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Modelling the effect of weed competition on long-term volume yield of *Eucalyptus globulus* plantations across an environmental gradient

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Abstract: Several studies have quantified the responses of *Eucalyptus globulus* plantations to weed control on its early development (2-3 years after establishment). However, long-term results of competing vegetation effects have been rarely incorporated into growth and yield models that forecast the long-term effects of reducing the intensity of competing vegetation control and its interaction with site resource availability on stem volume production close to rotation age. We compared several models predicting stand stem volume yield of *Eucalyptus globulus* plantations established across a water and fertility gradient growing under different intensity levels of free area of competing vegetation maintained during the first 3 years of stand development. Four sites were selected encompassing a gradient in rainfall and amount of competing vegetation. Treatments were applied at stand establishment and were monitored periodically until age 9 years. Competing vegetation control intensity levels considered 0, 5, 20, 44 and 100% weed-free cover around individual *E. globulus* seedlings. Maximum competing vegetation biomass production during the first growing season were 2.9, 6.5, 2.2 and 12.9 Mg ha^{-1}, for sites ranging from low to high annual rainfall. As expected, reductions in volume yield at age 9 years were observed as competing vegetation control intensity decreased during the first growing season. A strong relationship was established between stem volume yield loss and the intensity of competing vegetation control, the amount of competing vegetation biomass produced during the first growing season and mean annual rainfall. The slope of the relationship was different among sites and was related mainly to water and light limitations. Our results, suggest that the biomass of competing vegetation (intensity of competition) affecting site resource availability, contribute to observed long-term effects on *E. globulus* plantations productivity. The site with the lowest mean annual rainfall showed the highest volume yield loss at age 9 years. Sites with highest rainfall showed contrasting results related to the amount of competing vegetation biomass.

Keywords: Weed control; Competing vegetation; Yield modelling; *E. globulus*.

1. Introduction

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Expansion of planted *Eucalyptus* forests has been 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 worldwide [1], including more than 110 species of the genus that have been introduced in more than 90 countries [2]. In Chile, there are approximately 850,000 hectares of *Eucalyptus* plantations located mainly in the south-central zone (between latitude -35 and -41), of which 68% corresponds to *E. globulus* [3].

Sustainable forest management of these planted forest requires a good understanding of tree growth and site resource availability interaction, and how resources are modified throughout the rotation by forest management [4,5]. It is well known that reducing competing vegetation biomass during stand establishment increases water, nutrient and light site resource availability [6-8] allowing better survival and tree growth [9-12].

Previous studies about the managing of the intensity of competing vegetation or weed control, defined as the area free from competing vegetation around each tree, have shown that at lower intensity of control there is a reduction in stem volume production of fast growing species such as *Pinus taeda* [13], *Pinus radiata* [14,15], *Pseudotsuga menziesii* [10], and *Eucalyptus* spp. [16]. The intensity of weed control required to maximize the plantation productivity depends on specific conditions such as the species, resource availability and type and amount of competing vegetation at each site [14,16]. During last decades, there have been substantial research efforts to quantify growth responses associated with competing vegetation control in *Eucalyptus* plantation [8,16,17,18]. However, these results have not been included into growth models that incorporate different treatments of intensity of competing vegetation control on *Eucalyptus* plantations. The stem volume yield loss (or stand yield loss) due to weed competition has been shown to be influenced by several factors including: the amount of competing vegetation biomass, spatial proximity to the plantation trees, soil water holding capacity, rainfall and temperature experienced in the field over the growing season [19]. However, a model can predict the likely yield loss associated with different intensities of competing vegetation control [20]. Modelling plantation-weed interactions can help also to generate scientific insights and a better understanding of ecophysiological processes involved. Empirical approaches have been used to model the response to competing vegetation control on the juvenile growth for *Pinus radiata* [21-23], *Pinus taeda* [24] and *Pseudotsuga menziesii* [25]. A negative hyperbolic curve with downward concavity was a good descriptor for the relationship between stem volume and competing vegetation biomass.

The development of a growth model sensitive to competition from competing species would improve our capacity to predict long-term effects of weed competition on tree growth response. From a modelling perspective, there is a strong need to understand the effects of the amount of competing vegetation (intensity of competition) and site resource availability on long-term responses of *E. globulus* plantations on a site-specific basis in order to make more sustainable management decisions. The objective of this study was to model the effect of area free of competing vegetation on stem volume response of *E. globulus* plantations. We hypothesize that: i) the relationship between stand yield loss and intensity of competing vegetation control is not linear (there is an optimal level intensity of competing vegetation control, beyond this level the stand volume yield loss would be small). ii) sites with high water availability require smaller area free of competition at establishment than sites with low water availability to reach the maximum growth potential at 9 years of age in *E. globulus* plantations.

2. Materials and Methods

2.1. Site characteristics

Four experimental sites were selected representing an environmental gradient in south central Chile (Table 1), where other work has been completed [18]. Climate at the study sites showed a dry summer and precipitations mainly during winter (June-September). The sites were classified based on their annual mean rainfall (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 and had 2.9 Mg ha^{-1} of competing vegetation biomass production; site MR6.5 was located in a zone with medium rainfall and had 6.5 Mg ha^{-1} of competing vegetation biomass production; site HR2.2 was located in a zone with high rainfall and had 2.2 Mg ha^{-1} of competing vegetation biomass production; site HR12.9 was located in a zone with high rainfall and had 12.9 Mg ha^{-1} of competing vegetation biomass production (Figure 1).

At the LR2.9 site, herbaceous competition was dominated by *Arrhenaterum elatius* L. and common woody shrub was *Acacia dealbata* Link. At the MR6.5 site, herbaceous competition was dominated by *Senecio vulgaris* L. and common woody shrub was *Ulex europaeus* L. At the HR2.2 site, herbaceous competition was dominated by *Digitalis purpurea* L., *Taraxacum officinale* F.H. Wigg and *Holcus lanatus* L. and common woody shrub was *Aristotelia chilensis* (Molina) Stuntz. At the HR12.9 site, herbaceous competition was dominated by *Lolium multiflorum* Lam., and common woody shrub was *Rubus constrictus* P. J. Müll. & Lefevre.

The LR2.9 site came from a second rotation with a prescribed burn to treat harvest slash 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 second rotation and 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 a mix of the top 5 % half-sib families produced from cuttings and ranked by genetic performance.

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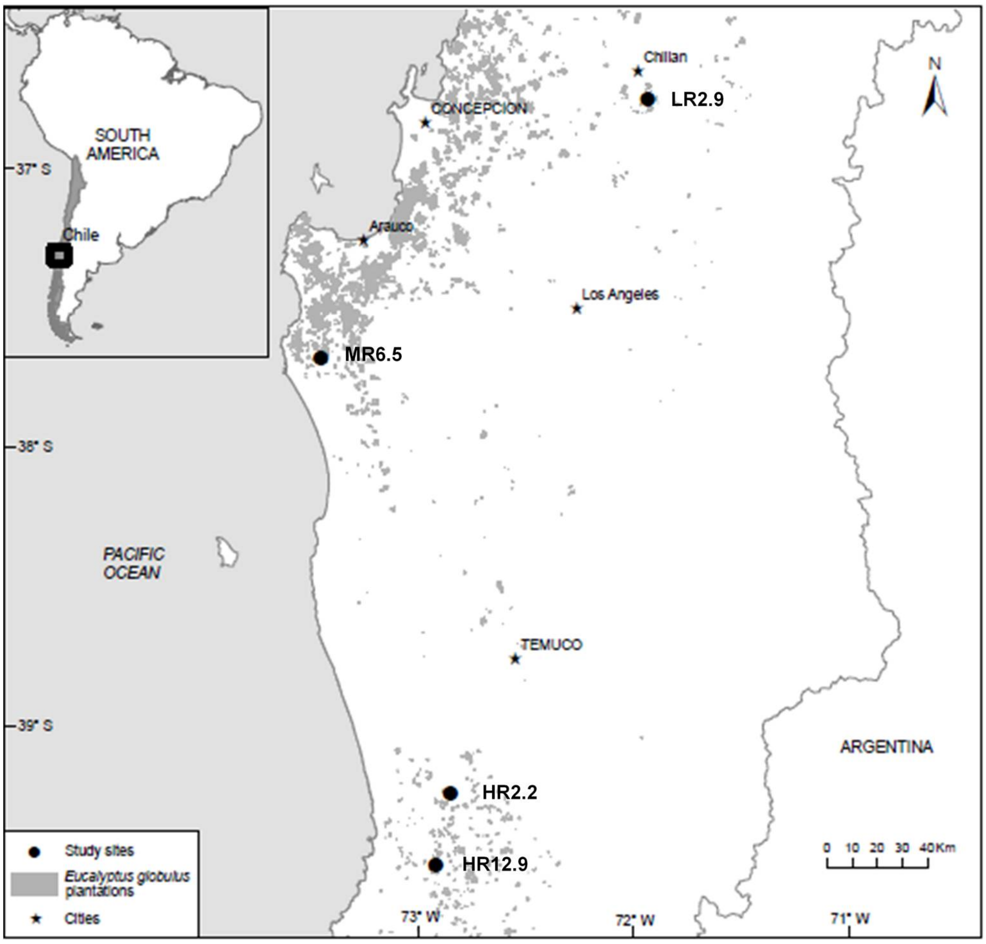

Figure 1. Location of the four sites used in this study in Chile

2.2. 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: 0 (I_0), 5 (I_5), 20 (I_{20}), 44 (I_{44}) and 100% (I_{100}) weed-free cover. At each experimental plot 90 cuttings were planted (9 rows x 10 plants), with an internal measurement plot of 30 cuttings (5 rows x 6 plants) and a buffer of two tree rows implemented around each measurement plot. The plots were laid out contiguously, where possible, before planting. All the sites were planted at a spacing of 2.4 x 2.4 m (1736 trees ha^{-1}), except for site LR2.9, where planting was spaced at 3.0 x 2.0 m (1666 trees ha^{-1}), because it was subsoiled before planting. To quantify the amount of competing vegetation biomass at each site, an additional plot (90 plants in total) with no competing vegetation control was established within each block.

At each site, an herbicide application was made prior to planting (glyphosate 2.5 kg ha^{-1} + simazine 3.0 kg ha^{-1} + Silwet surfactant 1ml L^{-1}) using backpack sprayers. Herbicides were applied in the early morning hours when wind speeds were less than 2 km h^{-1} using a volume rate of 120 litres ha^{-1}. Commercial products were Roundup max (48% glyphosate), Simazina 90 WG (90% simazine) and Silwet (surfactant to improve herbicide uptake). After planting, a second herbicide application

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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. A third herbicide application was made between September and October of the following year using the same chemicals, rates, and application method as in the previous application at all sites except at HR2.2 due to the low level of observed competing vegetation. The planted *E. globulus* cuttings were sheltered from the spray.

At site LR2.9 and MR6.5 all trees received fertilizer 30 days after planting, and received 32.4, 36.2 and 3.0 g plant^{-1} of elemental nitrogen, phosphorus, and boron, respectively, using a blend of 180 g tree^{-1} of diammonium phosphate and 30 g tree^{-1} of boronatrocalcite (commercial fertilizers).

Table 1. Average annual rainfall (Rain), mean annual maximum temperature (Tmax), mean annual minimum temperature (Tmin), clay content (Clay) and organic matter (OM), in the first 20 cm of soil depth for each site.

Sites characteristics	Sites			
	LR2.9	MR6.5	HR2.2	HR12.9
Latitude/Longitude	72°3'/36°42'	73° 29'/37°40'	72°52'/39°13'	72°56'/39°28'
Altitude (m)	82	112	335	73
Rain (mm y^{-1})	1198	1454	2055	2103
Tmax (°C)	19.8	17.4	16.7	17.1
Tmin (°C)	6.3	7.5	6.0	6.7
Clay (%)	43.0	40.1	18.3	33.2
OM (%)	5.0	9.2	16.5	13.0
Soil order	Ultisol	Alfisol	Ultisol	Andisol

2.3. Competing vegetation biomass measurements

During the first growing seasons, all the competing vegetation was monthly removed from two subplots within the additional biomass plot installed at each block. The detailed explanation of how samples of competing vegetation were taken from each subplot to determine their dry mass was reported by Vargas et al. (2018) [18].

2.4. Growth measurements

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 in each plot during dormant season (May-Jun). Individual stem volume was estimated using the Kozak's taper function, implemented in EUCASIM simulator version 4.4.1 [26], considering a top diameter limit (TDL) of 6 cm for each tree.

2.5. Data Analyses

The effect of the competing vegetation control treatments was evaluated at age 9 years considering stand yield losses defined as the percentage response in volume relative to the non-treated control (I_0).

2.6. Modelling approach

We used a non-linear model fitting approach to analyze stand yield losses as a function of site variables (mean annual rainfall, mean annual maximum temperature, mean annual minimum temperature) and competition variables (intensity of competing vegetation control and amount of competing vegetation biomass during the first and second growing seasons). Equations used to represent stand yield losses are hyperbolic family curves [27,28]. We used Akaike's information criteria (AIC) to evaluate goodness-of-fit for nonlinear regression models. AIC is an estimator of the relative quality of the statistical models for a given dataset. This estimator was calculated and ranked accordingly by minimum AIC. Table 2 presents a list of functions used to model stand yield loss.

Table 2. Equations used for stand yield loss modeling to different treatments of intensity of competing vegetation control of planted *E. globulus*.

Models	References
$Y_{ij} = a + (b - a)\,\mathrm{Exp}[-\mathrm{Exp}(c)X_j] + \varepsilon_{ij}$	Pinheiro and Bates 2000 [29]
$Y_{ijk} = a{*}\mathrm{Exp}[-\mathrm{Exp}(b)X_j] + c{*}\mathrm{Exp}[-\mathrm{Exp}(d)Z_k] + \varepsilon_{ijk}$	Pinheiro and Bates 2000 [29]
$Y_{ij} = \mathrm{Exp}(-a{*}X_j) + \varepsilon_{ij}$	Ratkowsky 1990 [30]
$Y_{ij} = a/((b{*}X) + \mathrm{Exp}(c{*}X_j)) + \varepsilon_{ij}$	Ratkowsky 1990 [30]

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After testing several models, a negative hyperbolic model was selected with the form:

$$Y_{ij} = a + (b - a)\,\mathrm{Exp}[-\mathrm{Exp}(c)X_j] + \varepsilon_{ij} \qquad (1)$$

where Y_{ij} is the percentage response in volume relative to the non-treated control at age 9 years and X_j is intensity of competing vegetation control (ranging from 0 to 100%) during the first and second growing seasons for the ith site and jth treatment. Exp is base of natural logarithm; ε_{ij} is the error of the model with $\varepsilon \sim N(0, \sigma^2)$; i is to denote 1-5 treatments; j is to denote 1-4 sites; a, b and c are curve fit parameters. Parameter a is the asymptote as $X_j \rightarrow \infty$, b represents the stand yield loss when no competing vegetation control, and c is the logarithm of the rate constant. We used the logarithm to enforce positivity of the rate constant so the model does approach an asymptote.

2.7. Estimating the parameter b

The parameter b of model (1) represents the value of Y_{ij} when X_j is equal to zero, so this parameter may be related with site and competition variables. Thus, the parameter b of the model (1) was reparametrized through a linear model to account for the influence of the amount of competing vegetation biomass and mean annual rainfall on stand yield loss.

$$Y_{ijk} = a + ((b_1 + b_2 V_{ijk} + b_3 R_i + b_4 V_{ijk} \times R_i) - a)\,\mathrm{Exp}[(-\mathrm{Exp}(c)\,X_j)] + \varepsilon_{ijk} \qquad (2)$$

where, Y_{ijk} is stand yield loss (%), V_{ijk} is maximum production of competing vegetation biomass (Mg ha^{-1}) during the first growing season of the kth block at the ijth site-treatment combination, R_i is average annual rainfall at the ith site and X_j is intensity of competing vegetation control of the jth treatment. $\mathcal{E}_{ijk}$ is the error of the model with $\mathcal{E} \sim N(0, \sigma^2)$; i = 1-5 treatments, j = 1-4 sites, k = 1-5 blocks; a, b_1, b_2, b_3, b_4 and c are curve fit parameters. Normality (Kolmogorov–Smirnov's test) and homogeneity test of variance (Levene's test) were checked. All statistical analyses were evaluated using a $P < 0.05$ as a significance level.

2.8. Model validation

In this study, the yield loss model was fitted to the entire data set. The predictive ability of the final fitted model was assessed by using leave one out (LOO) cross validation technique [31]. This method is an iterative process that is initiated using as training data set with all available observations (plots) except one, which each time is leaving out a different observation to be used as a test. If a single observation is used to calculate the error test, it varies greatly depending on which observation has been selected. To avoid this, the process is repeated as many times as available observations, excluding in each iteration a different observation, adjusting the model with the rest and calculating the error with that observation. Finally, the error rate test estimated by the LOO is the average of all the i errors calculated [32]. Two measures of accuracy were used to evaluate the goodness-of-fit between the observed and predicted values for stand yield loss: (i) root mean square error (RMSE); and (ii) coefficient of determination (R^2). For the variable stand yield loss, we used F-tests to determine if the relationship between predicted and observed values had a slope and intercept different than one and zero, respectively. All statistical analyses were performed using the statistical software program R-Project (version 3.3).

3. Results

3.1. Stand volume yield at age 9 years

Sites under study showed high variability in stem volume yield (Table 3). At age 9, stem volume yield for I_{100} treatment ranged from 127 m^3 ha^{-1} at the site with the lowest annual rainfall (LR2.9, 1198

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mm), to 288 m^3 ha^{-1} at the site with the highest annual rainfall (HR12.9, 2103 mm). For the I_0 treatment, stem volume yield at age 9 ranged from 26.8 m^3 ha^{-1} at the site with the highest amount of competing vegetation (HR12.9), to 164.9 m^3 ha^{-1} at the site with the lowest amount of competing vegetation (HR2.2).

Table 3. Average stand volume (VOL, m^3 ha^{-1}) and survival (SUR, %) at age 9 for *E. globulus* stands that received different treatments of vegetation control intensity. The sites were classified based on their annual mean rainfall (high: HR, medium: MR or low: LR rainfall) and the amount of accumulated competing vegetation biomass (Mg ha^{-1}) in the control treatment during the first growing season.

	LR2.9		MR6.5		HR2.2		HR12.9	
Treatments	VOL	SUR	VOL	SUR	VOL	SUR	VOL	SUR
I_0	9.5	41	159.0	58	164.9	97	26.8	31
I_5	25.4	62	222.0	65	184.6	94	101.5	72
I_{20}	61.9	83	276.6	73	195.3	99	155.4	89
I_{44}	71.3	78	324.5	92	222.9	99	233.6	93
I_{100}	127.2	97	343.4	73	251.9	92	288.9	86

3.2. Modelling the effects of weed competition on volume yield

After applying the step-wise procedure a negative hyperbolic curve with downward concavity was a good descriptor for the relationship between stand yield loss of *E. globulus* and area free of competing vegetation at establishment ($R^2 = 0.59$; $P < 0.001$). The b parameter of model (1), that represents stand yield loss with no competing vegetation control was reparametrized to account for the influence of mean annual rainfall and the amount of competing vegetation on stand yield loss. Model (2), was used to model yield losses of *E. globulus* and area free of competing vegetation, amount of competing biomass controlled during the first growing season and mean annual rainfall also showed a strong relationship (R^2: 0.79; $P < 0.001$). A summary of parameter estimates for model (2) is shown in table 4.

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Table 4. Parameters estimated for the model (2)

Parameters	Estimate	Error	*P*
a	-2.4479	4.4838	0.586
b_1	194.3529	19.6128	< 0.001
b_2	-19.0421	3.7018	< 0.001
b_3	-0.0820	0.0106	< 0.001
b_4	0.0113	0.0018	< 0.001
c	-3.5971	0.1821	< 0.001

When area free of competing vegetation, amount of competing biomass controlled during the first growing season and mean annual rainfall were combined, the model explained 79 % of the variation in stand yield loss (2). The reparametrized model showed a significant improvement over the univariate model. Mean annual maximum temperature and mean annual minimum temperature did not improve the reparametrized model.

Increases in area free of competing vegetation increased survival at all the sites (Table 3), except for the site with the lowest amount of competing vegetation biomass (HR2.2). All sites showed a general trend of stand yield loss as area free of competing vegetation decreased. However, sites under study showed high variability in plantation yield lost among sites (Figure 2).

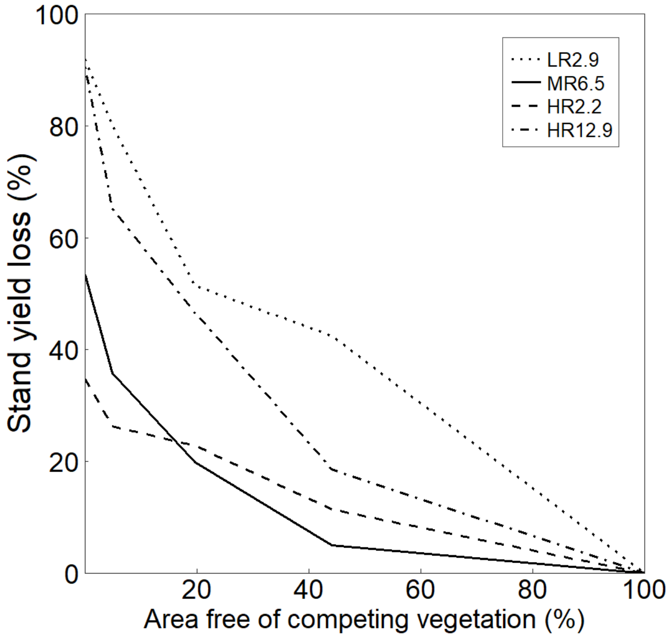

Figure 2. Proportion of stand yield loss under different vegetation control intensity across a rainfall and the amount of competing vegetation biomass gradient. The sites were classified based on their annual mean rainfall (high: HR, medium: MR or low: LR rainfall) and the

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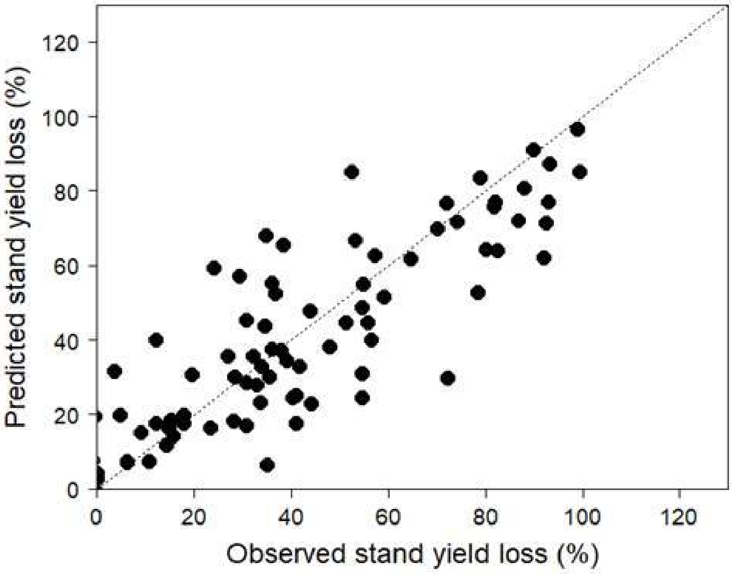
amount of accumulated competing vegetation biomass (Mg ha^{-1}) in the control treatment during the first growing season.

Comparing all sites, maximum stand yield loss occurred when area free of competing vegetation was equal to zero. In average, at age 9 years, stand yield loss ranged from 35 to 91% when no competing vegetation control was applied at establishment. Interestingly, maximum stand yield loss was observed at sites with the highest and lowest mean annual rainfall (LR2.9 and HR12.9).

3.3. Model validation

There was agreement between observed and predicted values, with no clear tendencies to over-estimate for the variable tested. However, there was a tendency to under-estimate when the stand yield loss was higher 70 %. Across all sites, both the slope and the intercept of the relationship between predicted and observed values were not statistically different from one (Estimated value: 0.77; $P < 0.001$) and zero (Estimated value: 7.63; $P < 0.001$), respectively (Figure 3). There was a strong correlation between observed and predicted values ($P < 0.001$; $R^2 = 0.76$).

Figure 3. Model validation for four tested sites (100 plots total). Observed versus predicted



values of proportion of stand yield loss. The dotted line corresponds to the 1-to-1 relationship.

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4. Discussion

We accepted our first hypothesis because the relationship between stand yield loss and intensity of competing vegetation control was not linear. There is an optimal intensity of competing vegetation control beyond which stand volume yield loss is small (Figure 2). We reject our second hypothesis because sites with high water availability (HR2.2 and HR12.9) do not require necessarily smaller area free of competition at establishment than sites with low water availability (LR2.9) to reach the maximum potential growth at age 9 years in *E. globulus* plantations.

The model described in this paper, was developed at sites with contrasting environmental conditions, successfully account for stand yield losses attributable to weed competition. This study represents, to our knowledge, the first reported model to predict the effect of weed competition on long-term volume yield of *E. globulus*. The sites under study showed high variability in productivity with volume yields for treatment I_{100} ranging from 127 m^3 ha^{-1} at the site with the lowest annual rainfall (LR2.9, 1198 mm), to 288 m3 ha^{-1} at the site with the highest annual rainfall (HR12.9, 2103 mm). It was observed a general trend of decreasing stand yield loss as the area free of competition vegetation increased across sites. Similar responses have been reported in other studies that included different levels of intensity of competing vegetation control in *E. globulus* [16,17] and *Pseudotsuga menziesii* [10]. In addition, a strong relationship was found between stand yield loss and area free of competing vegetation, amount of competing biomass during the first growing season and mean annual rainfall (Model 2, R^2=0.79). This response was consistent with the results reported by Little and Schumann (1996) [33], where stand yield loss related to competing vegetation was correlated to the amount of vegetation biomass present in *E. globulus* plantations. Similar results of stand yield loss as the intensity of competing vegetation control increased were observed in *P. radiata* by Mason and Kirongo (1999) [34]. The approach of stand yield loss, is particularly advantageous because it allows to observe as even slight variations in area free of competition vegetation that might result in substantial changes in stand yield loss. The above approach was observed in the treatment I_5 that covers only 5% of the total treated area, where there was a significant decrease in the stand yield loss compared to the treatment without control at sites with a high amount of competing vegetation biomass (MR6.5 and HR12.9). Similar results have been reported by Wagner (2000) [35], who confirmed that even a low intensity of competing vegetation control might greatly reduce limitations for cutting survival and growth.

In our study, the slope of the yield loss model curve increased considerably when area free of competing vegetation was less than 20 %, suggesting that *Eucalyptus* has a low tolerance to interference by competing vegetation during the establishment phase [17,36]. Changes in the slope of the relationship between stand yield loss and area free of competing vegetation were related to differences in the availability and the efficient use of site resources by the competing vegetation. 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 [37,38,39]. Although seasonal water deficits become less intense as rainfall increases, trees growing in moderate to high rainfall areas are still subject to some degree of water limitation, particularly if rainfall is irregular and soil water storage is low [40]. In addition, decreases in light availability may be critical at sites where competing vegetation had a large shadowing effect on *E. globulus* cuttings at stand establishment phase. Finally, decreased soil nitrogen availability may be of importance at the site with an abundance of graminoids [41]. Fine roots of herbaceous plants are concentrated in surface soil where nitrogen availability is high and root densities of competing vegetation are typically higher than those of trees [6,8].

To validate the model, we used data from a long-term experiment using plots with contrasting productivity. The slope of the relationship between observed and predicted stand yield loss was near one (Estimated value: 0.77; $P < 0.001$), supporting the strength of the model and its utility for assessing the effects of weed competition on long-term volume yield of *E. globulus* across an environmental gradient. Even though the fitted model performed well for the dataset used for validation, the

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predictions of the model outside the geographical range of the fitting data is uncertain. We recommend using this model only within the range of data used for fitness (see Table 1).

On sites with contrasting annual rainfall (LR2.9, 1198 mm, and HR12.9, 2103 mm), the high stand yield loss observed on non-treated control plots at age 9 years (93% and 91%, 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 increasing severely stand yield loss. Similar findings were reported by Richardson et al. (1993) [44] where studies on dryland sites have also suggested that growth reductions induced by competing vegetation are primarily mediated through competition for water. It is likely that seasonal water deficits will be exacerbated by competing vegetation, which can significantly contribute to evaporative losses. 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 increased the *E. globulus* cuttings yield loss. These results were consistent with the findings reported by Balandier et al. (2006) [7] and Garau et al. (2009) [17], where *E. globulus* yield loss decreases due to competing vegetation control have been related to increases in available soil water and light. The contrasting stand yield loss levels observed on non-treated control plots (35% at HR2.2 and 91% at HR12.9) between the two southern sites that had higher rainfall (HR2.2, 2055 mm; HR12.9, 2103 mm), 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. Similar results for *E. globulus* were reported by Garau et al. (2009) [17], where competing vegetation biomass accounted for 98% of the variation in stand volume. Comparable relationships have been reported for other species in different environments [28,36,42,43].

5. Conclusions

A strong relationship was established between stand yield loss and the intensity of competing vegetation control, the amount of competing vegetation biomass produced during the first growing season and mean annual rainfall. The relationship between stand yield loss and intensity of competing vegetation control was not linear. Accordingly, there is an optimal intensity of competing vegetation control beyond which stand volume yield loss is small.

The site with the lowest mean annual rainfall showed the highest volume yield loss at age 9 years. Sites with highest mean annual rainfall showed contrasting results of volume yield loss related to the amount of competing vegetation biomass.

Developing appropriate experimental approaches to interpret the effects of competing vegetation types, plantation trees and site resource availability is an important challenge to understand long-term responses on a site-specific basis. Understanding these interactions involves research about how weeds affect resource availability, and how the trees respond to this change in resource availability. One of the most important contributions of the model developed in this study, is to be able to predict the effect of weed competition on long-term volume yield of *E. globulus* across an environmental gradient.

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