyptus* spp. (Little and Rolando 2008). The intensity of control required to maximize plantation productivity depends on specific conditions of crop species, resource availability and type and amount of competing vegetation at each site (Richardson et al. 1996; Little and Rolando 2008).

The magnitude and duration of growth response to competing vegetation control has been shown to be influenced by several factors including site resource availability (Adams et al. 2003; Wagner et al. 2006), the composition (herbaceous/woody), amount of competing vegetation biomass (Wagner et al. 1989; Garau et al. 2009), and the timing and intensity of control, this last defined as the area free from competing vegetation around each tree (Rose and Rosner 2005; Little and Rolando 2008; Dinger and Rose 2009).

In the last decades there have been substantial research efforts to quantify growth responses associated with competing vegetation control in *Eucalyptus* plantations (Little and Rolando 2008; Garau et al. 2009; Eyles et al. 2012), but even though most reports showed early responses in *Eucalyptus* growth, there is still a gap in knowledge about the long-term effects of competing vegetation control intensity on the magnitude and duration of responses (Wagner et al. 2006).

Nilsson and Allen (2003) defined four types of growth responses to the application of silvicultural treatments (Type A, B, C, and D). Those response patterns, that are relative to an untreated control and reflect a modification on site resource availability, can be observed when analyzing long-term growth responses. Response types are distinguished by the amount and extent that resources (light, water and nutrients) become available and are used by trees throughout the rotation.

A treatment response is considered Type A if growth gains increase throughout the rotation and result in increased carrying capacity of the site (Albaugh et al. 2015). A response Type A has been observed in *P. taeda* plantations with treatments controlling woody competing vegetation (Zutter and Miller 1998; Nilsson and Allen 2003). A response is considered type B if growth increases in response to an early treatment relative to an untreated control for a limited time after treatment, then the additional available resources are exhausted, or are no longer available in the long-term, and treated trees stop responding (Albaugh et al. 2015). Type B responses have been observed in *P. radiata* plantations with control of competing herbaceous vegetation at fertile sites due to an improvement in the opportunity for resource acquisition (Mason and Milne 1999; Albaugh et al. 2004b). Type C responses, similar to type B, are those where a positive response is seen after treatment; however, the observed response will be lost over time. Type C responses have been observed in *P. radiata* and *P. taeda* plantations with control of competing vegetation at sites where nutritional constraints exists (Richardson 1993; Allen and Lein 1998). Finally, a type D response is observed as a negative growth response relative to an untreated control from the time of treatment (Albaugh et al. 2015). Type D responses have been observed in *P. radiata* plantations where fertilization has been applied and the competing vegetation has not been controlled (Albaugh et al. 2004b), and *P. taeda* plantations where treatments aimed to control competing vegetation have caused herbicide damage (Allen 1996).

From this point of view, there is a need to understand the long-term effect of weed control considering the amount of competing vegetation (intensity of competition) affecting site resource availability on *E. globulus* plantations growth. The objective of this study was to determine the effect of competing vegetation control intensity on the magnitude and duration of *E. globulus* volume response during a 9 year rotation, across gradients in rainfall and magnitude of competing vegetation. Our hypothesis are: i) competing vegetation control during stand establishment will show a sustained and temporary response in stand volume of *E. globulus* to age 9 year, and ii) the magnitude of the response in stand volume at age 9 years is proportional to the amount of competing vegetation controlled during the first growing season on each site.

Materials and methods

Site characteristics

Four experimental sites were selected considering a rainfall gradient (Table 1) and type of competing vegetation. Climate at the study sites showed a dry summer and precipitation mainly during winter (June–September). The sites were classified based on their annual mean rainfall as high (HR), medium (MR) or low (LR) rainfall, and by the amount of accumulated competing vegetation biomass (Mg ha^{-1}) in the control treatment during the first growing season. Thus, site LR2.9 was located in a zone with low rainfall (72°3′W and 36°42′S) and low competing vegetation biomass production; site MR6.5 located in a zone

Table 1 Average annual rainfall (Rain), mean annual maximum temperature (T_{max}), mean annual minimum temperature (T_{min}), soil depth (SD), clay content (Clay) and organic matter (OM) in the first 20 cm of soil depth for each site

Sites	Altitude (m)	Rain (mm year^{-1})	T_{max} (°C)	T_{min} (°C)	SD (m)	Clay (%)	Soil texture	OM (%)	Soil order
LR2.9	82	1198	19.8	6.3	1.2	43.0	Clay loam	5.0	Ultisol
MR6.5	112	1454	17.4	7.5	2.0	40.1	Clay loam	9.2	Alfisol
HR2.2	335	2055	16.7	6.0	1.5	18.3	Loam	16.5	Ultisol
HR12.9	73	2103	17.1	6.7	2.1	33.2	Silt loam	13.0	Andisol

with medium rainfall (73°29′W and 37°40′S) and medium competing vegetation biomass production; site HR2.2 located in a zone with high rainfall (72°52′W and 39°13′S) and low

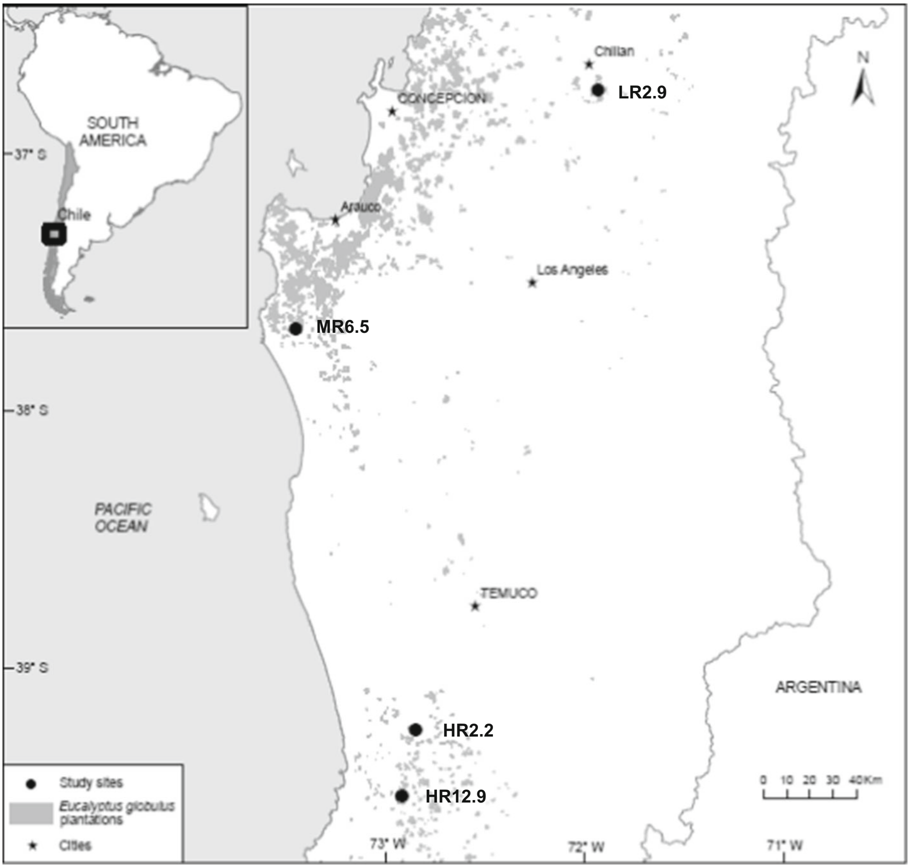

Fig. 1 Map showing the location of the four sites used in this study in Chile

competing vegetation biomass; site HR12.9 located in a zone with high rainfall (72°56′W and 39°28′S) and high competing vegetation biomass production (Fig. 1).

The type of herbaceous or woody vegetation at each site was assessed visually prior to herbicide application before planting, recording the dominant species. At LR2.9 herbaceous vegetation was dominated by *Arrhenaterum elatius* L., and woody vegetation was dominated by *Acacia dealbata* Link. At MR6.5 herbaceous vegetation was dominated by *Senecio vulgaris* L., and common woody vegetation was dominated by *Ulex europaeus* L. At HR2.2 herbaceous vegetation was dominated by *Digitalis purpurea* L., *Taraxacum officinale* F. H. Wigg., *Holcus lanatus* L., and woody vegetation was dominated by *Aristotelia chilensis* (Molina) Stuntz. At HR12.9 the herbaceous vegetation was dominated by *Lolium multiflorum* Lam., and the dominant species in the woody vegetation was *Rubus constrictus* P. J. Müll. & Lefevre. The LR2.9 site was second rotation with a prescribed burn to treat forest residues in March 2004, followed by soil preparation with 80 cm deep subsoiling and bedding (20 cm bed height), in April of the same year. The site was planted in July 2004. The MR6.5 site was also second rotation. Harvest slash was shredded in June 2004 and the site was planted in July 2004. The HR2.2 site was second rotation and harvest slash was mechanically arranged in strips (windrows) in April 2003. The site was planted in August 2003. The HR12.9 site was a first rotation plantation on a former pasture land and was planted in September 2004. All sites were planted with container stock from using a mix of genetically improved cuttings. All sites were planted at a spacing of 2.4 × 2.4 m (1736 trees ha^{-1}), except for site LR2.9, where planting was spaced at 3.0 × 2.0 m (1666 trees ha^{-1}), because it was subsoiled before planting. All sites were harvested at age 10 years.

Experimental design and treatments

At each site a randomized complete block design with five replicates (blocks) was used to test the effect of competing vegetation control intensity. Intensity treatments included five different areas of control around individual trees: no competing vegetation control (T_0), treatments with circular areas around each tree with 0.6 m diameter ($T_{0.6}$: 0.28 m^2); 1.2 m ($T_{1.2}$: 1.13 m^2) and 1.8 m ($T_{1.8}$:2.54 m^2), and a treatment with total competing vegetation control (T_T). The experimental plots had 90 trees in total (9 rows × 10 trees), with an internal measurement plot of 30 trees (5 rows × 6 trees) and a buffer of 2 rows implemented around each measurement plot. To quantify the amount of competing vegetation biomass at each site, an additional plot (90 trees in total) with no competing vegetation control was established in each block.

Herbicides were applied in the early morning hours when wind speeds were less than 2 km h^{-1} using a volume rate of 120 l ha^{-1}. At each site, herbicides (glyphosate 2.5 kg ha^{-1} + simazine 3.0 kg ha^{-1} + Silwet surfactant 1 ml l^{-1}) were applied using backpack sprayers prior to planting. Commercial products were Roundup Max (48% glyphosate), Simazina 90 WG (90% simazine) and Silwet surfactant was included to improve herbicide uptake. After planting, a second herbicide application was made at each site between February and March of the following year using the same chemicals, rates, and backpack spray equipment as in the first application prior to planting. Inverted plastic cones were placed over trees to provide protection from spray drift. Competing vegetation outside the cone was given a full cover spray. A third herbicide application was made between September and October of the following year using this method at all sites except at HR2.2 due to the low level of observed competing vegetation. In this application, plastic cones were not used because trees were too large and care was taken to prevent any herbicide drift to tree foliage.

At site LR2.9 and MR6.5 fertilizer was applied around each tree 30 days after planting, and received 32.4 g of N, 36.2 g of P and 3 g of B, using a blend of 180 g tree^{-1} of diammonium phosphate and 30 g tree^{-1} of boronatrocalcite (commercial fertilizers).

Competing vegetation biomass

During the first and second growing seasons, all competing vegetation was removed monthly from two 2 $\times$ 2 m subplots randomly selected within the additional biomass plot installed at each block. Samples of herbaceous and woody vegetation were taken from each subplot and green weights were recorded in the field. An aliquot of approximately 10% of the biomass collected from each sample was transported to the lab and oven-dried at 90 °C for 48 h to determine moisture content and dry mass.

Data analyses

From age 1 to 9 years total tree height (H, m) and stem diameter over bark at 1.3 m height (DBH, cm) were measured every year during the dormant season (May–June). Individual stem volume was estimated using the Kozak's taper function, implemented in EUCASIM simulator version 4.4.1 (Real 2010), considering a top diameter limit (TDL) of 6 cm for each tree. The effect of the competing vegetation control treatments was evaluated at age 9 years considering H, DBH, basal area (BA, m^2 ha^{-1}), volume (VOL, m^3 ha^{-1}), and survival (SUR, %), using analysis of variance (ANOVA) including by a Tukey's multiple comparison test.

In order to evaluate treatments effects on current annual volume increment (CAI, m^3 ha^{-1} year^{-1}), a repeated measures analysis was conducted. The effect of treatments on volume growth was calculated annually and plotted over time to determine the expected long-term response for each site to age 9 years.

Statistical analysis of mean treatment differences with respect to the control was developed using statistical software program R-Project (version 3.3). Repeated measures analysis was conducted to evaluate the effects of competing vegetation control intensity (C) over time (T) on current annual volume increment (CAI) for each site, using the following statistical model:

$$\mathrm{CAI}_{ijk} = \mu + \mathrm{C}_i + \mathrm{T}_k + (\mathrm{CT})_{ik} + \mathrm{e}_{ijk}$$

where CAI_{ijk} = current annual volume increment (m^3 ha^{-1} year^{-1}), μ = mean for treatment i at time k, C_i = treatment effect i, T_k = time effect k, $(\mathrm{CT})_{ik}$ = treatment $\times$ time interaction effect, e_{ijk} = random error associated with the measurement at time k on the jth subject that is assigned to treatment i.

Repeated measures analysis was developed by using a mixed model that considered several variance–covariance structures for each variable (Littell et al. 2006), including compound symmetric, non-structured and spatial power. The Bayesian information criterion was used to select the best fit to the data. All statistical analyses were evaluated using a $P < 0.05$ as a significance level.

Relationship between amount of competing vegetation biomass controlled and volume response

A non-linear model was fit to analyze the relationship between competing vegetation biomass controlled and volume response of *E. globulus* stands at age 9 years. After testing several models, we selected the following sigmoidal model:

$$Y_j = a * \left(1 - \exp\left(-b * X_j\right)\right) + \varepsilon_j$$

where Y_j is volume response ($m^3\ ha^{-1}$) at age 9 years and X_j is the amount of competing vegetation biomass controlled ($Mg\ ha^{-1}$) during the first growing season for the jth plot; exp is base of natural logarithm; ε_j is the error of the model with $\varepsilon \sim N(0, \sigma^2)$; j is 1,… n_i plot; a and b are curve fit parameters.

Results and discussion

Competing vegetation biomass production

Herbaceous competing vegetation was the dominant type of competition at all the sites during the first two growing season, except for site MR6.5 where a large proportion of woody competing vegetation was observed (52 and 56% of the total biomass) during the first and second growing seasons (Fig. 2).

Maximum values of competing vegetation biomass occurred at different times at each site. During the first growing season the maximum production of competing vegetation biomass was achieved in spring (November) of the planting year at site LR2.9, in mid-summer (February) of the year following planting at site HR12.9, and in late-autumn (May) of the following year after planting at sites HR2.2 and MR6.5. On the other hand, during the second growing season the maximum production of competing vegetation biomass was reached in late-spring (November and December) at all the sites (data not shown). Although the amount of competing vegetation biomass was not measured after 2 years from planting, a sustained increase was observed in the presence of woody vegetation at all the sites and treatments (visual observation).

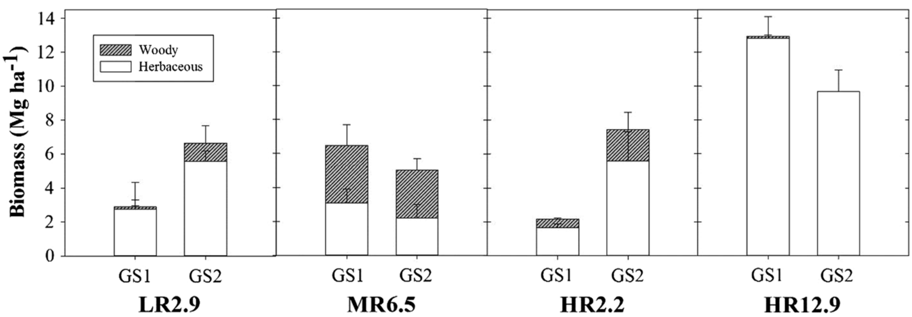

Fig. 2 Maximum average annual biomass production of herbaceous (open filled) and woody (black filled) components during the first (GS1) and second (GS2) growing seasons on four sites in south central Chile (LR2.9, MR6.5, HR2.2 and HR12.9)

Survival

Increases in competing vegetation control intensity increased survival at all the sites, except for the site with the lowest amount of competing vegetation biomass (HR2.2). At HR2.2 no significant differences in survival were observed among treatments (Fig. 3). Similarly to HR2.2, a weak relationship was found for survival and amount of competing vegetation biomass in *E. globulus* by Garau et al. (2009). The condition of HR2.2 site, associated with high rainfall conditions (2055 mm year^{-1}), higher altitude and lower temperatures, compared to the other sites under study, may have contributed to the reduced growth of competing vegetation during the first growing season.

On sites with contrasting annual rainfall (LR2.9, 1198 mm, and HR 12.9, 2103 mm), the high mortality observed on non-treated control plots at age 9 years (41 and 31%, respectively), may have different explanations. The northern site (LR2.9) had the lowest annual rainfall and higher vapor pressure deficit of all the sites being studied, suggesting lower soil water availability and higher evaporative demand during the growing season affecting severely seedling survival. This is consistent with responses observed in previous studies where competition for water can be intense as indicated by leaf water potential measured in contrasting weed control treatments (Nambiar and Sands 1993). In addition, decreasing in soil water availability may reduce xylem water potential and therefore alter canopy stomatal conductance which is closely related to changes in plant water status (Herrick et al. 2004). On the other hand, at the southern site (HR12.9), which had the highest annual rainfall, the lowest vapor pressure deficit and the highest competing vegetation biomass production across all sites, a high competition for light may had affected *E. globulus* seedlings. These results are consistent with the findings reported by Balandier et al. (2006) and Garau et al. (2009), where survival increments of *E. globulus* due to competing vegetation control have been related to increases in available soil water and light. Competition for light may explain the large differences in survival between the two southern sites that had higher rainfall (HR2.2, 2055 mm; HR12.9, 2103 mm). The contrasting survival levels observed on non-treated control plots (97% at HR2.2 and 31% at

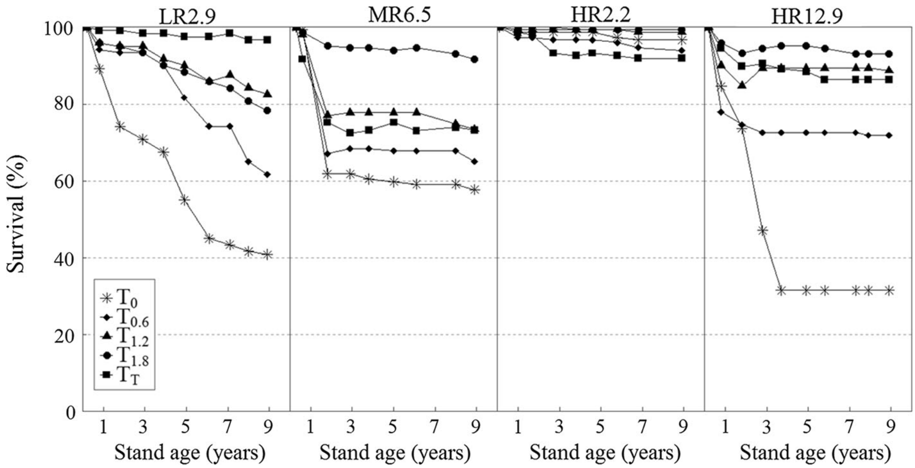

Fig. 3 Time series dynamics of survival percentage for *E. globulus* stands growing under different vegetation control intensity treatments on four sites in south central Chile (LR2.9, MR6.5, HR2.2 and HR12.9)

HR12.9), suggest that the high amount of competing vegetation biomass reduced light availability and induced to carbon starvation during early establishment at the HR12.9 site.

Stand yield at age 9 years

All sites showed significant growth responses in H, DBH, BA, VOL and SUR due to competing vegetation control treatments at age 9 years. However, treatment effects were not significant on H and SUR at site HR2.2 (Table 2). The sites under study showed high variability in productivity with volume yields for treatment T_T ranging from 127 m^3 ha^{-1} at the site with the lowest annual rainfall (LR2.9, 1198 mm), to 288 m^3 ha^{-1} at the site with the highest annual rainfall (HR12.9, 2103 mm). A general trend of increasing stand volume growth as the area free from competition vegetation increased across sites. A general trend of increasing stand volume growth was observed in studies that included different levels of competing vegetation control intensity in *E. globulus* (Garau et al. 2009; Little and Rolando 2008) and a study that included treatments with different areas of competing vegetation control around *P. menziesii* trees in Oregon (Rose et al. 2006).

Table 2 Average total height (H), stem diameter (DBH), basal area (BA), stand volume (VOL) and survival (SUR) at age 9 years for *E. globulus* stands that received different vegetation control treatments

Treatments	H (m)		DBH (cm)		BA (m^2 ha^{-1})		VOL (m^3 ha^{-1})		SUR (%)	
LR2.9										
T_0	8.8	c	6.1	c	2.6	c	9.5	c	41	c
$T_{0.6}$	10.7	bc	7.9	c	5.7	c	25.4	c	62	bc
$T_{1.2}$	12.9	ab	10.6	b	13.0	b	61.9	b	83	ab
$T_{1.8}$	13.6	a	11.2	ab	13.8	b	71.3	b	78	ab
T_T	15.4	a	12.9	a	22.3	a	127.2	a	97	ab
MR6.5										
T_0	19.7	b	15.5	c	20.8	c	159.0	c	58	b
$T_{0.6}$	20.9	ab	18.1	ab	28.8	bc	222.0	bc	65	b
$T_{1.2}$	21.8	ab	18.5	ab	35.0	ab	276.6	b	73	ab
$T_{1.8}$	21.4	ab	17.4	bc	40.4	a	324.5	a	92	a
T_T	23.3	a	20.4	a	41.3	a	343.4	a	73	ab
HR2.2										
T_0	17.9	a	13.2	c	24.7	c	164.9	c	97	a
$T_{0.6}$	17.9	a	14.2	bc	27.5	bc	184.6	bc	94	a
$T_{1.2}$	18.8	a	13.9	bc	27.8	bc	195.3	bc	99	a
$T_{1.8}$	18.6	a	15.1	ab	32.5	ab	222.9	ab	99	a
T_T	19.4	a	16.4	a	35.1	a	251.9	a	92	a
HR12.9										
T_0	14.1	c	10.9	d	4.9	c	26.8	d	31	b
$T_{0.6}$	16.9	b	12.2	cd	15.7	b	101.5	c	72	a
$T_{1.2}$	18.2	b	12.9	c	21.6	b	155.4	c	89	a
$T_{1.8}$	21.2	a	15.0	b	29.3	a	233.6	b	93	a
T_T	22.5	a	16.8	a	34.1	a	288.9	a	86	a

Within each site, different letters indicate significant difference using Tukey's multiple comparison test

Although all study sites are under the influence of a dry summer climate, at higher latitude there is an increase in soil water availability during the growing season (Flores and Allen 2004; Álvarez et al. 2013). When comparing sites in terms of most contrasting average annual rainfall, T_T plots stand volume yield at age 9 years was more than 2 times larger at the southern and wetter site (HR12.9 site had 76% greater rainfall than LR2.9). Across all sites, the largest stand volume yield was observed on T_T plots at the MR6.5 site (343.4 m^3 ha^{-1}). This response may be associated to a positive response to fertilization and milder temperatures, influenced by its proximity to the ocean, which constitutes a more favorable condition for *E. globulus* growth (Sands and Landsberg 2002). These authors reported that the minimum and optimum temperature for *E. globulus* growth are 8.5 and 16 °C. Conversely, the lowest volume yield at the T_T treatment was observed at the LR2.9 site (127 m^3 ha^{-1}). This response can be attributed to lower site water availability of the site (1198 mm rainfall) which occurs mainly during autumn and winter with longer dry summer periods. On non-treated control plots, volume yield at age 9 years was the lowest on both sites located at the extreme of the latitudinal gradient (LR2.9 and HR12.9), where reduced volume yield was associated with high mortality.

After 9 years, maximum response in volume relative to the non-treated control, was achieved with treatment T_T (118 m^3 ha^{-1}); $T_{1.8}$ (166 m^3 ha^{-1}); $T_{1.8}$ (58 m^3 ha^{-1}) and T_T (262 m^3 ha^{-1}) for sites LR2.9, MR6.5, HR2.2 and HR12.9, respectively (Fig. 4e–h). Volume response at age 7 years was 306 m^3 ha^{-1} where the total area was treated compared to 86 m^3 ha^{-1} in non-treated stands of *Eucalyptus grandis* and *Eucalyptus grandis* × *camaldulensis* in studies by de Toledo et al. (2003) and Little (1999).

Although rainfall was similar in both southern sites (HR2.2 and HR12.9), the HR12.9 site showed a response in stand volume 3 times larger than the HR2.2 site. This response may be explained by the large difference in the amount of competing vegetation biomass at each site (12.9 and 2.2 Mg ha^{-1}, respectively). The largest response in stand volume was observed in plots that had the highest amount of competing vegetation biomass controlled. Contrastingly, the HR2.2 site showed the lowest volume response, probably due to a low production of competing vegetation biomass. These results suggest that the high amount of competing vegetation biomass generates a high level of competition for site resources. This response is consistent with the results reported by Little and Schumann (1996), where growth response to competing vegetation control was correlated to the amount of vegetation biomass present in *Eucalyptus* plantations.

Although treatment $T_{0.6}$ covers only 5% of the total treated area, there was a significant increase in the stand volume yield compared to the treatment without control at sites MR6.5 and HR12.9. Similar results have been reported by Wagner (2000), who confirmed that even a low intensity of competing vegetation control may greatly reduce limitations for seedling survival and growth.

Our results suggest that the effect of competing vegetation control may be associated with an increment in soil water availability for early development of the stand at all sites (Nambiar and Zed 1980; Little and Van Staden 2003; Garau et al. 2008). In addition, decreases in light availability may be critical at sites where competing vegetation had a large shadowing effect on *E. globulus* seedlings at stand establishment phase. Finally, decreased soil nitrogen availability may be of importance at the site with an abundance of graminoids (Smethurst and Nambiar 1989). Fine roots of herbaceous plants are concentrated in surface soil where nitrogen availability is high and root densities of competing vegetation are typically much higher than those of trees (Nambiar and Sands 1993; Eyles et al. 2012). Reducing the negative effects of competing vegetation must balance the potential benefits of non-tree vegetation on nutrient conservation (Smethurst and Nambiar

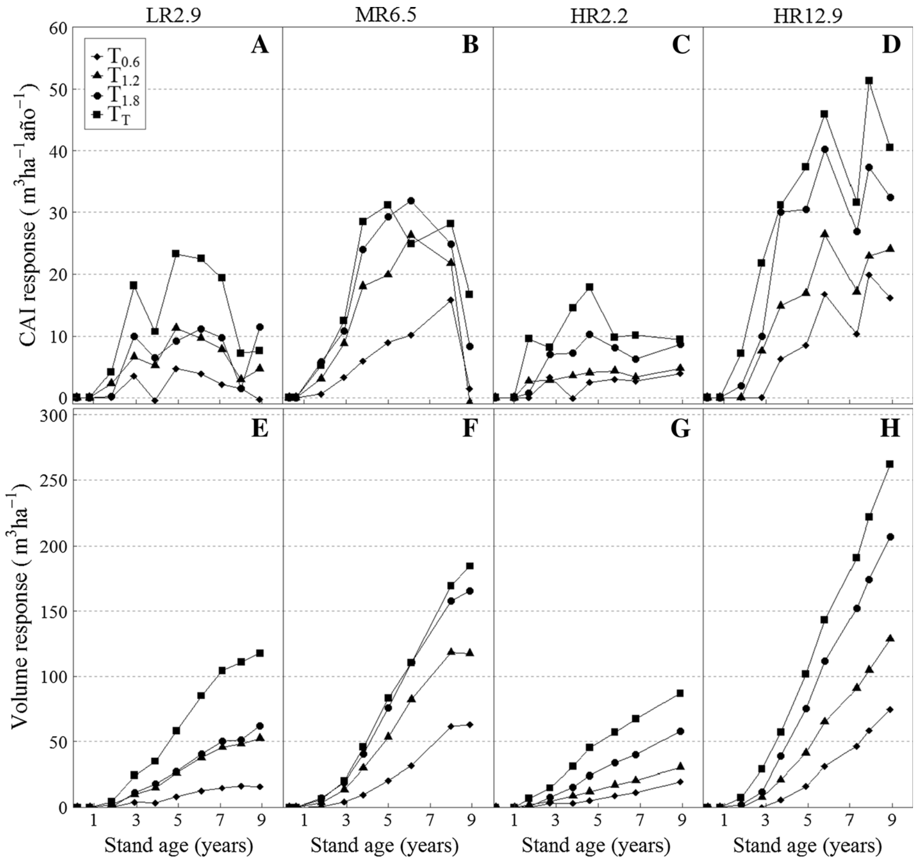

Fig. 4 Time series dynamics of current annual volume increment (m^3 ha^{-1} $year^{-1}$) and cumulative volume response (m^3 ha^{-1}) for *E. globulus* stands growing under different vegetation control intensity treatments on four sites in south central Chile (LR2.9, MR6.5, HR2.2 and HR12.9). Values shown reflect the difference relative to the non-treated control

1989), reduced erosion, biodiversity, and N fixation (Nambiar and Nethercott 1987), which may be obtained by reducing the free area of weed control.

Volume response over time

Across sites volume growth response increased as competing vegetation control intensity increased (Fig. 4e–h). However, a sustained gain (Type A response) in volume at age 9 was observed at the HR12.9 site for treatments $T_{1.2}$, $T_{1.8}$ and T_T; whereas, treatment $T_{0.6}$ had a temporary volume gain (Type B response) (Fig. 4d, h). A Type B response was observed at sites LR2.9, MR6.5 and HR2.2 (Fig. 4a, b, c, e, f, g). For sites LR2.9 and MR6.5, the response lasted 7 and 8 years, respectively, remaining constant until year 9 for treatments $T_{1.2}$, $T_{1.8}$ and T_T. On these sites, treatment $T_{0.6}$ showed no further volume response after age 8 years (Fig. 4e, f). For site HR2.2, the response lasted 5 years, remaining constant until year 9 for treatments $T_{1.8}$ and T_T. Type C and D responses were not observed over the evaluation period at all study sites.

Herbaceous vegetation is generally a strong competitor for resources during first years of stand establishment, while woody vegetation develops more slowly and may become a strong competitor for resources even after crown closure (Zutter and Miller 1998; Balandier et al. 2006). At the beginning of planting, roots of competitors and tree seedlings equally occupy the same soil horizons (Zutter et al. 1999; Balandier et al. 2002). Vertical stratification of root systems is an eventual pattern observed in different habitats, with shallow-rooted herbaceous species utilizing shallower resources and deep-rooted woody plants acquiring separate resources from deeper soil horizons (Nambiar and Sands 1993; Casper and Jackson 1997). In addition, once established, trees may be able to exploit deeper water in soil layers than most annual herbaceous species (Gonçalves et al. 2004). Even a low density of tree roots deep in the soil can have a strong influence on water availability to trees during dry periods (Nambiar and Sands 1992). At all study sites, treatments of competing vegetation control were carried out during the first 2 years from planting, controlling mainly herbaceous vegetation. At sites where the amount of competing vegetation biomass was lower than or equal to 6.5 Mg ha^{-1} (LR2.9, MR6.5 and HR2.2), volume responses lasted 7, 8 and 5 years, respectively, showing a constant value at age 9. Similarly, temporal Type B responses were reported for *Pinus radiata* (Mason and Milne 1999) and *Pinus taeda* (Nilsson and Allen 2003) stands. Competing vegetation control treatments during the first years from planting may improve the opportunity for site resource acquisition in the short term, because of the temporal effect of herbicides on smaller vegetation. However, competing vegetation is likely to reinfest the treated area when light availability favours understory establishment due to the relatively low canopy coverage and leaf area index of adult *E. globulus* stands (Whitehead and Beadle 2004). Conversely, at the HR12.9 site, a sustained and divergent volume response until age 9 years was observed in all the treatments with larger areas free of weeds (> 0.28 m^2), which relates to the large amount of herbaceous biomass present at the time of plantation establishment. A high intensity of competing vegetation control not only increases stand volume yield, but may also have other implications such as: reducing fuel loads and risk of fire, reduction in the seed bank, improved access for silvicultural operations, and control of exotic and invasive vegetation (Little and Rolando 2008). In addition, trees in the total competing vegetation control treatment may potentially also benefit from the release of nitrogen from weeds via nitrogen cycling (Forrester et al. 2007).

Relationship between amounts of competing vegetation biomass controlled and stand volume response

A strong relationship was found between stand volume response and the amount of competing biomass controlled during the first growing season (Fig. 5; $Y = 258.52 * (1 - \exp(-0.28 * X)$; $P < 0.001$; $R^2 = 0.78$). On average, at age 9 years, volume response was about 112 m^3 ha^{-1} when the amount of competing biomass controlled during the first growing season was about 2 Mg ha^{-1}. A maximum volume response of about 258 m^3 ha^{-1} was observed when the amount of competing vegetation biomass controlled during the first growing season was about 8 Mg ha^{-1}. Interestingly, there was little incremental response when competing vegetation control was above this amount.

Similar results for *E. globulus* were reported by Garau et al. (2009), where competing vegetation biomass accounted for 98% of the variation in stand volume. Comparable relationships have been reported for others species in different environments (Wagner et al. 1989; George and Brennan 2002; Coll et al. 2004; Harper et al. 2005). Changes in the slope

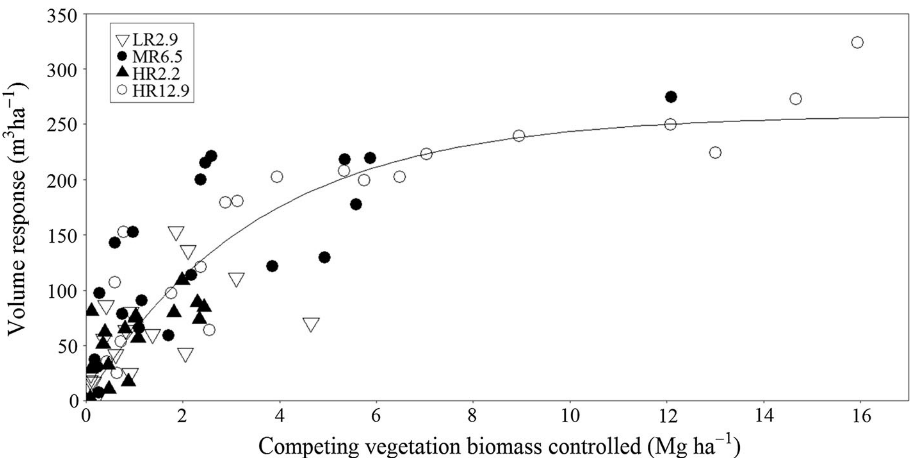

Fig. 5 Relationship between competing vegetation biomass controlled during the first growing season and volume response at age 9 years for *E. globulus* stands growing under different vegetation control intensity treatments on four sites in south central Chile (LR2.9, MR6.5, HR2.2 and HR12.9). Solid line represents the fitted model ($P < 0.001$; $R^2 = 0.78$)

of the relationship between the amount of competing vegetation biomass controlled and the volume response were related to differences in the amount or resources available and the efficiency of the use of those resources by the competing vegetation. In our study, the slope of the curve was higher when the amount of competing vegetation biomass controlled was less than 2 Mg ha^{-1}, suggesting that *Eucalyptus* has a low tolerance to interference by competing vegetation during the establishment phase (George and Brennan 2002; Garau et al. 2009). Conversely, the slope of the curve was low when the amount of competing vegetation biomass controlled was greater than 8 Mg ha^{-1}, suggesting that beyond this level additional vegetation control will not produce a substantial increase in stand volume. This emphasizes the importance of our experiment for understanding how reducing the amount of competing vegetation biomass influence long-term site productivity.

Vegetation control costs are an important component of early silvicultural costs, and such costs should to be considered according to the potential long-term response in volume, in order to determine the most profitable scenario. The intensity of competing vegetation control will depend whether the objective of control is to maximize stand volume yield regardless of cost, minimize costs at the expense of volume yield, or optimize yield at an acceptable cost.

Conclusions

An increase in stand volume response at age 9 years was observed as competing vegetation control intensity, and the amount of competing vegetation biomass controlled during the first growing season, increased. A temporary, but sustained, response until age 9 years was observed in sites with competing vegetation biomass controlled lower than 6.5 Mg ha^{-1}. However, at the site with the largest amount of competing vegetation biomass (12.9 Mg ha^{-1}), the response to vegetation control showed a sustained and divergent response until year 9. Across sites, maximum response in stand volume ranged between 58 and 262 m^3 ha^{-1} at age 9 years and was proportional to the amount of competing biomass controlled during the first growing season. Our current understanding of the physiological mechanisms driving growth differences associated with competition control across sites is limited. However, developing appropriate experimental approaches to interpret the effects of competing vegetation types, crop trees and site resource availability is an important challenge to understand long-term responses on a site-specific basis.

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