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Respuesta de largo plazo al control de vegetación competidora al establecimiento en plantaciones de *Eucalyptus globulus*

Tesis para optar al grado de Doctor en Ciencias Forestales

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RESPUESTA DE LARGO PLAZO AL CONTROL DE VEGETACIÓN COMPETIDORA AL ESTABLECIMIENTO EN PLANTACIONES DE *Eucalyptus globulus*

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TABLA DE CONTENIDO

ÍNDICE DE FIGURAS

ÍNDICE DE TABLAS

RESUMEN

El control de vegetación competidora durante el establecimiento de la plantación, aumenta la disponibilidad de agua, nutrientes y luz y, por consiguiente, incrementa la supervivencia y crecimiento de la plantación. Durante las últimas décadas importantes esfuerzos de investigación han sido realizados para cuantificar las respuestas asociadas al control de la vegetación competidora en el crecimiento de plantaciones de *Eucalyptus*. La mayoría de las investigaciones publicadas han mostrado claras respuestas en crecimiento durante los primeros años en plantaciones de *Eucalyptus*. Sin embargo, existe una brecha de conocimiento sobre los efectos a largo plazo de la intensidad de control de vegetación competidora en la magnitud y la duración de la respuesta en crecimiento de la plantación. Las causas sobre por qué determinados sitios muestran una respuesta temporal o divergente en el tiempo no están claros, pero también existe limitada comprensión en cómo la vegetación competidora altera la disponibilidad de recursos del sitio y cuáles son los recursos claves que afectan el crecimiento de la plantación. Este estudio evaluó el efecto a largo plazo de la intensidad de control de vegetación competidora (tamaño del área libre de vegetación competidora) sobre la magnitud y duración de la respuesta en volumen de *E. globulus* a través de un gradiente de lluvia y biomasa de vegetación competidora. Los modelos de respuesta al crecimiento fueron desarrollados para mejorar la capacidad de predecir el efecto de la competencia de la vegetación en la productividad de las plantaciones de *E. globulus*. La máxima respuesta en ganancia en volumen a través de los sitios varió entre 58 y 262 m^3 ha^{-1} a los 9 años y esta respuesta fue proporcional a la cantidad de biomasa de vegetación competidora controlada durante la primera temporada de crecimiento. Se observó una respuesta temporal y sostenida a los 9 años de edad en sitios con una biomasa de vegetación competidora controlada inferior a 6,5 Mg ha^{-1}. Sin embargo, en el sitio con la mayor cantidad de biomasa de vegetación competidora (12,9 Mg ha^{-1}), la respuesta al control de la vegetación fue sostenida y divergente hasta el año 9. La duración de la respuesta para los tratamientos de control de vegetación competidora varió entre 5 y 9 años. Además, el modelo mostró una fuerte relación entre la pérdida de rendimiento en volumen de la plantación y la intensidad del control de vegetación competidora, la cantidad de biomasa de vegetación competidora producida durante la primera temporada de crecimiento y la precipitación anual media.

ABSTRACT

Reducing competing vegetation during stand establishment increases water, nutrient and light resource availability and therefore tree survival and growth. In the last decades substantial research efforts have been made to quantify growth responses associated with control of competing vegetation in *Eucalyptus* plantations. Most reports have shown clear and strong responses during the first years of *Eucalyptus* plantation. However, there is still a large gap in knowledge about the long-term effects of early competing vegetation control intensity on the magnitude and duration of stand growth response. The fundamentals on why particular sites show a temporal or divergent growth response gain over time are not clear, but also there is limited understanding on how competing vegetation affect site resource availability over time and which key resources affect stand growth. Our study evaluated the long-term effect of competing vegetation control intensity (size of area free of weeds) on the magnitude and duration of *E. globulus* 9 years volume response across a gradient of rainfall and biomass of competing vegetation. Stand growth response models were developed in order to improve our ability to predict the effect of competing vegetation on *E. globulus* plantations productivity across sites. Responses across sites at age 9 showed that maximum stand volume gain ranged 58 to 262 m3 ha^{-1} and was proportional to the amount of competing vegetation biomass removed during the first growing season. A temporary, but sustained, response until age 9 was observed at sites where biomass of competing vegetation was lower than 6.5 Mg ha^{-1}. However, at the site with the largest amount of competing vegetation biomass (12.9 Mg ha^{-1}) stand growth showed a sustained and divergent response until year 9. Duration of response, considering treatments intensity ranged between 5 and 9 years. Additionally, models showed a strong relationship between stand 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.

INTRODUCCIÓN GENERAL

Las plantaciones de *Eucalyptus* han sido muy exitosas a nivel mundial, debido a sus altas tasas de crecimiento y adaptabilidad a un amplio rango de condiciones ambientales. En la actualidad existen más de 20 millones de hectáreas de plantaciones de *Eucalyptus* alrededor del mundo (FAO 2013), incluyendo más de 110 especies de este género que han sido introducidas en más de 90 países (Booth 2013). En la actualidad existen aproximadamente 850,000 hectáreas de plantaciones de *Eucalyptus* en Chile, ubicadas principalmente en la zona centro sur (entre latitudes 35S y 41S), de los cuales el 68% consiste en *E. globulus* (INFOR 2017).

La clave del manejo forestal sustentable radica en una comprensión de las interacciones entre la respuesta al crecimiento de las plantaciones y la disponibilidad de recursos del sitio, la forma en que esos recursos se modifican a lo largo de la rotación, y cómo pueden ser influenciados positivamente por el manejo (Albaugh et al. 2004a, Powers y Reynolds 1999). El control de la vegetación competidora durante el establecimiento de una plantación, permite aumentar la disponibilidad de agua, nutrientes y luz (Nambiar y Sands 1993; Kogan y Figueroa 1999; Balandier et al. 2006; Eyles et al. 2012) y, por lo tanto, aumenta la supervivencia y crecimiento de los árboles (Adams et al. 2003; Rose et al. 2006; Wagner et al. 2006; Little et al. 2007; Haywood 2011). Sin embargo, respuestas en crecimiento como consecuencia de un aumento en la disponibilidad de recursos del sitio al establecimiento, no garantiza que estas respuestas se mantengan a lo largo de la rotación (Nilsson y Allen 2003). Previos estudios han demostrado que la composición de la vegetación competidora (herbácea/leñosa) afecta la disponibilidad de los recursos del sitio a lo largo del desarrollo de la plantación. Un ejemplo es la vegetación herbácea, que generalmente es un fuerte competidor de los recursos del sitio al comienzo de la rotación, mientras que la vegetación leñosa se desarrolla más lentamente y puede convertirse en un fuerte competidor de los recursos del sitio posterior al cierre de copas (Zutter y Miller 1998; Balandier et al. 2006; Watt et al. 2015).

La magnitud y duración de la respuesta al control de la vegetación competidora están influenciadas por varios factores, entre los que se incluyen la disponibilidad de recursos del sitio (Adams et al. 2003 y Wagner et al. 2006), la composición y cantidad de biomasa de vegetación competidora (Wagner et al. 1989; Garau et al. 2009), y la oportunidad e intensidad de control, esta última definida como el área libre de vegetación competidora alrededor de cada árbol (Rose y Rosner 2005; Little y Rolando 2008; Dinger y Rose 2009).

Durante las últimas décadas han existido importantes esfuerzos de investigación para cuantificar las respuestas asociadas al control de vegetación competidora en el crecimiento de plantaciones de *Eucalyptus* (Little y Rolando 2008; Garau et al. 2009, Eyles et al. 2012). Sin embargo, la mayoría de las investigaciones publicadas corresponden a respuestas tempranas en crecimiento de *Eucalyptus*, y existe una brecha de conocimiento sobre el efecto de la intensidad de control de la vegetación competidora en la magnitud y la duración de la respuesta en volumen a largo plazo (Wagner et al. 2006). Estudios que incluyeron diferentes tamaños de áreas libres de competencia alrededor de la planta, mostraron que a menor intensidad de control de la vegetación competidora, hubo una reducción significativa en la respuesta en volumen en *Pinus taeda* (Dougherty y Lowery 1991), *Pinus radiata* (Richardson et al. 1996; Kogan et al. 2002), *Pseudotsuga menziesii* (Rose *et al*., 2006), y *Eucalyptus* spp. (Little y Rolando 2008). La intensidad de control requerida para maximizar el crecimiento de la plantación depende de las condiciones específicas de la especie de cultivo, de la disponibilidad de recursos del sitio y composición y cantidad de biomasa de vegetación competidora presente en cada sitio (Richardson et al. 1996; Little y Rolando 2008).

Nilsson y Allen (2003) definieron cuatro tipos de respuestas de crecimiento a la aplicación de tratamientos silvícolas (Tipo A, B, C y D). Estos patrones de respuesta, que son comparados con un control no tratado y reflejan una modificación en la disponibilidad de recursos del sitio, se pueden observar al analizar las respuestas de crecimiento a lo largo de la rotación. Los tipos de respuesta se diferencian por la cantidad y oportunidad en que los recursos (luz, agua y nutrientes) están disponibles y son utilizados por la plantación a lo largo de la rotación. Una respuesta a un tratamiento se considera Tipo A, si existe un aumento sostenido y divergente del crecimiento en relación con un área no tratada, a lo largo de la rotación, y se traduce en un aumento de la capacidad de carga del sitio (Albaugh et al. 2015). Respuestas Tipo A se han observado en plantaciones de *P. taeda* con tratamientos de control de la vegetación competidora leñosa (Zutter y Miller 1998; Nilsson y Allen 2003). Una respuesta a un tratamiento se considera

Tipo B, si existe un aumento sostenido y temporal del crecimiento en relación con un área no tratada, entonces los recursos adicionales disponibles inicialmente se agotan y los árboles tratados dejan de responder (Albaugh et al. 2015). Respuestas Tipo B se han observado en plantaciones de *P. radiata* con tratamientos de control de la vegetación competidora herbácea en sitios fértiles (Mason y Milne 1999; Albaugh et al. 2004b), explicado por una mejora en la oportunidad de adquisición de los recursos. Una respuesta a un tratamiento se considera Tipo C, si existe un aumento inicial del crecimiento que disminuye a lo largo de la rotación en relación con un área no tratada, resultando en una respuesta nula en el largo plazo. Respuestas Tipo C se han observado en plantaciones de *P. radiata* y *P. taeda* con tratamientos de control de vegetación competidora en sitios con limitaciones nutricionales no corregidas (Richardson 1993; Allen y Lein 1998). Finalmente, una respuesta a un tratamiento se considera Tipo D si existe una disminución del crecimiento en relación con un área no tratada, desde el momento de inicio del tratamiento. Respuestas Tipo D se han observado en plantaciones de *P. radiata* con aplicaciones de fertilización sin control de la vegetación competidora (Albaugh et al. 2004b), y en plantaciones de *P. taeda* con tratamientos de control de la vegetación competidora que han generado daño por herbicida a la plantación (Allen, 1996).

Nuestro actual conocimiento de los procesos involucrados en la competencia por los recursos del sitio entre planta y vegetación competidora es limitado, y por lo tanto, la capacidad de predecir el efecto de la competencia en el crecimiento de una plantación de *E. globulus* es escasa. Tratando de disminuir esta incertidumbre, se han establecido múltiples ensayos de control de la vegetación competidora al establecimiento en distintas especies, aplicando diferentes dosis y evaluando diversos sitios (Wagner 2006). En estos estudios se han encontrado diferentes magnitudes de respuesta que se relacionan principalmente con la cantidad de biomasa de vegetación competidora controlada (Garau 2009; Henkel-Johnson et al. 2016). Modelar la interacción entre planta y vegetación competidora puede ayudar a generar conocimientos científicos y una mejor comprensión de los procesos ecofisiológicos involucrados. Un enfoque para comprender estas interacciones es investigar cómo la vegetación competidora altera la disponibilidad de recursos y cómo los árboles responden a este cambio en la disponibilidad de recursos (Goldberg 1996). Los modelos empíricos de crecimiento y rendimiento son la principal herramienta de modelación utilizada en el sector forestal, ya que son fáciles de parametrizar y proporcionan predicciones razonablemente precisas de crecimiento (Kirongo 2000; Watt 2003). Los modelos empíricos de crecimiento y rendimiento son representaciones estadísticas del desarrollo de un rodal a través del tiempo. Para desarrollar estos modelos es necesario medir las variables de interés (número de árboles por hectárea, área basal, volumen o altura), a través del tiempo y en distintas condiciones de sitio y manejo (Flores y Allen 2004). Los enfoques empíricos se han utilizado en distintas especies para modelar la respuesta al control de la vegetación competidora sobre el crecimiento juvenil de *P. radiata* (Mason y Whyte 1997; Zhao 1999; Mason 2001), *P. taeda* (Westfall et al. 2004) y *P. menziesii* (Knowe et al. 2005). Aunque estos modelos mostraron que el control de la vegetación competidora es el tratamiento silvícola más importante para mejorar el crecimiento y la supervivencia de los árboles, su insensibilidad al tipo de maleza y cantidad de biomasa de vegetación competidora podría entregar estimaciones no apropiadas. Sin embargo, este enfoque empírico rara vez se ha utilizado en plantaciones de *Eucalyptus* para modelar la respuesta de corto y largo plazo al control de la vegetación competidora y su interacción con la disponibilidad de recursos del sitio.

Debido a la ausencia de antecedentes del efecto del control de vegetación competidora en el crecimiento a largo plazo en una plantación de *E. globulus*, surgen preguntas como, ¿Cuál es la duración de la respuesta en crecimiento a un control de la vegetación competidora al establecimiento en una plantación de *E. globulus*?, ¿La magnitud de la respuesta en volumen es afectada proporcionalmente por la cantidad de biomasa de vegetación competidora removida al establecimiento?, ¿Cuál es el área mínima libre de competencia al establecimiento en una plantación de *E. globulus*, requerida para maximizar la respuesta en volumen cercano a la edad de rotación en un gradiente de disponibilidad hídrica?. Comprender que factores gatillan la disponibilidad de recursos del sitio en el largo plazo, son claves para predecir la magnitud y duración de la respuesta en volumen para distintas intensidades de control de la vegetación competidora y determinar el área mínima libre de vegetación competidora requerida para alcanzar el máximo crecimiento a la edad de rotación.

HIPÓTESIS

- La duración de la repuesta en crecimiento a un control de vegetación competidora al establecimiento es temporal y positiva en una plantación de *E. globulus* a la edad de 9 años.

- Incrementos en la cantidad de biomasa de vegetación competidora removida al establecimiento afectan proporcionalmente la magnitud de la respuesta en volumen en plantaciones de *E. globulus* a la edad de 9 años.

- Sitios con alta disponibilidad hídrica requieren un área libre de competencia al establecimiento menor respecto a sitios con baja disponibilidad hídrica, para alcanzar el máximo crecimiento potencial a la edad de 9 años en plantaciones de *E. globulus*.

OBJETIVO GENERAL

Evaluar el efecto del área libre de competencia, la disponibilidad hídrica, cantidad y composición de vegetación competidora, sobre la magnitud y duración de la respuesta en crecimiento de largo plazo en plantaciones de *E. globulus* a la edad de 9 años.

Objetivos específicos

- Determinar el efecto de la intensidad de control de la vegetación competidora en la magnitud y duración de la respuesta en crecimiento en volumen a largo plazo en plantaciones de *E. globulus* a la edad de 9 años.

- Determinar el área mínima libre de vegetación competidora requerida para alcanzar el máximo crecimiento en plantaciones de *E. globulus* a la edad de 9 años.

- Modelar el efecto del área libre de competencia, disponibilidad hídrica y cantidad de biomasa de vegetación competidora en el crecimiento de una plantación de *E. globulus*.

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 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 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 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).

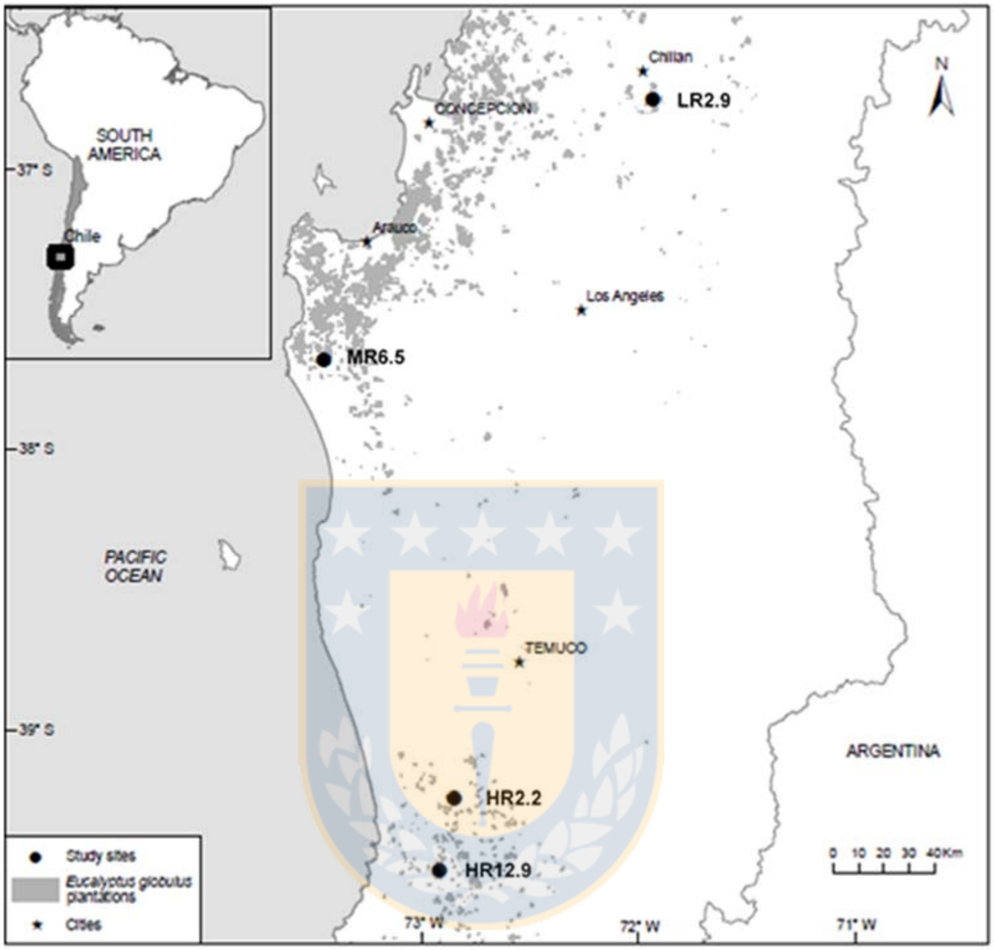

Fig. 1 Map showing the location of the four sites used in this study in Chile

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 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. All sites were harvested at age 10 years.

Table 1 Average annual rainfall (Rain), mean annual maximum temperature (Tmax), mean annual minimum temperature (Tmin), 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 y^{-1})	Tmax (°C)	Tmin (°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

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 x 10 trees), with an internal measurement plot of 30 trees (5 rows x 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 litres ha^{-1}. At each site, herbicides (glyphosate 2.5 kg ha^{-1} + simazine 3.0 kg ha^{-1} + Silwet surfactant 1ml 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 x 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:

$$CAI_{ijk} = \mu + C_i + T_k + (CT)_{ik} + e_{ijk}$$

Where:

CAI_{ijk} = current annual volume increment ($m^3 \cdot ha^{-1} \cdot year^{-1}$)

μ = mean for treatment *i* at time *k*

C_i = treatment effect *i*

T_k = time effect *k*

$(CT)_{ik}$ = treatment × time interaction effect

e_{ijk} = random error associated with the measurement at time *k* on the j^{th} 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:

$$Y_j = a*(1- \exp(-b*X_j)) + \mathcal{E}_j$$

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 j^{th} plot; exp is base of natural logarithm; $\mathcal{E}j$ is the error of the model with $\mathcal{E} \sim N(0, \sigma^2)$; 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 two years from planting, a sustained increase was observed in the presence of woody vegetation at all the sites and treatments (visual observation).

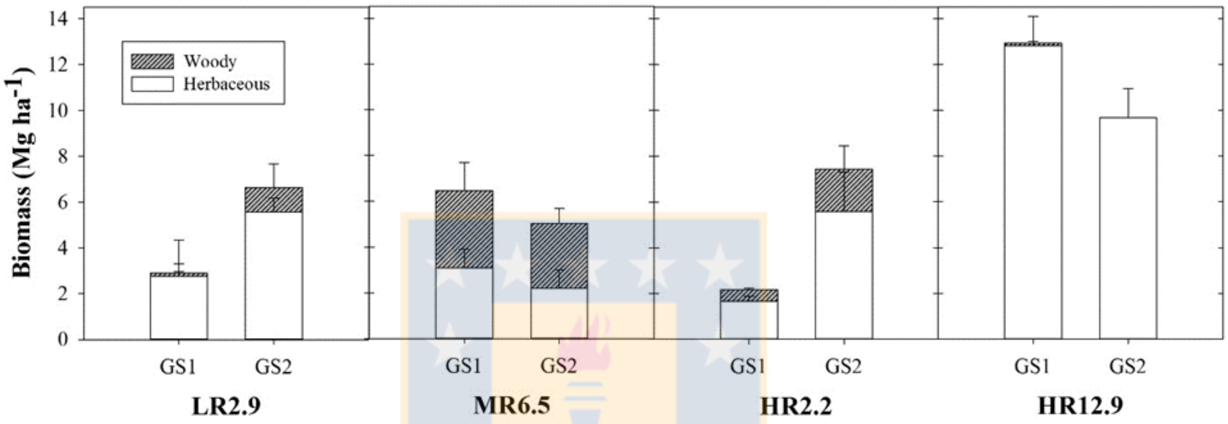

Fig. 2 Maximum average annual biomass production of herbaceous (open filled) and woody (black filled) competing vegetation during the first (GS1) and second (GS2) growing seasons on four sites in south central Chile (LR2.9, MR6.5, HR2.2 and HR12.9).

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 y^{-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 HR12.9, 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).

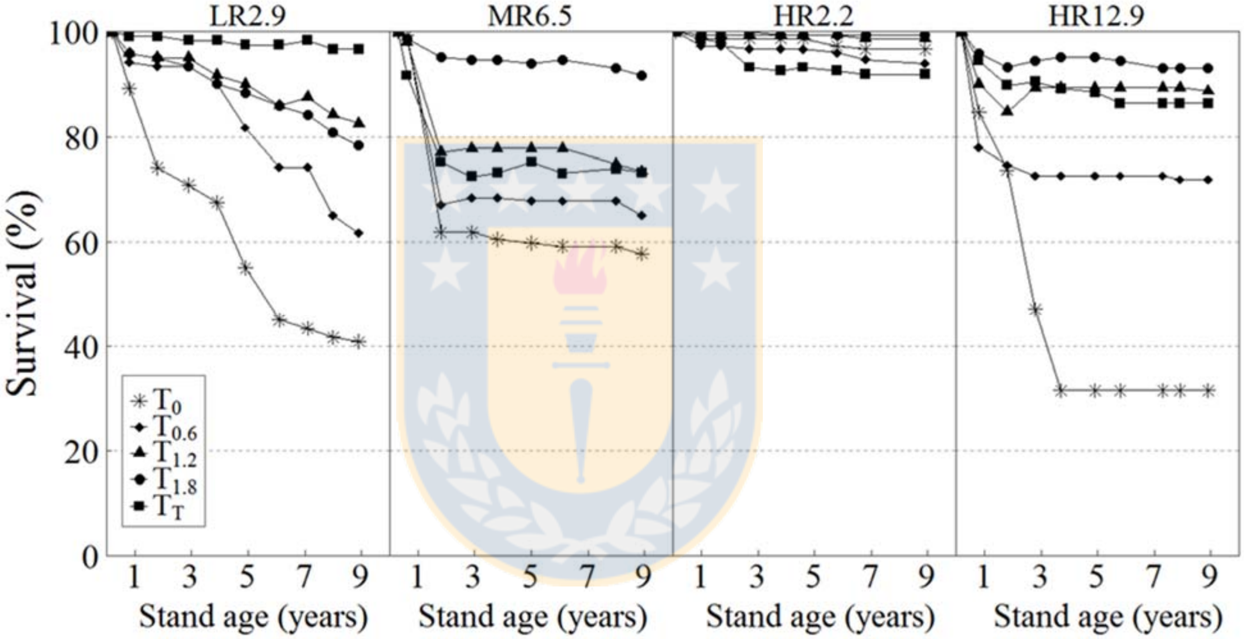

Fig. 3 Time series dynamics of survival percentage for *E. globulus* stands growing under different vegetation control intensity treatments on four sites in south central Chile (LR2.9, MR6.5, HR2.2 and HR12.9).

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 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 *Pseudotsuga menziesii* trees in Oregon (Rose et al. 2006).

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 y Landsberg 2002). These authors reported that the minimum and optimum temperature for *E. globulus* growth are 8.5 and 16 ºC. 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.

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. Within each site, different letters indicate significant differences among treatments using Tukey's multiple means comparison test.

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

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. 4, E, F, G y 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 x 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 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. 4, E, F, G, 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. 4 D, H). A Type B response was observed at sites LR2.9, MR6.5 and HR2.2 (Fig. 4 A, 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. 4, E, 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 y 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).

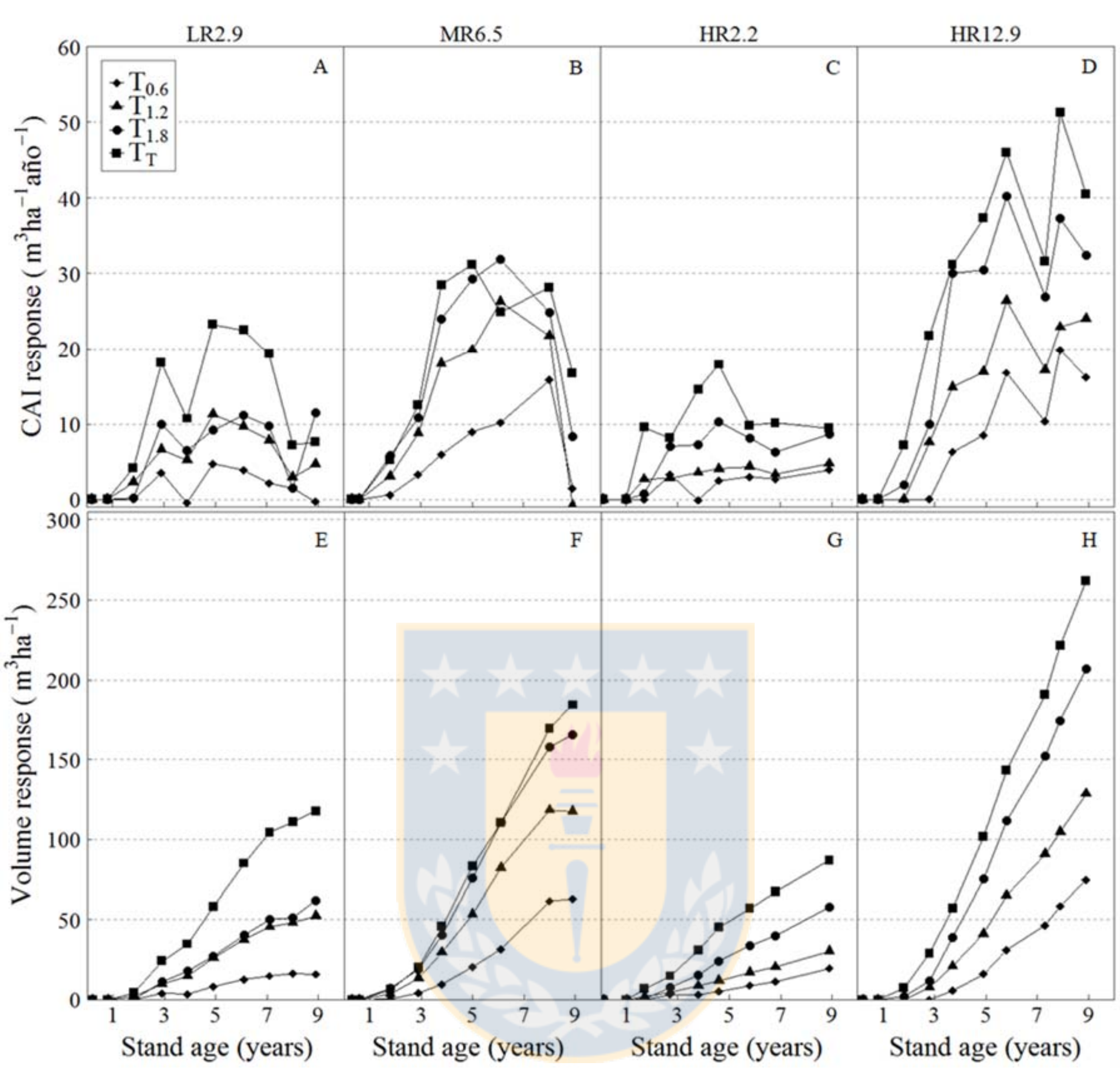

Fig. 4 Time series dynamics of current annual volume increment (m^3 ha^{-1} $year^{-1}$) and cumulative volume response (m^3 ha^{-1}) for *E. globulus* stands growing under different vegetation control intensity treatments on four sites in south central Chile (LR2.9, MR6.5, HR2.2 and HR12.9). Values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

At all study sites, treatments of competing vegetation control were carried out during the first two 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 other species in different environments (Wagner et al. 1989; George and Brennan 2002; Coll et al. 2004; Harper et al. 2005). Changes in the slope 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.

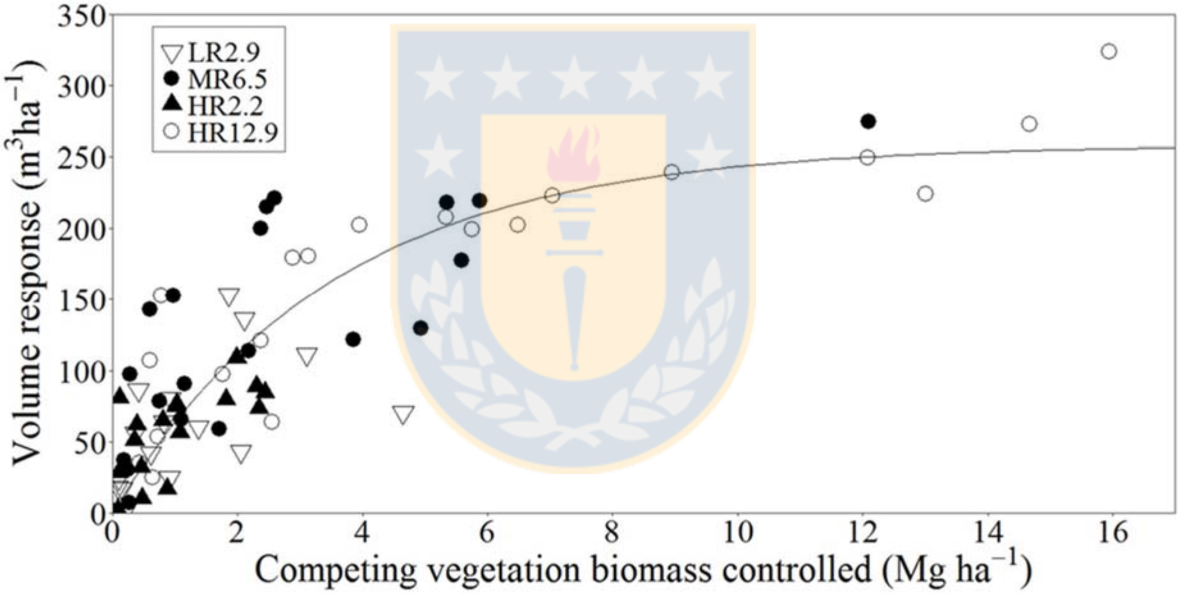

Fig. 5 Relationship between competing vegetation biomass controlled during the first growing season and volume response at age 9 years for *E. globulus* stands growing under different vegetation control intensity treatments on four sites in south central Chile (LR2.9, MR6.5, HR2.2 and HR12.9). Solid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

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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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 area free 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.

INTRODUCTION

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 (FAO, 2013), including more than 110 species of the genus that have been introduced in more than 90 countries (Booth, 2013). 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* (INFOR, 2017).

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 (Albaugh et al. 2004a; Powers and Reynolds 1999). It is well known that reducing competing vegetation biomass during stand establishment increases water, nutrient and light site resource availability (Nambiar and Sands 1993; Balandier et al. 2006; Eyles et al. 2012) allowing better survival and tree growth (Adams et al. 2003; Rose et al. 2006; Wagner et al. 2006; Little et al. 2007).

Previous studies about the managing of the intensity of competing vegetation or weed control, defined as the area free of 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* (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 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 (Richardson et al. 1996; Little and Rolando 2008). During last decades, there have been substantial research efforts to quantify growth responses associated with competing vegetation control in *Eucalyptus* plantation (Little and Rolando 2008; Garau et al. 2009; Eyles et al. 2012; Vargas et al. 2018). 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 (Henkel-Johnson et al. 2016). However, a model can predict the likely yield loss associated with different intensities of competing vegetation control (Renton and Chauhan 2017). 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 juvenile growth of *P. radiata* (Mason and Whyte 1997; Zhao 1999; Mason 2001), *P. taeda* (Westfall et al. 2004) and *P. menziesii* (Knowe et al. 2005). These studies reported that 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 potential growth at 9 years of age in *E. globulus* plantations.

MATERIALS AND METHODS

Site characteristics

Four experimental sites were selected representing an environmental gradient in south central Chile (Table 1), where other work has been completed (Vargas et al. 2018). 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).

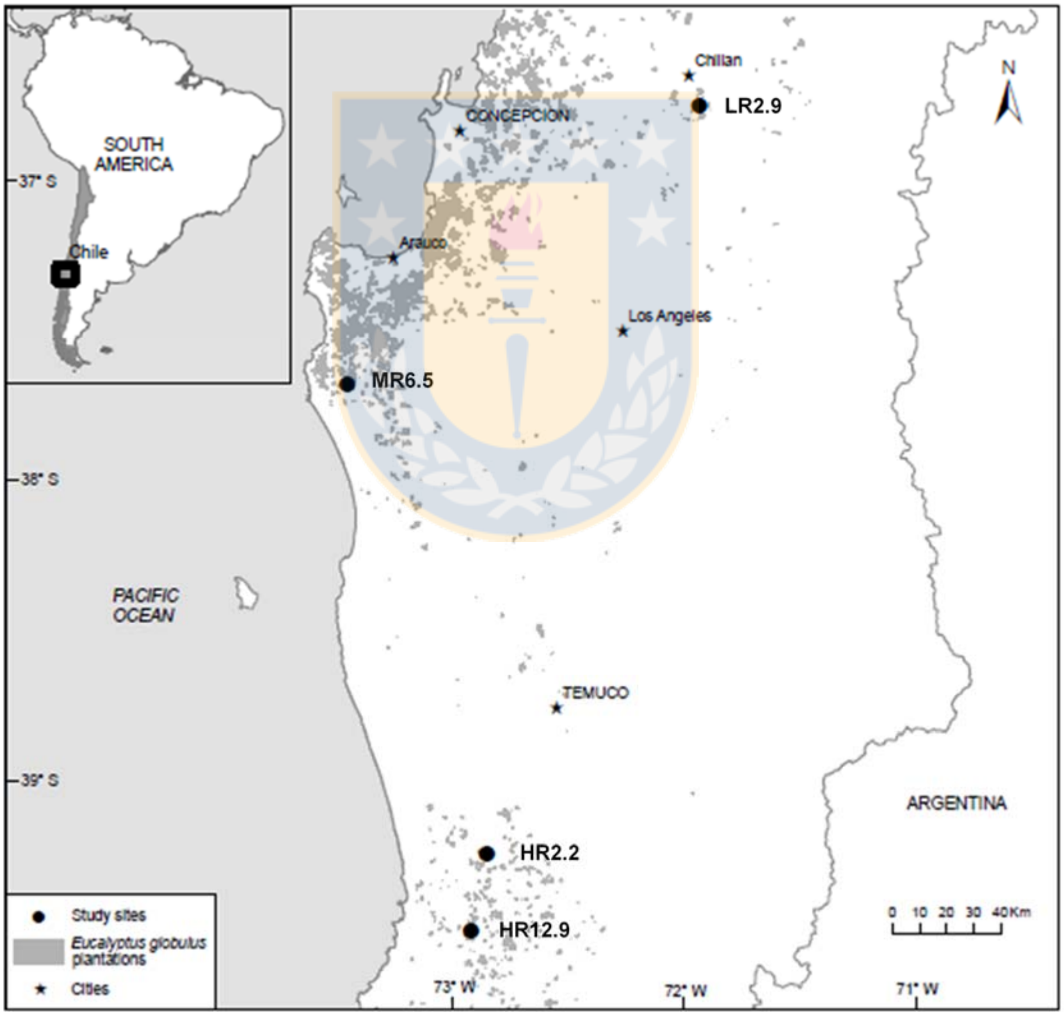

Figure 1. Location of the four sites used in this study in Chile

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.

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 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

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).

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 (Real 2010), considering a top diameter limit (TDL) of 6 cm for each tree.

Modelling approach

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). 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 (Cousens 1985; Wagner et al. 1989). 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
$Y_{ijk} = a{*}\mathrm{Exp}[-\mathrm{Exp}(b)X_j] + c{*}\mathrm{Exp}[-\mathrm{Exp}(d)Z_k] + \varepsilon_{ijk}$	Pinheiro and Bates 2000
$Y_{ij} = \mathrm{Exp}(-a{*}X_j) + \varepsilon_{ij}$	Ratkowsky 1990
$Y_{ij} = a/((b{*}X) + \mathrm{Exp}(c{*}X_j)) + \varepsilon_{ij}$	Ratkowsky 1990

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 i^{th} site and j^{th} 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.

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 k^{th} block at the ij^{th} site-treatment combination, R_i is average annual rainfall at the i^{th} site and X_j is intensity of competing vegetation control of the j^{th} 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. All statistical analyses were evaluated using a $P < 0.05$ as a significance level.

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 (Neter et al. 1996). 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 (Hawkins et al. 2003). 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).

RESULTS

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 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.

Treatments	LR2.9		MR6.5		HR2.2		HR12.9	
	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

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.

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).

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).

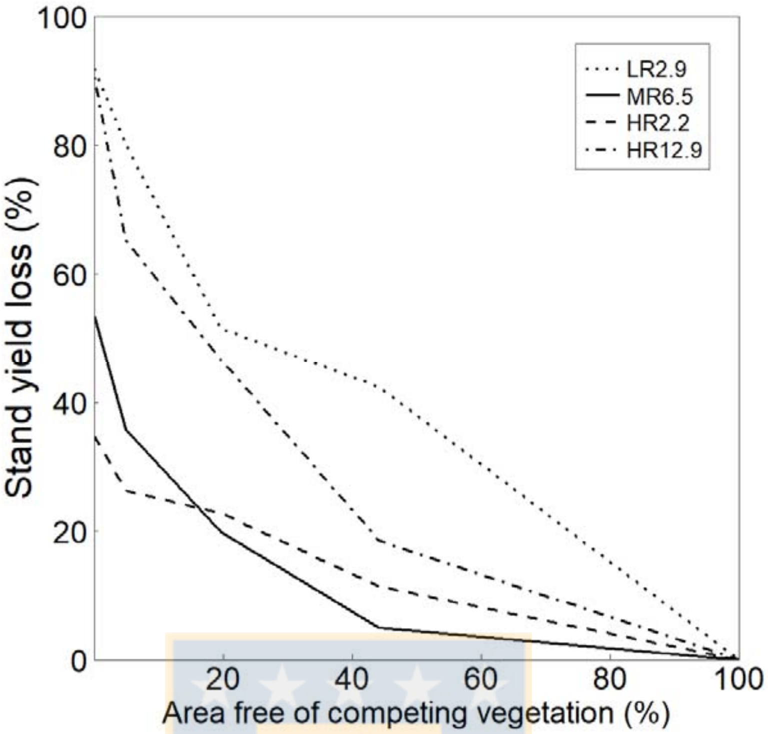

Figure 2. Proportion of stand yield loss under different vegetation control intensity across a rainfall and the amount of competing vegetation biomass gradient. The sites were classified based on their annual mean rainfall (high: HR, medium: MR or low: LR rainfall) and the amount of accumulated competing vegetation biomass (Mg ha^{-1}) in the control treatment during the first growing season.

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 ($P < 0.001$; $R^2 = 0.76$).

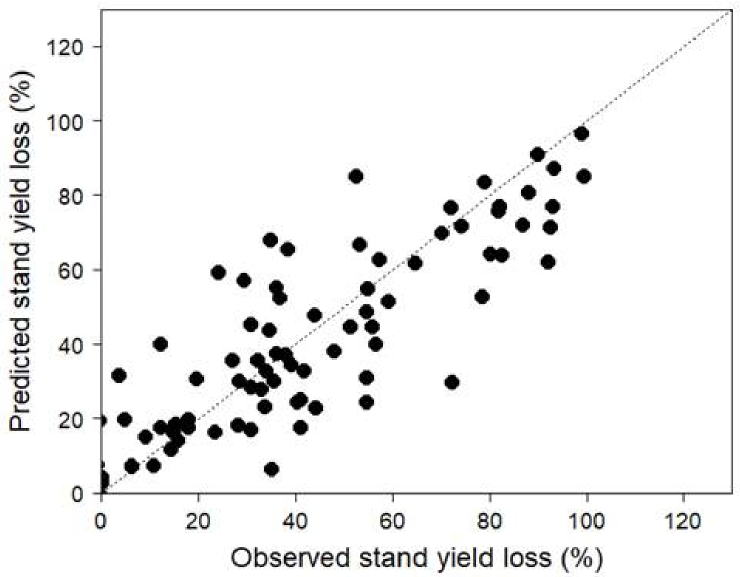

Figure 3. Model validation for four tested sites (100 plots total). Observed versus predicted values of proportion of stand yield loss. The dotted line corresponds to the 1-to-1 relationship.

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* (Garau et al. 2009; Little and Rolando 2008) and *P. menziesii* (Rose et al. 2006). 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), where stand yield loss related to competing vegetation was correlated to the amount of vegetation biomass measured 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). 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), 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 (George and Brennan 2002; Garau et al. 2009). 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 (Nambiar and Zed 1980; Little and Van Staden 2003; Garau et al. 2008). 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 (Watt 2003). 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 (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 higher than those of trees (Smethurst and Nambiar 1989).

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 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) 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) and Garau et al. (2009), 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), where competing vegetation biomass accounted for 98% of the variation in stand volume. Comparable relationships have been reported for other species in different environments (Wagner et al. 1989; George and Brennan 2002; Coll et al. 2004; Harper et al. 2005).

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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CONCLUSIÓN GENERAL

La magnitud de la respuesta en volumen para el mejor tratamiento en cada sitio varió entre 58 y 262 m^3 ha^{-1} a la edad de 9 años, y esta respuesta fue proporcional a la cantidad de biomasa de vegetación competidora controlada durante la primera temporada de crecimiento. La duración de la respuesta para los tratamientos de control de vegetación competidora varió entre 5 y 9 años. Además, se observó una respuesta temporal y sostenida, hasta los 9 años en sitios con biomasa de vegetación competidora controlada inferior a 6,5 Mg ha^{-1}. Sin embargo, en el sitio con la mayor cantidad de biomasa de vegetación competidora (12,9 Mg ha^{-1}), la respuesta al control de la vegetación fue divergente y sostenida hasta el año 9. Adicionalmente, se encontró una fuerte relación entre la pérdida de rendimiento en volumen de la plantación y la intensidad del control de vegetación competidora, la cantidad de biomasa de vegetación competidora producida durante la primera temporada de crecimiento y la precipitación media anual. La pendiente de la relación fue diferente entre los sitios y se relacionó principalmente con las limitaciones de agua y luz.

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