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Efecto de la intensidad de poda y disponibilidad de recursos hídricos del sitio en el crecimiento de *Pinus radiata* D. Don.

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EFECTO DE LA INTENSIDAD DE PODA Y DISPONIBILIDAD DE RECURSOS HÍDRICOS DEL SITIO EN EL CRECIMIENTO DE *Pinus radiata* D. Don.

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DEDICATORIA

"A Dios,
mi esposa Paola,
y mis hijas Javiera y Martina"

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RESUMEN

Pinus radiata D. Don ha sido establecido en Chile en un amplio rango de suelos y condiciones climáticas, donde la disponibilidad de recursos hídricos es uno de los factores principales que determinan la productividad de esta especie y la respuesta a diversas prácticas silvícolas. Varios estudios han investigado las respuestas de crecimiento a la poda de plantaciones de pino, sin embargo, existe una brecha en el conocimiento sobre su efecto con la disponibilidad de agua del sitio, además la mayoría de las investigaciones muestran resultados locales, son a corto plazo, con parcelas pequeñas a nivel de árbol; por consiguiente, los resultados tienden a ser restringidos en su aplicación. El presente trabajo evalúa la respuesta en crecimiento de *P. radiata* a diferentes niveles de intensidad de poda a través de un gradiente hídrico de sitios en la zona centro sur de Chile. Los tratamientos de poda consideraron tres niveles de intensidad: sin poda, poda leve donde se removió cerca del 30% de la copa viva y poda severa donde se removió cerca del 60% de la copa viva. El índice de déficit hídrico utilizado presentó fuertes relaciones lineales y positivas con el área foliar y el crecimiento; además en conjunto con el largo de copa viva remante se construyó un modelo simple predictor de la respuesta en crecimiento a la poda. Se determinó que a medida que la disponibilidad de agua del sitio aumenta, la pérdida de crecimiento por efecto de la intensidad de poda es mayor. Luego de 8 años de efectuado los tratamientos de poda y haber practicado un raleo intermedio, la poda severa mostró rendimientos menores para los 500 árboles finales a la edad 14-15 años tanto en volumen, como en área basal, diámetro y altura, que el tratamiento de poda leve y el testigo (tratamiento sin poda). De igual manera, y a excepción del sitio con mayor déficit hídrico, los tratamientos de poda leve mostraron rendimientos menores, tanto en volumen, área basal y diámetro, que el tratamiento sin poda; sin embargo, no en todos los casos se obtuvieron diferencias significativas entre estas comparaciones. Adicionalmente se evaluó el efecto de los árboles seguidores (sin poda) dentro de los tratamientos con poda, encontrando que los árboles seguidores, independiente de la intensidad de poda, mostraron menores rendimientos que los tratamientos sin seguidores, tanto en volumen, área basal, diámetro y altura, siendo este efecto más negativo en los tratamientos con poda severa.

ABSTRACT

Pinus radiata D. Don has been established in a wide range of soils and climatic conditions, where water availability is one of the main factors that determine the productivity of this species and the response to diverse silvicultural practices. Several studies have examined the growth responses to pruning of pine plantations, however, there is a gap in knowledge about its interaction with the water availability of the site, in addition most of the previous investigations show local results, in short term, with small plots at tree level, therefore, the results tend to be restricted in their application. The present work evaluates the growing response of *Pinus radiata* to different levels of pruning intensities through a water gradient of sites in the south-central zone of Chile. The pruning treatments considered three levels of intensity: no pruning, light pruning where about 30% of the living crown was removed and severe pruning where about 60% of the living crown was removed. An index of water deficit, used in this research, showed strong linear and positive relationships with the leaf area and growth, and in addition, with the length of live remaining crown, a simple predictor of the growth response to pruning was constructed. An important trend is observed that as the water availability of the site increases, the loss of growth due to the intensity of pruning is greater. After 8 years of pruning treatments and intermediate thinning, severe pruning showed lower yields for the final 500 trees at age 14-15 years in volume, basal area, diameter or height, than the treatment of light pruning and treatment without pruning. Similarly, except for the site with the highest water deficit, light pruning treatments showed lower yields, in volume, basal area and diameter, than treatment without pruning, however, it should be noted that not all cases were obtained significant differences between these comparisons. Additionally, the effect of the follower trees (trees without pruning) within the treatments with pruning was evaluated, finding that the followers trees independent of the intensity of pruning showed lower yields than the treatments without followers either in volume, basal area, diameter or height, this effect is more relevant in treatments with severe pruning.

INTRODUCCIÓN GENERAL

Pino radiata (*Pinus radiata D. Don*) es sin duda la especie conífera originaria de América del Norte más ampliamente plantada en el mundo (Mead 2013). Hoy en día existen sobre cuatro millones de hectáreas plantadas de pino radiata en el mundo, siendo las plantaciones más extensas las encontradas en Chile, Nueva Zelanda (aproximadamente 1,6 millones de hectáreas cada una) y Australia (0,77 millones de hectáreas) (Mead 2013). En Chile, las plantaciones de pino radiata están ubicadas en una amplia zona geográfica entre Valparaíso y Puerto Montt cubriendo una gran variedad de suelos y condiciones climáticas (Álvarez 2010). La mayor concentración se localiza en la Región del Bío Bío, la que alcanza a 44% del total de plantaciones (Sotomayor *et al*. 2002; Mead, 2013).

Hoy en día la mayor parte del recurso de pino radiata en Chile se maneja maximizando la producción de volumen incorporando raleos y podas (Mead 2010) que buscan elevar el valor comercial de las plantaciones, mediante la producción de madera de alta calidad (Gerding 1991; Mead 2013). La poda, dentro de las prácticas de manejo intensivo de plantaciones, consiste en la remoción de las ramas vivas de la parte basal de la copa hasta una determinada altura sobre el piso en una operación, o en múltiples levantes, permitiendo que los nudos y los defectos relacionados con las ramas removidas se restrinjan a un núcleo nudoso central y el crecimiento subsecuente del diametral del fuste produzca madera de mayor calidad dando un mayor valor al bosque (Cown 1999; Pinkard y Beadle 2000; Montagu et al. 2003; Amateis y Burkhart 2011).

La eliminación de las ramas vivas producto de la poda puede reducir el crecimiento (Sutton y Crowe 1975; Pinkard y Beadle 1998b; Nutto y Touza 2003; Alcorn et al. 2008; Amateis y Burkhart 2010, 2011; Hevia 2012), debido a que se remueve área foliar fotosintéticamente activa. Por lo tanto, las estrategias de manejo deben sopesar el impacto positivo de la poda en la calidad de la madera, contra los efectos negativos de la eliminación de la copa viva en el crecimiento. La comprensión de los efectos de la severidad de poda sobre el crecimiento es fundamental para el desarrollo de regímenes de poda que no reduzcan el crecimiento y el volumen de madera de los árboles en rodales podados (Amateis y Burkhart 2011). Aun cuando la tendencia mayoritaria es la reducción de crecimiento al podar, existen experiencias donde no se observan efectos negativos sobre el crecimiento, por ejemplo, cuando existe remoción de una pequeña cantidad de copa verde, cuando el follaje inferior de la copa está parcialmente a la sombra o cuando los árboles muestran ramas basales en vías de secarse (Muñoz *et al*. 2005); incluso algunos autores (Möller 1960; Fujimori y Wasada 1972; Wang et al. 1980; Davel y Sepúlveda 2000; Schoelzke 2003; Cyr 2006; Tonguc y Guner 2017) han encontrado efectos positivos de la poda sobre el crecimiento, sugiriendo que un cierto nivel de poda puede promover el crecimiento fustal en los árboles. Pinkard y Beadle (2000) señalan que desde una perspectiva fisiológica esto es posible, dado que en sitios con recursos limitados si las ramas inferiores del árbol utilizan los recursos solo para mantenerse, respirando más de lo que fotosintetizan, la remoción de estas podría liberar recursos para un mayor crecimiento fustal.

La variabilidad observada en diferentes estudios para el efecto de la poda sobre la tasa de crecimiento del árbol ha sido asociada, en su mayoría, con la intensidad del tratamiento, atendiendo especialmente al rol del porcentaje de copa remanente que contribuye a la asimilación de carbono y por tanto al crecimiento. Así, por ejemplo, la menor longitud de la copa viva remanente tras la intervención de poda ha sido frecuentemente relacionada con el menor crecimiento de los árboles (O´Hara 1991; Montagu *et al*. 2003, Mead 2013). Desde esta perspectiva, todas las especies tienen un nivel de poda (remoción de copa) que reduce el crecimiento (dependiendo de la longitud de copa remanente y de cuan intensa es la poda); sin embargo, distintas especies varían ampliamente en este nivel. En algunos eucaliptos y acacias existe evidencia de que entre 40% y 50% y en coníferas entre el 25% y el 40% del largo de copa viva puede ser removida sin causar pérdidas de crecimiento (Pinkard y Beadle 2000). En pino radiata, varios autores indican que el crecimiento puede verse afectado solo cuando se remueve alrededor del 30% de la copa (Lückhoff 1949; Sutton y Crowe 1975; Lange et al. 1987). En *Cryptomeria japonica (L.f.)* D. Don, la reducción en incremento en volumen fustal aumenta exponencialmente con el porcentaje de copa removido (Fujimori y Waseda 1972). Esta misma relación ha sido observada de manera lineal con *Chamaecyparis obtusa* (Siebold & Zucc.) Endl. (Fujimori y Waseada 1972). Relaciones lineales han sido reportadas entre severidad de poda e incremento en área basal en pino radiata (Sutton y Crowe 1975) y entre severidad de poda y masa seca fustal en *Pinus resinosa Aiton* (Reich *et al*. 1993).

Además de la intensidad de la poda, la literatura reporta otros factores tales como frecuencia de podas, tiempo transcurrido entre podas, numero de podas, estructura del rodal, época, condiciones del sitio, número y distancia entre verticilos y otros tratamientos silvícolas que pueden influenciar la respuesta de crecimiento de los árboles a la poda (Fujimori y Waseda 1972; Sutton y Crowe 1975; Karani 1978; Pinkard y Beadle 1998; Fassola *et al*. 1999a, 1999b, 2002; Montagu et al. 2003; Forrester et al., 2010; Forrester, 2013; Hevia et al. 2016)

El costo de podar las plantaciones es alto, por lo tanto, para minimizar los costos, generalmente solo se podan los árboles elegidos para la cosecha final (árboles objetivo) (Neilsen y Pinkard, 2003). Estos árboles objetivo deberían presentar características específicas como rectitud, tamaño de nudos pequeños y pertenecer al dosel superior del rodal (Neilsen y Pinkard, 2003; Hevia et al. 2016). Es importante que los árboles podados mantengan su dominancia, por lo tanto, es necesario que la intensidad de poda no afecte el crecimiento normal de los árboles (Sutton y Crowe, 1975; Gerrand et al., 1997; Courdier et al., 2002; Alcorn et al., 2008), de igual manera, si se dejan árboles vecinos dominantes y codominantes sin poda (árboles seguidores), éstos pueden suprimir el crecimiento de los árboles podados (Sutton y Crowe, 1975), impactando el volumen de madera de alta calidad en el rodal. Teniendo en cuenta que es importante que los árboles podados mantengan su dominancia respecto a los árboles sin poda (Sutton y Crowe, 1975) y para optimizar una mayor cantidad de madera libre de nudos, la combinación de podas y raleos a edades tempranas (Neilsen y Pinkard, 2003; Pinkard, 2003), favorecen el crecimiento de los mejores árboles finales, aumentando la producción de madera de alta calidad.

El efecto de la poda es a menudo limitado y temporal. Sutton y Crowe (1975) reportaron que la eliminación del 20-35% de la copa viva redujo el crecimiento de pino radiata, aunque la respuesta fue solo durante un año después de la poda. Amateis y Bukhart (2011) también mostraron que un año después de la poda, los árboles de *Pinus taeda* L. a las edades de 3, 6 y 9 años restauraron la biomasa de sus copas y el crecimiento se reanudó de manera comparable a un control sin poda. Si bien el impacto de esta intervención silvícola en el crecimiento de los árboles puede ser limitado y temporal, a largo plazo las reducciones del crecimiento producidas durante un año después de la poda pueden generar grandes diferencias entre las intensidades de poda.

Respecto a la relación entre la poda y las condiciones del sitio para pino radiata, no existe mucha información y la existente está relacionada con otras especies y es contradictoria. Por ejemplo, Lückhoff (1956) señala que las reducciones de crecimiento por la poda son menos severas en sitios pobres que en los mejores sitios, mientras que otros autores declaran que en los sitios de alta calidad, los efectos de la poda son menores que en los sitios pobres (Fujimori y Wasedsa 1972; Schönau 1974; Bredenkamp *et al*. 1980; Pinkard y Beadle 1998a, 2000; Pinkard 2002, 2003). Las diferencias de sitio son importantes en la productividad de las plantaciones (Gerding y Schlatter 1995; Flores y Allen 2004), ya que pueden determinar la biomasa de follaje, la longevidad del follaje y su distribución en la copa de los árboles que influirá a su vez en la cantidad de luz interceptada (Gower et al. 1992; Albaugh et al. 1998; Guo y Gifford 2002; Rubilar et al. 2013b). Con este enfoque, al tener una prescripción de poda a una altura fija, la cantidad de follaje remanente en la copa puede ser diferente según el sitio (O'Hara 1991). La mayoría de las prescripciones de poda son empíricas por naturaleza y combinan requerimientos operacionales, relaciones altura/diámetro o respuestas en volumen a varios tratamientos (Luckhoff 1967; Gerrand *et al*. 1997). Este enfoque tiene la ventaja de ser directamente relevante para la actual producción de madera e involucra el uso de variables de fácil medición relacionadas directamente con la respuesta del crecimiento del fuste. Sin embargo, la respuesta a la poda no es solo influenciada por la especie (Hevia et al. 2016), sino también por la fertilidad del sitio, disponibilidad de agua y factores climáticos (Saure 1987; Forrester et al. 2010; Forrester 2013), variables que pueden variar espacial y temporalmente (Álvarez *et al.* 2012).

La productividad de pino radiata está fuertemente influenciada por las condiciones del sitio (Gray 1989), y en Chile esta especie se ha establecido en un amplio rango de suelos y condiciones climáticas, lo que resulta en una gran variación en la productividad de estas plantaciones (Gerding y Schlatter 1995; Flores y Allen 2004; Álvarez 2010). El agua disponible en la plantación, determinada por la lluvia y la capacidad de retención de agua del suelo, es el principal determinante de la productividad real y potencial del pino radiata en

Nueva Zelanda (Jackson y Gifford 1974; Hunter y Gibson 1984), en Australia (Czarnowski et al. 1971), en Sudáfrica (Grey 1989) y en Chile (Gerding y Schlatter 1995; Flores y Allen 2004). Álvarez et al. (2012) mostraron que tanto la disponibilidad de agua como la demanda por evaporación parecen ser los factores más limitantes del crecimiento y el área del foliar de la especie en Chile.

El estrés hídrico afecta fuertemente la producción y la longevidad del follaje, la fotosíntesis, la fijación de carbono y, finalmente, el crecimiento de pino radiata (Benecke 1980; Raison et al. 1992; Rubilar et al. 2013b). Rubilar et al. (2013a) establecieron una relación lineal entre el área foliar y el crecimiento del fuste en tres rodales de pino radiata ubicados en sitios con diferente productividad y donde la tasa de crecimiento de los sitios estuvo determinada principalmente por las restricciones hídricas de estos. Relaciones similares han sido encontradas entre LAI y productividad para otras especies (Gower et al. 1992; Albaugh et al. 1998; Guo y Gifford 2002) y entre la disponibilidad de agua y el área foliar para una amplia gama de tipos de bosques y condiciones climáticas (Grier y Running, 1977; Gholz, 1982). Sin embargo, hay poca información disponible sobre esta importante relación para plantaciones de pino radiata en edades intermedias y particularmente para rodales manejados con raleos y podas. Por lo tanto, es importante entender las relaciones existentes entre el agua disponible del sitio, la producción del área foliar y el consiguiente crecimiento de las plantaciones de pino radiata en Chile.

La mayoría de los estudios de poda muestran resultados locales, a corto plazo, con parcelas pequeñas a nivel de árbol, por consiguiente, los resultados tienden a ser restringidos en su aplicación. Para poder extrapolar los resultados de este tipo de ensayos de manejo de plantaciones a través de un rango de condiciones de sitio, es necesario incorporar variables de suelo o clima en el diseño.

Debido a lo anterior, surge la pregunta: ¿Qué efecto tiene el agua disponible del sitio en el crecimiento y en la respuesta a diferentes intensidades de poda en las plantaciones de pino radiata? Comprender el comportamiento de las plantaciones sujetas a tratamientos de manejo a edad juvenil en un gradiente hídrico de sitios, puede contribuir a diseñar esquemas de manejos específicos para cada sitio que favorezcan la productividad del rodal final a cosechar.

HIPÓTESIS

Sitios con más disponibilidad de recursos hídricos presentarán mayores pérdidas de crecimiento ante podas de alta intensidad en *Pinus radiata*.

OBJETIVO GENERAL

Analizar el efecto de la intensidad de poda sobre el crecimiento de *Pinus radiata* en un gradiente de disponibilidad hídrica de sitios.

Objetivos específicos

• Evaluar la respuesta en crecimiento de *Pinus radiata* ante diferentes intensidades de poda en un gradiente de sitios de baja a alta disponibilidad hídrica en el corto plazo.

•Modelar el efecto en el crecimiento de *Pinus radiata* a la intensidad de poda y la disponibilidad de recursos hídricos.

•Evaluar el efecto de la intensidad de poda en el crecimiento de los árboles residuales finales posterior a un segundo raleo en un gradiente de disponibilidad hídrica de sitios.

LEAF AREA AND GROWTH OF CHILEAN RADIATA PINE PLANTATIONS AFTER THINNING ACROSS A WATER STRESS GRADIENT

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ABSTRACT

Background: *Pinus radiata* D. Don has been established in a wide range of soils and climatic conditions, showing high variability in both leaf area and volume productivity. Previous research has shown that plantation yield is affected by water availability, but the majority of this work has been done in unthinned stands and provided little insight on the effect of water availability on the productivity of thinned plantations. In order to improve forest productivity for plantations under a climate change scenario, we must understand the effect of plantation management, including thinning on the relationships among available water, leaf area index, and productivity. The aim of this work is to evaluate the effect of site water availability on the leaf area production and consequent volume growth in thinned radiata pine plantations over a water availability gradient. **Methods:** The effect of site available water on leaf area production and consequent volume growth in thinned *Pinus radiata* plantations over a water availability gradient across five sites in central and southern-central Chile was determined. **Results:** Regression analysis revealed water deficit to be related to both leaf area index and volume growth accounting for 77 and 78% of the variation respectively. Eighty-one percent of the variation in volume growth was explained by the leaf area index. Results showed a growth efficiency of 5 m^3 ha^{-1} per unit of leaf area index. **Conclusions:** Strong linear positive relationships between site water availability, leaf area, and stand growth after thinning found in this research suggest that water is the key factor controlling current productivity of radiata pine plantations across sites. A simple and robust water index that is well correlated with leaf area and stand annual volume growth allows for the construction of a simple predictive model that may support management decisions for radiata pine plantations.

Keywords: Growth efficiency; Leaf area index; *Pinus radiata*; Productivity; Water deficit.

BACKGROUND

Radiata pine (*Pinus radiata* D. Don) is the most widely distributed of commercial pine species. There are more than 4 million hectares planted with radiata pine in the world, with the largest areas in New Zealand (1.7 million ha), Chile (1.5 million ha), Australia (0.77 million ha), Spain (0.29 million ha) and South Africa (57,000 ha) (Mead 2013; Ministry for Primary Industries et al. 2016).

The productivity of this species is strongly influenced by site conditions (Grey 1989) and varies more than twofold from 12 to 34 m^3 ha^{-1} year in commercial plantations (Del Lungo et al. 2006; Alvarez et al. 2012). Early work relating the growth of radiata pine to site and climatic factors showed that rainfall and its seasonal distribution, effective soil depth, total nitrogen, available phosphorous and temperature all affected productivity (Jackson and Gifford,1974).

Plantation available water, determined by rainfall and soil water holding capacity, is the main determinant of both actual and potential radiata pine productivity in New Zealand (Jackson and Gifford 1974; Hunter and Gibson 1984), Australia (Czarnowski et al. 1971), South Africa (Grey 1989) and Chile, (Gerding and Schlatter 1995; Flores and Allen 2004). Alvarez et al. (2012) showed that both water availability and evaporative demand were important limits to the growth of the species in Chile.

Forest productivity is positively correlated with leaf area index (LAI) (Jarvis and Leverenz 1983; Linder 1987; Vose and Allen 1988; Alvarez et al. 2012) which determines the rate of energy and gas exchange (CO_2, O_2 and H_2O) between the forest canopy and the atmosphere (Vose et al. 1994). The leaf area index is in turn affected by the supply of nutrients and water and by temperature (Battaglia et al. 1998; White et al. 2010).

In many situations, especially in plantations where nutrient supply is adequate, available water is the primary determinant of leaf area index and tree growth (Benecke 1980; Cromer et al. 1983; Linder et al. 1987; Raison et al. 1992; Albaugh et al. 1998; Benson et al. 1992; Rubilar et al. 2013a). For instance, Rubilar et al. (2013a) established a linear relation between LAI and stem growth in three stands of radiata pine, located in sites with different productivities, finding that the growth efficiency (slope of this relation) was affected by water availability of the sites. Similar relations between LAI and productivity have been found by other researchers (Gower et al. 1992; Albaugh et al. 1998; Guo and Gifford 2002). Strong correlations between LAI and water availability have been observed for a wide range of forest types and climatic conditions (Grier and Running 1977; Gholz 1982). However, little information is available on this important relationship for radiata pine plantations of intermediate ages and particularly for thinned stands.

In recent decades in Chile, climatic trends have reduced water availability and resulted in more erratic rainfall within years and more frequent and severe summer droughts, this has been associated with reduced forest growth (Neuenschwander 2010). It is anticipated that this trend of reduced rainfall in temperate and Mediterranean plantation zones will continue in the future (Mullan et al. 2005; Galindo and Samaniego 2010; Neuenschwander 2010; Kirschbaum et al. 2012). It is therefore important to quantify the effect of water availability on leaf area index and consequently stand growth. In order to improve forest productivity for plantations under a climate change scenario we must understand the effect of plantation management, including thinning on the relationships amongst available water, leaf area index and productivity.

The aim of this study was to evaluate the effect of site available water on leaf area production and consequent volume growth in thinned radiata pine plantations over a water availability gradient.

METHODS

Study area

Five sites were selected in central and southern-central Chile between latitudes 35°S and 40°30´S (Figure 1). These sites represent a gradient of climate and soils with known differences in productivity (Table 1). In 2000 or 2001, all sites were planted with radiata pine at an initial stocking of 1,250 trees per hectare. Sites were labelled according to their average annual rainfall (833 mm: *P800*; 1078 mm: *P1100*; 1492 mm: *P1500*; 1683 mm: *P1700*; 1733 mm: *P1750*). Within each site, four 0.36 ha plots were located on smooth hills with no drainage problems and no signs of fungi, insects or nutritional deficits. Plot locations were selected to cover the range of local variation in productivity. All plots had pre-planting weed control as well as two years of competition release after planting. Stands were thinned down to

800 trees per ha at the time at either age 6 or 7 years. Trees were removed from all diameter classes. Buffers that were 15 metres wide were set aside around each plot, leaving measured plots of 0.09 ha (30 x 30 m); which each contained 72 trees.

Table 1 Site and stand characteristics.

Site	*P800*	*P1100*	*P1500*	*P1700*	*P1750*
Latitude	35°29'39"S	37°58'48"S	40°12'2"S	37°37'6"S	39°28'22"S
Longitude	72°14'8"W	72°26'2"W	73°10'26"W	73°16'40"W	72°53'8"W
Annual mean temperature (°C)	13.2	12.0	10.5	11.1	11.4
Annual mean rain (mm)	833*	1078*	1492*	1683*	1733*
Geology	metamorphic	old volcanic ash	old volcanic ash	metamorphic	recent volcanic ash
Soil taxonomy	Typical Rhodoxeralfs	Typical Paleudalfs	Typical Paleudults	Rhodic Paleudults	Typical Haplohumults
Texture	clay	clay	clay	clay	silt-loam
Organic matter (%)	1.2	3.9	6.8	4.2	11.1
pH	5.8	5.3	5.3	5.2	5.4
Stand Age (yr)	6	6	7	6	6
Stocking before thinning (tree ha^{-1})	1250 *(16)*	1093 *(15)*	1156 *(13)*	1074 *(21)*	1022 *(22)*
Stocking after thinning (tree ha^{-1})	800 *(0)*	800 *(0)*	800 *(0)*	800 *(0)*	800 *(0)*
Height (m)	8.7 *(0.2)*	9.5 *(0.3)*	7.9 *(0.2)*	8.6 *(0.2)*	8.3 *(0.4)*
Diameter (cm)	10.9 *(0.2)*	13.6 *(0.8)*	15.3 *(0.3)*	14.6 *(0.2)*	13.9 *(0.4)*
Basal area (m^2 ha^1)	7.7 *(0.3)*	11.9 *(1.3)*	15 *(0.7)*	13.6 *(0.3)*	12.6 *(0.7)*
Volume (m^3 ha^{-1})	26.7 *(1.2)*	45 *(6.3)*	47.3 *(2.6)*	46.8 *(1.7)*	44.1 *(4.1)*

standard error in brackets.
* *mean value last 25 years.*

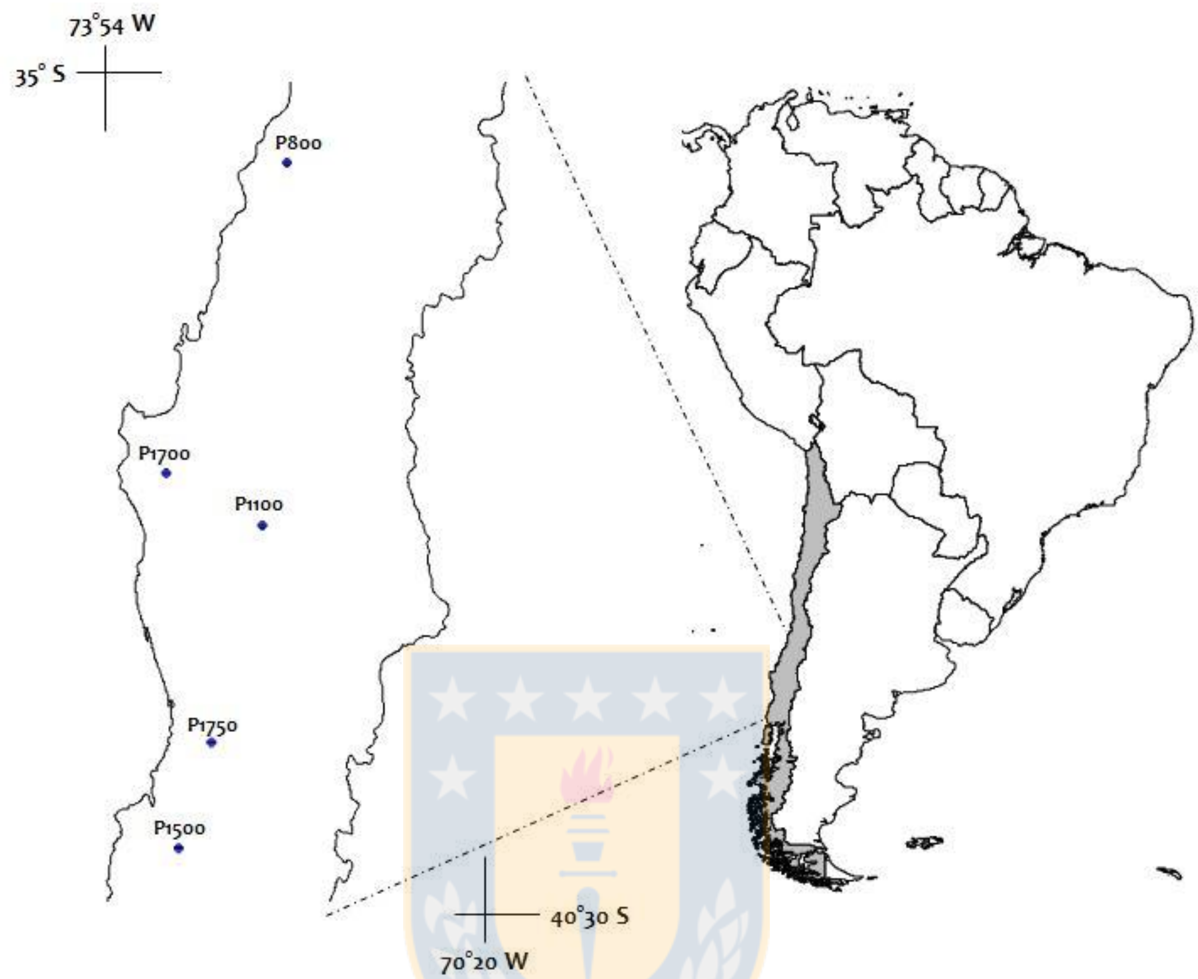

Figure 1. Location of the study areas in central and southern-central Chile.

Tree foliage biomass

At the time of thinning, foliage biomass was estimated on ten trees representing the diameter distribution for each stand. After, the diameter of trees stem, located at 1.3 metres above the ground (DBH) was measured, the sample trees were cut at the ground line and divided into stem, leaves and branches. Branch diameter and distance from the tree top were measured for all branches on each felled tree. Between 10 and 15 branches were selected from each tree to cover the range of branch diameters on the felled trees. Foliage and branch tissues were separated for each sampled branch and dried at 70ºC to a constant weight.

Regression was used to derive a relationship between foliage biomass from branch and both relative distance from the top and branch diameter as described by Rubilar et al. (2010). The resultant relationship (Equation 1) was used to estimate foliage biomass for the other branches.

$$\ln(1000 * Y_i + 1) = a + b * \ln(BD_i + 1) + c * (RDFT^2{}_i + 1) + \varepsilon_i \qquad (1)$$

Where:

Y_i is the foliage biomass (g) at the i^{th} branch

BD_i is branch diameter in cm at the i^{th} branch

$RDFT_i$ is the relative distance of insertion of the branch from the top of the tree (0.0 - 1.0) at the i^{th} branch

ε_i is the error associated with the i^{th} branch

The total foliage biomass was then calculated as the sum of the values for all branches. Finally, a model was fitted between foliage biomass at the tree level and DBH for each site. The adjusted model (Equation 2) has the following form:

$$bf_{ij} = \alpha * d_i^{(\beta + b_j)} + \varepsilon_{ij}, \qquad (2)$$

Where:

bf_{ij} is the leaf biomass of the i^{th} tree in site j (kg)

α, β are fixed parameters

d_i is the diameter of the i^{th} tree (cm)

b_j is site specific parameter

ε_{ij} is the model error

Specific leaf area and leaf area index

Five trees were selected at each site and 20 fascicles were selected at random and removed from within each vertical third of the tree canopy. Sampled fascicles were refrigerated at -1°C until they were processed. The projected leaf area was estimated using an optical projection system (LI-COR LI-3100C area meter, Li-Cor, Lincoln, NE, EE. UU.). Samples were oven-dried at 70°C until constant weight, and the specific leaf area of each was estimated by dividing the projected leaf area by the dry weight. The leaf area of each tree was estimated by multiplying the specific leaf area by the total dry weight of the total foliage of each tree (Equation 1). Leaf area index (LAI) was then estimated from the total sum of the entire estimated leaf area of all post-thinning remnant trees at the plot, derived from the allometric equation described before, divided by the total area of the plot. This estimate represents LAI for each stand. Although the optical projection method used could produce some bias compared to the displacement method in the estimation of specific leaf area, the final leaf area values used in this study produced satisfactory relationships across the study sites.

Growth measurements

The height and diameter of all trees in each plot were measured immediately after thinning, during the vegetative recess period (June) and one year later (period 2007-2008). The increment in diameter growth (IDG) and the increment in height growth (IHG) were calculated as the difference between initial measurements and those after one year following thinning. The individual volume of each tree was estimated through a function fitted for young radiata pine trees within the central-south zone of Chile used by Albaugh et al. (2015), Equation (3):

$$V_i = -\,0.00214 + 0.0000295 * d_i^2 + 0.001349 * h_i + 0.00002486 * d_i^2 * h_i \quad (3)$$

Where:

V_i is the volume of the i^{th} tree ($m^3\ tree^{-1}$)

d_i is the diameter of the i^{th} tree (cm)

h_i is the height of the i^{th} tree (cm)

Individual tree volumes were summed to obtain volume per plot and then scaled at the hectare level. Periodic volume growth (IVG) was calculated by subtracting the estimated volumes between measurement periods (2007-2008).

Climate information

Daily precipitation and temperature values were obtained from meteorological weather stations located less than 25 km from each site, belonging to the Chilean Institute of Agricultural Research and the Forestal Arauco S.A. Company. Monthly averages of air temperature and precipitation were calculated as the average of all stations within 25 km weighted by the inverse of their distance to the site location. Annual precipitation (AP) was calculated from the total sum of the monthly precipitation (August-July). For the estimation of reference evapotranspiration of the sites, the method described by Hargreaves and Samani (1985) was used. Annual water deficit (WD) was calculated as the sum of the monthly deficits (when Evapotranspiration is greater than Annual precipitation for the study period (Equation 4)).

$$WD = \sum_{i=1}^{n} (PP_i - ET_{0i}), \qquad \text{when } |ET_{0i}| > |PP_i|, \tag{4}$$

Where:

WD is the water deficit during the year (mm·year^{-1})

PP_i is the precipitation of the ith month (mm·month^{-1})

ET_{0i} is the evapotranspiration of the ith month (mm·month^{-1})

Soil water holding capacity

Soil water holding capacity (WSC) was estimated through soil pits and soil sampling at each study site. Soil profile was evaluated up to 2 m depth on each plot. For each horizon soil thickness was recorded and 400 g samples were obtained for laboratory determination of permanent wilting point (PWP) and field capacity (FC) to estimate soil water retention capacity (Richards, 1941). Percentage of stones of each soil horizon was estimated using the point-count method described by Daniels et al. (1968). The soil water holding capacity was defined in Equation 5 as:

$$WSC = \sum_{i=0}^{n} (FC_i - PWP_i) * (D_i * (1 - S_i)), \quad (5)$$

Where:

WSC is the soil water holding capacity (mm)

FC_i is the soil water retention capacity at 0.33 bar of the i^{th} horizon (%)

PWP_i is the soil water retention capacity at 15 bar of the i^{th} horizon (%)

D_i is the soil depth of the i^{th} horizon (mm)

S_i is the volumetric proportion of stones of the i^{th} horizon (%)

Water deficit index

Water deficit index (WDI) was estimated as the difference between water deficit and soil water holding capacity (Equation 6):

$$WDI = WD - WSC, \quad (6)$$

Where:

WDI is the water deficit index during the year ($mm \cdot year^{-1}$)

WD is the water deficit during the year ($mm \cdot year^{-1}$)

WSC is the soil water holding capacity (mm)

Despite of the lower within site rainfall variation between the four replicates, water storage capacity was calculated using intensive soil sampling within each plot, resulting in a gradient of water deficit index within site.

Statistical analysis

We adjusted a nonlinear mixed effects model using maximum likelihood for the estimation of leaf biomass of individual trees from diameter at breast height (Equation 2), depending on the study site (Table 2).

Table 2 Parameters of the nonlinear model of mixed effects adjusted for maximum likelihood to predict leaf biomass of radiata pine.

Fixed effects					
Parameter	*Value*	*Standard error*	*Degrees of freedom*	*t-value*	*p-value*
α	0.0075	0.0025	44	3.0470	0.0039
β	2.6328	0.1289	44	20.4229	<0.0001
Random effects					
Parameter	*Site P800*	*Site P1100*	*Site P1500*	*Site P1700*	*Site P1750*
b_j	-0.1674	0.0898	0.0460	0.0640	-0.0325

Akaike information criterion	*Bayesian information criterion*	*log-likelihood value*	*N*
171.3124	178.9605	-81.6562	50

We performed analysis of variance (ANOVA) and multiple comparison test (Tukey) to evaluate differences between sites in LAI, water variables (WDI, WD and AP) and incremental growth post-thinning variables (IVG, IDG and IHG). We adjusted simple linear regression models using IVG as the dependent variable and water variables (WDI, WD and AP) and LAI as independent variables. In addition, we ran regressions using LAI as the dependent variable and water variables (WDI, WD and AP) as independent variables. The assumptions of the ANOVAS were checked by graphic analysis (independence), Barlett test (homoscedasticity) and Shapiro-Wilk test (normality). Adjusted regression models were diagnosed through graphical and analytical analysis, verifying the assumptions of linearity (graphic analysis), normality (Kolmogorov-Smirnov test), homoscedasticity (Breusch-Pagan test) and residual independence (Durbin-Watson test). Results are reported as significant where $p < 0.05$. All analyses were carried out using R software version 3.0.1 (R Core Team 2014).

The relationships between the annual average temperature versus the growth and the leaf area were also explored, but their correlations presented values of r^2 less than the water deficit, therefore the water deficit presented a greater force in the determination of the response variable (IVG and LAI).

RESULTS

Effect of water availability on leaf area

At the age of six years, the average LAI was 1.9 m^2 m^{-2}, with a range of 0.6 to 3.1 m^2 m^{-2} (Figure 2). The significant differences between sites are presented in Table 3. The LAI was larger at sites *P1500* and *P1750* being 3.3 and 3.7 times greater than *P800* site respectively. The AP varied between 972 and 1624 mm $year^{-1}$ across the study sites. This was associated with a range of 70 and -751 mm $year^{-1}$ for the WDI and 285 and -809 mm $year^{-1}$ for the WD (Table 3). The site with the most severe water limitation was *P800* site, showing the lowest AP and the most negative values for WD and WDI from all the sites. The LAI had a positive linear relationship with AP, the WD and WDI (Figure 2), showing the strongest correlation with the WDI (r=0.91), followed by the WD (r=88) and finally with AP (r=0.64). Adjusted regression models between LAI and water variables (Table 4) were highly significant (p<0.003); 83%, 77% and 41% of the variation in LAI could be predicted with WDI, WD and AP, respectively.

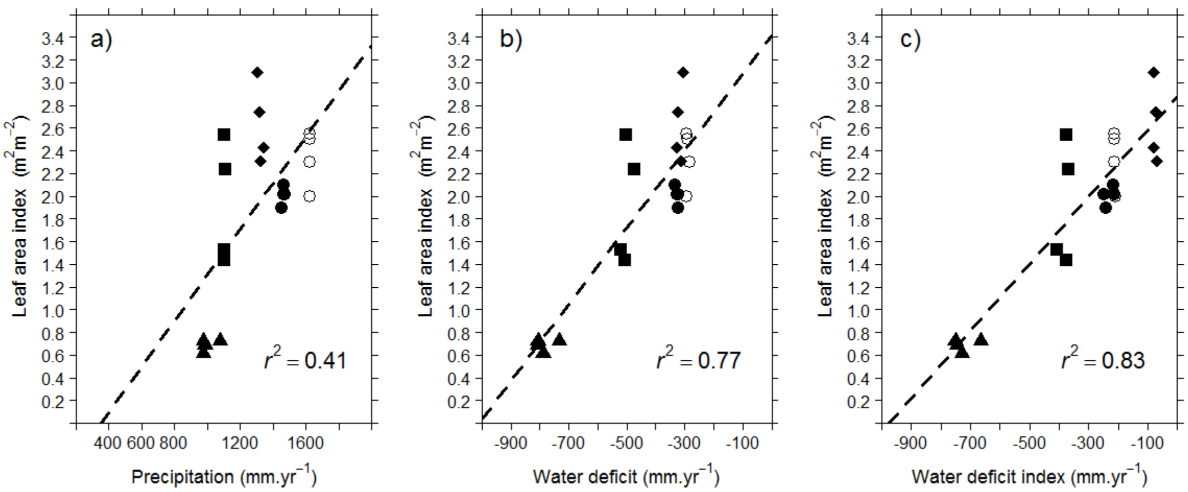

Figure 2. Relationship between leaf area index and precipitation (a), water deficit (b) and water deficit index (c) for sites *P800* (filled triangle), *P1100* (filled square), *P1500* (open circles), *P1700* (filled circles) and *P1750* (filled diamond).

Effect of water availability on growth

The IVG varied between 12.5 and 25.4 m^3 ha^{-1} (Figure 3) and the volume and diameter growth varied significantly among sites (Table 3). The highest volume and diameter growth was observed at the *P1500* site, which showed 86% and 67% greater growth in volume and diameter respectively than the site with lowest growth (*P800*). A positive linear relation was found between IVG and WDI, WD and AP (Figure 3). The best correlation was with WD (r=0.89), then with WDI (r=0.83) and finally with AP (r=0.78). Adjusted regression models between IVG and water variables (Table 3) were highly significant (p<0.001) and 69%, 78% and 60% of the variation in IVG could be explained by WDI, WD and AP, respectively.

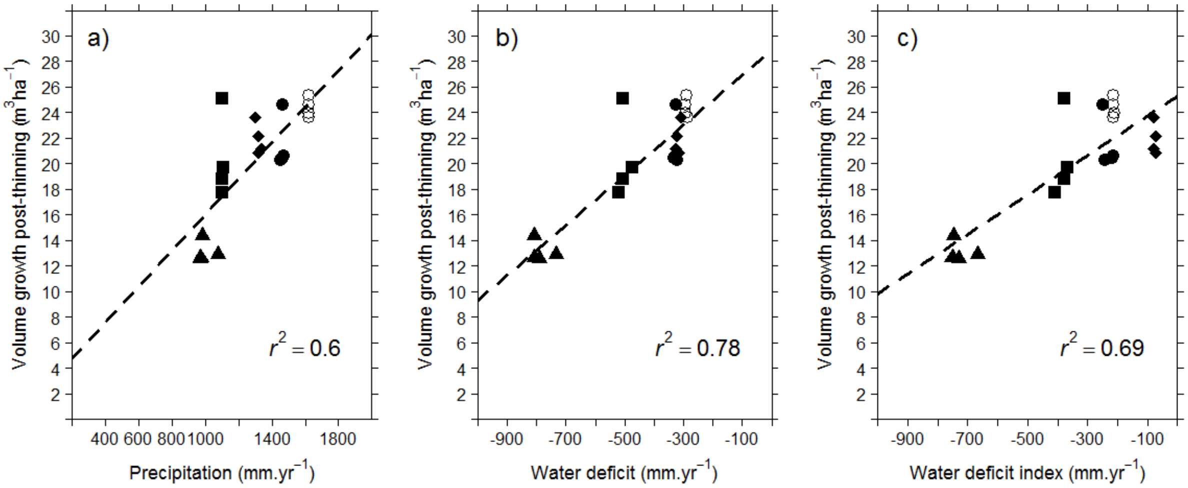

Figure 3. Relationship between incremental volume growth one year post thinning and precipitation (a), water deficit (b) and water deficit index (c) for sites *P800* (filled triangles), *P1100* (filled squares), *P1500* (open circles), *P1700* (filled circles) and *P1750* (filled diamonds).

Table 3 Averages of leaf area index (LAI), water deficit index (WDI), water deficit (WD), annual precipitation (AP), volume growth (IVG), diameter growth (IDG) and height growth (IHG) for study sites.

Site	**LAI** (m^2 m^{-2})	**WDI** (mm yr^{-1})	**WD** (mm yr^{-1})	**AP** (mm yr^{-1})	**IVG** (m^3 ha^{-1})	**IDG** (cm)	**IHG** (m)
mean							
P800	0.7 *c*	-723 *d*	-784 *c*	1002 *e*	13.1 *b*	1.5 *c*	1.5 *a*
P1100	1.9 *b*	-382 *c*	-501 *b*	1103 *d*	20.3 *a*	1.9 *bc*	1.4 *a*
P1500	2.3 *ab*	-212 *b*	-290 *a*	1623 *a*	24.4 *a*	2.5 *a*	1.4 *a*
P1700	2.0 *ab*	-231 *b*	-326 *a*	1462 *b*	21.5 *a*	2.0 *b*	1.3 *a*
P1750	2.6 *a*	-75 *a*	-316 *a*	1322 *c*	22.0 *a*	2.2 *ab*	1.6 *a*
Standard errors							
P800	*0.03*	*19.76*	*17.56*	*25.03*	*0.41*	*0.08*	*0.08*
P1100	*0.27*	*8.75*	*9.33*	*1.53*	*1.63*	*0.11*	*0.01*
P1500	*0.13*	*0.60*	*2.19*	*0.59*	*0.39*	*0.14*	*0.05*
P1700	*0.04*	*9.14*	*2.17*	*4.16*	*1.05*	*0.08*	*0.10*
P1750	*0.17*	*2.59*	*4.41*	*7.24*	*0.61*	*0.05*	*0.04*

---n=4; *--- Different letters indicate significant differences (p<0.05) between sites.*

Effect of leaf area on growth

A positive and strong (r=0.9) linear relation was found between IVG and LAI (Figure 4). The adjusted regression model between IVG and LAI (Table 4) proved to be highly significant ($p<0.001$) and in addition showed that 81% of the variation in IVG can be explained by LAI. For the range of sites studied, a growth efficiency (slope of regression line) of 5 m^3 ha^{-1} per LAI unit was found.

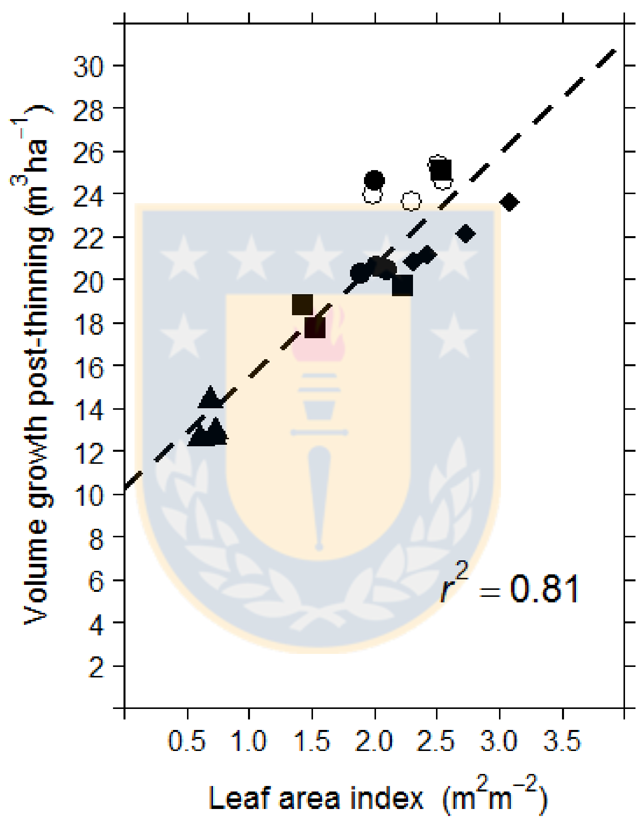

Figure 4. Relationship between leaf area index and incremental volume growth one year post thinning for sites *P800* (filled triangles), *P1100* (filled squares), *P1500* (open circles), *P1700* (filled circles) and *P1750* (filled diamonds).

Table 4 Linear regression models between leaf area index (LAI), volume growth (IVG) and water deficit index (WDI), water deficit (WD) and precipitation (AP) in the studied sites.

Model	b_0		b_1		Residual standard error	R-squared	p-value
$IVG = b_0 + b_1 * WDI$	25.2894	*	0.0155	*	2.42	0.69	<0.001
$IVG = b_0 + b_1 * WD$	28.9730	*	0.0197	*	2.03	0.78	<0.001
$IVG = b_0 + b_1 * AP$	1.9264		0.0141	*	2.76	0.60	<0.001
$IVG = b_0 + b_1 * LAI$	10.2873	*	5.1907	*	1.90	0.81	<0.001
$LAI = b_0 + b_1 * WDI$	2.8767	*	0.0029	*	0.31	0.83	<0.001
$LAI = b_0 + b_1 * WD$	3.4210	*	0.0034	*	0.36	0.77	<0.001
$LAI = b_0 + b_1 * AP$	-0.7139		0.0020	*	0.58	0.41	<0.003

**significance level of the parameter ($p<0.05$)*

DISCUSSION

Effect of water availability on leaf area

In this study, LAI direct measured through destructive sampling were made because LAI estimates based on indirect methods can significantly underestimate LAI values. Mason et al. (2012) showed that LAI-2000 underestimated LAI in radiata pine by 60% for low LAI values, and between 30% and 45% for high LAI values (depending on stocking). Furthermore, they showed that directly measured LAI was less well correlated with LAI estimates from hemispherical images. Breda (2003) also showed that methods based on hemispherical photographs can also suffer from similar underestimation.

Using the strong gradient in soil moisture deficit across sites we have shown strong relationships between soil water deficit, LAI and volume increment. Our study confirms previous findings about a positive linear relationship between water availability (WDI, WD and AP) and LAI (e.g. Grier and Running 1977; Gholz 1982; Battaglia et al. 1998). However, our contribution relies on the simplification of these relationships using a water index that integrates the effects of rainfall, potential evaporation and available soil water. Alvarez et al.

(2012) also used a water index which differs from our WDI because our index gives a greater weight to the lack of water at the site (water deficit).

In our study, correlations between WDI or AP with LAI in radiata pine were greater than those reported by Alvarez et al. (2012) in unthinned stands. We attributed these differences to our lower range of stockings, our smaller climatic annual variability, and the use of destructive sampling to measure LAI to have a greater accuracy in the estimation instead of using indirect measurements (e.g. LI-COR LAI-2000 or remote sensing). Our observation that an increase in leaf area occurs at sites with little or no water limitations is also supported by the Biology of Forest Growth (BFG) study in Australia. The BFG study, investigating radiata pine under irrigation, showed substantial increases in needle size, and number of needles, and branch growth, which increased stand LAI (Linder et al. 1987; Benson et al. 1992).

Silvicultural treatments can also affect this relationship. For example, Rubilar et al. (2013a) reported that LAI increased when weeds were controlled, increasing water availability of the site. In this regard, it is possible that the WDI could act as a surrogate of water competition index accommodating weed competition as well as nitrogen uptake. Variation in water availability is only one of the potential site effects on the leaf area index. LAI can also be affected by nutrition (Linder et al. 1987, Cannell 1989, Raison et al. 1992, Albaugh et al. 1998), light (Gholz 1982), air pollution (Stow et al. 1992) and temperature (Gholz 1986).

The LAI range observed in this study (0.6 - 3.1 m^2 $m-^2$) is similar to the range reported by Rubilar et al. (2013a) (0.51 - 3.13 m^2 $m-^2$), who also estimated LAI through destructive samples, in 4-year old radiata pine on contrasting sites in Chile. Alvarez et al. (2012) reported LAI values between 1.2 and 3.7 m^2 m^{-2} using remote sensing techniques in 11-year-old unthinned radiata pine plantations with an environmental range of sites similar to our study but the upper limit of their observations was slightly greater than those found in this study. This small difference between the values in our study and those of Alvarez et al. (2012) could be due to sampling age, effect of thinning, or method of LAI estimation.

Effect of water availability on growth

The level of water stress at any given site, indicated by the WDI, also showed a strong linear and positive relation with IVG. This effect compares well with the one reported by many authors (Jackson and Gifford 1974; Cromer at al. 1983; Hunter and Gibson 1984; Raison and Myers 1992; Benson at al. 1992; Alvarez et al. 2012).

In Chile, Flores and Allen (2004) using the 3-PG-process based model, evaluated the factors limiting the potential productivity of radiata pine, they also found that the most limiting factor across sites was mean annual rainfall, which is highly consistent with the results of our study. Similar to LAI, IVG showed a stronger relationship with WD or WDI compared to AP models. Nevertheless, the use of AP, a simpler predictor variable as an indirect measure of site water availability, may be highly valuable for developing a model explaining stand growth after thinning across a broad gradient of sites with limited soil information.

Site productivity relationships between IVG and either WDI or AP in our study were stronger than those found by Alvarez et al. (2012) or Gerding and Schlatter (1995) who observed significant relationships between AP and stand site index. Higher correlations observed in this study may be attributed to the use of annual information about both growth and water availability. Highest IVG values were observed in southern and coastal-southern sites, where greater water availability levels were found. This is consistent with Alvarez et al. (2012) and Flores and Allen (2004).

Lack of rainfall during summer in Chile (Mediterranean climate) results in severe water limitations for tree growth even on wetter sites, this is especially relevant in northern regions where radiata pine is planted. Greater growth values for radiata pine can be found in stands located in the foothills of the Andes and the southern coast where water deficit value is low.

Both WD and WDI take into account the annual seasonal water availability (rainfall and evapotranspiration) allowing a better understanding of growth differences between radiata pine plantations growing at sites with contrasting water regimes such as Chile, South Africa, Australia and New Zealand. Although an index that takes into account leaf area considering seasonal transpiration could be more precise, the greater inference is given by the large water differences between sites, which allows us to explore that the WDI could be considered independent of the leaf area. Our intention is to use a simple index that would allow practitioners in forest biometrics to add water balance components in an easy way to serve as an applied tool by being a proxy from the current water balance. Therefore, given the wide water gradient between sites, our water deficit index proxy for a more complete water balance sufficed the purpose.

Undoubtedly, other factors will affect the LAI or growth response. In addition to water stress, other authors (Jackson and Gifford 1974; Hunter and Gibson 1984; Gerding and Schlatter 1995; Watt et al. 2010; Alvarez et al. 2012) have concluded that the variability found in growth is also influenced by other climate variables, such as maximum average growing season temperature and vapor pressure deficit, but also by soil variables such as organic soil carbon, organic matter, and water soil water holding capacity. Mean annual temperature, closely related to vapor pressure deficit, strongly influences evapotranspiration in Chile and both variables decrease with latitude contrasting with precipitation, which increases with latitude. Given the above, it can be argued concordance with the exposed by Alvarez et al. (2012), who suggested temperature and vapor pressure deficit as the variables that mostly explain the growth of radiata pine plantations in Chile, also mean annual rainfall can be considered as a strong predictor alone.

Effect of leaf area on growth

The strong linear relationship between LAI and IVG is consistent with the observation that both LAI and IVG are well correlated with water availability. Interestingly, although stands in this study were thinned at or near canopy closure decreasing their maximum leaf area and our study only consider records for one single growing period, the observed relationship is similar to unthinned radiata pine stands reported in Australia, New Zealand and Chile (Linder et al. 1987; Beets and Pollock 1987; Raison and Myers 1992; Alvarez et al. 2012; Rubilar et al. 2013a) and also for unthinned *Pinus taeda* L. (Albaugh et al. 1998).

The adjusted regression model to estimate IVG from LAI (Table 3) showed a good fit (r^2=0.81) similar to that reported by Rubilar et al. (2013a) (r^2>0.8) and above the one shown by Alvarez et al. (2012) (r^2=0.46). However, it should be noted that for a Mediterranean climate and within the water gradient of sites presented in this research, the leaf area is directly related to water stress.

Similar relationships have also been shown in the literature by process-based models considering the impact of site water availability on leaf area production and its efficiency in growth. It should be noted that the leaf area could not only be affected by the water condition of the site, but also by other variables such as soil characteristics (nutritional, extreme textures) or other climatic variables (vapor pressure deficit, temperature), and biotic agents.

The slope of the linear relationship between LAI and IVG, growth efficiency, represents the efficiency of captured light and its conversion into annual stand growth (current annual increment or CAI) per unit of leaf area. Results of our study show a slope of 5.2 m^3 ha^{-1} per unit of LAI, which is within the range reported by Rubilar et al. (2013a) for younger unthinned stands and under the mean value reported by Alvarez et al. (2012) for older unthinned stands showing larger growth rates. Changes in the slope between LAI and CAI indicate differences in growth efficiency (GE) among stands. Increases in water and nutrient availability have shown increases in GE for radiata pine (Linder et al., 1987, Raison and Myers, 1992). Rubilar et al. (2013a) presented large differences in GE in radiata pine between low fertility dry sands and medium fertility red clay sites sustaining similar leaf area levels for younger stands. Sites in our study did not show nutritional limitations or low fertilities that affect growing trees, although the water gradient of the sites could have an impact on nutrients uptake. However, and despite the large water gradient considered in our study, we were not able to observe differences in GE among stands.

Although the focus of the research was on the water gradient of the sites, it should be noted that the soil types affect the water availability, and hence leaf area and tree growth. Among the soil characteristics that can affect water availability and productivity, Gerding and Schlatter (1995) highlight the negative effect of sandy textures and high bulk density and the positive effect of a higher soil water holding capacity, higher total volume of pores and higher content of organic matter. The types of soil present in this study, varied from metamorphic to volcanic ashes, showing mostly clay soil texture, the biggest differences that could affect water availability between the sites, were related to the levels of organic matter, depth and soil water holding capacity. Metamorphic soils especially with low rainfall showed the lowest values of organic matter and soil water holding capacity, in addition the metamorphic soils showed to be the least deep, on the other hand, the soils of recent volcanic ash, showed the highest values of organic matter and soil water holding capacity.

Declines in spring-summer rainfall are expected in areas where radiata pine is planted due to climate change in Chile (Galindo and Samaniego 2010). Our results suggest that reductions in site water availability may be expected to cause reductions in leaf area of radiata pine plantations, which will cause significant productivity declines. A large challenge for foresters is to implement thinning regime and better genetic materials that may be more effective at utilizing water resources as the most limiting factor underpinning forest productivity.

CONCLUSIONS

Strong linear positive relationships among site water availability, leaf area and stand growth after thinning suggest that water availability plays an important role on predicting current productivity of radiata pine plantations across sites.

A simple and robust water index, which integrates the effects of rainfall, potential evapotranspiration and available soil water, is well correlated with leaf area and stand annual volume growth. This index allowing the construction of a simple predictive model that may support management decisions for radiata pine plantations.

The results of our study provide useful information for forest managers to estimate stand growth after thinning of radiata pine plantations under an expected climate change scenario with reductions in site water availability for radiata pine plantations in Chile.

Further research should be carried out to establish relationships between site water availability and growth responses to other plantation management activities such as stocking or pruning where the leaf area is also modified.

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EFFECT OF WATER AVAILABILITY ON EARLY GROWTH RESPONSE TO PRUNING OF RADIATA PINE PLANTATIONS IN SHORT TERM

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ABSTRACT

Radiata pine *(Pinus radiata* D. Don) is established in a wide range of soils and climatic conditions where water availability is one of the main factors that define the productivity of this Mediterranean species. Several studies have examined growth responses to pruning of radiata pine plantations, but there is a gap in knowledge about its effect with site water availability. This study evaluated the stand growth response of radiata pine to different levels of pruning intensity across a gradient of water availability. Treatments, evaluated in five sites, considered three pruning intensities, i.e. no pruning or control (*C*), light pruning (*LP*), and severe pruning (*SP*). For each site, water availability (water deficit index) and basal area, diameter and height annual growth were evaluated after pruning. One year after treatment application, growth response to pruning was related to the length of the remaining crown, leaf area index and water availability of the site. Water deficit affected leaf area, growth and foliage distribution within the crown. LP, where about 30% of the crown was removed, showed no growth losses. SP, where more than 50% the crown was removed, showed growth losses. Largest observed growth losses were at sites with the lowest water deficit. Our results showed that growth loss to pruning increases as the water deficit decreases and suggest that site water deficit should be strategically considered in forest management pruning treatments.

Keywords: Leaf area; *Pinus radiata*; Productivity; Pruning, Water deficit.

INTRODUCTION

Silviculture of radiata pine plantations has evolved from an initial situation characterized by the almost total absence of interventions, to the current reality, with the application of intensive forestry. The incorporation of intensive forestry practices, such as pruning and thinning in plantations are aimed to increase the commercial value of the forest by producing high quality timber (Gerding 1991; Mead 2013). Pruning allows that knots and defects related to branches are restricted to a central knotted core (Montagu et al. 2003) and the subsequent growth in diameter results in knot-free wood, thus increasing the value of harvested trees (Hevia et al. 2016).

The sudden elimination of live branches resulting from pruning can reduce growth (Alcorn et al. 2008). Therefore, management strategies seek to promote both amount of wood through increased growth and the quality of that wood by eliminating the live crown must weigh the positive impact of pruning on the quality of timber, against the negative effects of such pruning on growth (Amateis and Burkhart 2011).

The negative effect on the growth due to elimination of live branches has been well documented for many pine plantations, highlighting the existence of a certain level of crown reduction to which growth is little affected. This critical value varies according to the species (Pinkard and Beadle 1998). Several authors indicate the radiata pine growth can be affected only when around 30% of the crown is removed (Lückhoff 1949; Sutton and Crowe 1975; Lange et al. 1987).

Growth of height and diameter of trees can be affected by pruning, but the impact of pruning on diameter growth is considerably greater than the growth in height (Lückhoff 1949; Sutton and Crowe 1975; Neilsen and Pinkard 2003; Amateis and Burkhart 2011; Hevia et al. 2016).

The effect of pruning is often limited and temporary. Sutton and Crowe (1975) informed that an elimination of 20-35% of the live crown reduced the growth of radiata pine, though the response was only during one year after the pruning. Amateis and Bukhart (2011) also reported that one year after the pruning, *Pinus taeda* L. trees at ages of 3, 6 and 9 years restored the mass of their crowns and the growth resumed comparable to a control without pruning. Although the impact of this silvicultural intervention on tree growth may be limited and temporary, in the long-term growth reductions produced during a year after pruning can generate large differences between pruning treatments.

Radiata pine in Chile have been established in a variety of soils and climatic condition (Álvarez et al. 2012), which creates a great variation in productivity of the plantations (Flores and Allen 2004). In addition, the limited availability of resources in some sites can unchain changes in allometry (Gower et al. 1992; Albaugh et al. 1998; Guo and Gifford 2002; Rubilar et al. 2013a). Water stress strongly affects production and longevity of the foliage, photosynthesis, carbon fixation, and lately growth of radiata pine trees (Benecke 1980; Raison et al. 1992; Rubilar et al. 2013b). Rubilar et al. (2013a) established a linear relation between leaf area and stem growth in three radiata pine stands located in sites with different productivity and where the difference in growth of sites was determined mainly by water constraints. On the other hand, Álvarez et al. (2012) examined the factors that affect radiata pine growth in Chile, also including water availability (affected by rainfall, soil water retention capacity and potential evapotranspiration) seem to be the most limiting factor of leaf area and growth.

Most pruning prescriptions are empirical by nature and combine operational requirements, height/diameter ratios or volume responses to various treatments (Luckhoff 1967; Gerrand et al. 1997). This approach has the advantage of being directly evaluated for the current timber production and involves the collection of easily measuring response variables directly related to stem growth.

This approach has the advantage of being directly relevant to the current timber production and involves the collection of easily measuring the response variables directly related to stem growth. However, the responses of trees to pruning are not only influenced by species (Hevia et al. 2016), but also by the structure of the stand (Karani 1978) soil fertility, water availability and climatic factors (Saure 1987; Forrester et al. 2010; Forrester 2013). These variables can vary considerably spatially and temporarily between sites (Alvarez et al. 2012).

Given the above, it is not easy to develop empirical prescriptions, and these tend to be restricted in their application, given the need to conduct long-term experiments on a wide range of sites. To optimize the production of high quality timber through a range of site and environmental conditions, it is necessary to consider a series of variables at tree and site levels. A better ecophysiological understanding is also necessary to develop predictive models that allow optimizing the pruning regimen and can help in the decision-making process that consider the selection of sites, severity, frequency and timing of pruning, as well as considering the effects of climate and spatial variation of the site in forest productivity (Flores and Allen 2004).

Nowadays, there is no response model in growth to pruning management schemes that incorporate water variables of the site. Having this tool would allow projecting the result of initial stocking decisions according to water constraints that allow identifying specific crown removals schemes that minimize the possible growth reductions of the stand.

The following research is aimed to evaluate and model the effect of pruning intensity and water availability of the site on the growth of radiata pine in the short term.

MATERIALS AND METHODS

Study area

The study area is located between latitudes 35°S and 40°30´S in central and southern-central Chile, were five sites were selected (Fig. 1). These study sites cover a wide range of climates and soils with known differences in productivity (Table 1). Each of them is described according to its average annual rainfall (833 mm: *P800*; 1,078 mm: *P1100*; 1,492 mm: *P1500*; 1,683 mm: *P1700*; 1,733 mm: *P1750*). The initial stocking at the time of the plantation was 1,250 trees per hectare, established in 2000 or 2001. The stands were located on smooth hills with no signs of fungi and no drainage problems, nutritional deficits or insects, as well as pre-planting weed control and two years of banded weed control after planting. At the time when the stands were six and seven years old, they had a mean planting density of 1,109 trees per hectare and averaged eight m in height (Table 1) with no previous thinning or pruning.

Experimental design and treatments

To test the effect of pruning on radiata pine stand growth, at each site, a randomized complete block design with four replicates (blocks) was used. In each site, twelve plots were settled. Each treatment plot had a 0.36 ha (60 x 60 m) surface with an internal measuring plot of 0.09 ha (30 x 30 m) with 15 meters buffer at each side. To homogenize the initial stocking, plots were thinned to 800 trees per ha at six or seven years. This process, removed trees from all diameter classes leaving 72 trees in each treatment plot. The variation in forest stocking density among sites were minimize, by establishing four blocks grouped accordingly with its basal area, with three treatments each. Pruning treatments were randomly assigned to experimental units of each block. Treatments considered the following pruning intensities: no pruning - *C* - (control), light pruning - *LP* - (up to 2.1 m), severe pruning - *SP* - (up to 5.5 m). Each pruning treatment was performed in autumn (March-June) using shears and scales to access the upper whorls.

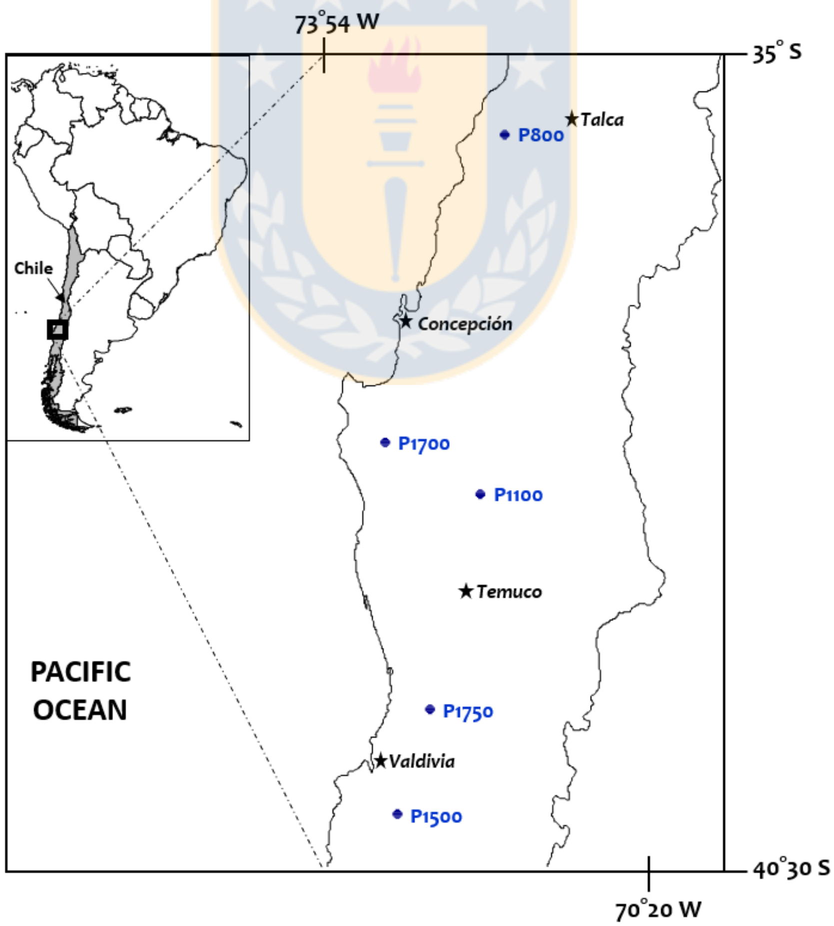

Fig. 1 Location of the study areas in central and southern-central Chile.

Table 1 Site and stand characteristics.

Site	*P800*	*P1100*	*P1500*	*P1700*	*P1750*
Latitude	35°29’39”S	37°58’48”S	40°12’2”S	37°37’6”S	39°28’22”S
Longitude	72°14’8”W	72°26’24”W	73°10’26”W	73°16’40”W	72°53’8”W
Annual mean temperature (°C)	13.2	12.0	10.5	11.1	11.4
Annual mean rainfall (mm)	833	1078	1492	1683	1733
Geology	metamorphic	old volcanic ash	old volcanic ash	metamorphic	recent volcanic ash
Soil taxonomy	Typical Rhodoxeralfs	Typical Paleudalfs	Typical Paleudults	Rhodic Paleudults	Typical Haplohumults
Texture	clay	clay	clay	clay	silt-loam
Organic matter (%)	1.2	3.9	6.8	4.2	11.1
pH	5.8	5.3	5.3	5.2	5.4
Before thinning					
Stocking (tree ha^{-1})	1200 *(28)*	1093 *(35)*	1156 *(29)*	1074 *(25)*	1022 *(49)*
Height (m)	7.9 *(0.4)*	8.2 *(0.5)*	7.9 *(0.4)*	8.3 *(0.4)*	7.8 *(0.6)*
Diameter (cm)	9.6 *(0.5)*	11.3 *(1.0)*	13.9 *(0.7)*	11.5 *(0.5)*	12.6 *(0.7)*
Basal area (m^2 ha^{-1})	9.6 *(0.7)*	12.4 *(1.7)*	17.9 *(1.4)*	14.5 *(0.8)*	14.2 *(1.2)*
Stand age (yr)	6	6	7	6	6
After thinning					
Stocking (tree ha^{-1})	800 *(0)*	800 *(0)*	800 *(0)*	800 *(0)*	800 *(0)*
Height (m)	8.7 *(0.2)*	9.5 *(0.3)*	7.9 *(0.2)*	8.6 *(0.2)*	8.3 *(0.4)*
Diameter (cm)	10.9 *(0.2)*	13.6 *(0.8)*	15.3 *(0.3)*	14.6 *(0.2)*	13.9 *(0.4)*
Basal area (m^2 ha^{-1})	7.7 *(0.3)*	11.9 *(1.3)*	15.0 *(0.7)*	13.6 *(0.3)*	12.6 *(0.7)*

standard error in brackets.
** mean value last 25 years.*

Tree foliage biomass

Foliage biomass (FB) was estimated on ten trees extracted on thinning, that represented the diameter distribution of each stand. The diameter at breast height (DBH) was measured per each selected tree, which were cut at ground level and then divided into stem, leaves and branches. In each felled tree, the diameter of the branches and distance from the crown were measured. To develop an allometric model based on branch diameter to estimate branch and foliage biomass, between 10 and 15 branches were selected per tree, and then used to cover the distribution range of branch diameters on felled trees. Foliage and branch tissues were separated for each sampled branch and dried at 70ºC to constant weight.

Using the following allometric model (1), the foliage biomass was calculated with a natural logarithmic regression between branch diameter and relative crown distance (Rubilar et al. 2010)

$$\ln(1000 * Y_i + 1) = a + b * \ln(BD_i + 1) + c * (RDFT^2_i + 1) + \varepsilon_i \quad (1)$$

Where:

Y_i is the foliage biomass (g) at the i^{th} branch,

BD_i is branch diameter in cm at the i^{th} branch,

$RDFT_i$ is the relative distance of insertion of the branch from the crown of the tree (0.0 - 1.0) at the i^{th} branch, and

ε_i is the error associated with the i^{th} branch.

Total foliage biomass of each individual tree was calculated as the sum of all branches. Finally, an allometric model was fit between individual tree foliage biomass and DBH and WDI of each site. The adjusted model (2) has the next expression:

$$fb_{ij} = b_0 * d_{ij}^{(b_1 + b_2 * WDI_j)} + \varepsilon_{ij}, \quad (2)$$

where:

fb_{ij} is the leaf biomass of the i^{th} tree in site j (kg),

b_0, b_1, b_2 are fixed parameters,

d_i is the diameter of the i^{th} tree in site j (cm),

WDI_j is the water deficit index ($mm \cdot year^{-1}$), and

ε_{ij} is the error of the model.

Foliar biomass distribution

A vertical distribution model (3) of foliage biomass was adjusted with foliage biomass estimates, branch diameters and branch insertion distances to the crown of each individual selected tree at each site. The model described the cumulative percent of foliar biomass from the base to the crown of each individual tree and allowed to compare the initial vertical distribution of foliar biomass among sites and the distribution of foliage biomass removed at each site after pruning at a given height. The final model has the form

$$Fbr_{ij} = 1 - (1 - Hr_i{}^{a_j})^{b_j} + \varepsilon_{ij}, \qquad (3)$$

Where:

Fbr_{ij} is the relative leaf biomass of the i^{th} tree in site j,

Hr_i is the relative height of the i^{th} tree, (branch insertion distance from the base/height tree)

a_j, b_j are the parameters of site j, and

ε_{ij} is the error of the model

Specific leaf area and leaf area index

Five trees were selected at each site and 20 fascicles samples were selected at random and removed from within each vertical third of the tree canopy. Samples were refrigerated at -1°C until final processing. Using an optical projection system leaf area was estimated (LI-COR LI-3100C area meter, Li-Cor, Lincoln, NE, USA). Sampled fascicles were oven-dried at 70°C until constant weight, and then, each specific leaf area was estimated by dividing the projected leaf area with dry weight. By multiplying specific leaf area and its total foliage dry weight it was estimated leaf area of each tree (1). Leaf area index (LAI) was estimated as the sum of leaf areas of all remaining trees after thinning divided by the total area of each treatment plot.

Growth measurements

Diameter (DBH) and height (Ht) in each tree per plot were measured immediately after thinning, during June 2007 and 2008. Live branches height (HSLB) was measured after pruning along with the length of the remaining crown (LRC), which was estimated by the difference between HSLB and total tree height. Live crown percentage was determined by dividing Ht and LRC. Height growth (HI) and diameter growth (DI) were calculated as the difference between initial measurements (after thinning) in comparison with their growth a year after. Using the following equation (4), used by Albaugh et al. (2015), the individual volume of each tree was estimated:

$$V_i = -0.00214 + 0.0000295 * d_i^2 + 0.001349 * h_i + 0.00002486 * d_i^2 * h_i \qquad (4)$$

where:

V_i is the volume of the i^{th} tree (m^3 $tree^{-1}$),

d_i is the diameter of the i^{th} tree (cm), and

h_i is the height of the i^{th} tree (cm).

Individual tree volumes were calculated, enabling us to obtain a volume estimation per plot per hectare. Subtracting the estimated volumes between measurement periods (2007-2008), periodic volume growth (VI) was calculated.

Climate information

Temperature and daily rainfall information were obtained from meteorological weather stations located less than 25 km from each site. Both air temperature and precipitation monthly average were calculated as the average of all stations within the next 25 km wide. Annual precipitation (AP) was calculated from the total sum of the monthly precipitation (August-July). The method described by Hargreaves and Samani (1985) was used to estimate the evapotranspiration amount per site. The Annual water deficit (WD) was calculated with the following equation (when evapotranspiration is greater than annual precipitation for the study period (5)):

$$WD = \sum_{i=1}^{n} (PP_i - ET_{0i}), \qquad \text{when} |ET_{0i}| > |PP_i|, \tag{5}$$

where:

WD is the annual water deficit ($mm \cdot year^{-1}$),

PP_i is the rainfall of the i^{th} month ($mm \cdot month^{-1}$)

ET_{0i} is the evapotranspiration of the i^{th} month ($mm \cdot month^{-1}$)

n is the number of months

Soil water holding capacity

Soil water holding capacity (WSC) was estimated through soil pits and soil sampling at each site. Soil profile was evaluated up to 2 m depth on each plot. For each horizon soil thickness was recorded and 400 g samples were obtained for laboratory determination of permanent wilting point (PWP) and field capacity (FC) to estimate soil water retention capacity (Richards, 1941). Percentage of stones of each soil horizon was estimated using the point-count method described by Daniels et al. (1968). The soil water holding capacity was defined in Equation 6 as:

$$WSC = \sum_{i=0}^{n} (FC_i - PWP_i) * (D_i * (1 - S_i)), \tag{6}$$

Where:

WSC is the soil water holding capacity (mm)

FC_i is the soil water retention capacity at 0.33 bar of the i^{th} horizon (%)

PWP_i is the soil water retention capacity at 15 bar of the i^{th} horizon (%)

D_i is the soil depth of the i^{th} horizon (mm)

S_i is the volumetric proportion of stones of the i^{th} horizon

n is the number of horizons

Water deficit index

Water deficit index (WDI) was estimated by discounting the WSC from WD (equation 7), Alvarez et al. (2012.)

$$WDI = WD - WSC, \quad (7)$$

Where:

WDI is the water deficit index during the year ($mm{\cdot}year^{-1}$)

WD is the water deficit during the year ($mm{\cdot}year^{-1}$)

WSC is the soil water holding capacity (mm)

Statistical analysis

Foliar biomass of individual trees was estimated using a nonlinear allometric model from DBH, depending on WDI per site. Distribution of foliar biomass through the vertical profile of the tree was estimated fitting a nonlinear model by each site. Analysis of variance (ANOVA) and multiple comparison test (Tukey) enable us to evaluate statistical differences among sites (WDI, FB, LAI) and pruning treatments (VI, DI and HI).

To assess the effects of LRC and LAI on the growth, non-linear models were fitted. Further adjusting were made using linear regression models based on the relationship of WDI as the dependent variable and VI, and LAI as independent variables. Nonlinear models were fit for estimation of incremental growth variables (DI and VI) depending on WDI and LCR together. The assumptions of the ANOVAS were checked by graphic analysis (independence), Barlett test (homoscedasticity), and Shapiro-Wilk test (normality). Adjusted regression models were diagnosed through graphical and analytical analysis. Results reporting as significant difference considered a p-value < 0.05. All analyses were made using R software version 3.0.1 (R Core Team 2014).

RESULTS

Leaf biomass (FB) and leaf area index (LAI)

Leaf biomass of the tress in the different sites varied between 3 and 10 kg tree^{-1} (Table 2), presenting average values of 9.6 kg tree^{-1} in most sites (exception of site *P800*). Trees from site *P800* showed one third of the leaf biomass of the remaining sites. The parameters of the model adjusted to study leaf biomass in function of DBH and WDI (Table 3) suggest an important effect of WDI in leaf biomass of the trees, where the trees of the site with the highest water deficit (site *P800*) presented lower amount of leaf biomass at equal tree diameter. On the other hand, trees from sites with lower water stress showed higher quantity of leaf biomass at equal diameter (Fig. 2a).

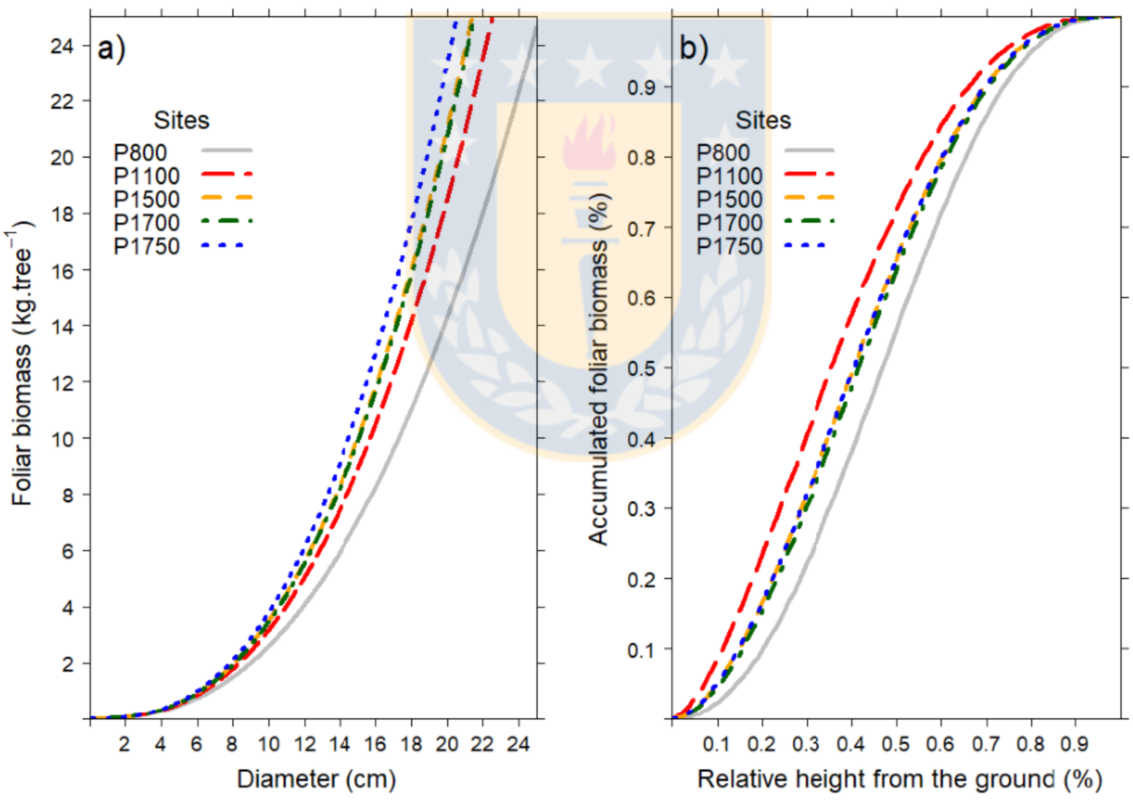

Fig. 2. Foliar biomass according to diameter (a) and vertical profile of leaf biomass (b) for each study site

Distribution of FB through the vertical profile of the tree in the different sites studied (Fig. 2b) showed that 50% of the FB was found in average at 40% of the height of the trees, though site

P800 corresponded to an extreme case where the trees presented half of their biomass at 48% of the height and for site *P1000*, half of its leaf biomass was at 46% of the height.

The average LAI before pruning treatment was 1.9 $m^2 m^{-2}$, with a range of 0.6 to 3.1 $m^2 m^{-2}$ (Fig. 4b). LAI was larger at *P1750* site and being 3.3 times greater than at *P800* site. LP treatments decreased their LAI from 20% to 35% and reduced the length of the live crown between 27% and 31%, growing with averages of live crown lengths of 6.2 m. On the other hand, HP treatments decreased their IAF from 57% to 89% and reduced the length of the live crown between 51% and 63%, growing with average lengths of live crown of 3.8 meters.

Table 2. Water deficit index (WDI), leaf biomass per tree (FB), leaf area index before pruning (LAI_0), leaf area index after pruning (LAI_1), height before pruning (Ht_0), length of the remaining crown after pruning (LRC), according to treatments: control-without pruning (*C*), light pruning (*LP*) and heavy pruning (*HP*) in the 5 sites studied.

Site	**WDI**	**FB**	***Control (C)***			***Light pruning (LP)***				***Heavy pruning (HP)***			
			LAI_0	Ht_0	LRC	LAI_0	LAI_1	Ht_0	LRC	LAI_0	LAI_1	Ht_0	LRC
	(mmyr-^{1})	kgtree^{-1}	$m^2 \cdot m^{-2}$	m	m	$m^2 \cdot m^{-2}$	$m^2 m^{-2}$	m	m	$m^2 \cdot m^{-2}$	$m^2 \cdot m^{-2}$	m	m
Mean													
P800	-723 c	3.1 b	0.7 c	8.7	8.2	0.8	0.6	8.9	6.4	0.7	0.3	8.7	4.0
P1100	-382 d	8.7 a	1.9 b	9.5	8.9	2.0	1.3	9.2	6.6	1.8	0.2	9.4	3.5
P1500	-212 ab	9.6 a	2.3 ab	7.9	7.2	2.3	1.6	8.3	5.9	2.3	0.4	8.7	3.3
P1700	-231 ab	10.1 a	2.0 ab	8.6	7.8	2.4	1.8	9.1	6.6	2.3	0.6	9.4	3.9
P1750	-75 a	9.9 a	2.6 a	8.3	7.7	2.4	1.6	8.1	5.6	2.3	0.7	8.5	4.2
Standard error													
P800	19.76	0.3	0.0	0.2	0.2	0.1	0.1	0.4	0.3	0.1	0.0	0.2	0.2
P1100	8.75	1.1	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.2	0.1
P1500	0.60	0.5	0.1	0.2	0.2	0.1	0.1	0.3	0.3	0.2	0.1	0.3	0.2
P1700	9.14	0.6	0.1	0.3	0.1	0.2	0.2	0.3	0.3	0.2	0.1	0.3	0.2
P1750	2.59	0.7	0.2	0.3	0.4	0.2	0.2	0.3	0.3	0.2	0.1	0.4	0.3

Table 3. a) Model adjusted to predict foliar biomass of radiata pine (FB) according to diameter (DBH) and water deficit index (WDI). b) General model adjusted to predict the relative leaf biomass of the tree (Fbr) according to relative height of the tree (Hr)

Model	Parameter of model		Residual standard error	Standard error model	Degrees of freedom
a) $FB = b_0 * DBH^{(b1+b2*WDI)}$	b_0	0.00925*	0.0045	1.575	47
	b_1	2.63306*	0.1719		
	b_2	0.00025*	8.2E-05		
b) $Fbr = 1-(1-Hr^{a})^{b}$	a	1.78503*	0.0470	0.086	726
	b	3.07342*	0.1428		

**significance level of the parameter* (*$p<0.05$*)

Growth response

C treatment showed average growths in volume, diameter and height of 20.3 $m^3 \cdot ha^{-1}$, 2.0 cm and 1.5 m respectively (Table 4). Site *P1500* presented the highest growths in *C* treatment, showing higher growth in volume and 24% higher in diameter than the average of sites. On the other hand, the smaller growths in volume and diameter of treatment *C* were presented in site *P800*, which showed 35% and 24% lower growth in volume and diameter respectively than the average of the sites.

LP treatment presented no significant differences in growth in volume, diameter and height respect to *C* treatment in most farms, except for site *P800*, where the *LP* treatment grew 16% more in volume than *C* treatment and in site *P1700*, where *LP* treatment grew 18% less in diameter, respectively than *C* treatment. *HP* treatment showed growths in volume and diameter that were significantly lower than treatments *C* and *LP* in all sites. Height growth of *HP* treatment was significantly lower than treatments *C* and *LP* only in sites *P1700* and *P1500* The height growth of the *HP* treatment was significantly lower than the *C* and *LP* treatments only at sites *P1700* and *P1500*.

Table N°4. Annual growth in volume (VI), diameter (DI) and height (HI) according to treatments; control-without pruning (*C*), light pruning (*LP*) and heavy pruning (*HP*) in the 5 sites studied.

Pruning Treatment		***Sites***									
		P1750		***P1500***		***P1700***		***P1100***		***P800***	
VI	***C***	22.0	a/AB	24.4	a/A	21.5	a/AB	20.3	a/B	13.1	b/C
	LP	21.1	a/AB	23.6	a/A	20.2	a/AB	17.9	a/BC	15.2	a/C
	HP	17.7	b/A	15.8	b/A	9.6	b/B	10.5	b/B	9.9	c/B
DI	***C***	2.2	a/AB	2.5	a/A	2.0	a/B	1.9	a/BC	1.5	a/C
	LP	2.1	a/A	2.3	a/A	1.6	b/B	1.7	a/B	1.6	a/B
	HP	1.5	b/A	1.2	b/AB	0.8	c/C	1.0	b/BC	1.2	b/ABC
HI	***C***	1.6	a/A	1.4	a/A	1.3	a/A	1.4	a/A	1.5	a/A
	LP	1.5	a/A	1.4	a/A	1.5	a/A	1.5	a/A	1.5	a/A
	HP	1.5	a/A	1.1	b/AB	0.9	b/B	1.1	a/AB	1.4	a/A
Standard error											
VI	***C***	0.61		0.39		1.05		1.63		0.41	
	LP	1.96		0.83		1.45		1.38		2.22	
	HP	0.88		2.33		1.86		0.97		0.69	
DI	***C***	0.05		0.14		0.08		0.11		0.08	
	LP	0.13		0.13		0.04		0.02		0.08	
	HP	0.08		0.18		0.12		0.04		0.04	
HI	***C***	0.04		0.05		0.1		0.01		0.08	
	LP	0.05		0.05		0.09		0.06		0.13	
	HP	0.07		0.07		0.12		0.15		0.12	

* Different lowercase letters indicate significant differences ($p<0.05$) within sites. (Tukey test)

** Different capital letters indicate significant differences ($p<0.05$) between sites. (Tukey test)

Effects of length of remaining crown and leaf area index on growth

A positive non-linear relation was found between the length of the live crown and growth (DI and HI). It is observed that as the remaining crown decreases the diameter and height of trees is reduced. The reduction of remaining crown affects to DI in a greater extent in comparison to HI (Fig. 3a and 3b).

Similar performance to the above was found between LAI and VI for the studied sites (Fig. 3c). The model constructed to explain the growth in volume in function of LAI (Table 5) shows a high growth rate in volume per leaf area unit for low values of LAI to then decrease the growth rate with higher LAI values at each site.

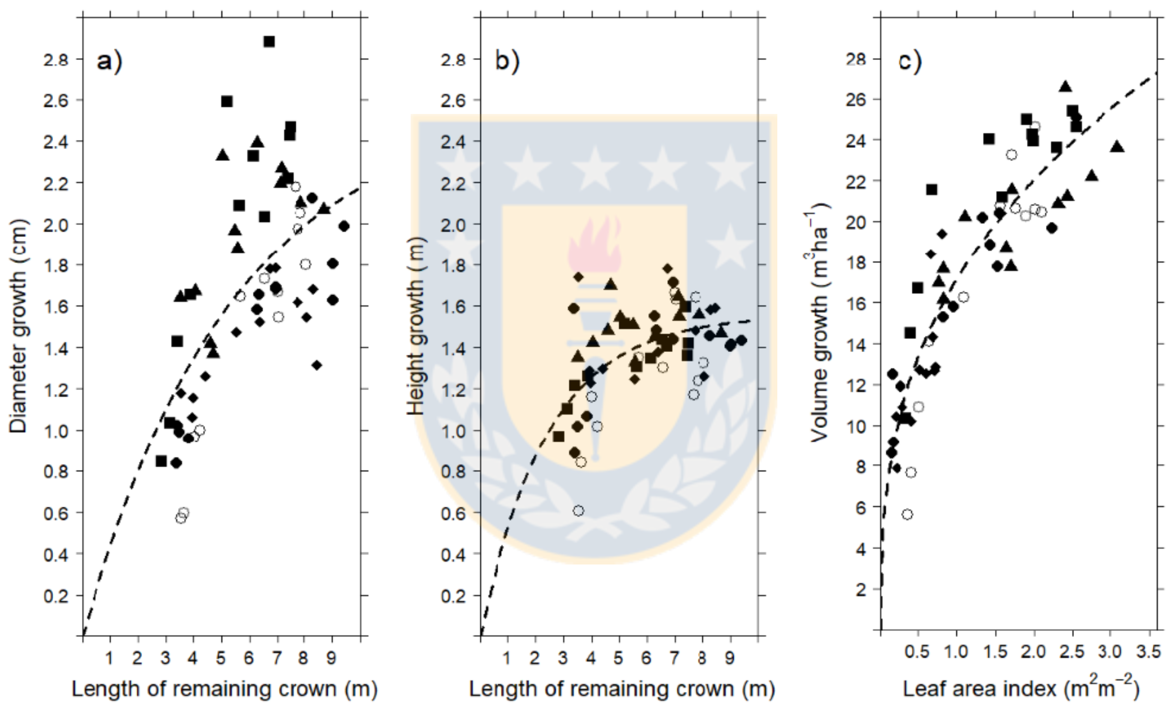

Fig. 3 Relations between incremental diameter growth and length of remaining crown (a), incremental height growth and length of remaining crown (b) and incremental volume growth and leaf area index (c) for *P800* (filled triangle), *P1100* (filled square), *P1500* (open circles), *P1700* (filled circles) and *P1750* (filled diamond) sites.

Table 5. Models adjusted to predict annual growth in diameter (DI) and height (HI) according to length of the remaining crown after pruning (LRC) and model adjusted to predict annual growth in volume (VI) according to leaf area index (LAI)

Model	Parameter of model		Residual standard error	Standard error model	Degrees of freedom
DI $=b_0 * (1 - exp(-b_1 * LRC))$	b_0	2.5770*	0.4008	0.3859	58
	b_1	0.1855*	0.0548		
HI $= b_0 * (1 - exp(-b_1 * LRC))$	b_0	1.5548*	0.0629	0.1969	58
	b_1	0.4124*	0.0637		
VI $=b_0 * LAI^{b1}$	b_0	17.1647*	0.3339	2.422	58
	b_1	0.3609*	0.0266		

**significance level of the parameter (p<0.05)*

Relation between water availability and LAI and Growth

WDI varied between -70 and -751 mm year^{-1} across the study sites. The site with the most severe water limitation was *P800* site where the WDI were more negative than at any of the other sites.

A positive linear relation was found between LAI and WDI (Fig. 4a) and between VI and WDI (Fig. 4b) for control plots. Adjusted regression models between VI and WDI, and LAI and WDI were highly significant (p<0.01).

Fig. 4 Relations between leaf area index and water deficit index (a) and incremental volume growth and water deficit index (b), for *P800* (filled triangle), *P1100* (filled square), *P1500* (open circles), *P1700* (filled circles) and *P1750* (filled diamond) sites.

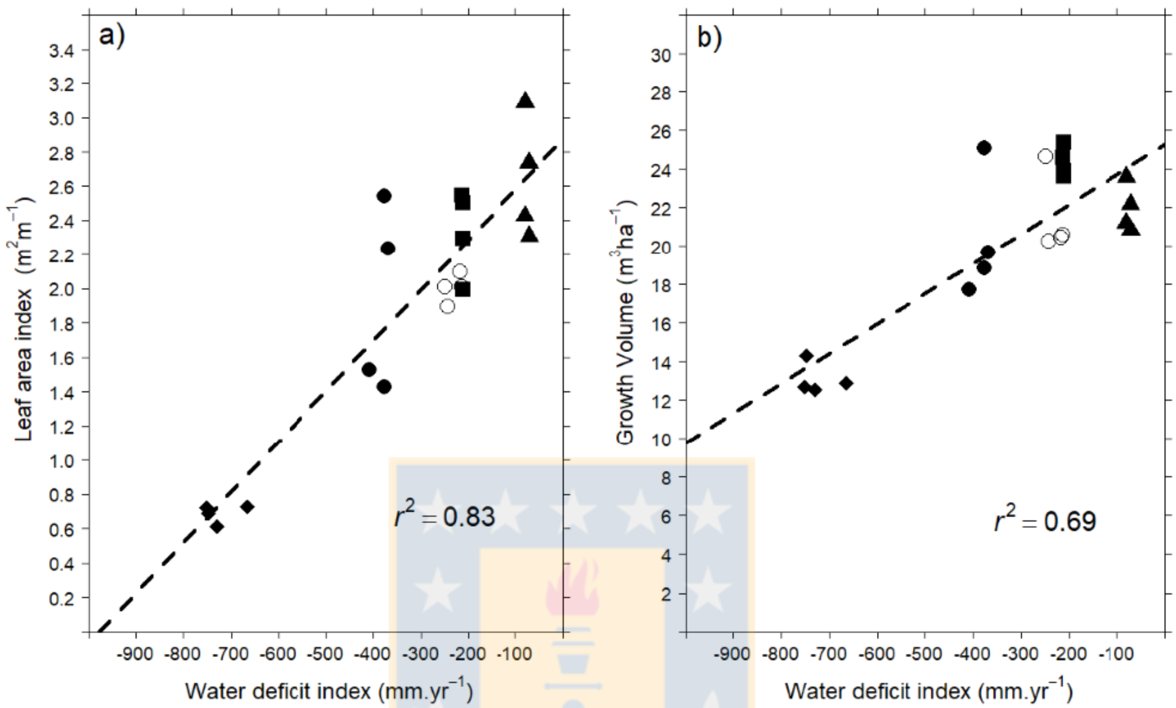

Table 6. Linear regression models for leaf area index (LAI) and IV with water deficit index (WDI) considering all study sites.

Model	Parameter of model		Residual standard error	Standard error model	Degrees of freedom	R-squared
*LAI=b₀+b₁*WDI*	b_0	2.8767*	0.1230	0.31	18	0.83
	b_1	0.0030*	0.0003			
VI=b₀+b₁ WDI*	*b0*	*25.2894**	*0.9568*	2.42	18	0.69
	b1	*0.0155**	*0.0024*			

**significance level of the parameter (p<0.05)*

Growth models based on remaining crown length and site water availability

Models adjusted for VI y DI based on LCR and WDI presented significant values in their parameters (Table 5), showing a strong effect in both LCR and WDI. For similar LCR, the highest growths were produced in sites with lowest water deficits (Fig 5). The model shows that for LCR between 5 to 7 meters, the average growth in volume and diameter was 3 m^3 ha^{-1} and 0.2 cm, respectively for each 200 mm decrease in WDI.

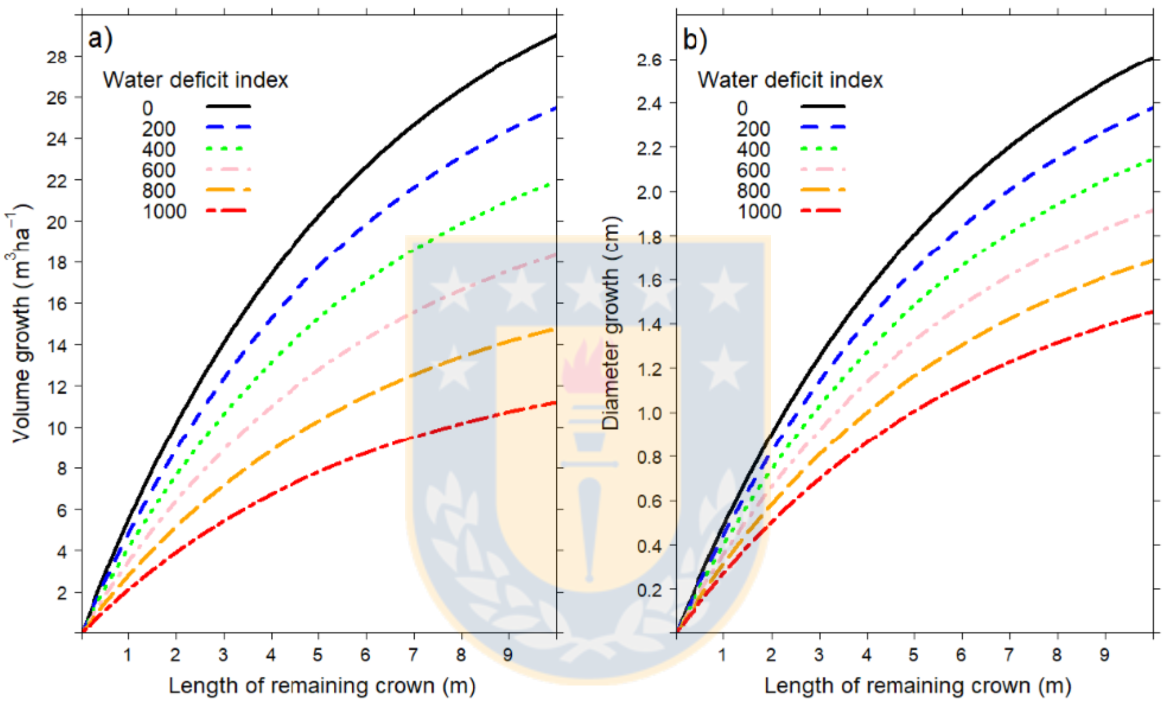

Fig. 5. Relations between incremental volume growth and length of remaining crown (a) and incremental diameter growth and length of remaining crown (b), according to water deficit index.

Table 7. Model adjusted to predict annual growth in volume (VI) and diameter (DI), according to water deficit index (WDI) and length of remaining crown (LRC)

Model	Parameter of model		Residual standard error	Standard error model	Degrees of freedom
$\boldsymbol{VI}=(b_0+b_1*WDI)*(1-\exp(-b_2*LRC))$	b_0	35.7467*	5.0007	3.0890	57
	b_1	0.0220*	0.0043		
	b_2	0.1672*	0.0402		
$\boldsymbol{DI}=(b_0+b_1*WDI)*(1-\exp(-b_2*LRC))$	b_0	3.2544*	0.5407	0.3345	57
	b_1	0.0014*	0.0004		
	b_2	0.1616*	0.0452		

**significance level of the parameter ($p<0.05$)*

DISCUSSION

Leaf biomass and leaf area index

A great number of authors conclude that water stress and high temperatures reduce the leaf area (Vose et al. 1994; Hebert and Jack 1998; Battaglia et al. 1998; Álvarez et al. 2012; Rubilar et al. 2013a). This is in accordance with results of this study, where site *P800*, affected by conditions of greater water deficit, higher temperature and lower rainfall shows the lowest values of leaf biomass and leaf area within the studied sites. In contrast, the sites that presented lower water deficits showed higher leaf biomass and leaf area values.

Despite that trees with lower leaf area were found in the site with highest water deficit (*P800*), the leaf biomass estimation model showed trees with greater diameter at equal amount of leaf biomass in this site, compared to the other studied sites. This may be because the site with greater water restriction could have had higher mortality of lower branches. Dickson and Isebrands (1991) and Sprugeld et al. (1991) suggest that if a branch produces an insufficient carbon balance to maintain itself, this branch dies.

The analysis of leaf biomass distribution through the vertical profile of the tree showed difference between sites. Site *P800* presented a higher proportion of leaf biomass in the highest part of the crown, compared to the other sites. This performance can be explained by the greater number of trees (stocking) before pruning. In this sense, some authors (Vose and Allen 1988; Long and Smith 1990, 1992) indicate distribution upward biases motivated by high stem density or fertilization, which could have influenced the shape of the tree crowns of the trees in this site. On the other hand, the rest of the sites were close to the closing of the crowns and therefore, the mild distribution bias towards the lowest part of the crown is in accordance with was presented by Schreuder and Swank (1974). These authors concluded that in forests before crown closure may skew the distribution of foliar biomass downward.

According to O'Hara (1991) and Alcorn et al. (2013), the foliage mass and the vertical leaf distribution influence the light interception and tree growth and may vary by site. This is relevant, since, differences in the growth response of trees subjected to a similar level of elimination of live crown (prescription of pruning with a fixed height) can be explained by factors such as the architecture of the crown.

Growth response

The growth of the trees, especially in volume and diameter in the different sites studied was mainly affected by water deficit, which is in accordance with various authors who conclude that water availability is one of the factors that affect the growth of radiata pine in Chile (Gerding and Schlatter 1995; Flores and Allen 2004; Álvarez et al. 2012; Rubilar et al. 2013a). Given the above, site *P800* showed lower growths (site most limited by water) and sites *P1750*, *P1500* and *P1700* presented the highest growths (sites less limited by water).

Regarding the differences in growth of basal area, diameter and height in relation to pruning, it was observed that in treatments with light pruning (*LP*), where an average of 29% of the length of the live crown and 27% of leaf area is removed, in general show no differences with situations without pruning. This is in accordance with results of various authors such as Lückhoff (1949) who indicated that growth of radiata pine was not affected by pruning when only 20 – 30% of live crown was removed. Sutton and Crowe (1975) indicate that this level is close to 35% of removal of the crown length that the percentage of living crown to be removed is limited to about 30% for this species.

A special performance occurred in *P800* site (site with the highest water deficit), where light pruning (*LP*) presented a significantly higher growth in volume compared to the control treatment *C*. This is in accordance with that explained by Pinkard and Beadle (2000), who point out that lower branches have a net carbon balance equal to zero for resources. Then, their removal could leave these resources for further growth of the stem. A similar situation was found by Stein (1955) when pruning 25% of the live crown of *Pseudotsuga menziesii* concludes that depending upon the density of the stand, the portion of the lower crown that receives little light, and falls below its light compensation point, is unproductive at best and has been hypothesized to be a drain on the resources of the tree. In this site there was less foliage removal due to having leaf biomass more biased up, compared to the other sites.

In heavy pruning (HP), where the removal reached 50% of the length of the live crown and 78% of the leaf area, differences in volume and diameter were observed in comparison with the control without pruning. This is in accordance with previous research (Lückhoff 1949; Sutton and Crowe 1975; Lange et al. 1987; Hevia et al. 2016), who point out that levels of removal over 35% of the length of the live crown affect the growth of trees. In the current research, the effect of pruning was higher on the growth in diameter than the growth in height and even a difference of growth in height between heavy pruning and treatments without pruning was not found in several of the evaluated sites. This is consistent with several authors who indicate that growth in height is less affected by pruning than growth in diameter (Sutton and Crowe 1975; Lange et al. 1987; Langstrom and Hellqvist 1991; Cannell 1994; Pinkard and Beadle 1998; Amateis and Burkhart 2011; Mead 2013; Hevia et al. 2016).

Effects of length of remaining crown and leaf area index on growth

The effect of pruning on the growth rate of the tree has been associated with the intensity of the treatment, especially considering the length of the remaining crown, because this is the part that contributes to the assimilation of carbon and therefore, the growth. The lower length of the remaining live crown has been frequently related to the lower growth of trees (O´Hara 1991; Montagu et al. 2003). The ratio between the lengths of the live crown after pruning and growth showed positive non-linear relations, like those presented by Hevia et al. (2016) and Neilsen and Pinkard (2003) for radiata pine, who stated that increased as the length of the live crown was greater up to a maximum length of the crown, above which the increase in diameter and height is not significantly affected, they emphasize that this length of the live crown is close to 8 meters of live crown, approximately a length similar that presented in this study.

Leaf area index also showed positive and non-linear relations with growth in volume. The performance of this relation was slightly different to that showed by Álvarez et al. (2012) and Rubilar et al. (2013a), who presented more linear relations between these variables. This difference in the performance of this relation may be because in our study many of the lower leaf areas were produced by heavy pruning and not all values of leaf area correspond to the water stress of the site. Therefore, results with lower leaf areas presented greater deficiency in growth per leaf area unit in comparison to results with greater leaf areas, since the crown remaining after pruning, located in the upper part of the crown presents greater photosynthetic rates than the crown located in the basal part of the tree (Forrester et al. 2012).

Relation between water availability and LAI and Growth

Using the strong gradient in soil moisture deficit across sites we have shown strong relationships between soil water deficit, LAI and volume increment. Our study confirms previous findings about a positive relationship between water availability (WDI, WD or AP) and LAI (e.g. Grier and Running 1977; Gholz 1982; Battaglia et al. 1998; Alvarez et al. 2012; Ojeda et al. 2018). Correlations between WDI and LAI in radiata pine were greater than those reported by Alvarez et al. (2012) in unthinned stands. We attribute these differences to our lower range of stockings, our smaller climatic annual variability and the use of destructive sampling to measure LAI instead of using indirect measurements (e.g. LI-COR LAI-2000 or remote sensing). The water status of the site, indicated by its WDI, also showed a strong linear and positive relationship with IV. This effect has been reported by many authors (Jackson and Gifford 1974; Cromer et al. 1983; Hunter and Gibson 1984; Raison and Myers 1992; Benson et al. 1992; Alvarez et al. 2012).

Growth Models based on length of remaining crown and water availability of the site

In general, the models that explain the response to pruning are based on empirical models, where stem growth and severity of pruning are related. Sometimes, they include some measurements of the crown size, such as the relation with the remaining length of the live crown (O´Hara 1991; Hevia et al. 2016). Therefore, it is improbable to estimate differences between sites.

In our study, WDI showed a strong relation with growth, confirming previous findings about a positive relation between these variables (Jackson and Gifford 1974; Cromer et al. 1983; Hunter and Gibson 1984; Raison and Myers 1992; Benson et al. 1992; Alvarez et al. 2012; Ojeda et al. 2018). The adjusted models show that the performance of growth (volume and diameter) in function of the remaining crown length varies between sites, depending on the WDI. Trees located on sites with the highest water deficit (lower quality) grew less per meter of the remaining live crown compared to sites with lower deficit (higher quality), showing a greater effect of pruning in sites with lower water deficit by reducing the length of the live crown.

There is very little information where the effect of pruning is compared according to water availability of the site for a species and the reported information is focused on evaluating the effect of pruning according to the fertility of the site. In this sense, the results show that the negative effect of pruning has been greater in lower quality sites than higher qualities sites (Pinkard and Beadle 1998; Pinkard 2002, 2003; Pinkard et al. 2007; Forrester, 2013). The water availability differences between our sites are much greater than fertility difference, therefore we can think that water resources in the site could influence a behavior distinct from the response. Given the above, the results of our study provide useful information for understand the effect of pruning in regions where there is a large water gradient where radiata pine is managed.

CONCLUSIONS

Water deficit not only affects productivity and growth of radiata pine plantations, but also foliar area, growth and distribution of foliage within the crown. Light pruning where about 30% of the live crown is removed show no growth losses. On the other hand, heavy pruning where about 50% of the live crown is removed show decreases in the radiata pine growth. The greatest growth losses due to heavy pruning where more than 50% of the crown is removed occurred in sites with lower water stress. Our results indicate a growth-loss gradient due to pruning as water deficit decreases. This study suggests that water deficit should be considered in the prescriptions of forest management such as pruning, especially areas where a wide water gradient is present.

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EFECTO DE LA INTENSIDAD DE PODA EN EL CRECIMIENTO DE LOS ÁRBOLES FINALES POSTERIOR A UN SEGUNDO RALEO EN UN GRADIENTE DE DISPONIBILIDAD HÍDRICA DE SITIOS

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Artículo en preparación.

RESUMEN

Este trabajo estudia la respuesta en crecimiento a largo plazo de árboles de pino radiata (*Pinus radiata* D. Don) podados a diferentes intensidades de poda (sin poda, poda leve y poda severa), con y sin árboles seguidores (árboles sin poda), con un raleo cuatro años después de la poda en un gradiente hídrico de sitios en la zona centro sur de Chile. Los sitios experimentales fueron monitoreados por ocho años desde el inicio de los tratamientos de poda. Los resultados indican que a medida que la disponibilidad de agua del sitio aumenta, la pérdida de crecimiento por efecto de la intensidad de poda es mayor. Además, se observó que el efecto de la poda especialmente de alta intensidad afecta el crecimiento en forma permanente, principalmente en sitios de menor déficit hídrico. La presencia de árboles seguidores mostró una tendencia de reducción en el crecimiento en volumen de los árboles finales (500 arb ha^{-1}). En general, los resultados obtenidos sugieren que la disponibilidad hídrica de los sitios es un factor clave que debería ser incorporado en la toma de decisiones de manejo sitio específica para las plantaciones de pino radiata en Chile.

INTRODUCCIÓN.

Dentro del manejo intensivo de plantaciones, la poda permite que los nudos y los defectos relacionados con las ramas se restrinjan a un núcleo nudoso central y el crecimiento subsecuente del diámetro produzca madera de mayor calidad dando un mayor valor al bosque (Montagu et al., 2003). La poda de ramas vivas para minimizar los defectos y producir madera libre de nudos es una actividad silvícola ampliamente practicada en plantaciones de pino radiata manejadas intensivamente (West 1998).

Para optimizar una mayor cantidad de madera libre de nudos, la poda se realiza a edades tempranas (Neilsen y Pinkard, 2003; Pinkard, 2003), combinándola con raleos para favorecer el crecimiento de los mejores árboles finales, para de esta manera aumentar la producción de madera de alta calidad (Forrester et al., 2010).

El costo de esta operación es alto, por lo tanto, se recomienda podar solo los árboles que serán seleccionados para la cosecha final (Neilsen y Pinkard, 2003). Estos árboles deberían presentar características específicas, como rectitud, tamaño de nudos pequeños y pertenecer al dosel superior del rodal (Neilsen y Pinkard, 2003; Hevia et al. 2016).

Es importante que los árboles podados mantengan su dominancia, por lo tanto, es necesario que la intensidad de poda no afecte el crecimiento normal de los árboles (Sutton y Crowe, 1975; Gerrand et al., 1997; Courdier et al., 2002; Alcorn et al., 2008). Si se dejan árboles vecinos dominantes y codominantes sin poda, éstos pueden suprimir el crecimiento de los árboles podados (Sutton y Crowe, 1975), impactando negativamente el volumen de madera de alta calidad en el rodal.

La respuesta de los árboles finales a la intensidad de poda y a los seguidores puede ser afectado por varios factores, entre otros por la especie, las características del sitio, el tiempo de ejecución y la interacción con otros tratamientos silvícolas (Sutton y Crowe, 1975; Montagu et al., 2003; Forrester et al., 2010; Forrester, 2013).

La mayoría de los estudios de poda muestran resultados locales, en un solo sitio y a corto plazo, sin tomar en cuenta las variaciones medioambientales, además de trabajar con parcelas pequeñas a nivel de árbol donde no se evalúa el comportamiento de los árboles finales en su conjunto, luego de manejos (raleos) posteriores a los tratamientos de poda.

Aunque existe investigación sobre el efecto de la intensidad de poda en el crecimiento, muy pocos estudios se han diseñado para probar el efecto a largo plazo de la intensidad de poda y el sitio, sobre los árboles objetivos (*croop-trees*) en rodales con árboles seguidores (árboles con ramas vivas).

El propósito de este trabajo es estudiar el efecto de diferentes intensidades de poda sobre el crecimiento de los árboles finales de pino radiata definidos para cosecha, luego de un raleo, en un rango hídrico de diferentes sitios.

Nuestra hipótesis plantea que la disminución del crecimiento de los árboles finales del rodal producto de podas intensas no es afectado por la aplicación de raleos posteriores y que este efecto está influenciado por las características hídricas del sitio.

MATERIAL Y METODO

Área de estudio

Se seleccionaron cuatro sitios en el centro-sur de Chile (Fig. 1) entre las latitudes 35 ° S y 40 ° 30 'S (originalmente eran cinco sitios pero uno de ellos no continuó con mediciones a largo plazo). Los sitios representan un gradiente de clima y suelos con diferencias conocidas en productividad (Tabla 1). Los sitios, se nombraron según la precipitación anual promedio dentro del periodo de 1980 a 2010 (833 mm: *P800*; 1,078 mm: *P1100*; 1,492 mm: *P1500*; 1,683 mm: *P1700*), fueron plantados con plantas de pino radiata a una densidad inicial de 1.250 árboles por hectárea durante los años 2000-2001. Los rodales no presentaron problemas de drenaje, como tampoco signos de daño por hongos, insectos o déficit nutricional. Los rodales tuvieron controles de malezas pre y post-plantación. Entre los seis y siete años de edad, los rodales tenían una densidad promedio de 1.109 árboles por hectárea y una altura promedio de 8 m (Tabla 1), sin raleos o podas previas.

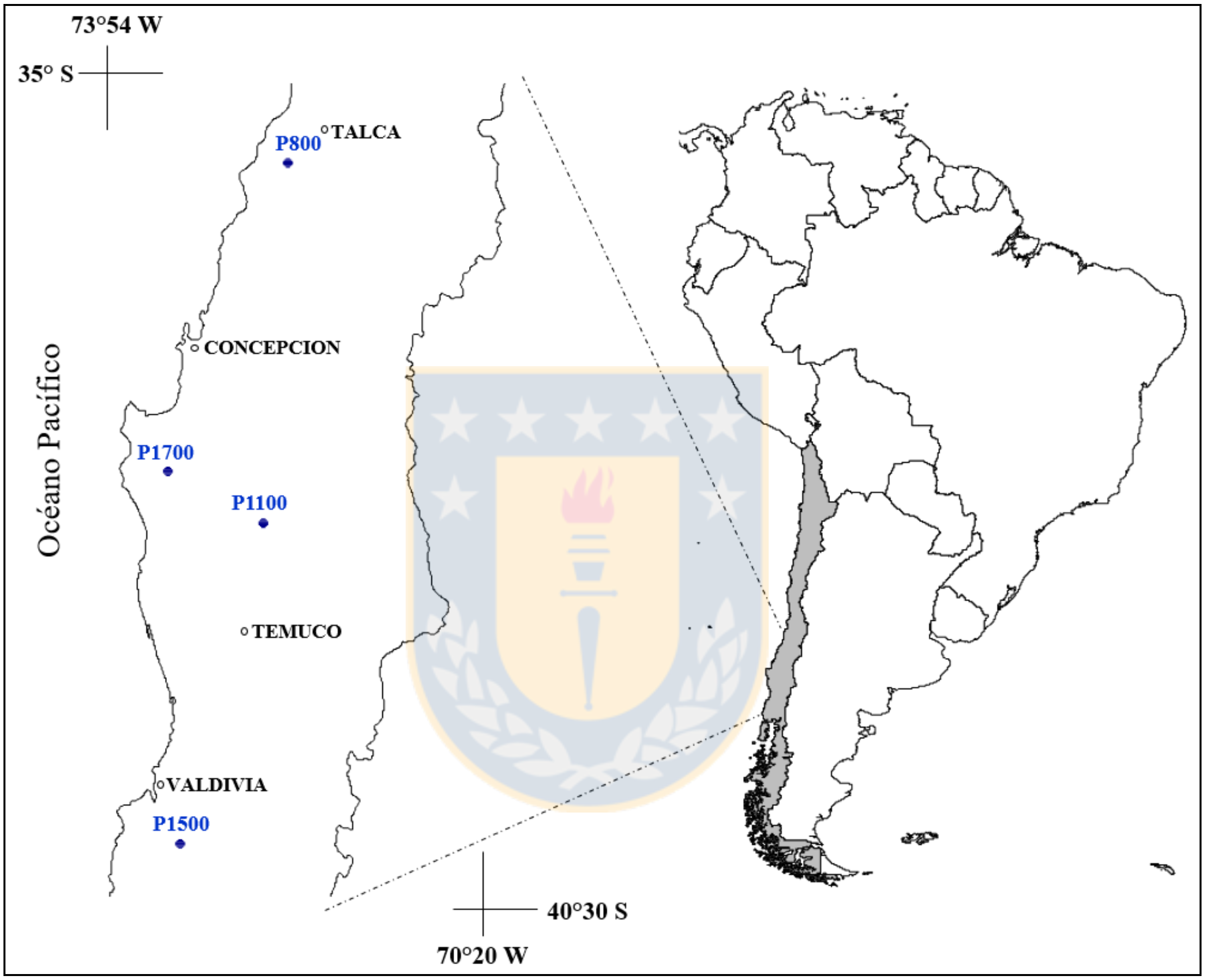

Figura 1. Ubicación de los sitios de estudio.

Diseño experimental y tratamientos.

En cada sitio se utilizó un diseño de bloques completos al azar con cuatro repeticiones (bloques) para evaluar el efecto de la poda y de los árboles seguidores en el crecimiento de pino radiata. Dentro de cada sitio, se localizaron 20 parcelas de 0,36 ha (60 x 60 m) cada una, con parcelas internas de medición de 0,09 ha (30 x 30 m) y una zona buffer de 15 metros en cada lado de las parcelas de medición. Para homogeneizar la densidad de plantación, se realizó un primer raleo, dejando las parcelas con 800 árboles por hectárea, a la edad de seis o siete años (2007), según el sitio (Tabla 1). Los árboles raleados correspondían a árboles con algún grado de defecto (torcido, bifurcado, quebrado o suprimido) de todas las clases de diámetro, dejando 72 árboles finales en cada parcela. Con el fin de minimizar la variación del área basal entre bloques, se formaron cuatro bloques de cinco parcelas con un área basal similar en cada sitio y aleatoriamente se asignaron los tratamientos a las unidades experimentales de cada bloque. Los tratamientos estudiados fueron:

SP100: El 100% de los árboles sin poda.

PL100: El 100% de los árboles con poda leve (poda a 2.1 metros de altura).

PL63: El 63% de los árboles con poda leve (poda a 2.1 metros de altura).

PS100: EL 100% de los árboles con poda severa (poda a 5.5 metros de altura)

PS63: El 63% de los árboles con poda severa (poda a 5.5 metros de altura).

La poda se llevó a cabo en otoño (marzo-junio 2007) utilizando tijeras de podar y escalas para acceder a los verticilos superiores en la poda más alta. Luego de cuatro años de realizadas las intervenciones de poda (2011), las parcelas fueron raleadas por segunda vez dejando una densidad final de plantación de 500 árboles por hectárea.

Tabla 1. Características de los sitios y rodales de estudio

Sitio	*P800*	*P1100*	*P1500*	*P1700*
Latitud	35°29'39"S	37°58'48"S	40°12'2"S	37°37'6"S
Longitud	72°14'8"W	72°26'24"W	73°10'26"W	73°16'40"W
Temperatura media anual (°C)	13,2	12,0	10,5	11,1
Precipitación media anual (mm)	833*	1078*	1492*	1683*
Geología	metamórfica	cenizas volcánicas antiguas	cenizas volcánicas antiguas	metamórfica
Taxonomía de suelo	Typical Rhodoxeralfs	Typical Paleudalfs	Typical Paleudults	Rhodic Paleudults
Textura	arcillosa	arcillosa	arcillosa	arcillosa
Materia orgánica (%)	1,2	3,9	6,8	4,2
pH	5,8	5,3	5,3	5,2
	Estado de los rodales antes del primer raleo			
Densidad (árbol ha^{-1})	1200 *(28)*	1093 *(35)*	1156 *(29)*	1074 *(25)*
Altura (m)	7,9 *(0,4)*	8,2 *(0,5)*	7,9 *(0,.4)*	8,3 *(0,4)*
Diámetro (cm)	9,6 *(0,5)*	11,3 *(1,0)*	13,9 *(0,.7)*	11,5 *(0,5)*
Área basal (m^2 ha^{-1})	9,6 *(0,7)*	12,4 *(1,7)*	17,9 *(1,4)*	14,5 *(0,8)*
Edad del rodal (años)	6	6	7	6
	Estado de los rodales después del primer raleo			
Densidad (árbol ha-1)	800 *(0)*	800 *(0)*	800 *(0)*	800 *(0)*
Altura (m)	8,7 *(0,2)*	9,5 *(0,3)*	7,9 *(0,2)*	8,6 *(0,2)*
Diámetro (cm)	10,9 *(0,2)*	13,6 *(0,8)*	15,3 *(0,3)*	14,6 *(0,2)*
Área basal (m^2 ha-1)	7,7 *(0,3)*	11,9 *(1,3)*	15,0 *(0,7)*	13,6 *(0,3)*

Error estándar en paréntesis.
* Valor promedio últimos 25 años

Mediciones de crecimiento

La altura (Ht) y el diámetro a la altura del pecho (DAP) de todos los árboles de cada parcela se midieron durante el mes de junio (otoño) en tres oportunidades: inmediatamente después de las intervenciones de poda (6-7 años), justo antes del segundo raleo (10-11 años) y luego de cuatro años posterior al segundo raleo (14-15 años). Se definieron dos periodos de evaluación de cuatro años cada uno. El primero fue desde el inicio del estudio (2007) hasta el momento del segundo raleo (2011), donde se analizó el crecimiento de todos los árboles (800 arb/ha) y los árboles elegidos para seguir hasta el final del estudio post-raleo (500 arb/ha). El segundo periodo de evaluación fue desde el segundo raleo hasta cuatro años posterior a este (2015), donde se analizó el crecimiento de los árboles residuales que quedaron hasta el final del estudio (500 arb/ha). El crecimiento del diámetro (DI) y el crecimiento en altura (HI) se calcularon como la diferencia entre los periodos de evaluación. El volumen individual de cada árbol se estimó utilizando una ecuación (1) ajustada para plantaciones de árboles jóvenes de pino radiata creciendo en diferentes sitios dentro de la zona centro-sur de Chile, utilizada por Albaugh et al. (2015).

$$V_i = - 0{,}00214 + 0{,}0000295 * d_i^2 + 0{,}001349 * h_i + 0{,}00002486 * d_i^2 * h_i \qquad (1)$$

dónde:

V_i es el volumen del i-ésimo árbol (m^3 $arbol^{-1}$),

d_i es el diámetro del i-ésimo árbol (cm), y

h_i es la altura del i-ésimo árbol (cm).

Para obtener estimaciones del volumen por parcela, se sumaron los volúmenes individuales de todos los árboles de la parcela, luego se escalaron a nivel de hectárea. De igual manera se realizaron las estimaciones de área basal, las cuales, primeramente, se estimaron a nivel de árbol, luego se sumaron a nivel de parcela, para luego escalarlo a nivel de hectárea. El crecimiento del volumen (VI) y del área basal (GI) se calcularon restando los volúmenes o áreas basales estimados entre períodos de medición.

Información climática

Los valores diarios de lluvia y temperatura se obtuvieron a partir de estaciones meteorológicas ubicadas a menos de 25 km de cada sitio. Los promedios mensuales de la temperatura del aire y la precipitación se calcularon como el promedio de todas las estaciones dentro de los 25 km ponderadas por el inverso de la distancia. La precipitación anual se calculó a partir de la suma total de la precipitación mensual (agosto-julio). Para la estimación de la evapotranspiración de referencia de los sitios, se utilizó el método descrito por Hargreaves y Samani (1985). El déficit hídrico anual (WD) se calculó como la suma de los déficits mensuales (cuando la evapotranspiración es mayor que la precipitación) para el período de estudio, de acuerdo a la siguiente función (2):

$$WD = \sum_{i=1}^{n} (PP_i - ET_{0i}), \qquad \text{cuando} |ET_{0i}| > |PP_i|, \tag{2}$$

donde:

WD es el déficit hídrico anual ($mm \cdot año^{-1}$)

PP_i es la precipitación del i-ésimo mes ($mm \cdot mes^{-1}$)

ET_{0i} es la evapotranspiración del i-ésimo mes ($mm \cdot mes^{-1}$)

n es el número de meses

Agua aprovechable del suelo

Se instalaron calicatas en cada sitio de estudio, describiendo cada horizonte del suelo hasta una profundidad máxima de 2 metros. El porcentaje de piedras se estimó utilizando el método de recuento de puntos descrito por Daniels et al. (1968). Se extrajeron muestras de suelo de 400 gramos de cada horizonte y se determinó en laboratorio la curva de retención de agua del suelo de acuerdo con el método de membrana de presión descrito por Richards (1941). Se asumió que el agua disponible es la diferencia de retención de agua entre la capacidad del campo (0,33 atmósferas) y el punto de marchitez permanente (15 atmósferas). El agua aprovechable del suelo (WSC) se definió en la Ecuación (3).

$$WSC = \sum_{i=0}^{n} (FC_i - PWP_i) * (D_i * (1 - S_i)), \qquad (3)$$

Donde:

WSC es el agua aprovechable del suelo (mm)

FC_i es la capacidad de retención de agua en el suelo a 0,33 bares del i-ésimo horizonte (%)

PWP_i es la capacidad de retención de agua en el suelo a 15 bares del i-ésimo horizonte (%)

Di es la profundidad del i-ésimo horizonte (mm)

Si es el porcentaje volumétrico de piedras en el i-ésimo horizonte (%)

n número de horizontes

Índice de déficit hídrico

El índice de déficit hídrico (WDI) se estimó descontando el WSC de WD, siguiendo el método descrito por Alvarez et al. (2012) utilizando la ecuación (4).

$$WDI = WD - WSC, \qquad (4)$$

Donde:

WDI es el déficit hídrico durante el año ($mm \cdot año^{-1}$)

WD es el déficit hídrico durante el año ($mm \cdot año^{-1}$)

WSC es el agua aprovechable del suelo (mm)

Análisis estadístico

Para evaluar las diferencias de crecimiento (VI, GI, DI y HI) entre los tratamientos de poda de cada sitio y de cada periodo, se realizaron análisis de varianza (ANOVA) y pruebas de comparación múltiple (Tukey). Debido a la alta variabilidad de los crecimientos en cada periodo de evaluación, los análisis fueron evaluados usando un nivel de significancia del 10% (valor-p <0,1)

Para evaluar el efecto de la disponibilidad de recursos hídricos del sitio sobre el crecimiento de los árboles ante diferentes intensidades de poda, se ajustaron modelos de regresión lineal considerando WDI como la variable dependiente y el crecimiento en: VI, GI, DI y HI como variables independientes, para cada periodo de evaluación definido. Todos los análisis se llevaron a cabo utilizando el software R versión 3.0.1 (R Core Team 2014).

RESULTADOS Y DISCUSIÓN

Efecto de la intensidad de poda sobre el crecimiento (Periodo I: 2007-2011 – previo al segundo raleo).

Durante el periodo comprendido entre el primer y segundo raleo (3,8 años), los 800 árboles de los tratamientos *SP100* en los diferentes sitios estudiados, crecieron en volumen a una tasa anual de 23 a 40 m^3 ha^{-1} año (Tabla 2). Estos resultados se encuentran dentro del rango reportado por Álvarez et al. (2012) y Flores y Allen (2004), quienes muestran crecimientos en volumen similares para pino radiata creciendo en Chile en un amplio rango de suelos y climas dentro de los paralelos 35° y 40° S. Los mayores crecimientos en volumen, área basal y diámetro, durante el periodo entre raleos se presentaron en los tratamientos *SP100* para todos los sitios, a excepción del sitio con mayor déficit hídrico (*P800*), donde el tratamiento *PL100* mostró mayores crecimientos en volumen (4%) y área basal (3%) que el tratamiento *SP100*, aun cuando esta diferencia no fue significativa. Este comportamiento podría estar relacionado con lo sugerido por Pinkard y Beadle (2000), quienes concluyen que en sitios con recursos limitados (e.g. agua), si las ramas inferiores del árbol utilizan los recursos sólo para mantenerse, respirando más de lo que fotosintetizan, la remoción de estas podría liberar recursos para un mayor crecimiento fustal; además, la poda de tales secciones de la copa puede resultar en un aumento en la eficiencia del uso de la luz, aumentando las tasas de fotosíntesis en la sección superior restante de la copa (Forrester, 2013). Situaciones donde el crecimiento de los árboles por efecto de la poda ha sido favorecido, no son comunes aun cuando existe investigación al respecto Wang et al. (1980), encontró mejores crecimientos en *Cryptomeria japónica* al remover un porcentaje ligeramente superior al 10 por ciento de la copa viva y Tonguc y Guner (2017) también reportan mayores crecimientos en *Pinus nigra* al podar un tercio de la copa.

En el resto de los sitios, el crecimiento mostró la tendencia más reportada respecto a la intensidad de poda (Sutton y Crowe 1975, Pinkard 2003, Amateis y Burkhart 2011, Hevia et al. 2016), quienes mostraron disminuciones en el crecimiento a medida que aumentaba la intensidad de poda, de esta manera, el tratamiento *PL100* mostró mermas de crecimiento entre un 4% a 16% en volumen en comparación al tratamiento *SP100*, mientras que el tratamiento *PS100* creció desde 15% a 32% menos en volumen de lo que crecieron los tratamientos *SP100*.

Las diferencias de crecimiento en volumen entre *PL100* y *SP100* no fueron significativas. Esto puede deberse a que la remoción promedio de copa viva en el tratamiento *PL100* bordeó 29%. Sutton y Crowe (1975) reportaron que sólo valores de remociones sobre 30% de la copa viva producen mermas significativas en el crecimiento de esta especie.

El tratamiento *PS100* removió el 60% de la copa viva, mostrando los menores crecimientos entre los tratamientos estudiados con un 15% a un 27% menos en volumen de lo que crecieron los tratamientos *PL100*. Los dos sitios con menor déficit hídrico (*P1700 y P1500*) mostraron diferencias significativas entre los tratamientos *PL100* y *PS100* en el crecimiento de todas las variables estudiadas (VI, GI, DI y HI). Los dos sitios con mayor déficit hídrico (*P800* y *P1100*) no mostraron diferencias estadísticas en el crecimiento de área basal y diámetro para los diferentes tratamientos de poda. Esta situación puede atribuirse a que el factor que afecta principalmente al crecimiento de pino radiata en Chile es la disponibilidad de agua (Gerding y Schlatter 1995; Flores y Allen 2004; Álvarez et al. 2012; Rubilar et al. 2013a; Ojeda et al. 2018). En sitios donde la disponibilidad de agua no es un problema relevante (menor déficit hídrico) y no restringe fuertemente el crecimiento de la plantación, la reducción de la intercepción luminosa (fotosíntesis) provocada por mermas importantes en el área foliar de la plantación sería el factor más importante que afectaría el crecimiento. En contraposición, el efecto de la reducción de la intercepción luminosa en sitios con baja disponibilidad de agua (alto déficit hídrico) sobre el crecimiento de la plantación, podría impactar menos que la baja disponibilidad de agua del sitio, lo que concuerda con el modelo de recursos limitantes de Wise y Abrahamson (2007), quienes sugieren que la respuesta a la poda y defoliación depende de los recursos que estén actualmente limitando el crecimiento y como éstos modifiquen su captura por pérdidas de área foliar.

Tabla 2. Crecimiento en volumen (VI), área basal (GI), diámetro (DI) y altura (HI), según sitio y tratamiento de poda para los 800 árboles hasta el segundo raleo (Periodo I)

Sitio	Código	*VI* (m^3/ha)			*GI* (m^2/ha)			*DI* (cm)			*HI* (m)		
		media	*sd*		*media*	*sd*		*media*	*sd*		*media*	*sd*	
P800	*SP100*	83,6	4,5	a	12,2	0,5	a	6,7	0,3	a	7,1	0,1	ab
	PL100	87,2	19,8	a	12,5	2,3	a	6,7	0,7	a	7,0	0,3	ab
	PL63	81,9	10,6	ab	11,9	1,1	a	6,7	0,4	a	7,2	0,2	a
	PS100	71,2	8,14	b	10,5	1,1	a	6,1	0,3	a	6,7	0,3	bc
	PS63	76,3	11,6	ab	11,7	0,9	a	6,4	0,3	a	6,4	0,5	c
P1100	*SP100*	118,1	24,9	a	16,0	3,4	a	7,3	1,2	a	7,2	0,4	a
	PL100	99,0	22,4	ab	13,6	2,9	a	6,5	0,8	a	6,9	0,3	a
	PL63	101,1	25,8	ab	13,8	3,2	a	6,6	0,9	a	7,1	0,5	a
	PS100	83,2	16,7	b	11,7	1,9	a	6,1	0,7	a	6,3	0,5	b
	PS63	93,3	17,6	b	13,1	2,6	a	6,4	1,0	a	6,9	0,3	a
P1500	*SP100*	153,2	8,0	a	23,9	1,4	a	9,4	0,6	a	6,9	0,2	ab
	PL100	147,6	6,8	a	21,7	1,6	ab	8,6	0,7	ab	7,0	0,3	a
	PL63	142,3	6,5	ab	21,5	2,3	ab	8,7	1,1	ab	6,9	0,1	ab
	PS100	125,6	19,8	c	17,9	2,3	c	7,4	0,7	c	6,5	0,5	b
	PS63	129,8	15,6	bc	18,8	2,4	bc	7,6	0,9	bc	6,6	0,2	ab
P1700	*SP100*	143,9	5,7	a	21,0	1,6	a	8,7	0,6	a	7,1	0,3	a
	PL100	133,6	15,5	a	18,4	1,5	b	7,8	0,4	b	7,2	0,3	a
	PL63	131,0	18,8	a	18,3	2,1	b	7,9	0,6	b	7,3	0,2	a
	PS100	97,3	30,4	b	13,2	3,3	c	6,8	0,4	c	6,1	1,0	b
	PS63	110,9	11,2	b	15,8	0,7	bc	7,3	0,3	bc	6,4	0,4	b

n = 4 repeticiones por sitio.
Letras diferentes indican diferencias significativas ($p < 0,1$) entre tratamientos, dentro de cada sitio

En relación con el crecimiento de los 500 árboles que continúan hasta el final del estudio, durante el periodo comprendido entre el primer y segundo raleo, en general los mayores crecimientos se observaron en los tratamientos *SP100* y los menores crecimientos se presentaron en los tratamientos con poda severa, pero con seguidores (*PS63*). A pesar de que las diferencias de crecimiento entre los tratamientos de poda leve, con y sin seguidores (*PL63* y *PL100*) en la mayoría de las veces no fueron significativas, se observó que los tratamientos con seguidores (*PL63*) crecieron entre 0,4% y 12% menos en volumen, 2% a 10% menos en área basal, 2% a 6% menos en diámetro y 0% a 3% menos en altura. Esta misma tendencia se observó en los tratamientos con poda severa, donde los sitios con menor índice de déficit hídrico mostraron diferencias significativas (VI, GI y DI) entre los tratamientos con y sin seguidores (*PS63* y *PS100*), presentando los tratamientos sin seguidores crecimientos en volumen de hasta un 28% más que los tratamientos con seguidores. El efecto de mayor crecimiento en los tratamientos sin seguidores (100% árboles podados) en comparación a los tratamientos con seguidores (63% árboles podados) muestra que la poda selectiva puede disminuir la habilidad competitiva de los árboles objetivo podados que se quieren dejar para edades finales, comparados con sus vecinos sin poda, esto es especialmente relevante cuando se diseñan esquemas de poda muy intensas. Lo anterior concuerda con lo reportado por Sutton y Crowe (1975) para pino radiata, quienes muestran pérdidas de crecimiento de los árboles objetivo en podas selectivas, las cuales se incrementan al realizar podas más intensas y que se vuelven aún más importantes al remover largos de copa viva por sobre el 40%. Karani (1978) mostró que la poda de *Pinus patula* a niveles superiores al 25% del largo de la copa, dio lugar a una pérdida de crecimiento, y en densidades superiores a 750 árboles ha^{-1}, incluso el tratamiento del 25% de remoción de copa viva resultó en pérdida de crecimiento, esto último sugiere que si en nuestro estudio no hubiese existido un raleo previo antes de la poda y que si la proporción de árboles podados respecto al total de árboles fuese menor a la presentada en este estudio (63%), el efecto de los árboles seguidores sobre el crecimiento de los árboles objetivo podría haber sido aún mayor. Actualmente en Chile por un tema de costos, se poda selectivamente restringiendo la poda, a los árboles más aceptables en diámetro y rectitud, por lo tanto, al diseñar esquemas de poda, es necesario considerar tanto la intensidad de poda, la proporción de árboles podados, la intensidad y tiempo entre los raleos.

Tabla 3. Crecimiento en volumen (VI), área basal (GI), diámetro (DI) y altura (HI), según sitio y tratamiento de poda para los 500 árboles finales (Periodo I)

Sitio	Código	***VI*** *(m^3/ha)*			***GI*** *(m^2/ha)*			***DI*** *(cm)*			***HI*** *(m)*		
		media	*sd*		*media*	*sd*		*media*	*sd*		*media*	*sd*	
	SP100	59,4	2,8	a	8,58	0,4	a	7,2	0,3	a	7,2	0,1	a
	PL100	61,6	13,1	a	8,74	1,5	a	7,1	0,8	a	7,1	0,3	a
P800	*PL63*	54,2	8,4	ab	7,83	0,7	ab	6,8	0,3	ab	7,1	0,3	a
	PS100	50,6	6,2	bc	7,31	0,7	bc	6,3	0,3	bc	6,9	0,4	a
	PS63	44,6	7,4	c	6,68	0,7	c	5,9	0,4	c	6,2	0,5	b
	SP100	84,9	23,1	a	11,8	2,9	a	8,4	1,3	a	7,1	0,4	a
	PL100	68,7	13,3	b	9,39	1,6	ab	7,1	0,8	ab	6,9	0,3	a
P1100	*PL63*	68,4	17,7	b	9,22	2,2	b	6,9	1,0	ab	7,1	0,4	a
	PS100	56,5	11,3	bc	8,17	1,5	bc	6,6	1,3	b	6,3	0,5	b
	PS63	52,1	10,7	c	5,89	2,9	c	5,7	0,8	b	6,6	0,2	ab
	SP100	101,8	4,2	a	15,8	0,8	a	9,9	0,5	a	7,0	0,2	ab
	PL100	100,9	4,3	a	14,8	0,9	a	9,0	0,6	ab	7,1	0,3	a
P1500	*PL63*	93,2	4,7	ab	13,9	0,8	ab	8,8	0,8	bc	6,9	0,2	abc
	PS100	87,4	16,9	b	12,5	1,8	b	8,0	0,8	c	6,7	0,5	bc
	PS63	75,5	8,8	c	10,5	0,9	c	6,9	0,4	d	6,6	0,2	c
	SP100	93,0	0,9	ab	13,4	0,9	a	9,1	0,5	a	7,3	0,4	a
	PL100	94,4	14,4	a	12,9	1,3	ab	8,5	0,3	ab	7,3	0,4	a
P1700	*PL63*	84,6	15,4	bc	11,7	1,7	bc	7,9	0,7	bc	7,3	0,3	a
	PS100	76,8	18,6	c	10,8	1,5	c	7,4	0,5	c	6,3	1,0	b
	PS63	55,3	8,3	d	7,6	0,9	d	6,0	0,5	d	6,1	0,4	b

n = 4 repeticiones por sitio.
Letras diferentes indican diferencias significativas ($p < 0,1$) entre tratamientos, dentro de cada sitio

Efecto de la intensidad de poda sobre el crecimiento (Periodo II: 2011-2015 – post segundo raleo).

Los árboles finales (500 arb ha^{-1}) de los tratamientos *SP100*, durante el periodo comprendido entre el segundo raleo y el fin del estudio (3,8 años), crecieron en volumen a una tasa anual de 33 m^3 ha^{-1} año en promedio, similar a lo que venían creciendo los 800 arb ha^{-1} del mismo tratamiento, con rangos de 27 a 46 m^3 ha^{-1} año entre los sitios (Tabla 4). Los mayores crecimientos en volumen y área basal se presentaron en los tratamientos *SP100* en todos los sitios, mientras que los menores crecimientos en volumen se observaron en los tratamientos con poda severa y con seguidores (PS63), los cuales mostraron crecimientos en volumen entre 13% y 38% menos que los tratamientos sin poda, aun cuando estas diferencias fueron significativas sólo en los sitios de menor déficit hídrico. Esto último concuerda con Sutton y Crowe (1975), Karani (1978), Uotila y Mustonen (1994), Amateis y Burkhart (2011) quienes concluyen que aun cuando el efecto de la poda puede durar unos pocos años y un raleo posterior a las podas puede liberar recursos a los árboles objetivo, el efecto de podas severas junto con la competencia de árboles seguidores puede hacer que el crecimiento de la plantación no se recupere.

El crecimiento post raleo de los dos sitios con más déficit hídrico (*P800* y *P1100*) no mostró diferencias significativas en ninguna de las variables estudiadas (VI, GI, DI y HI), sugiriendo que el recurso hídrico está restringiendo de mayor manera el crecimiento que mermas en la intercepción luminosa producto de la poda. En concordancia con lo señalado por varios autores (Sutton y Crowe 1975; Neilsen y Pinkard 2003; Amateis y Burkhart 2011; Hevia et al. 2016), el crecimiento en altura no fue afectado significativamente por los tratamientos de poda, en ninguno de los sitios. Solo en los sitios con menor déficit hídrico (*P1500* y *P1700*) existieron diferencias significativas en VI, GI y DI entre los tratamientos SP100 y algunos de los tratamientos podados.

Tanto los tratamientos con poda leve como los con poda severa, no mostraron diferencias significativas en crecimiento (VI, GI, DI y HI) entre los tratamientos con o sin seguidores; sin embargo, se observó una tendencia de menor crecimiento para los tratamientos con seguidores.

Tabla 4. Crecimiento en volumen (VI), área basal (GI), diámetro (DI) y altura (HI), según sitio y tratamiento de poda para los 500 árboles finales (Periodo II)

Sitio	Código	***VI*** *(m³/ha)*			***GI*** *(m²/ha)*			***DI*** *(cm)*			***HI*** *(m)*		
		media	*sd*		*media*	*sd*		*media*	*sd*		*media*	*sd*	
P800	*SP100*	100,2	9,7	a	9,8	0,9	a	5,7	0,4	a	5,9	0,3	a
	PL100	98,7	26,9	a	9,7	2,6	a	5,6	1,0	a	5,6	0,2	a
	PL63	94,0	13,8	a	9,6	1,1	a	5,8	0,4	a	5,7	0,3	a
	PS100	94,0	11,9	a	9,8	1,5	a	5,9	0,5	a	5,7	0,3	a
	PS63	86,7	23,2	a	9,1	1,8	a	5,8	0,7	a	5,6	0,9	a
P1100	*SP100*	153,7	43,3	a	13,1	3,5	a	6,8	1,1	a	7,0	0,7	a
	PL100	126,2	28,8	a	11,2	2,4	a	5,6	0,4	a	6,7	0,5	a
	PL63	126,8	36	a	11,3	3,1	a	5,7	0,8	a	6,7	0,6	a
	PS100	112,2	22	a	10,0	2,5	a	6,1	0,4	a	6,8	0,5	a
	PS63	96,1	66,2	a	10,7	4,1	a	6,3	1,2	a	6,4	0,8	a
P1500	*SP100*	165,3	13,8	a	16,9	1,6	a	7,4	0,5	a	5,6	0,4	a
	PL100	155,6	6,51	ab	14,7	1,5	b	6,5	0,5	b	6,0	0,4	a
	PL63	154,3	4,74	ab	14,6	0,9	b	6,5	0,7	b	6,2	0,1	a
	PS100	145,6	21	bc	13,7	1,4	b	6,5	0,0	b	6,1	0,3	a
	PS63	136,1	10,8	c	13,3	1,7	b	6,5	0,9	b	6,0	0,3	a
P1700	*SP100*	176,6	32,8	a	17,8	4,2	a	8,8	0,6	a	5,9	0,4	a
	PL100	168,3	23,8	ab	15,2	2,0	abc	7,1	0,5	b	6,5	0,2	a
	PL63	147,4	29,2	b	13,8	1,9	c	6,7	0,7	b	6,2	1,2	a
	PS100	166,7	19,9	ab	16,4	1,4	ab	8,0	0,4	a	6,6	0,6	a
	PS63	143,6	12,0	b	14,9	2,4	bc	8,1	0,4	a	6,4	0,5	a

n = 4 repeticiones por sitio.
Letras diferentes indican diferencias significativas ($p < 0,1$) entre tratamientos, dentro de cada sitio

Respecto al rendimiento final en volumen, área basal y diámetro de los tratamientos a los 14-15 años en los diferentes sitios, los mayores rendimientos se observaron en los tratamientos *SP100*, a excepción del sitio con mayor déficit hídrico donde los mayores registros se observaron en el tratamiento *PL100*. Por otro lado, los tratamientos con poda severa y con seguidores (*PS63*) mostraron los menores rendimientos, con diferencias entre 17% y 36% menos en volumen y entre 6% y 14% menos en diámetro, en comparación a los tratamientos *SP100*, aun cuando solo en tres de los cuatro sitios los rendimientos en volumen y diámetro fueron significativamente diferentes. Lo que sugiere que en general el efecto de las podas severas, pueden provocar mermas que afectarían el desarrollo a largo plazo de las plantaciones y que estas no se recuperarían.

La poda leve (con o sin seguidores) no mostró diferencias significativas en el rendimiento en volumen con el tratamiento sin poda; sin embargo, el rendimiento en diámetro fue significativamente diferente en todos los sitios a excepción del sitio con mayor índice de déficit hídrico. El sitio con mayor índice de déficit hídrico no mostró diferencias significativas en el rendimiento de ninguna variable evaluada (volumen, área basal, diámetro y altura) con ningún tratamiento de poda. El rendimiento en altura no fue afectado por los tratamientos de poda, a excepción del sitio (*P1500*) donde se observó diferencia entre el tratamiento *SP100* con los tratamientos de poda leve (PL100 y PL63) y poda severa de todos los árboles (PS100). En general, los tratamientos con poda leve con y sin seguidores no mostraron diferencias significativas, a excepción del rendimiento en diámetro para un solo sitio (P1700); sin embargo, los rendimientos en volumen, área basal, diámetro y altura en los tratamientos de poda leve con seguidores mostraron valores inferiores a los presentados por los tratamientos de poda leve sin seguidores en todos los sitios. Los tratamientos con poda severa con y sin seguidores solo mostraron diferencias significativas en el rendimiento en volumen y área basal en un solo sitio (*P1700*), aun cuando en todos sitios los tratamientos con seguidores mostraron menores rendimientos en todas las variables evaluadas. Posiblemente, la alta variabilidad de los crecimientos en las cuatro repeticiones de los tratamientos en los diferentes sitios evaluados pudo haber contribuido a no encontrar diferencias significativas en algunas de las comparaciones entre tratamientos.

Tabla 5. Rendimiento en volumen, área basal, diámetro y altura, según sitio y tratamiento de poda para los 500 árboles finales a la edad de 14 años (P800, P1100, P1700) y 15 años (P1500).

Sitio	Código	***Volumen*** *(m^3/ha)*			***Área Basal*** *(m^2/ha)*			***Diámetro*** *(cm)*			***Altura*** *(m)*		
		media	*sd*		*media*	*sd*		*media*	*sd*		*media*	*sd*	
	SP100	175,9	11,9	a	23,7	1,1	a	24,5	0,5	a	22,1	0,5	a
	PL100	178,3	42,8	a	24,2	4,9	a	24,6	2,4	a	21,9	0,9	a
P800	*PL63*	163,5	25,2	a	22,4	2,4	a	23,8	1,3	a	21,7	1,4	a
	PS100	160,2	19,7	a	22,3	2,8	a	23,6	1,5	a	21,5	0,5	a
	PS63	146,7	32,0	a	21,0	2,8	a	23,0	1,4	a	20,7	1,9	a
	SP100	263,6	73,0	a	32,6	7,9	a	29,2	3,3	a	23,7	1,2	a
	PL100	218,5	46,4	ab	27,9	5,1	a	26,4	2,3	b	23,1	1,0	a
P1100	*PL63*	218,1	58,9	ab	27,7	6,6	a	26,2	3,2	b	23,0	1,3	a
	PS100	189,3	34,8	bc	24,5	3,7	a	25,4	1,9	b	22,7	1,2	a
	PS63	169,2	71,7	c	22,1	9,1	a	25,1	2,1	b	22,1	1,3	a
	SP100	292,6	17,3	a	42,1	2,1	a	32,8	0,8	a	20,7	0,5	b
	PL100	284,8	10,7	ab	39,5	1,7	ab	31,3	0,4	b	21,5	1,0	a
P1500	*PL63*	274,9	12,6	ab	38,2	0,7	bc	30,9	0,4	b	21,4	1,0	a
	PS100	262,0	42,9	bc	35,9	4,0	cd	30,2	1,4	bc	21,6	1,3	a
	PS63	240,0	18,9	c	33,6	2,3	d	29,3	1,3	c	21,1	0,7	ab
	SP100	294,9	31,7	a	39,8	4,9	a	33,0	0,7	a	22,0	0,5	a
	PL100	291,4	46,7	a	37,5	4,7	ab	30,8	1,9	b	22,8	1,1	a
P1700	*PL63*	257,7	45,6	ab	34,1	3,9	bc	29,4	1,4	c	22,4	2,0	a
	PS100	271,8	43,8	a	35,9	3,6	ab	30,1	1,5	bc	22,5	1,9	a
	PS63	222,8	16,7	b	30,4	2,3	c	29,1	1,2	c	21,6	0,6	a

n = 4 repeticiones por sitio.
Letras diferentes indican diferencias significativas ($p < 0,1$) entre tratamientos, dentro de cada sitio

Efecto del Clima

Como se ha señalado anteriormente, la disponibilidad de agua de los sitios es un factor clave que afecta directamente el crecimiento de pino radiata en Chile (Gerding y Schlatter 1995; Flores y Allen 2004; Álvarez et al. 2012; Rubilar et al. 2013; Ojeda et al. 2018), lo que explica la fuerte relación lineal positiva entre el crecimiento en volumen de los 800 árboles de los tratamientos sin poda durante el periodo comprendido entre el primer y segundo raleo y el IDH de los sitios estudiados (r=0,9). A medida que se redujo la capacidad de interceptar la luz, provocada por la intensidad de poda, esta relación mostró ser más débil (poda leve r =0,79 y poda severa r =0,69).

Los modelos de regresión ajustados entre el crecimiento en volumen y el IDH (Tabla 7) fueron altamente significativos (p<0,005), donde el 81%, 63% y 47% de la variación en volumen podría ser predicha por el IDH para los tratamientos sin poda, poda leve y poda severa, respectivamente. La misma relación lineal y positiva se determinó para el crecimiento en área basal y diámetro con el IDH, pero la correlación fue menor que la con el volumen. El crecimiento en altura no mostró una buena correlación con el IDH.

Debido a que la relación del crecimiento en volumen, área basal (Fig. 2a) y diámetro de los niveles de poda SP100, PL100 y PS100 a lo largo del gradiente de índice de déficit hídrico muestra una mayor pendiente para los tratamientos sin poda y una menor para los tratamientos con poda, se infiere que la diferencia de crecimiento entre estos tratamientos aumenta a medida que disminuye el déficit hídrico de los sitios (Fig. 2)

Los registros de precipitación medidos en los sitios para los periodos de estudio alcanzan valores inferiores a la precipitación promedio de referencia (1980-2010), con disminuciones en las precipitaciones los últimos años, incrementando el déficit hídrico de los sitios en la zona centro sur de Chile. Esto concuerda con lo señalado por Neuenschwander (2010) quien muestra una tendencia decreciente del régimen pluviométrico en la mayor parte del territorio chileno y que de acuerdo con los pronósticos basados en datos estadísticos históricos, existe una probabilidad importante de que la zona Central del país sufra una disminución de sus recursos hídricos, lo que produciría en general una menor productividad de las plantaciones y menores efectos de las intervenciones de poda en un futuro.

Tabla 6. Precipitación (PP) e Índice de déficit hídrico (IDH), en los cuatro sitios de estudio.

Sitio	Precipitación (mm) *Periodo (años)*				IDH (mm) *Periodo (años)*		
	1985-2010	2007 - 2011	2011 - 2015	2007 - 2015	2007 - 2011	2011 - 2015	2007 - 2015
P800	833	675	718	697	-564	-544	-554
P1100	1,078	1,014	1,022	1,018	-318	-317	-318
P1500	1,492	1,290	1,214	1,252	-164	-198	-181
P1700	1,683	1,311	960	1,135	-267	-294	-281

Tabla 7. Modelo de regresión lineal entre el crecimiento de los 800 árboles en volumen (*CV1*, m^3/ha)), área basal (CG_1, m^2/ha), diámetro (CD_1, cm) y altura (CH_1, *m*), y el índice de déficit hídrico (IDH_1, *mm*). (Periodo I: 4 años – pre-raleo).

Tratamiento	Modelo	b_0		b_1		Error estándar residual	R^2	Valor-p
SP100	$CV_1 = b_0 + b_1\ IDH_1$	182,857	*	0,1765	*	13,68	0,81	< 0,001
PL100	$CV_1 = b_0 + b_1\ IDH_1$	166,899	*	0,1516	*	18,79	0,63	< 0,001
PS100	$CV_1 = b_0 + b_1\ IDH_1$	133,982	*	0,1262	*	20,94	0,47	< 0,005
SP100	$CG_1 = b_0 + b_1\ IDH_1$	27,659	*	0,0284	*	2,41	0,77	< 0,001
PL100	$CG_1 = b_0 + b_1\ IDH_1$	23,788	*	0,0219	*	2,70	0,63	< 0,001
PS100	$CG_1 = b_0 + b_1\ IDH_1$	18,496	*	0,0164	*	2,61	0,49	< 0,005
SP100	$CD_1 = b_0 + b_1\ IDH_1$	10,100	*	0,0064	*	0,85	0,59	< 0,001
PL100	$CD_1 = b_0 + b_1\ IDH_1$	8,879	*	0,0045	*	0,84	0,42	< 0,001
PS100	$CD_1 = b_0 + b_1\ IDH_1$	7,549	*	0,0030	*	0,60	0,39	< 0,005
SP100	$CH_1 = b_0 + b_1\ IDH_1$	6,944	*	-0,0004		0,26	0,06	0,38
PL100	$CH_1 = b_0 + b_1\ IDH_1$	7,074	*	0,0001		0,30	0,01	0,79
PS100	$CH_1 = b_0 + b_1\ IDH_1$	6,133	*	-0,0009		0,60	0,05	0,41

* Nivel de significación del parámetro (p<0,05)

El crecimiento de los 500 árboles finales, durante el periodo comprendido entre el segundo raleo y el fin del estudio (2011-2015), también mostró una relación lineal positiva entre el crecimiento en volumen, área basal (Fig. 2b) y diámetro con el IDH a lo largo del gradiente hídrico de los sitios estudiados, pero las correlaciones encontradas fueron menores a las del periodo anterior (previo al segundo raleo), siendo el crecimiento en volumen la variable con mayor correlación con el IDH (r=0,79), para los tratamientos sin poda y mostrando la misma tendencia de disminución de correlación a medida que aumenta la severidad de poda. Al igual que en el periodo anterior, los modelos de regresión ajustados entre el crecimiento en volumen, área basal y diámetro y el IDH (Tabla 8) fueron altamente significativos (p<0,05).

Tabla 8. Modelo de regresión lineal entre el crecimiento de los 500 árboles finales en volumen (CV_2, m^3/ha), área basal (CG_2, m^2/ha), diámetro (CD_2, cm) y altura (CH_2, m), y el índice de déficit hídrico (IDH_2, mm). (Periodo II: 4 años – post-raleo).

Tratamiento	Modelo	b_0		b_1		Error estándar residual	R^2	Valor-p
SP100	$CV_2 = b0+b1\ IDH_2$	219,3624	*	0,2120	*	24,85	0,62	< 0,001
PL100	$CV_2 = b0+b1\ IDH_2$	197,0000	*	0,1836	*	23,85	0,55	< 0,005
PS100	$CV_2 = b0+b1\ IDH_2$	187,5703	*	0,1800	*	25,17	0,48	< 0,005
SP100	$CG_2 = b0+b1\ IDH_2$	21,8866	*	0,0222	*	2,67	0,61	< 0,001
PL100	$CG_2 = b0+b1\ IDH_2$	17,8596	*	0,0155	*	2,28	0,49	< 0,005
PS100	$CG_2 = b0+b1\ IDH_2$	17,0123	*	0,0141	*	2,75	0,33	< 0,05
SP100	$CD_2 = b0+b1\ IDH_2$	9,2514	*	0,0063	*	0,94	0,50	< 0,005
PL100	$CD_2 = b0+b1\ IDH_2$	7,2716	*	0,0033	*	0,77	0,27	< 0,05
PS100	$CD_2 = b0+b1\ IDH_2$	7,7306	*	0,0034	*	0,83	0,23	< 0,05
SP100	$CH_2 = b0+b1\ IDH_2$	6,0126	*	-0,0001		0,66	0,00	0,91
PL100	$CH_2 = b0+b1\ IDH_2$	6,7880	*	0,0018		0,51	0,21	0,09
PS100	$CH_2 = b0+b1\ IDH_2$	6,9518	*	0,0020		0,55	0,19	0,09

* Nivel de significación del parámetro (p<0,05)

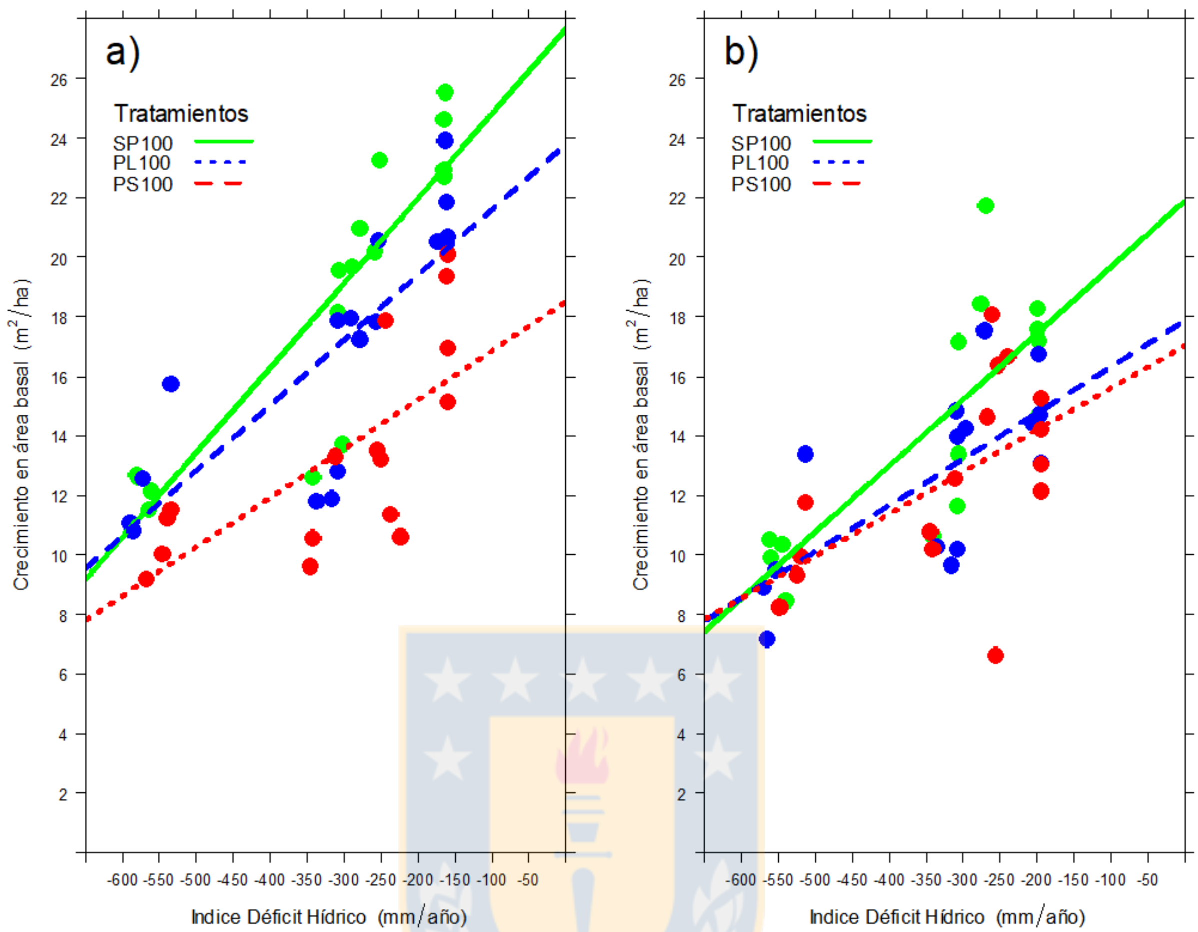

Fig. 2. a) Relación entre el crecimiento en área basal de los 800 árboles y el índice de déficit hídrico para el periodo (pre segundo raleo - 2007-2011). **b**) Relación entre el crecimiento en área basal de los 500 árboles y el índice de déficit hídrico para el periodo (post segundo raleo - 2011-2015).

Al examinar el crecimiento en volumen de los 500 árboles objetivo, en el periodo comprendido desde el inicio (2007) y el término del estudio (2015) a través del gradiente hídrico de los sitios (Fig. 3), se puede observar que el efecto de los seguidores afecta mayormente el crecimiento de los tratamientos con podas severas (*PS100* vs *PS63*) que los con podas leves (*PL100* vs *PL63*)

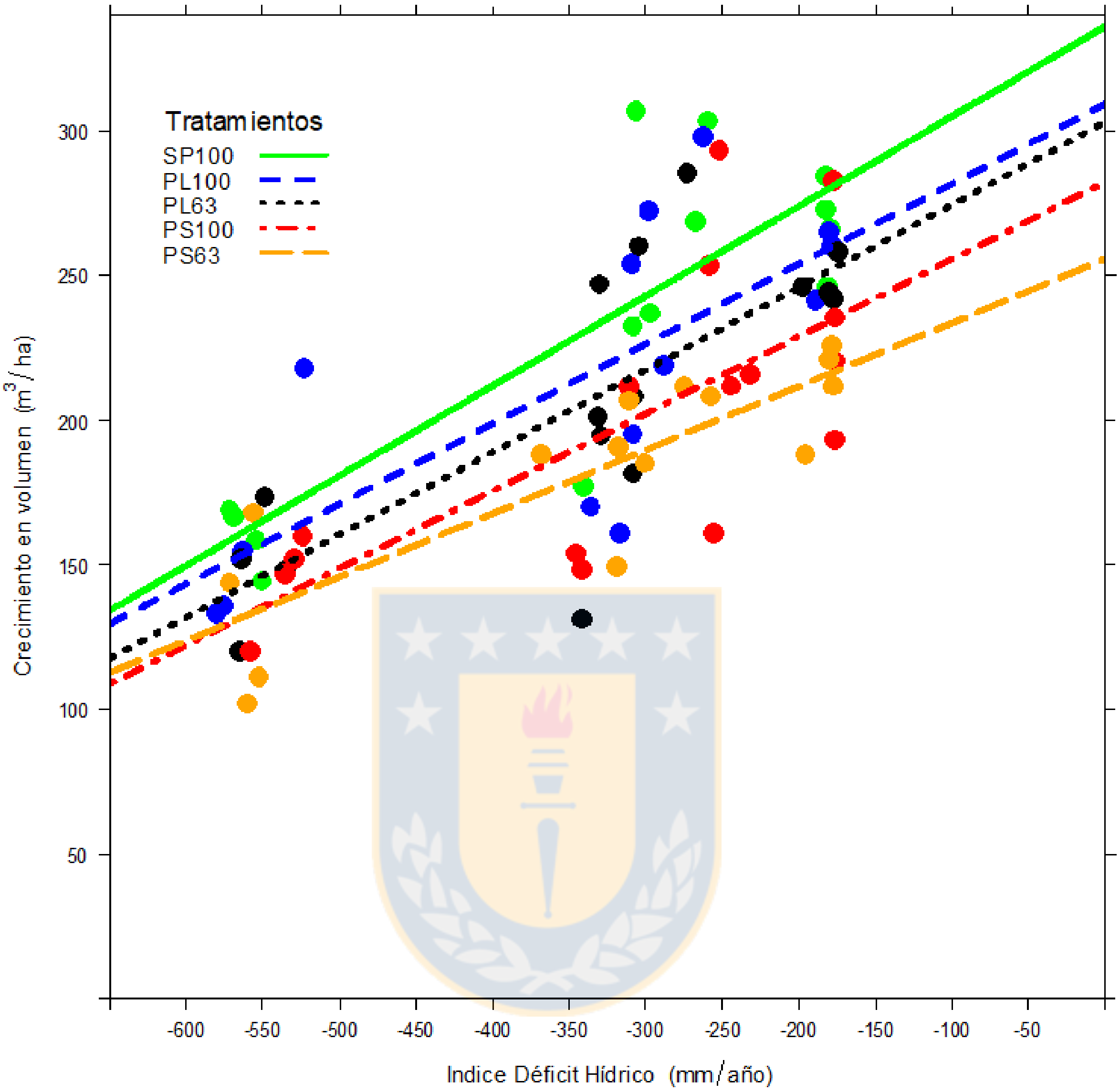

Fig. 3. Crecimiento de los 500 árboles finales, durante el periodo comprendido desde el inicio (año 2007) y el término del estudio (año 2015).

CONCLUSIONES

Existe una fuerte relación lineal y positiva entre la disponibilidad de agua del sitio (índice de déficit hídrico) y el crecimiento de pino radiata.

A medida que la disponibilidad de agua del sitio aumenta, la pérdida de crecimiento por efecto de la intensidad de poda es mayor.

Podas severas de alta intensidad, afectan el crecimiento y productividad del rodal en el largo plazo, principalmente en sitios de menor déficit hídrico.

Los árboles seguidores (sin poda) redujeron el crecimiento en volumen de los árboles finales (500 arb ha^{-1}) principalmente en sitios de menor déficit hídrico, en podas de alta intensidad y en el periodo de cuatro años antes del segundo raleo, aun cuando la tendencia de disminución de crecimiento se registró hasta el final del estudio para todos los sitios en los dos niveles de poda analizados.

Los resultados obtenidos sugieren que la disponibilidad hídrica de los sitios es un factor clave que debería ser incorporado en la toma de decisiones de manejo para realizar una silvicultura sitio específica para las plantaciones de pino radiata en Chile.

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CONCLUSIONES GENERALES

Fuertes relaciones lineales y positivas entre la disponibilidad de agua del sitio, el área foliar y el crecimiento muestran que el factor hídrico del sitio juega un rol importante en la predicción de la productividad de las plantaciones de pino radiata.

El índice de déficit hídrico, utilizado en este trabajo, el cual integra los efectos de la precipitación, la evapotranspiración potencial y el agua disponible en el suelo, se correlaciona bien con el área foliar, el crecimiento y la respuesta a la poda en pino radiata, pudiendo ser una variable de apoyo, para modelos de crecimiento utilizados en la toma de decisiones de manejo de plantaciones.

En el corto plazo (1 año) podas leves con remociones cercanas al 30% de la copa viva, no producen diferencias en crecimiento en volumen en comparación a tratamientos sin poda.

A excepción del sitio con mayor déficit hídrico, los tratamientos de poda leve, luego de 8 años de haber realizado los tratamientos de poda, muestran rendimientos menores para los 500 árboles finales a la edad 14-15 años, tanto en volumen como en área basal y diámetro, que el tratamiento sin poda; sin embargo, solo el rendimiento en diámetro mostró diferencias significativas.

Para los 500 árboles finales a la edad 14-15 años y luego de 8 años de realizado los tratamientos de poda, la poda severa con remociones cercanas al 60% de la copa viva, muestra rendimientos menores tanto en volumen como en área basal, diámetro y altura, que los tratamientos sin poda y poda leve.

Independiente de la intensidad de poda, el sitio con mayor déficit hídrico no mostró diferencias significativas en el rendimiento de los 500 árboles finales a la edad 14-15 años tanto en volumen como en área basal, diámetro y altura.

Se observa una tendencia que en la medida que la disponibilidad de agua del sitio aumenta, la pérdida de crecimiento por efecto de la intensidad de poda es mayor.

Para los 500 árboles finales a la edad 14-15 años, los tratamientos con seguidores independiente de la intensidad de poda, mostraron menores rendimientos que los tratamientos sin seguidores tanto en volumen como en área basal, diámetro y altura, siendo esta diferencia mayor en los tratamientos con poda severa.

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