Stone pine (*Pinus pinea*) growth and cone yield as a function of planting density in Chile

Crecimiento y producción de piñas de pino piñonero (*Pinus pinea*) en Chile en función de la densidad de plantación

Verónica Loewe Muñoz [a]*, Rodrigo Del Río [a], Mónica Balzarini [b]

Corresponding author: [a] Chilean Forest Institute (INFOR), Metropolitan Office, Sucre 2397, Santiago, Chile, tel.: 56-2-23667111, vloewe@infor.cl

[b] Universidad Nacional de Córdoba, College of Agriculture, CONICET Biometry Unit, Córdoba, Argentina.

SUMMARY

Pinus pinea (stone pine) is an important species for its delicious seeds –the pine nuts–, the most expensive dry fruit worldwide. In native habitats, planting density is a key silvicultural tool in this highly heliophile species due to its impact on growth and cone yield. In Chile, the densities of adult plantations are medium and high. The goal of this study was to assess the impact of density on growth and cone yield in established plantations. Thirty plantations, 15 at high density (1,667 trees ha^{-1}) and 15 at medium density (500 trees ha^{-1}), were matched into 15 pairs of similar plantations regarding age and site characteristics. Planting density had a significant impact on *P. pinea* growth and cone yield. The medium density was associated with 46 % higher diameter-at-breast-height (DBH) and 2.8 times higher cone yield than those presented by a high-density plantation scheme. However, at 500 trees ha^{-1}, average tree height might turn cone harvesting difficult and expensive. In humid areas (Chilean South macrozone), the medium planting density had a more important effect on cone yield than on growth. Our study confirms previous research in stone pine native habitats and highlights the need to find an optimum planting density to favor cone yield and harvest.

Key words: vegetative growth, cone yield, intensive silviculture, plantation spacing.

RESUMEN

El pino piñonero (*Pinus pinea*) es una especie importante por sus deliciosas semillas (piñones), el fruto seco más caro del mundo. En su hábitat nativo, la densidad de plantación es una decisión silvicultural clave en esta especie heliófila debido a su impacto en el crecimiento y producción de piñas. En Chile, las densidades de plantaciones adultas son medias y altas. El objetivo de este estudio fue evaluar el impacto de la densidad en el crecimiento y producción de piñas en plantaciones establecidas. Treinta plantaciones, 15 con alta densidad (1.667 árboles ha^{-1}) y 15 con densidad media (500 árboles ha^{-1}) se agruparon en pares de plantaciones de similar edad y características del sitio. La densidad de plantación tuvo un impacto significativo en el crecimiento y producción de piñas de *P. pinea*. La densidad media estuvo asociada con 46 % mayor diámetro a la altura del pecho y 2,8 veces mayor producción de piñas que en el esquema de alta densidad. No obstante, en la densidad de 500 árboles ha^{-1}, la altura media puede dificultar y encarecer la cosecha de piñas. En áreas húmedas (macrozona sur de Chile), la densidad media de plantación tuvo un efecto mayor en la producción de piñas que en el crecimiento. Este estudio confirma investigaciones previas realizadas en hábitats nativos del pino piñonero y subraya la necesidad de encontrar una densidad de plantación óptima para favorecer la producción de piñas y la cosecha.

Palabras clave: crecimiento vegetativo, producción de piñas, silvicultura intensiva, efecto del espaciamiento.

INTRODUCTION

Pinus pinea Linneo (stone pine) is important for its delicious and expensive seeds, the pine nuts. The species has shown a good adaptation in Chile (Loewe *et al.* 2016, 2017a), where it is considered an emerging fruit crop, with over 2,000 hectares planted in the last years. In Argentina, the species has been planted mainly in coastal areas for dune stabilization, covering about 300 hectares. As a pioneer species, it is highly heliophile and very sensitive to intra- or interspecific competition, which determines its crown shape. Therefore, planting density is an important factor to be considered for maximizing cone production (Piqué 2013). On the other hand, height growth can be controlled by pruning or using an adequate spacing to maintain the crown low and large enough to facilitate harvesting. Moreover, mechanized cone harvesting is easier and significantly more cost-effective in sparse than in denser stands, where manual harvesting may be required (Pasalodos-Tato *et al*. 2016).

Information about the effects of stand density is determinant for a good planting design, particularly in intensive

silviculture; the effects on cone yield were studied for the species in the main producer countries (Piqué *et al.* 2011, Moreno-Fernandez *et al.* 2013). The desirable final density in plantations oriented to cone production was determined in 100 trees ha^{-1} (10´10 m) in Portugal (Correia *et al.* 2010) and Spain (Mutke *et al.* 2012); density was found to boost tree cone production (Montero *et al.* 2008)

Pinus pinea is a promising species for intensive silviculture in Chile and Argentina in a context of climate change due to its low hydric requirement (Loewe *et al.* 2020). Therefore, this paper addresses the key question of the impact of medium and high-density schemes on cone yield in adult plantations. This study is complementary to a previous work by Loewe *et al.* (2019), which analyzed the initial impact of low-density schemes (204 to 400 trees ha^{-1}) on growth and fruiting of young plantations, by including adult plantations established and managed at higher density. In fact, *P. pinea* plantations established with non-productive purposes (erosion control and cattle shadowing) have medium density (500 trees ha^{-1}, 4x5 m) to high density (1,667 trees ha^{-1}, 2x3 m or even higher), a pattern that could be inappropriate for cone production, and that also induces excessive height growth (Loewe and Delard 2016).

Management techniques for *P. pinea* cropping for cone production were proposed (Loewe *et al.* 2017b), including techniques commonly used in horticulture, such as fertilization and irrigation. Considering that the vegetative growth of the species across the species macrozones in Chile (Loewe *et al.* 2015) is higher than in its native area, we hypothesize that the highest density reduces diameter growth and cone yield. The main goal of this study is to evaluate the effect of medium and high *P. pinea* planting density on (1) diameter and height growth, and (2) cone yield across three macrozones of Chile. This information may be useful for the establishment of new plantations and management of already established ones.

METHODS

Observational study. Over the past decade, given the interest in *P. pinea* cultivation, the Chilean Forest Institute (INFOR) has conducted a long-term, large-scale national research to gather data from Chile, covering a wide area between Coquimbo (30.8 S°) and Araucanía (39.0 S°) Regions. Inventories of *P. pinea* populations were performed, including plantations established for commercial and environmental purposes. A survey was conducted in 41 plantations, where all *P. pinea* trees were measured for diameter-at-breast-height (DBH) at 130 cm above the ground with a caliper, and height with a hypsometer. Annual growth in DBH and height was estimated by dividing the measured DBH and height by the plantation age. All 3-year-old mature cones per tree were counted from a standing position on the ground. However, given the high density and tree sizes, cone counting might have been bia-

sed, and, consequently, the true cone number may have been underestimated, since the upper third of the crown was not always totally visible from the standing position. Cone yield was estimated as the total cone production per hectare. Plantation age, as reported by the owners, ranged from 12 to 50 years. According to Loewe *et al.* (2016), plantations aged 8 years and older are considered productive in Chile.

A total of 30 plantations from the above-described survey (see their description in table 1) were matched in 15 pairs of similar age and site characteristics and different planting density: high density (on average 1,667 trees ha^{-1}) and medium density (on average 500 trees ha^{-1}). Considering the regional differences in cone yield reported by Calama *et al.* (2016), the 15 pairs were distributed across the three macrozones delimited for the species in Chile by Loewe *et al.* (2015) (figure 1).
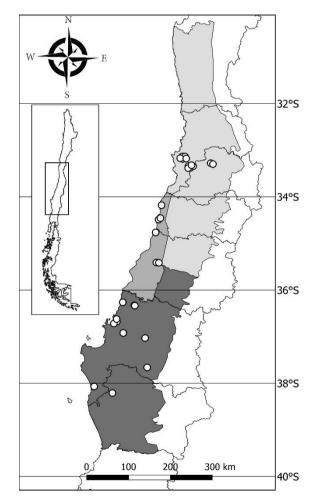

Figure 1. *Pinus pinea* plantation sites included in the study in Chile. Light grey: North, Grey: Dry Coast, Dark grey: South macrozones, as described in Loewe *et al.* (2015).

Distribución de plantaciones de *Pinus pinea* incluidas en el estudio en Chile. Macrozonas Norte: gris claro; Secano costero: gris; Sur: gris oscuro.

Table 1. Pairs of similar *Pinus pinea* plantations with a different number of trees per hectare.

Pares de plantaciones de *Pinus pinea* con diferente cantidad de árboles por hectárea.

Plantation pairwise	Plantation age (years)	High density [††]		Medium density [††]		Macrozone
		Diameter at breast height (cm)	Dominant height [†] (m)	Diameter at breast height (cm)	Dominant height [†] (m)	
1-2	25	13.8±0.8	6.0±0.0	17.3±0.3	7.8±0.1	Dry Coast
3-4	26	16.9±0.7	11.2±0.4	20.2±0.4	9.4±0.2	Dry Coast
5-6	23	11.4±1.4	5.1±0.0	33.6±0.7	14.6±0.2	Dry Coast
7-8	25	10.3±0.8	6.3±0.6	25.7±0.5	12.8±0.2	North
9-10	30	14.1±0.9	8.8±0.4	37.1±2.0	16.5±0.7	North
11-12	30	21.8±1.3	12.4±0.3	32.9±1.1	14.9±0.5	North
13-14	35	30.9±1.9	13.8±0.3	30.7±1.1	13.9±0.5	North
15-16	25	8.5±0.7	6.8±0.1	27.4±0.5	12.5±0.1	North
17-18	23	15.8±1.6	5.9±0.0	37.0±1.7	16.2±0.7	North
19-20	50	44.2±1.7	14.6±0.4	54.0±3.2	36.6±1.6	South
21-22	12	21.9±0.6	7.8±0.0	21.3±1.4	10.6±0.7	South
23-24	40	55.2±0.9	25.3±0.8	38.5±2.9	11.6±0.9	South
25-26	17	23.6±1.4	9.0±0.1	24.0±1.7	13.2±0.6	South
27-28	50	40.6±1.3	17.3±0.4	82.6±1.9	28.9±1.2	South
29-30	50	44.1±1.6	16.9±0.6	62.3±3.6	17.0±0.6	South

[†] Dominant height was obtained as the mean height of the 100 largest diameter trees per hectare (Soares *et al.* 2013) and is used as an expression of the site index. [††] Medium density: 500 trees ha^{-1}, High density: 1,667 trees ha^{-1}.

Plot size for this study was determined by an average of 65 trees per plot, totaling 1,950 *P. pinea* trees. The climate of the North macrozone is characterized by the most challenging variables, with annual average temperature of 14.1 °C, annual maximum average temperature of 21.9 °C, thermal oscillation of 14.3 °C, and annual rainfall of 383.7 mm. In the South macrozone, the coldest and most humid one, climate is characterized by annual average temperature of 13.2 °C, annual maximum average temperature of 19.8 °C, thermal oscillation of 12.3 °C, and annual rainfall of 1,047 mm. The transition Dry Coast macrozone is characterized by intermediate values (average temperature 13.6 °C, maximum average temperature 21.0 °C; thermal oscillation 14 °C; rainfall 648.3 mm) (Lutz *et al.* 2017).

Statistical analyses. An ANOVA model including density, macrozone and plantation pair effects was fitted. The plantation age was used as covariate. Annual DBH and height growths as well as cone yield means were compared between densities using Fisher LSD test ($\alpha = 0.05$). Statistical analyses were performed using the software InfoStat (Di Rienzo *et al.* 2020) and their interface with R 3.5.3 (R Development Core Team 2019).

RESULTS

Average growth and cone yield for each planting density are presented in table 2. Plantations showed significant differences in DBH and height growth ($P < 0.004$ and $P = 0.01$, respectively). The medium density resulted in 46 % higher DBH growth and 2.8 times higher cone yield than in the high-density scheme. The macrozone effect was statistically significant for annual DBH growth ($P = 0.004$) and cone yield ($P < 0.001$). Because of the plantation pairing, plantation age was not significant for any of the variables (height, $P = 0.273$; DBH, $P = 0.228$; cone yield, $P = 0.210$).

Across macrozones (table 3), significant differences between densities were found for growth and cone yield in the North macrozone, and for cone yield in the North and South macrozones.

DBH and height growth, as well as cone yield, were negatively affected under the high-density scheme in the North macrozone, the one of highest annual average temperature and thermal oscillation, and lowest rainfall. In the South macrozone, in the medium density cone yield was 3.6 times higher than the high density.

Table 2. Current annual growth rate and cone yield in *Pinus pinea* stands for each planting density.

Tasa de crecimiento corriente y producción de piñas en plantaciones de *Pinus pinea* según densidad.

Density		Diameter at breast height**	Height*	Cone yield*
Level	trees ha^{-1} †	cm year^{-1}	cm year^{-1}	cones ha^{-1}
High	1,667	0.81 ± 0.09 b	34.8 ± 0.5 b	892 ± 563 b
Medium	500	1.18 ± 0.09 a	51.0 ± 0.5 a	2,511 ± 563 a

† Average across 15 *P. pinea* plantations at high density and 15 plantations at medium density.
Mean ± standard error. By column, same letter indicates non-statistical differences between densities.
* = $P < 0.05$; ** = $P < 0.01$.

Table 3. Annual growth rate per tree and cone yield in *Pinus pinea* plantations established at medium and high densities across macrozones.

Tasa de crecimiento anual y producción de piñas en plantaciones de *Pinus pinea* establecidas a densidad media y alta en diferentes macrozonas.

Variable	Macrozone	Medium density (500 trees ha^{-1})	High density (1,667 trees ha^{-1})
Annual average diameter at breast height growth (cm year^{-1})	North***	1.32 ± 0.07 a	0.49 ± 0.07 b
	Dry Coast	0.75 ± 0.02 a	0.63 ± 0.02 a
	South	1.39 ± 0.06 a	1.28 ± 0.06 a
Annual average height growth (cm year^{-1})	North***	0.57 ± 0.03 a	0.20 ± 0.03 b
	Dry Coast	0.37 ± 0.03 a	0.31 ± 0.03 a
	South	0.52 ± 0.06 a	0.49 ± 0.06 a
Cone yield (cones ha^{-1})	North*	739 ± 185 a	0 ± 0 b
	Dry Coast	2,628 ± 334 a	1,546 ± 334 a
	South*	3,997 ± 1,118 a	1,096 ± 1,118 b

Average across *P. pinea* plantations at high density and medium density by macrozone.
Mean ± standard error. By row, same letter indicates non-statistical differences between densities.
* = $P < 0.05$; *** = $P < 0.001$

DISCUSSION

Our results confirm our working hypothesis of a reduction of diameter growth and cone yield at the highest planting density, confirming the importance of silviculture in *P. pinea* crop development and cone yield. Both high and medium density levels tested in this study correspond to high and medium density levels used to establish *P. pinea* plantations in the species native habitat (Spain) (Montero 2004).

Cone and seed production in any given year are conditioned by vigor, health and size of trees (Calama and Montero 2007), especially by DBH (Moreno-Fernandez *et al.* 2013, Loewe *et al.* 2016). DBH and height growth of *P. pinea* trees was higher in the medium density plantation; Piqué *et al.* (2011) reported a similar effect of planting density on DBH growth.

Loewe and Delard (2016) found that high density plantations in Chile (1.5x1.5 to 3x3 m) induced excessive height growth. In this study, the medium density also induced high height growth, evidencing that this density makes cone harvesting difficult. This is in agreement with findings reported by Correia *et al.* (2010) and Mutke *et al.* (2012), who stated that a density of 500 trees ha^{-1} is too high for the species, since it stimulates height growth.

The lowest planting density (500 trees ha^{-1}) induced a higher cone yield than that presented by the denser one (1,667 trees ha^{-1}) in most of the species production area in Chile (North and South macrozones). This is in agreement with results of Calama *et al.* (2008) and Montero *et al.* (2008), who indicated that lower density stands in Spain yield larger fruit production than do stands of higher density. Similarly, pine nut production of *Pinus resinosa* Ait., a species comparable to *P. pinea* in its long fruit development cycle, was found to decrease at high stand density (Stiell 1971). A density of 400 trees ha^{-1} in seed orchards of *Pinus sylvestris* L., which is lower than the medium

density here studied, was reported as appropriate for cone production (Jonsson *et al.* 1976).

Accordingly, medium to low densities (5x5 to 10x10 m) have been recommended to enhance cone production and facilitate harvesting (Costa and Evaristo 2008), allowing tree crown development and light interception (Piqué 2013). In fact, Boutheina *et al.* (2013) observed that bigger trees bear more cones, with crown development being more important in determining cone production than age, suggesting that spacing is an important factor to improve *P. pinea* cone yield. Loewe *et al.* (2019) also observed that a density of 204 trees ha^{-1} (7×7 m spacing) was associated with higher crown diameter and earlier and higher female strobili production than those presented by a 400 trees ha^{-1} density (5×5 m spacing); both densities are within the most common ranges in new specialized plantations in Chile. This is in agreement with findings of Mutke *et al.* (2012), who reported that low density plantations (278 trees ha^{-1} or even less) have higher cone yield than that shown by high density plantations (1,111 trees ha^{-1}), allowing mechanical harvesting and tilling at the same time.

The impact of planting density on tree growth and cone yield in the North macrozone, the most arid and warm environment, would be caused by higher water availability to trees in the medium density plantations, since the water supply is shared by a lower number of trees, improving stand growth rates and cone yield, as reported by Mazza *et al.* (2011) and Gonçalves and Pommerening (2012); in fact, no cones were recorded in the high-density plantations in that macrozone. In the South macrozone, the coldest and most humid environment, the medium density increased cone yield 3.6 times compared to that from the high density, indicating that a wider spacing favors tree fruiting, even in less challenging hydric environments.

This study highlights the impact of planting density on tree growth, especially under arid and warm conditions. Stands growing at medium density may be benefited by less water deficit, improving plantation resilience under a climate change scenario. Considering the expected increases in frequency and duration of drought periods, especially in Mediterranean areas (Quintana-Seguí *et al.* 2016), our findings may help in the adoption of adequate silvicultural schemes in *P. pinea* plantations. Furthermore, cone yield in high-density plantations is lower than that observed in less dense ones. The fact that production is concentrated in fewer trees also implies a lower cost, higher harvest yield and higher profitability (Montero *et al.* 2008).

Considering that planting density is a key factor in cone yield, further controlled experimental studies on the effects of spacing on growth and cone yield are necessary to improve the species management in South America.

CONCLUSIONS

Our study confirms, in different environments of Chile, previous researches in native habitats with *P. pinea* re-

lated to the influence of planting density on growth and cone yield. Cone yield negatively correlates with density; although, the lowest density studied (500 trees ha^{-1}) is still too high to limit height growth, hindering cone harvest. In future research works, it would be important to identify the optimum planting density to enhance cone yield and facilitate harvest.

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