forests

MDPI

Article

Modelling the Effect of Weed Competition on Long-Term Volume Yield of *Eucalyptus globulus* Labill. Plantations across an Environmental Gradient

Felipe Vargas [1,2,*], Carlos A. Gonzalez-Benecke [3], Rafael Rubilar [4] and Manuel Sanchez-Olate [2]

1 Bioforest S.A., Concepción 83422, Chile
2 Departamento de Silvicultura, Facultad de Ciencias Forestales, Universidad de Concepción, Concepción 83422, Chile; msanche@udec.cl
3 Department of Forest Engineering, Resources and Management, Oregon State University, Corvallis, OR 97331, USA; Carlos.Gonzalez@oregonstate.edu
4 Cooperativa de Productividad Forestal, Departamento de Silvicultura, Facultad de Ciencias Forestales, Universidad de Concepción, Concepción 83422, Chile; rafaelrubilar@udec.cl
* Correspondence: felipe.vargas@arauco.cl; Tel.: +56-412-728803

Received: 10 July 2018; Accepted: 30 July 2018; Published: 8 August 2018

check for updates

Abstract: Several studies have quantified the responses of *Eucalyptus globulus* Labill. plantations to weed control on its early development (2–3 years after establishment). However, long-term results of competing vegetation effects have not been included into growth and yield models that incorporate treatments of competing vegetation control, and its interaction with site resource availability. In this article, we compared several models predicting stand volume yield of *E. globulus* plantations established across an environmental gradient, growing under different intensity levels of competing vegetation control. 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* cuttings. 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

Expansion of *Eucalyptus* plantations in the world has been very successful because of their high-volume production and adaptability to a wide range of sites. The *Eucalyptus* plantations exceed 20 million hectares worldwide [1], including more than 110 species of *Eucalyptus* introduced in more than 90 countries [2]. In Chile, *Eucalyptus* plantations exceed 850,000 hectares, of which 68% corresponds to *E. globulus* [3].

The application of competing vegetation control treatments requires a good understanding of tree growth and how competing vegetation affect site resource availability over time and which key resources affect stand growth [4,5]. It is well known that reducing weeds biomass during early stand establishment can increase light, water and nutrient and site resource availability [6–8] allowing better survival and tree growth [9–12].

Previous studies about managing of the intensity of competing vegetation or weed control (defined as the size of area free of competing vegetation around each tree) have shown an increase in stem volume—as the intensity of control increases in fast growing species such as *Pinus taeda* L. [13], *Pinus radiata* D.Don [14,15], *Pseudotsuga menziesii* (Mirb.) Franco [10], and *Eucalyptus* spp. [16]. The optimal intensity of weed control required to reach the maximum stand volume yield depends on the species planted, amount of competing vegetation and site resource availability and at each site [14,16]. Even though there are numerous studies that quantify growth responses associated with control of competing vegetation in Eucalyptus plantations [8,16–18], these results have not been included into growth models that incorporate different treatments of intensity of weed control on *Eucalyptus* plantations. The stem volume yield loss (or stand yield loss) due to weed competition is affected by several factors including: The abundance of weed biomass, spatial proximity to the plantation trees, soil water holding capacity, rainfall and temperature during the growing season [19]. A model can predict the yield loss associated with different intensities of competing vegetation control [20]. Modelling plantation-weed interactions can help also to improve 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 showed a good correlation between the amount of weed biomass, the survival and the volume yield of the *Pinus ponderosa* Douglas ex C. Lawson seedlings [26].

The development of a stand growth response model would improve our ability to predict long-term effect of competing vegetation on *E. globulus* plantations productivity across sites. From a modelling perspective, there is a strong need to understand how competing vegetation affect site resource availability over time and how resources affect stand growth in order to make more sustainable management decisions. The purpose 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 intensity of competing vegetation control to reach the maximum stand volume yield). (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

The experiment was established in four sites selected in south-central zone of Chile, consisting of an environmental gradient (Table 1), where other work has been completed [18]. Climate at the study sites showed a dry summer and rainfall mainly during winter (June-September). The study sites were characterized according to their annual mean rainfall (low rainfall (LR), medium rainfall (MR), or high rainfall (HR)) (Table 1) and by the amount of weed biomass produced (Mg ha^{-1}) during the first growing season. Thus, site LR2.9 had a low rainfall, and produced 2.9 Mg ha^{-1} of weed biomass; site MR6.5 had a medium rainfall, and produced 6.5 Mg ha^{-1} of weed biomass; site HR2.2 had a high rainfall, and produced 2.2 Mg ha^{-1} of weed biomass; and site HR12.9 had a high rainfall and produced 12.9 Mg ha^{-1} of weed biomass (Figure 1).

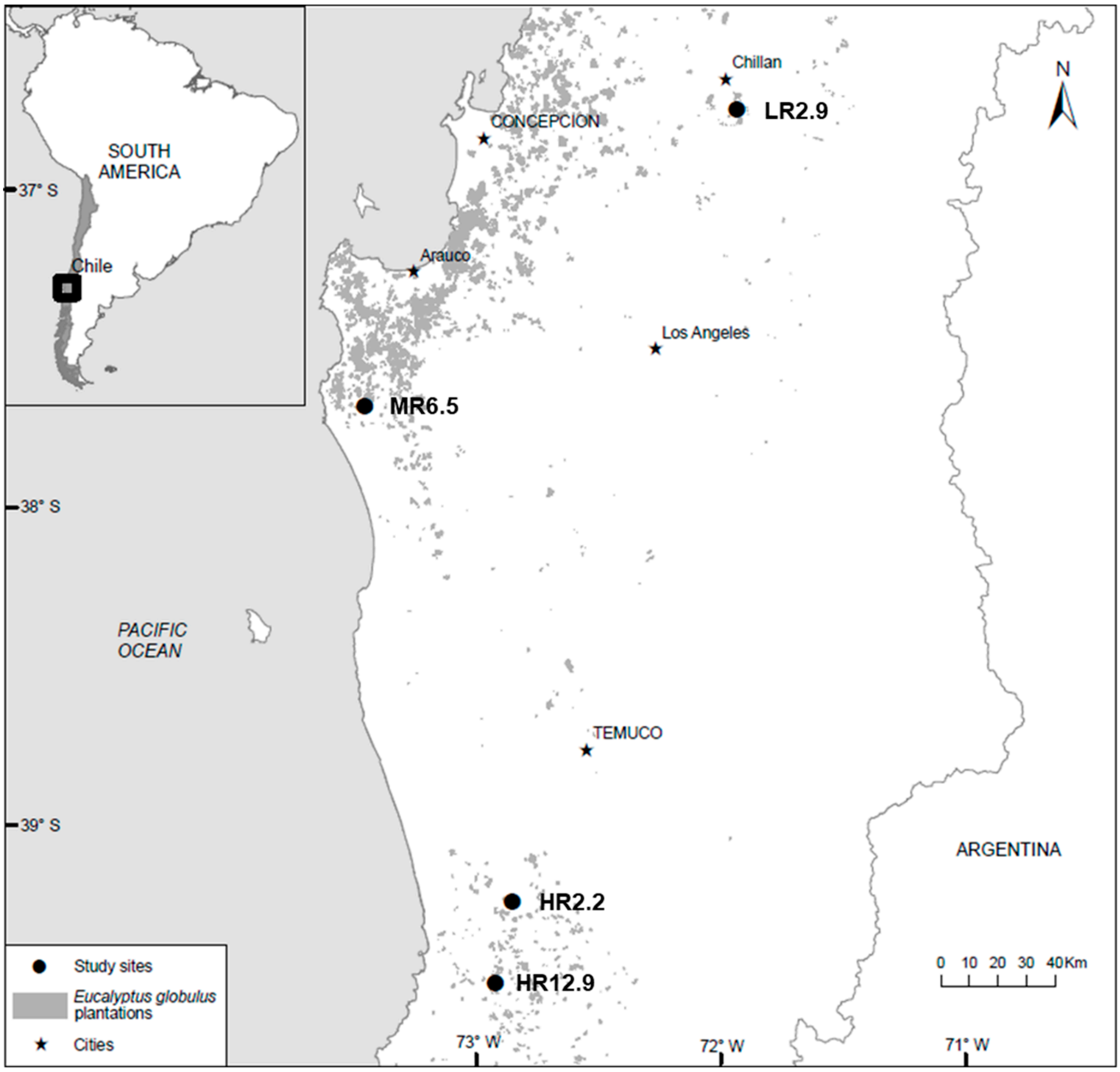

Figure 1. Location of sites used in this study for *E. globulus* in Chile.

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

The LR2.9 site came from a reforestation, harvest slash was burnt, follow by a soil preparation (80 cm deep). This site was planted in July 2004 with a planting shovel. The MR6.5 site was reforestation, harvest slash was shredded and planted in July 2004 with a planting shovel. The HR2.2 site was reforestation, harvest slash was mechanically arranged in strips (windrows) and planted in August 2003 with a planting shovel. The HR12.9 site was a forestation plantation on a former pasture land and was planted in September 2004 with a planting shovel. All sites were planted with a mix of the top 5% half-sib families produced from cuttings and ranked by genetic performance.

2.2. Experimental Design and Treatments

The effect of weed control intensity was evaluated through a randomized complete block design (five replicates). Treatments included five levels of intensity of competing vegetation control around individual *E. globulus* cuttings: 0 (I0), 5 (I5), 20 (I20), 44 (I44), and 100% (I100) weed-free cover. At each experimental plot 90 cuttings were planted (9 rows × 10 plants), with a measurement plot of 30 cuttings (5 rows × 6 plants) and a buffer of two tree rows implemented around each measurement plot. All the sites were planted at a density of 1736 trees ha^{-1} (spacing of 2.4 × 2.4 m), except for site LR2.9, with a density of 1666 trees ha^{-1} (spacing of 3.0 × 2.0 m), because it was subsoiled before planting.

At each site, an herbicide application was made prior to planting (3.0 kg ha^{-1} simazine + 2.5 kg ha^{-1} glyphosate + 1 mL L^{-1} Silwet surfactant) using backpack sprayers. Herbicides and surfactant were applied when wind speeds did not exceed 2 km h^{-1} using a volume rate of 120 litres ha^{-1}. The simazine was Simazina 90 WG (Water dispersible granules) (Formulation of 90% simazine), glyphosate used was Roundup Max (Formulation of 48% glyphosate), and Silwet surfactant. A second herbicide application was made between February and March of the subsequent year at each site, using the same prescription (application method, chemicals and rates) as in the herbicide application prior to planting. A third herbicide application was made between September and October of the subsequent year at each site, using the same prescription (application method, chemicals and rates) as the previous application, except at HR2.2 due to the low level of competing vegetation present. The planted *E. globulus* cuttings were sheltered from the spray.

At site LR2.9 and MR6.5 a fertilizer application was made 30 days after planting. Fertilizer was applied manually a blend of 180 g plant^{-1} of diammonium phosphate and 30 g plant^{-1} of boronatrocalcite (commercial fertilizers), equivalent a 32.4, 36.2 and 3.0 g plant^{-1} of elemental nitrogen, phosphorus, and boron, respectively.

Table 1. Mean 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

At each site, the amount of weed biomass was quantified through an additional plot (90 plants in total) with no competing vegetation control. During the first growing seasons, the amount of weed was monthly evaluated from two subplots of 2 × 2 m randomly selected 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. Volume Yield

From planting up 9 years, stem diameter at 1.3 m height (cm) and total tree height (m) were measured every year between May and June. Individual commercial stem volume was determined using the Kozak's taper function [27] and considering a top diameter limit (TDL) of 6 cm for each tree (Table 2).

Table 2. Average stand volume (m^3 ha^{-1}) at age 9 for *Eucalyptus globulus* stands that received different treatments of vegetation control intensity. The study sites were characterized according to their annual mean rainfall (low rainfall (LR), medium rainfall (MR), or high rainfall (HR)) and by the amount of weed biomass produced (Mg ha^{-1}) during the first growing season. Adapted from Vargas et al. 2018 [18].

Treatment	LR2.9	MR6.5	HR2.2	HR12.9
I_0	9.5	159.0	164.9	26.8
I_5	25.4	222.0	184.6	101.5
I_{20}	61.9	276.6	195.3	155.4
I_{44}	71.3	324.5	222.9	233.6
I_{100}	127.2	343.4	251.9	288.9

2.5. Data Analysis

Statistical analysis was performed using the statistical software program R-Project (version 3.3, www.r-project.org). We compared several Non-linear models predicting the effect of different intensity levels of competing vegetation control on long-term volume yield loss. CurveExpert Básico version 2.1.0 (www.curveexpert.net) (Hyams Development) was used for exploratory curve analysis. The statistical software program R-Project (version 3.3) was used to create all figures.

2.5.1. Modelling Approach

We used a non-linear model fitting approach to analyze stand yield loss as a function of site variables (mean annual rainfall, mean annual maximum temperature, mean annual minimum temperature) and competition variables (intensity of weed control and amount of weed biomass during the first and second growing seasons). Equations used to represent stand yield loss are hyperbolic family curves [26,28]. 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 [29]. Table 3 presents a list of equations used to stand yield loss modeling.

Table 3. Equations used for stand yield loss modeling to different treatments of intensity of competing vegetation control of planted *E. globulus*.

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

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

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

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.

2.5.2. 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.

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

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. ε_{ijk} is the error of the model with $\varepsilon \sim N(0, \sigma^2)$; 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. The significance level used to evaluate all statistical analysis was $p < 0.05$.

2.5.3. 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 the leave one out cross validation (LOOCV) technique [31,32]. In this method we pick only one plot as the test set. Then we build a model with all the plots remaining (training plots) and evaluate its error with the test plot. 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 estimate by LOOCV is obtained by repeating this procedure for each of the training plots available, averaging the results [32]. Two measures of accuracy were used to evaluate the goodness-of-fit between predicted and observed values for stand yield loss: Coefficient of determination (R^2) and root mean square error (RMSE). For the variable stand yield loss, a F-tests was used to determine if the relationship between observed and predicted values had an intercept and slope different than zero and one, respectively.

3. Results

3.1. Modelling the Effects of Weed Competition on Volume Yield

After applying the step-wise method and evaluating AIC, a negative hyperbolic curve with upward concavity (Equation (1)) was the selected model to predict the relationship between stand yield loss of *E. globulus* and area free of competing vegetation at establishment (Table 4).

Table 4. Fit statistics for the tested yield loss models, using Akaike's information criteria (AIC), Coefficient of determination (R^2) and root mean square error (RMSE).

Models	AIC	R^2	RMSE
(1) $Y_{ij} = a + (b - a)\ \text{Exp}[-\text{Exp}(c)X_j] + \varepsilon_{ij}$	781	0.59	19.66
(2) $Y_{ijk} = a \times \text{Exp}[-\text{Exp}(b)X_j] + c \times \text{Exp}[-\text{Exp}(d)Z_k] + \varepsilon_{ijk}$	861	0.51	26.35
(3) $Y_{ij} = \text{Exp}(-a \times X_j) + \varepsilon_{ij}$	994	0.43	44.72
(4) $Y_{ij} = a/((b \times X_j) + \text{Exp}(c \times X_j)) + \varepsilon_{ij}$	847	0.56	21.99

The b parameter of Equation (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. Equation (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 parameters estimated for Equation (2) is shown in Table 5.

Table 5. Parameter asymptotic estimates and their standard error and *P* for the stand yield loss equation based on competing vegetation biomass (V), average annual rainfall (R) and intensity of competing vegetation control (X).

Parameter	Asymptotic Estimate	Standard 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 intensity of weed control, amount of weed biomass controlled during the first growing season and mean annual rainfall were combined, the model explained 79% of the variation in stand yield loss (Equation (2)). The reparametrized model showed a significant improvement over the univariate model (Equation (2)). Mean annual minimum temperature and mean annual maximum temperature did not improve the reparametrized model.

All sites showed a general trend of stand yield loss as intensity of weed control decreased. However, sites under study showed high variability in plantation yield loss among sites (Figure 2).

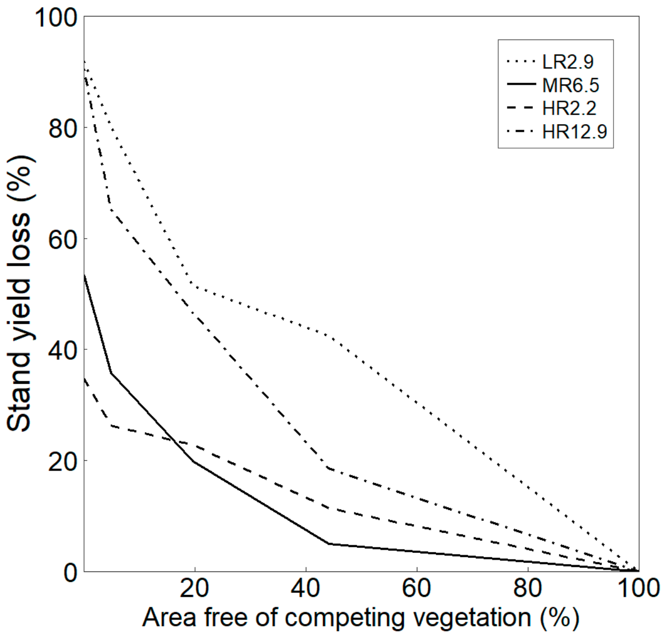

Figure 2. Proportion of stand yield loss under different vegetation control intensity across a rainfall and the amount of competing vegetation biomass gradient. The study sites were characterized according to their annual mean rainfall (LR, MR or HR) and by the amount of weed biomass produced (Mg ha^{-1}) 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 the age of nine 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).

3.2. Model Validation

A strong correlation was observed between predicted and observed values ($p < 0.001$; $R^2 = 0.76$; RMSE = 16.6), without clear tendencies to over-estimate for the tested variable. However, there was a tendency to under-estimate when the stand yield loss was higher 70%. Across all sites, the relationship between observed and predicted values were not statistically different from one to the slope (estimated value: 0.77; $p < 0.001$) and zero to the intercept (estimated value: 7.63; $p < 0.001$), respectively (Figure 3).

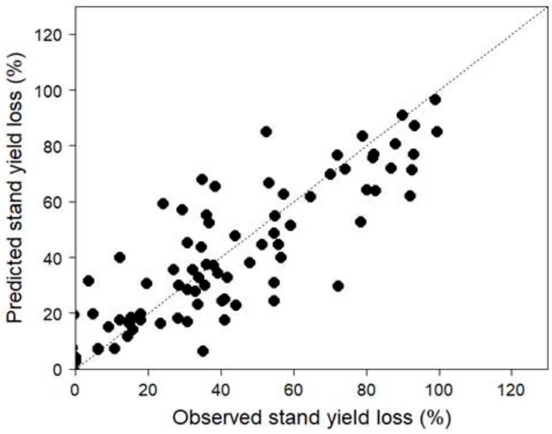

Figure 3. Model validation for four tested sites (100 plots total). Observed versus predicted values of proportion of stand yield loss. The dotted line represents to the 1 to 1 relationship.

4. Discussion

The first hypothesis was accepted because the relationship between stand yield loss and intensity of weed control was not linear. Therefore, there is an optimal intensity of competing vegetation control to reach the maximum stand volume yield (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 study, was developed by incorporating sites with contrasting environmental conditions, successfully account for stand yield losses attributable to weed competition. This study represents, the first reported model to predict the effect of weed competition on long-term volume yield of *E. globulus*. It was observed a tendency of decreasing stand yield loss as the intensity of weed control increased across sites. Similar responses have been reported in previous studies that included different intensities of competing vegetation in *E. globulus* [16,17] and *Pseudotsuga menziesii* [10]. In addition, a strong relationship was found between stand yield loss and intensity of competing vegetation, amount of weed biomass during the first growing season and mean annual rainfall (Equation (2), $R^2 = 0.79$). Little and Schumann (1996) [33], reported similar results in *E. globulus* plantations, where stand yield loss was correlated to the amount of weed biomass observed. 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 above approach was observed in the treatment I_5 (5% of the total treated area), where there was a significant decrease in the stand yield loss compared to the treatment I_0 (without weed control) at sites with a high amount of weed biomass (MR6.5 and HR12.9). Similar response was observed by Wagner (2000) [35], who observed that even a small area free of weed might substantially decrease for cutting survival and growth.

In our study, the slope of the yield loss curve for each site increased considerably when intensity of weed control was less than 20% (Figure 2), suggesting that *E. globulus* has a low tolerance to competition by weed during the stand establishment [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 weed. Our results suggest that stand yield loss related the effect of weed competition may be associated with a decline in soil water availability [37–39]. Seasonal water deficit becomes smaller in sites with higher rainfall. However, trees growing at sites with moderate to high rainfall may have some degree of water limitations, even more if rainfall is irregular and soil water storage is low [40]. Additionally, at sites with high amount of weed (LR12.9), light availability may be critical for shadowing effect of the weed on *E. globulus* cuttings at stand establishment. At sites with high abundance of graminoids, low soil nitrogen availability may be critical in sites with low fertility [41].

The model was validate using data from 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 ability for assessing long-term effect of competing vegetation on *E. globulus* plantations productivity considering a sites gradient. Although the fitted model performed well for the data used for validation, the prediction of the model outside the geographical range of the sites under study (Fitted data) is uncertain. Therefore, we recommend using this model exclusively within the area geographical of the sites under study (see Table 1).

On sites with contrasting annual rainfall (LR2.9 and HR12.9), the high stand yield loss observed on I_0 treatment (93% and 91%, respectively), has different causes that explain the yield loss. At site LR2.9 had the lowest annual rainfall of all the study sites, suggesting lower soil water availability during the growing season, increasing severely stand yield loss. Similar findings have been reported by Richardson et al. (1993) [42], on dryland sites, suggesting that growth reductions related to weed competition may be associated primarily with competition for water. On the other hand, the site HR12.9 had the highest annual rainfall and the highest amount of weed biomass across all sites, suggesting that a high competition for light may had increased the *E. globulus* cuttings yield loss. These responses were consistent with the results observed by Balandier et al. (2006) [7] and Garau et al. (2009) [17], where *E. globulus* yield loss due to weed competition was related to decreases in available light and soil water. 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 weed biomass reduced light availability, decreasing survival and tree growth. Similar results have been reported for *E. globulus* by Garau et al. (2009) [17], where weed biomass accounted for 98% of the variation in stem volume. Similar relationships were observed for other forest planted in different environments [26,36,43,44].

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. Therefore, there is an optimal intensity of competing vegetation control to reach the maximum stand volume yield.

The site LR2.9 with the lowest mean annual rainfall and the site HR12.9 with the highest weed biomass, showed the highest volume yield loss at the age of nine years, when no weed control was applied. Sites with highest mean annual rainfall showed contrasting results of volume yield loss related to the amount of competing vegetation biomass.

Modelling plantation-weed interactions can help also to improve understanding of ecophysiological processes involved and how competing vegetation affect site resource availability over time and which key resources affect stand growth. One of the most important contributions of the response model developed in this study, is improve our ability to predict the effect of weed control on long-term volume yield loss of *E. globulus* across sites.

Author Contributions: F.V. analyzed the data and wrote the paper; C.A.G.-B. and R.R. conducted the statistical analysis, contributed to the writing of the paper and data interpretation. M.S.-O. contributed to the writing of the paper.

Funding: This research was supported by Bioforest S.A. and Forestal Arauco S.A.

Acknowledgments: We thanks to Forestal Arauco S.A. and Bioforest S.A. for financial and technical support. We thank P. Aracena and J. Zapata-Valenzuela for their useful comments prior to publication. We thank field staff from Bioforest S.A. and Forestal Arauco S.A. who provided fieldwork and site management assistance.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. FAO. *Global Forest Resources Assessment 2010*; FAO Technical Paper; Food and Agriculture Organization of the United Nations: Rome, Italy, 2013.
2. Booth, T.H. Eucalypt plantations and climate change. *For. Ecol. Manag.* **2013**, *301*, 28–34. [CrossRef]
3. INFOR. *Anuario Forestal 2017 Boletín Estadístico Nº 159*; Instituto Forestal: Santiago, Chile, 2017.
4. Albaugh, T.; Allen, L.; Dougherty, P.; Johnsen, K. Long term growth responses of loblolly pine to optimal nutrient and water resource availability. *For. Ecol. Manag.* **2004**, *192*, 3–19. [CrossRef]
5. Powers, R.; Reynolds, P. Ten-year responses of ponderosa pine plantations to repeated vegetation and nutrient control along an environmental gradient. *Can. J. For. Res.* **1999**, *29*, 1027–1038. [CrossRef]
6. Nambiar, E.K.S.; Sands, R. Competition for water and nutrients in forests. *Can. J. For. Res.* **1993**, *23*, 1955–1968. [CrossRef]
7. Balandier, P.; Collet, C.; Miller, J.; Reynolds, P.; Zedaker, S. Designing forest vegetation management strategies based on the mechanisms and dynamics of plantation tree competition by neighboring vegetation. *Forestry* **2006**, *79*, 3–27. [CrossRef]
8. Eyles, A.; Worledge, D.; Sands, P.; Ottenschlaeger, M.L.; Paterson, S.C.; Mendham, D.; O'Grady, A.P. Ecophysiological responses of a young blue gum (*Eucalyptus globulus*) plantation to weed control. *Tree Physiol.* **2012**, *32*, 1008–1020. [CrossRef] [PubMed]
9. Adams, P.; Beadle, C.; Mendham, N.; Smethurst, P. The impact of timing and duration of grass control on the growth of a young *Eucalyptus globulus* Labill plantation. *New For.* **2003**, *26*, 147–165. [CrossRef]
10. Rose, R.; Rosner, L.; Scott, J. Twelfth-year response of Douglas-fir to area of weed control and herbaceous versus woody weed control treatments. *Can. J. For. Res.* **2006**, *36*, 2464–2473. [CrossRef]
11. Wagner, R.; Little, K.; Richardson, B.; McNabb, K. The role of vegetation management for enhancing productivity of the world's forests. *Forestry* **2006**, *79*, 57–79. [CrossRef]
12. Little, K.; Rolando, C.; Morris, C. An integrated analysis of 33 Eucalyptus trials linking the onset of competition-induced tree growth suppression with management, physiographic and climatic factors. *Ann. For. Sci.* **2007**, *64*, 585–591. [CrossRef]
13. Dougherty, P.; Lowery, R. Spot-size of herbaceous control impacts loblolly pine seedling survival and growth. *South. J. Appl. For.* **1991**, *15*, 193–199.
14. Richardson, B.; Davenhill, N.; Coker, G.; Ray, J.; Vanner, A.; Kimberly, M. Optimizing spot weed control: First approximation of the most cost-effective spot size. *N. Z. J. For. Sci.* **1996**, *26*, 265–275.
15. Kogan, M.; Figueroa, R.; Gilabert, H. Weed control intensity effects on young radiata pine growth. *Plant. Protection* **2002**, *21*, 253–257. [CrossRef]
16. Little, K.; Rolando, C. Regional vegetation management standards for commercial *Eucalyptus* plantations in South Africa. *South. For.* **2008**, *70*, 87–97. [CrossRef]
17. Garau, A.; Ghersa, C.; Lemcoff, J.; Barañao, J. Weeds in *Eucalyptus globulus* subsp. *maidenii* (F. Muell) establishment: Effects of competition on sapling growth and survivorship. *New For.* **2009**, *37*, 251–264.
18. Vargas, F.; Rubilar, R.; Gonzalez-Benecke, C.; Sanchez-Olate, M.; Aracena, P. Long-term response to area of competition control in *Eucalyptus globulus* plantations. *New For.* **2018**, *49*, 383–398. [CrossRef]
19. Henkel-Johnson, D.; Macdonald, S.; Bork, E.; Thomas, B. Influence of weed composition, abundance, and spatial proximity on growth in young hybrid poplar plantations. *For. Ecol. Manag.* **2016**, *362*, 55–68. [CrossRef]
20. Renton, M.; Chauhan, B.S. Modelling plantation-weed competition: Why, what, how and what lies ahead? *Plant. Prot.* **2017**, *95*, 101–108.
21. Mason, E.G.; Whyte, A.G.D. Modelling initial survival and growth of *Pinus radiata* in New Zealand. *Acta For. Fenn.* **1997**, *255*, 1–38.

22. Zhao, W. Growth and yield modelling of Pinus radiata in Canterbury, New Zealand. Ph.D. Thesis, University of Canterbury, Christchurch, New Zealand, 1999.
23. Mason, E.G. A model of the juvenile growth and survival of *Pinus radiata* D. Don adding the effects of initial seedling diameter and plant handling. *New For.* **2001**, *22*, 133–158. [CrossRef]
24. Westfall, J.; Burkhart, H.; Allen, H. Young stand growth modeling for intensively-managed loblolly pine plantations in Southeastern U.S. *For. Sci.* **2004**, *50*, 823–835.
25. Knowe, S.A.; Radosevich, S.R.; Shula, R.G. Basal area and diameter distribution prediction for young Douglas-fir plantations with hardwood competition: Coast Ranges. *West. J. Appl. For.* **2005**, *20*, 73–93.
26. Wagner, R.; Petersen, T.; Ross, D.; Radosevich, S. Competition thresholds for the survival and growth of ponderosa pine seedlings associated with woody and herbaceous vegetation. *New For.* **1989**, *3*, 151–170. [CrossRef]
27. Real, P. *Reajuste de Funciones Implementadas en Simulador EUCASIM Documento de Trabajo N° 12*; Proyecto modelo nacional de simulación: Concepción, Chile, 2010.
28. Cousens, R. An empirical model relating plantation yield to weed and plantation density and a statistical comparison with other models. *J. Agric. Sci.* **1985**, *105*, 513–521. [CrossRef]
29. Pinheiro, J.; Bates, D. *Mixed-Effects Models in S and S-Plus*, 3rd ed.; Springer: New York, NY, USA, 2000; p. 528, ISBN 0387989579.
30. Ratkowsky, D. *Handbook of Nonlinear Regression Models*, 1st ed.; Marcel Dekker Inc.: New York, NY, USA, 1990; p. 241, ISBN 0824781899.
31. Neter, J.; Kutner, M.H.; Nachtsheim, C.J.; Wasserman, W. *Applied Linear Statistical Models*, 4th ed.; McGraw-Hill/Irwin: New York, NY, USA, 1996; p. 770. ISBN 0256086010.
32. Hawkins, D.; Basak, S.; Mills, D. Assessing Model Fit by Cross-Validation. *J. Chem. Inf. Comput. Sci.* **2003**, *43*, 579–586. [CrossRef] [PubMed]
33. Little, K.; Schumann, A. A new systematic trial design for the optimization of interspecific weed control. In Proceedings of the 11th Australian weeds conference, Melbourne, Australia, 30 September–3 October 1996; Weed Science Society of Victoria Frankston. pp. 440–444.
34. Mason, E.G.; Kirongo, B.B. Responses of radiata pine clones to varying levels of pasture competition in a semiarid environment. *Can. I. For. Res.* **1999**, *29*, 934–939. [CrossRef]
35. Wagner, R.G. Competition and critical period thresholds for vegetation management decisions in young conifer stands. *For. Chron.* **2000**, *76*, 961–968. [CrossRef]
36. George, B.; Brennan, P. Herbicides are more cost-effective than alternative weed control methods for increasing early growth of *Eucalyptus dunnii* and *Eucalyptus saligna*. *New For.* **2002**, *24*, 147–163. [CrossRef]
37. Nambiar, S.; Zed, P. Influence of weeds on the water potential, nutrient content and growth of young radiata pine. *Aust. For. Res.* **1980**, *10*, 279–288.
38. Little, K.; Van Staden, J. Interspecific competition affects early growth of a *Eucalyptus grandis* × *E. camaldulensis* hybrid clone in Zululand. *S. Afr. J. Bot.* **2003**, *69*, 505–513. [CrossRef]
39. Garau, A.; Lemcoff, J.; Ghersa, C.; Beadle, C. Water stress tolerance in *Eucalyptus globulus* Labill subsp. maidenii (F. Muell.) saplings induced by water restrictions imposed by weeds. *For. Ecol. Manag.* **2008**, *255*, 2811–2819. [CrossRef]
40. Watt, M. Modelling the influence of weed competition on growth of juvenile Pinus radiata at a dryland site. Ph.D. Thesis, University of Canterbury, Christchurch, New Zealand, 2003.
41. Smethurst, P.; Nambiar, S. Role of weeds in the management of nitrogen in a young *Pinus radiata* plantation. *New For.* **1989**, *3*, 203–224. [CrossRef]
42. Coll, L.; Balandier, P.; Picon-Cochard, C. Morphological and physiological responses of beech (*Fagus sylvatica*) seedlings to grass-induced belowground competition. *Tree Physiol.* **2004**, *24*, 45–54. [CrossRef] [PubMed]
43. Harper, G.; Comeau, P.; Biring, B. A comparison of herbicide and mulch mat treatments for reducing grass, herb, and shrub competition in the BC Interior Douglas-Fir zone—Ten years results. *West. J. Appl. For.* **2005**, *20*, 167–176.
44. Richardson, B. Vegetation management practices in plantation forests of Australia and New Zealand. *Can. J. For. Res.* **1993**, *23*, 1989–2005. [CrossRef]