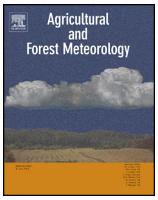
Agricultural and Forest Meteorology 214–215 (2015) 106–116

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Impact of climate and management variables on stone pine (*Pinus pinea* L.) growing in Chile

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ARTICLE INFO

Article history:
Received 11 March 2015
Received in revised form 29 July 2015
Accepted 8 August 2015

Keywords:
Climate impact
Stone pine plantations
Vegetative growth

ABSTRACT

Pinus pinea is an interesting species especially for its fruit production, which depends upon vegetative growth. Growth of this species was analyzed along a climatic gradient in Chile, in all sites where it was planted in the last century. Three macrozones (MZs) located in the north, south and coastal range were identified according to height and DBH growth rates. We also examined growth in relation to several climatic variables (annual and seasonal temperatures, thermal oscillation, rainfall and a hydric index measuring water stress) and two cultural practices (irrigation and pruning). The relative contribution of each variable on growth measurements was assessed through regression trees and linear models. Growth of stone pine showed marked differences among the three MZs. In the South MZ, growth rate was the highest for height (0.35 m year^{-1}) and DBH (1.50 cm year^{-1}), whereas in the Dry Coast MZ, the species showed the lowest growth rate in height (0.23 m year^{-1}) and DBH (0.87 cm year^{-1}). Temperature and rainfall had a high significant impact on height growth, which was favored by an annual average temperature below 14 °C, with high winter thermal oscillation (>14 °C), spring water deficit lower than 400 mm and annual rainfall over 1400 mm year^{-1}. DBH growth was also favored by an average annual temperature below 14 °C. Significant effects of pruning and irrigation were found. Stone pine growth throughout Chile was high compared to growth rates reported for other countries. However, in light of climate change, we should expect a reduction in growth rates especially in the North and Dry Coast MZs. Heat tolerance is proposed as a key breeding trait for increasing potential growth of stone pine.

1. Introduction

Stone pine (*Pinus pinea* L.) is a species well known for its role as colonizer and eroded soil stabilizer, and for the economic use of its edible pine nuts. It is native to the European Mediterranean area, and has evidenced an expansion over the last century, especially in the southern and eastern Mediterranean basin, as well as a large increase of planted areas in its origin countries through forest restoration and farmland afforestation (Boutheina et al., 2013). *P. pinea* is a highly interesting species given its multiple uses, and especially its fruit production, which depends upon vegetative growth. Pine nuts are the most expensive dried fruit in the world; with its demand increasing constantly. However, production is undergoing a significant reduction worldwide caused by *Leptoglossus occidentalis*, an insect native to North America, which has affected the species forests across the northern hemisphere. Another factor that may be threatening production is climate change, which is also causing a decrease in growth rates in its native habitat (Mutke et al., 2015).

The species was introduced in Chile by European immigrants (mainly Spaniards and Italians). Since the beginning of the 20th century, it has been used as a forest tree in a successful coastal sand dunes stabilization program (Albert, 1909) and was later included in other afforestation and rural development programs (Loewe and Delard, 2012).

As a result of these plantation activities, a total of 100 ha were established in Chile in different regions, settings (isolated trees, groves and forest plantations) and management conditions. Since the 1990s, a series of studies on stone pine were performed to assess its potential as an alternative crop to forest species (*Pinus radiata*

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http://dx.doi.org/10.1016/j.agrformet.2015.08.248
0168-1923/

or *Eucalyptus* sp.) or some fruit species (almonds or other higher water demanding species) for the Chilean Mediterranean zone, confirming its ecological adaptation expressed through a vegetative growth superior to the one presented in the main distribution areas across the world (Loewe et al., 1998, 2012, 2014; Loewe and González, 2003). Potential areas for its cultivation in the country were studied by Ávila et al. (2012), showing that the species can grow in more than 8.6 million hectares and that there are over 4.8 million hectares suitable for medium and high pine nut production level.

The species has been found to have a low provenance differentiation in relation to growth parameters, high phenotypic plasticity, tolerance to poor soils and to adverse climatic conditions such as drought and extreme or late frosts, and strong sensitivity to intra and interspecific competition (Thuiller et al., 2003; Mutke et al., 2008; Sánchez-Gómez et al., 2009; Boutheina et al., 2013). In particular, several authors (Gonçalves and Pommerening, 2012; Correia and Freire, 2014) have observed that the biggest trees produce more cones than smaller trees, being crown variables closely more related to cone production than age or tree density.

The study of growth dependence upon climatic and management variables is key for understanding the best conditions and practices for cultivation of stone pine with commercial purposes. More than one hundred years ago the species was characterized in several ecological aspects, including climatic characteristics, indicating that it prefers warm climates, with annual average temperature between 9 and 21 °C, low valleys and altitude under 1000 m a.s.l. (Romero and Gilsanz, 1888). Pardos et al. (2014) reported that, being a temperate pine, adult stone pine trees show a cyclic, preformed growth pattern occurring mainly in spring (in the northern hemisphere from April to early July). A correlation between tree-ring width and September–June rainfall was reported by Raventós et al. (2001), pointing out that the high correlation between tree growth and water availability is the main factor influencing the species growth under dune Mediterranean conditions. Accordingly, Gadbin (1994) indicated that spring rainfall favors diameter growth in the species, as well as autumn rainfall, but to a lower extent. In Turkey, Akkemik (2000) also reported a positive effect of the current annual rainfall and spring temperature on diameter growth. Other authors, such as Thuiller et al. (2003), stated the importance of extreme temperature and annual precipitations in the ability of this species, as well as other species, to survive and grow, defining its spatial distribution.

Despite the high growth reached by the species in Chile, no studies have addressed the relationship among growth performance and climatic and management variables; here, we make a contribution to the knowledge of these aspects. In this study, we addressed the following specific objectives: (i) to establish growth macrozones (MZs) for stone pine in Chile, (ii) to compare growth (height and DBH) responses to climate in relation to MZ climatic variability, and (iii) to assess growth response to management practices (irrigation and pruning) subjected to different climatic conditions.

2. Material and methods

2.1. Study area

Over the past years, given the interest for stone pine cultivation, the Chilean Forest Institute (INFOR) has been focused on a long-term, large-scale national research effort to gather data from Chile, covering the area between Coquimbo (30.819817 S°) and Araucanía (38.990393 S°) regions. Inventories of stone pine populations were performed including plantations, windbreaks, groves and isolated trees established for commercial and environmental purposes. As a result of a census, 143 sites were visited and 4094 trees of stone pine (*P. pinea* L.) were measured for diameter-at-breast-height (DBH) at 130 cm above the ground with a caliper, height with a hypsometer; vigor using a combination of foliage damage classes, including both needle losses and discoloration built based on the categories stated by Lakatos and Mirtchev (2014), as follows: (1) high, (2) medium, (3) low; straightness according to the methodology proposed by Toral et al. (2011) considering four categories: (1) straight, (2) curve < average, (3) curve > average, (4) very curved or double curved; biotic and abiotic damages through a visual observation following indications of Eichhorn et al. (2010); and age based on plantation data available from the owners. Plot establishment (100 tree plots whenever the formation contained more than 100 trees) and measurement methods followed those outlined by Prodan et al. (1997).

2.2. Identification of growth macrozones

For MZ identification study, a subset of 56 sites including 3030 measured trees in groves and plantations were selected, excluding isolated trees. A multivariate classification analysis was performed on sites, including average height and DBH growth rates as well as site spatial coordinates. The analysis was performed with Unweighted Pair Group Method with Arithmetic Mean (UPGMA) clustering (Johnson and Wichern, 2007) using Euclidean distance. UPGMA is used for the classification of sampling units on the basis of their pairwise similarities in the descriptor variables; the potential distortion produced in the clustering process is estimated by the cophenetic correlation (Sneath and Sokal, 1973).

In each cluster a spatial autocorrelation analysis was performed for DBH and height annual growth rates of stone pine trees growing in comparable conditions, considering trees in groves and plantations with comparable management practices. Spatial correlation models, including Gaussian, Linear, Spherical and Exponential (Schabenberger and Gotway, 2004), were adjusted to model the spatial variability. Among the adjusted models the exponential model was the best according to the Akaike Information Criteria (Anderson, 2007). Variability maps were constructed using Kriging interpolation for each variable according to the exponential model. Using the site classification as initial information, the total area with stone pine formations in Chile was divided into three MZs by elaborating convex polygon contour conecting the most distant sites inside each cluster. After drawing empirical polygons, we delimited the MZs with further details based on topography (water courses), proximity to the Andes Mountain chain and limits established in a previous study (Ávila et al., 2012). Fig. 1S presents the MZ map overlapping administrative regions and agro-ecological zones previously defined by Hajek (1991).

2.3. Analysis of the impact of climatic variables and management practices on stone pine growth

To estimate the potential impact of climatic and management variables on stone pine growth, climatic information data were built based on the Environmental Information Network of Chile.[1] Datasets containing relevant environmental predictors were available in GIS grid format at a resolution of 500 m × 500 m and comprised 50 climate variables and altitude (ALT). All environmental variables were resampled according to the WGS 1984-UTM Zone 19S geographical coordinate system at a resolution of ~10 m. The recorded meteorological data were: annual average

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[1] http:\\www.dga.cl.

temperature (TAT); annual maximum average temperature (TXT); annual maximum absolute temperature (TXAT); annual minimum average temperature (TNT); annual minimum absolute temperature (TNAT); annual total rainfall (TAR); annual potential evapotranspiration (ETP); number of dry months; an annual hydric index (THI) as an indicator of water deficit (Rainfall-ETP); and the annual thermal oscillation (TTO). All climatic variables were also built by season (winter, spring, summer and autumn).

Climatic data were obtained from a 10-year climatic series from the meteorological station closest to the study site, 20 km being the average distance to the selected meteorological station. Other criteria, such as information on topography and bioclimatic areas (Uribe, 2012), were used to decide whether the climate at the weather station was representative of the site being evaluated. Site altitude was assigned to one of five classes: 0–400; 400–800; 800–1200; 1200–1600; and over 1600 m a.s.l.

The surrounding vegetation was characterized using average values of four vegetation indices: Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), Normalized Canopy Index (NCI) and Green Normalized Difference Vegetative Index (GNDVI) (INEGI, 2013) calculated for a 30-m radius neighborhood from the evaluated stone pine trees, obtained from Landsat 5 TM and 7 ETM+ images for average seasonal values (winter, spring, summer and autumn) from a 7-year database (2006–2012). Regarding management practices, we recorded presence/absence of irrigation (35% of trees) and pruning (traditional trunk cleaning in 39% of trees). The analysis did not consider fertilization or thinning, since only 3% of trees were fertilized and 1% thinned. Of the 143 sites, 14 sites were discarded after the identification of outliers (values outside of range of mean ± 3SD). The dropped sites showed data outside the expected range for density (over 2500 trees ha^{-1}) or growth (over 2.5 cm year^{-1} in DBH or 1 m year^{-1} in height).

The relative variable contribution was estimated using CART (Classification and Regression Trees) algorithm (Breiman, 2001). CART is an analytic approach used to assess causes of variation for a response variable. It is named “classification tree” when the response variable is categorical and “regression tree” when the response to be explained is continuous, such as height and DBH annual growth. A regression tree can be built by using several variables as predictors which can be correlated, as is frequently the case when working with climatic variables. Moreover, in this method, the response variable is not necessarily modeled as a linear function of the predictors; on the contrary, the model is a piecewise constant function. Unlike regression models, CART allows us to work under multi-collinearity and non-linear relationships among variables. During data processing, the whole data (root node) are first split into two subsets based on the predictor variable and the value of that variable (threshold) that optimizes the explanation of the response variable. Each subset (daughter node) is then analyzed independently using the same binary partitioning procedure and recursively until a stop criterion is reached. The result of this recursive binary partitioning is a model whose structure can be displayed as a tree-like graph, with each split in the tree labeled according the variable and threshold used to define the split. CARTs have been successfully used to model growth and yield from highly correlated climatic variables (Lobell et al., 2005; Heredia et al., 2010).

For each variable identified as relevant to explain growth according to the regression trees, we performed an ANOVA to analyze the average growth differences between the two conditions defined by the threshold of each explanatory variable using data from all sites and without conditioning upon other climatic variables. Categorical data were analyzed using a Chi square test. The analyses were performed using the software INFOSTAT and its interface with the software R (Di Rienzo et al., 2013).

3. Results

3.1. Growth macrozones

Four groups of sites with stone pine formations were identified regarding DBH and height growth rates (Fig. 1). The cophenetic correlation coefficient was higher than 0.9. Considering geographical proximity of sites from clusters 3 and 4, and that cluster 4 sites correspond to special growth site conditions in the southern area, we defined three clusters of sites. Growth of stone pine shows marked differences among the three areas, one located in the north, another in the south and the remaining one in the coastal range, between the other two groups; they were named North, South and Dry Coast, respectively.

Stone pine growth MZ total area reaches 11,505,611 ha, and is included in agro-ecological zones according to the following distribution: Desert (0%), Arid (12.2%), Mediterranean (64.4%), Humid temperate (23.4%) and Dry temperate (0%) (Fig. 1S). The North MZ is delimited between the IV and Metropolitan regions and in the central valley between the VI and VII regions. The Dry Coast MZ is located between the VI and VII regions in areas with marine influence, including Cauquenes province, whereas the South MZ includes VIII and IX, and part of the southeastern VII (Fig. 2).

Mapping of the spatial variability of DBH and height growth rate showed a higher spatial variability in DBH growth than in height growth. We did not observe spatially structured variability for annual height growth on the Dry Coast MZ (spatial variability model or spatial autocorrelation was not significant, $p > 0.05$).

The characterization of stone pine growth and the surrounding vegetation (NDVI) by MZs is presented in Table 1. Growth was higher in the South MZ, and lower in the intermediate Dry Coast MZ; high values in the North MZ can be explained by the wide latitudinal range of this MZ (including five regions, from Coquimbo to Maule) and by the presence of some plantations with irrigation.

In most of the plantations, independently of the MZ, damage by wind, frost and branch breaking derived from trunk or branch inclination for reaching light was observed. No damage by pests or diseases was detected. Regarding vigor, 62.8% of the studied trees presented high vigor. The highest vigor was found in the South MZ (74.1%), and the lowest (44.4%) in the Dry Coast MZ. Contrarily, straightness was higher in the Dry Coast MZ, where trees presented the lowest growth rates.

NDVI values represent the environment vegetation condition. We observed that NDVI recorded in the study areas, and independently of seasonal variations, always increased from north to south. Winter is the season with highest rainfall in the distribution area of the species in Chile. The observed winter NDVI values are relatively high in all MZs; particularly in the South MZ, where NDVI values were also high in spring. Similar observations were derived from the other vegetation indices and for the stone pine crown area.

The climatic characterization by MZ (Table 2) shows a higher variability of climatic variables between sites of the North MZ. Annual average and annual maximum temperatures decreased from north to south. On the other hand, the annual minimal average temperature was lowest in the Dry Coast MZ. Rainfall increased from north to south, and simultaneously the hydric indices diminished from north to south, suggesting lower water stress in the South MZ. Spatial variability of rainfall was higher than temperature variability.

3.2. Analysis of the impact of climate and management variables on stone pine growth

3.2.1. Height

Considering all sites (Fig. 3a), annual average temperature (TAT) was the variable with highest contribution in explaining height

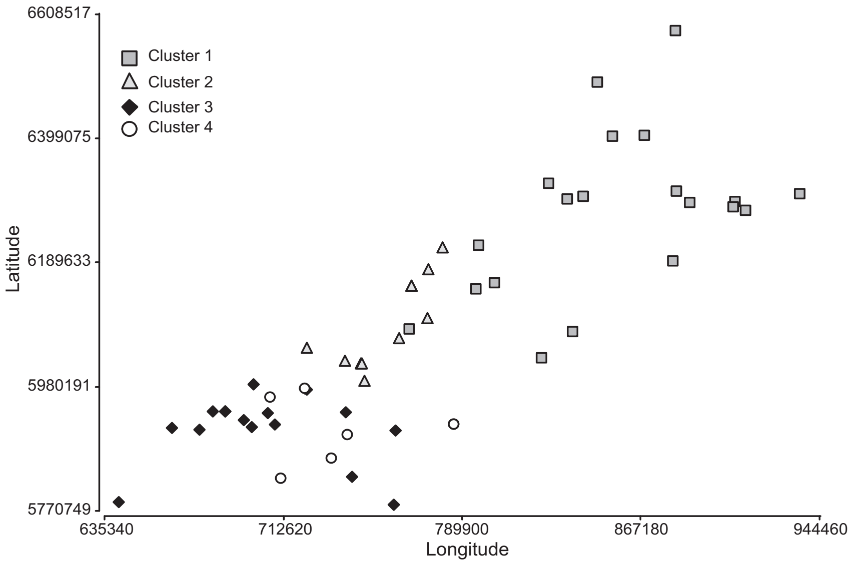


Fig. 1. Spatial site dispersion. Sites are grouped according to pairwise similarities in DBH and height growth identified by cluster analysis.

growth. Height growth diminished at TAT higher than 14.3 °C, with the estimated annual average growth being 36 cm year^{-1} and 21 cm year^{-1} when TAT was lower and higher than this threshold, respectively. The second variable with explanatory potential of height growth was winter thermal oscillation (WTO), with a value above 14.3 °C favoring growth (79 versus 35 cm year^{-1} for higher or lower WTO than that threshold, respectively). The highest height growth was observed at winter thermal oscillation lower

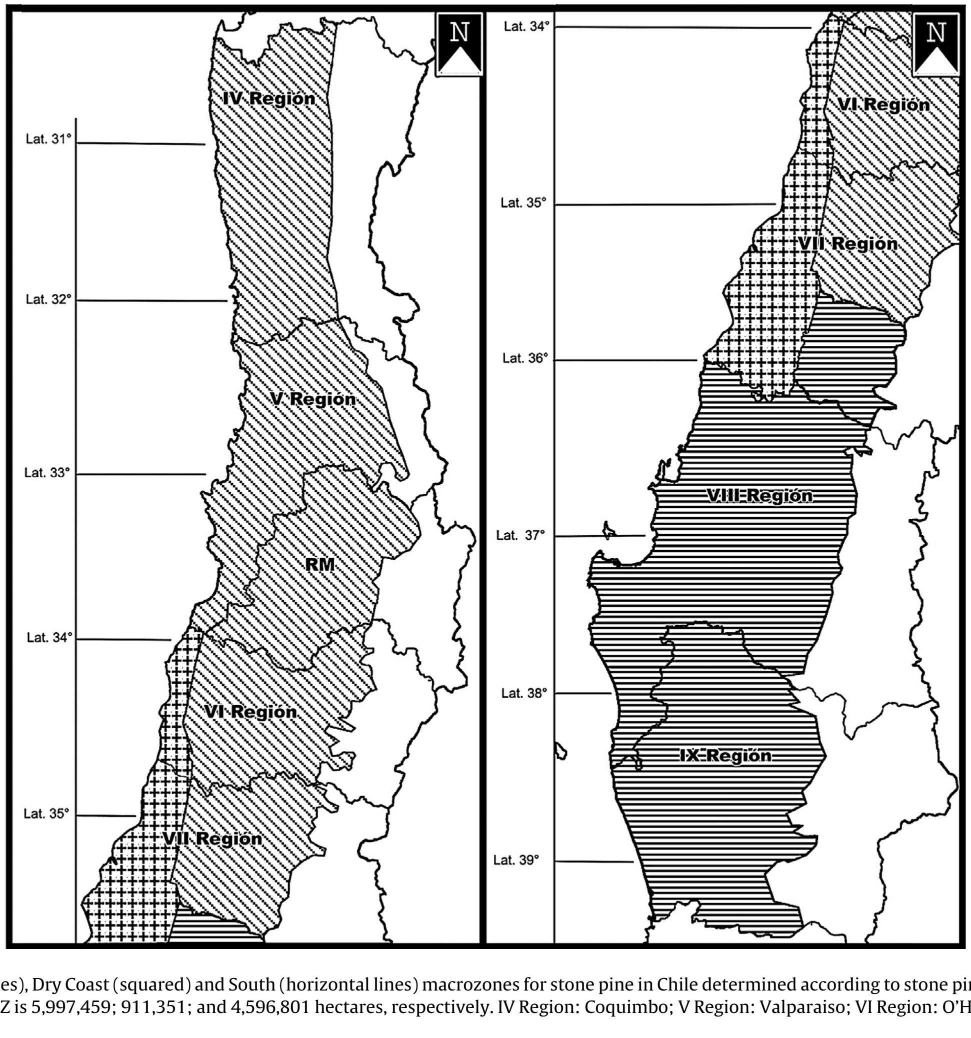


Fig. 2. North (diagonal lines), Dry Coast (squared) and South (horizontal lines) macrozones for stone pine in Chile determined according to stone pine DBH and height growth rates. Total area of each MZ is 5,997,459; 911,351; and 4,596,801 hectares, respectively. IV Region: Coquimbo; V Region: Valparaiso; VI Region: O'Higgins; VII Region: Maule; VIII Region: Bio Bio.

Table 1
Characterization of stone pine growth and the surrounding vegetation index (NDVI) by macrozone.

	North MZ ($n = 48$)	Dry Coast MZ ($n = 27$)	South MZ ($n = 54$)	All sites ($n = 129$)
Stone pine growth				
Height growth (m year^{-1})	0.34 (55)	0.23 (61)	0.35 (35)	0.32 (49)
DBH growth (cm year^{-1})	1.21 (49)	0.87 (45)	1.50 (29)	1.24 (43)
Crown area (m^2 tree^{-1})	83.0 (116)	95.9 (105)	113.7 (95)	98.5 (104)
Vigor (% by category)	1:60.4 2:31.3 3:8.3	1:44.4 2:37.0 3:18.5	1:74.1 2:24.1 3:1.9	1:62.8 2:29.5 3:7.8
Straightness (% by category)	1:8.32:33.33:56.34:2.1	1:0.02:48.13:40.74:11.1	1:1.92:40.73:42.64:14.8	1:3.92:39.53:47.34:9.3
Trees with abiotic damage (%)	2.8	4.4	3.5	3.6
NDVI				
Autumn	0.11	0.20	0.22	0.17
Winter	0.18	0.30	0.32	0.26
Spring	0.15	0.25	0.33	0.25
Summer	0.16	0.19	0.27	0.21

Values in parentheses correspond to coefficient of variation (CV). Vigor: (1) high, (2) medium, (3) low. Straightness: (1) straight (2) curved < average, (3) curved > average, (4) very curved or double curved. Season definitions: Autumn: March 21st to June 20th; Winter: June 21st to September 20th; Spring: September 21st to December 20th; and Summer: December 21st to March 20th.

Table 2
Climatic characterization of stone pine growth macrozones in Chile.

Variable	North MZ ($n = 48$)	Dry Coast MZ ($n = 27$)	South MZ ($n = 54$)	All sites ($n = 129$)
Annual average Temp. (°C) (TAT)	14.1 (11.8; 16.7)	13.6 (12.5; 15.1)	13.2 (11.0; 14.2)	13.6 (11.0; 16.7)
Annual max average Temp. (°C) (TXT)	21.9 (17.6; 25.1)	21.0 (17.9; 23.0)	19.8 (16.3; 22.5)	20.8 (16.3; 25.1)
Annual min average Temp. (°C) (TNT)	7.5 (5.5; 9.9)	7.0 (5.5; 7.7)	7.5 (5.3; 9.2)	7.4 (5.3; 9.9)
Annual total rainfall (mm)(TAR)	383.7 (116.2; 1260.1)	648.3 (416.3; 816.0)	1047.0 (523.6; 1666.9)	716.7 (116.2; 1666.9)
Spring rainfall (mm) (PTR)	37.2 (1.5; 143.9)	61.8 (38.4; 89.8)	131.8 (80.8; 218.9)	81.9 (1.5; 218.9)
Summer rainfall (mm) (STR)	8.42 (0; 36.4)	29.1 (10.3; 46.3)	58.6 (31.7; 113.0)	33.8 (0.0; 113.0)
Annual hydric index (mm) (THI)	−995.4 (−1349.7; −107.3)	−743.7 (−914.4; −474.2)	−244.1 (−736.4; −332.9)	−628.2 (−1349.7; 332.9)
Spring hydric index (mm) (PHI)	−394.1 (−483.7; −269.5)	−376.9 (−439.5; −269.9)	−267.7 (−346.4; −121.3)	−337.1 (−483.8; −121.3)
Summer hydric index (mm) (SHI)	−485.8 (−563.1; −328.3)	−460.4 (−571.3; −332.6)	−399.9 (−517.7; −260.5)	−444.1 (−571.3; −260.4)
Annual thermal oscillation (°C) (TTO)	14.3 (9.2; 17.3)	14.0 (10.7; 17.0)	12.3 (8.2; 15.1)	13.4 (8.2; 17.3)

Values in parentheses correspond to minimum and maximum values recorded per variable. Hydric index was calculated as accumulated rainfall minus potential evapotranspiration in the period.

than 14.3 °C, and with low values of the annual hydric index (THI), meaning a lower water deficit, being 43 and 33 cm year^{-1} for a lower and higher deficit, respectively. In sites with higher water deficit, rainfall over 1398 mm year^{-1} favored height growth, the average height growth in each node being 51 and 32 cm year^{-1}, respectively.

The analysis by MZ (Fig. 3b) shows that the most relevant variable in the North MZ for height growth is the same as for all the study area, annual average temperature, with height growth values relatively low (22 cm year^{-1}) if TAT was higher than 14.3 °C, a situation in which irrigation was favorable (16 versus 28 cm year^{-1}, without and with irrigation, respectively). When TAT was lower than 14.3 °C, the average growth was 43 cm year^{-1}. In this situation, we found seven sites with extreme spring water deficit, but with high height growth (62 cm year^{-1}) due to the presence of irrigation. Sites with spring hydric indices above −400 mm (also indicating water deficit situations) were favored by higher accumulated annual rainfall (TAR) (above 468 mm year^{-1}), showing better height growth than those with lower TAR (46 versus 32 cm year^{-1}).

Height growth in the Dry Coast MZ was most influenced by spring water deficit, being lower if it was above −409 mm (averages of 15 and 23 cm year^{-1}, respectively). When spring water deficit was under that threshold, we observed the effect of pruning (26 versus 22 cm year^{-1} according to pruned or unpruned trees).

In the South MZ the accumulated annual rainfall (TAR) was an explanatory variable of height growth, striking positively when it was over 1398 mm year^{-1} (51 versus 34 cm year^{-1}). When TAR was lower than that threshold, height growth was favored by minimum annual average temperatures above 6.3 °C (34 versus 21 cm year^{-1}), and by irrigation (40 versus 33 cm year^{-1}).

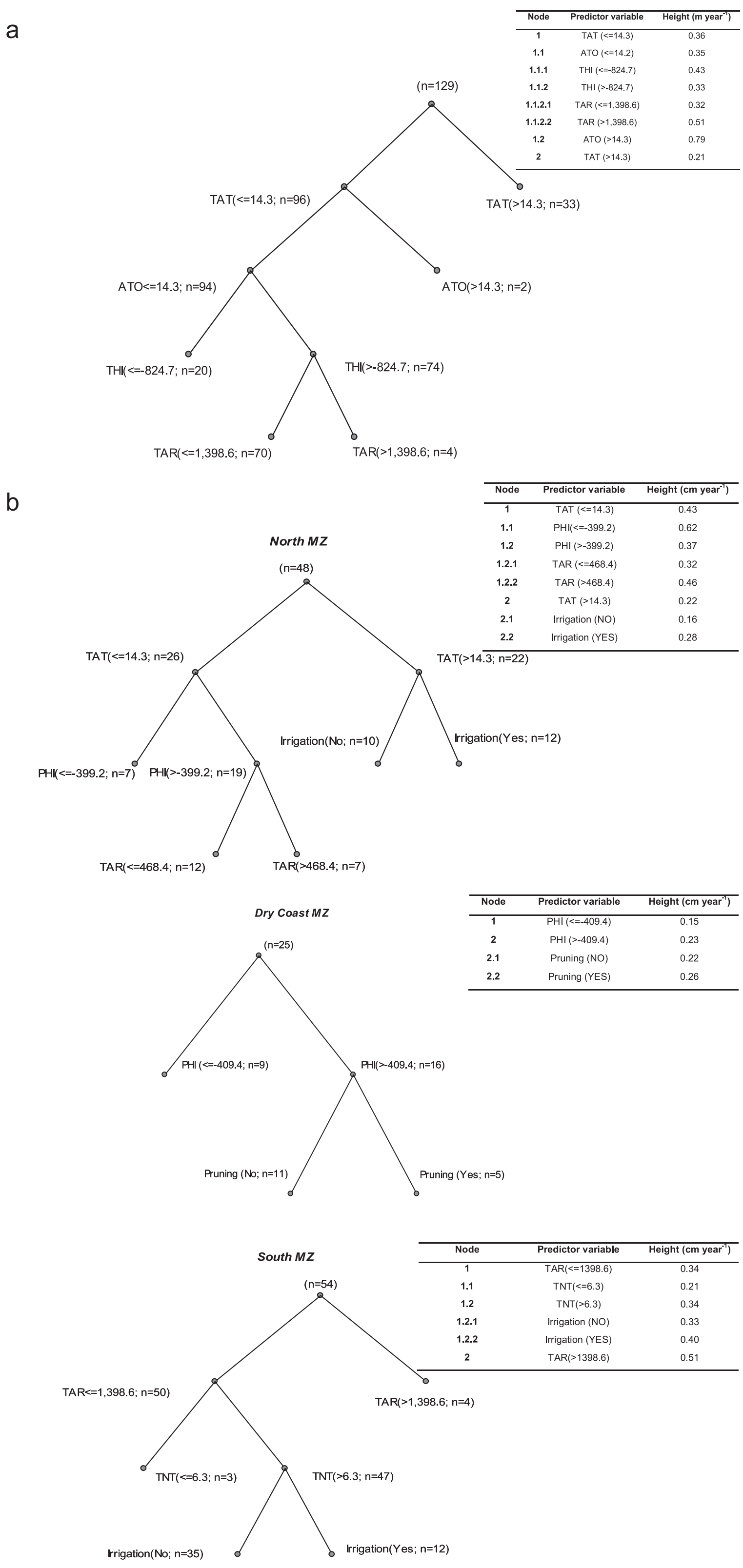
Overall, growth limiting factors were dependent on MZs. TAT was the most relevant factor in the North MZ, with irrigation being a recommended practice in sites with TAT above 14.3 °C. In the Dry Coast and South MZs the water stress index and the accumulated rainfall were the most important climatic variables to explain height growth, respectively. Management practices of pruning in the Dry Coast MZ and irrigation in the South MZ favored height growth.

The variables suggested as potential to explain height growth by the regression trees were further analyzed with ANOVA. The results (Fig. 4) showed differences in statistically significant height growth between sites with values above and below 14.3 °C for winter annual thermal oscillation, with height growth reached being under a high winter thermal oscillation (WTO), 163% higher than that observed in sites with low WTO. Statistically significant differences were also found between sites with annual total rainfall above and below 1398 mm year^{-1}, with growth being 70% higher in sites with rainfall above that value. Growth in sites with annual average temperature below 14.3 °C was 67% higher. Differences of more than 30% in growth were observed between weather conditions defined by spring annual hydric index and annual minimum average temperature.

Height growth was reduced with altitude. Even though this reduction was one third when altitude was over 1200 m a.s.l., differences in average growth rate among altitude categories were not statistically significant ($p > 0.05$).

3.2.2. DBH

Considering all the studied sites (Fig. 5a), the variable that best explained DBH growth was annual average temperature (TAT), with this growth decreasing in sites with TAT above 14.3 °C. Thus, sites favorable for height growth were also the most favorable for DBH growth in Chile. Average DBH growth values of 0.92



Node	Predictor variable	Height (m year^{-1})
1	TAT (<=14.3)	0.36
1.1	ATO (<=14.2)	0.35
1.1.1	THI (<=-824.7)	0.43
1.1.2	THI (>-824.7)	0.33
1.1.2.1	TAR (<=1,398.6)	0.32
1.1.2.2	TAR (>1,398.6)	0.51
1.2	ATO (>14.3)	0.79
2	TAT (>14.3)	0.21

Node	Predictor variable	Height (cm year^{-1})
1	TAT (<=14.3)	0.43
1.1	PHI(<=-399.2)	0.62
1.2	PHI (>-399.2)	0.37
1.2.1	TAR (<=468.4)	0.32
1.2.2	TAR (>468.4)	0.46
2	TAT (>14.3)	0.22
2.1	Irrigation (NO)	0.16
2.2	Irrigation (YES)	0.28

Node	Predictor variable	Height (cm year^{-1})
1	PHI (<=-409.4)	0.15
2	PHI (>-409.4)	0.23
2.1	Pruning (NO)	0.22
2.2	Pruning (YES)	0.26

Node	Predictor variable	Height (cm year^{-1})
1	TAR(<=1398.6)	0.34
1.1	TNT(<=6.3)	0.21
1.2	TNT(>6.3)	0.34
1.2.1	Irrigation (NO)	0.33
1.2.2	Irrigation (YES)	0.40
2	TAR(>1398.6)	0.51

Fig. 3. (a) Climatic variables that best explained height annual growth across the stone pine distribution in Chile (all sites). Total growth data were first split into two subsets based on the predictor variable (TAT) and its threshold (14.3). Each subset, or node, was then analyzed independently using the same procedure. Variables making top nodes are the most important to explain growth rates. Average height growth rates for each node are reported in the embedded table. TAT: annual average temperature; ATO: autumn thermal oscillation; THI: annual hydric index; TAR: annual total rainfall. (b) Climatic variables that best explained height annual growth by stone pine macrozones in Chile. For each MZ, total growth data were first split into two subsets based on the predictor variable (TAT, PHI and TAR for North, Dry Coast and South MZs, respectively) and its thresholds (14.3 °C; −409.4 mm and 1398.6 mm, respectively). Each subset, or node, was then analyzed independently using the same procedure. Variables close to top nodes are the most important to explain growth rates. Average height growth rates for each node are reported in the embedded tables. TAT: annual average temperature; PHI: spring hydric index; TAR: annual total rainfall; TNT: annual minimum average temperature.

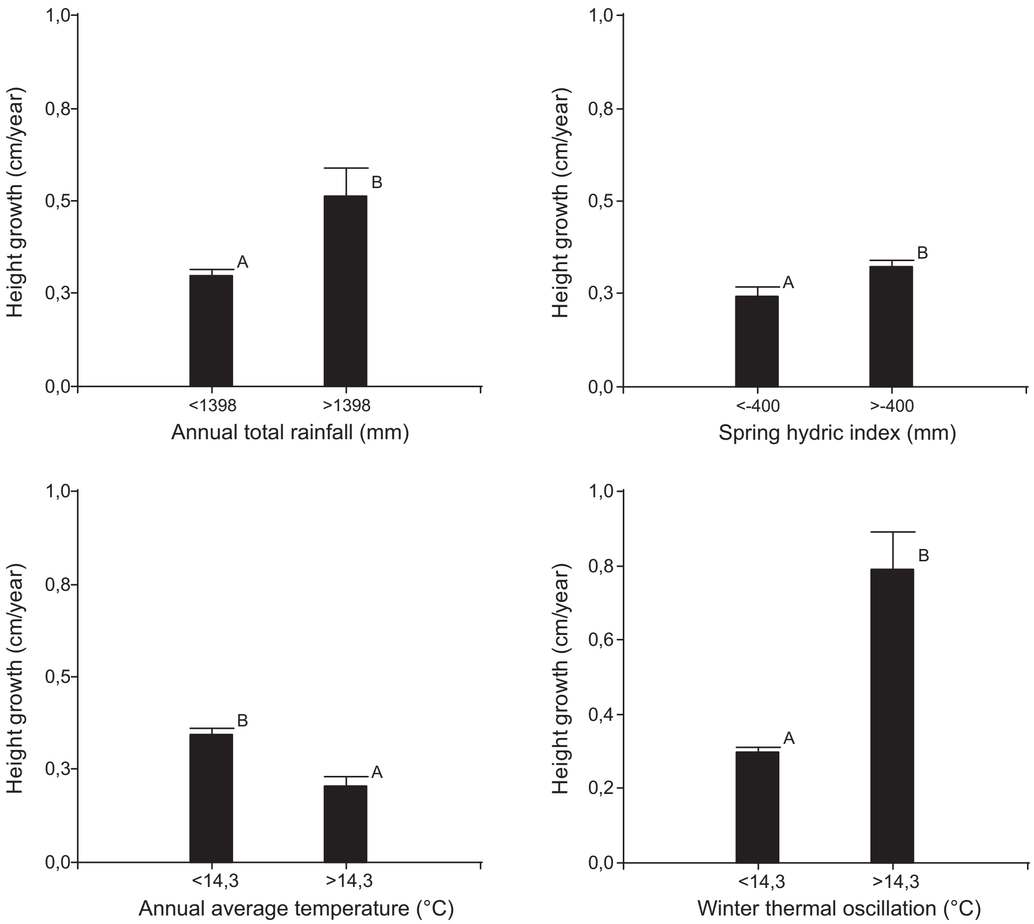


Fig. 4. Climatic variables affecting height growth. Each threshold was detected by means of CART analyses using data from all sites without conditioning upon other climatic variables. Different letters indicate statistically significant differences ($p < 0.05$).

and 1.37 cm year^{-1} were found above and below the TAT threshold value. In sites with TAT values below the threshold, DBH growth was higher when annual water deficit (THI) was lower than 1100 mm (2.60 versus 1.34 cm year^{-1}, respectively). In sites with water deficit above that threshold, DBH growth was favored by irrigation, with averages of 1.56 and 1.25 cm year^{-1} with and without irrigation, respectively. In plantations without irrigation, there was a positive impact of accumulated annual rainfall (1.43 versus 0.98 cm year^{-1} above and below 781 mm year^{-1}, respectively).

The analysis by MZ (Fig. 5b) shows that for DBH growth the most relevant environmental variable in North MZ was annual minimal average temperature, with a threshold of 5.8 °C, with DBH growth values of 1.97 and 1.10 cm year^{-1} below or above that TNT threshold. DBH growth in the Dry Coast MZ was also influenced by annual average temperature, with higher growth at TAT below 12.8 °C (0.99 versus 0.79 cm year^{-1}). In the South MZ maximum annual average temperature was important to explain growth. High DBH growth was recorded with relatively high temperatures; in fact, the highest growth took place with maximum temperatures above 17.8 °C but below 19.6 °C (1.81 cm year^{-1}).

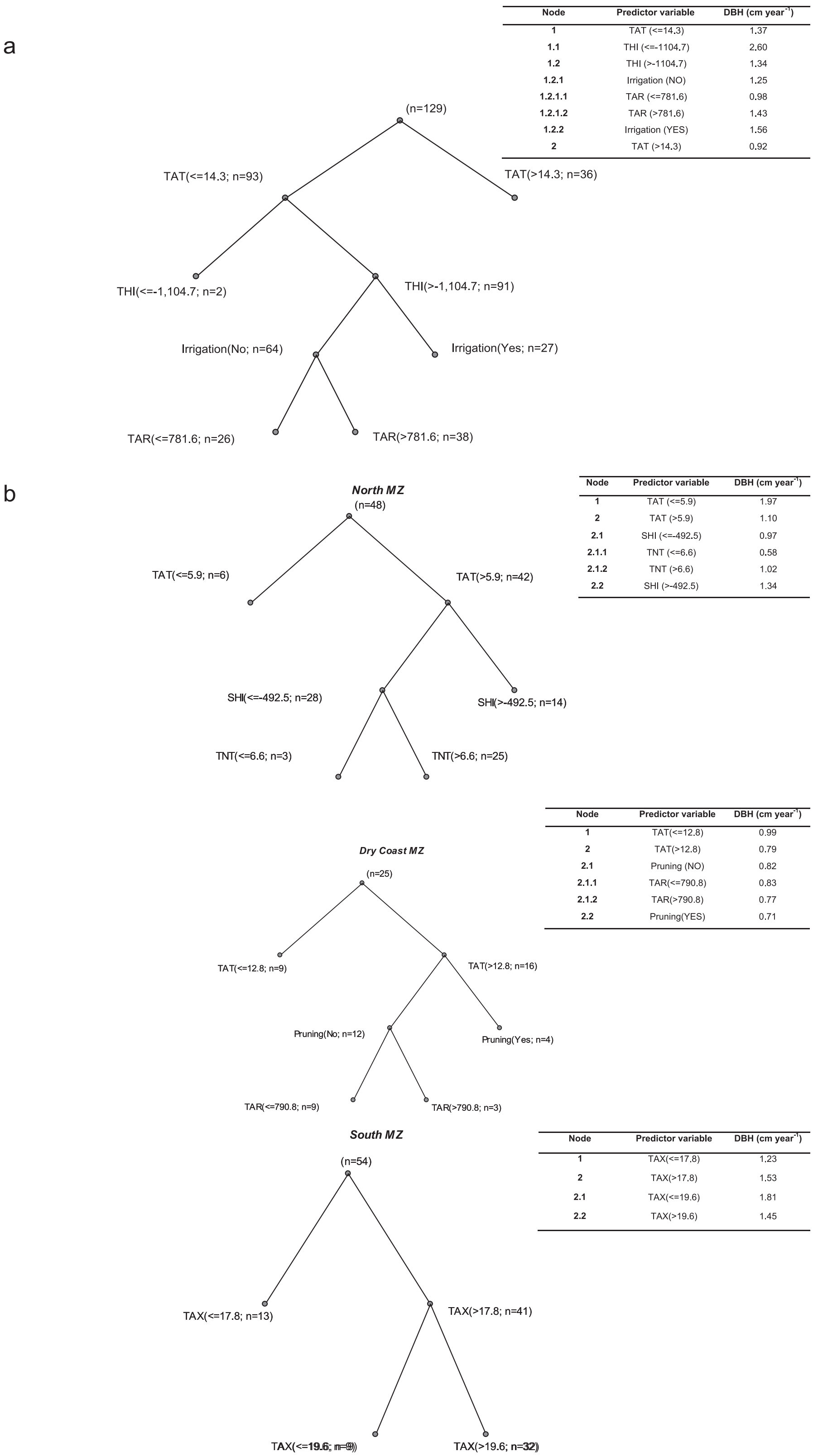
Therefore, in all MZs the highest average, minimum or maximum annual temperatures were found to be the most limiting DBH growth factors. At all sites, the impact of annual average temperature was indicated by a mean difference of 3.6 mm year^{-1} between sites at above and below TAT of 14.3 °C (Fig. 6).

DBH growth was reduced from an altitude of 800 m a.s.l. and higher, with statistically significant ($p \leq 0.05$) differences among categories 400–800 (1.43 cm year^{-1}) and over 1600 m a.s.l. (0.60 cm year^{-1}).

4. Discussion

The stone pine growth rates observed in Chile were found to be higher than in other parts of the world, including its native habitat. In fact, the average DBH growth of 1.24 cm year^{-1} is higher than the one reported in Spain (0.9 cm year^{-1} at 40 years old in good sites) (Montero and Candela, 1998) and in plantations in Morocco (1 cm year^{-1}) (FAO, n.d.) and Tunisia (0.8 cm year^{-1} in coastal dunes) (Boutheina et al., 2013). Mean height growth in Chile reached 32 cm year^{-1}, which is similar to the best situations in Italy, where reported DBH growth values range between 19 and 35 cm year^{-1} (Bianchi et al., 2005).

In this study, we established three growth MZs for stone pine in Chile. The approach of establishing macrozones for the study of stone pine was also performed in Spain by Sánchez-Palomares et al. (2013), who classified the species as megamesothermic (potential evapotranspiration over 700 mm). However, the average annual temperature in Spain was higher than the values found in the current distribution area of Chilean stone pine. Annual average temperature in all Chilean MZs (14.1 °C in the North, 13.6 °C in the Dry Coast and 13.2 °C in the South MZs) are within the temperature interval described by Guzmán et al. (2013) for stone pine in Spain (12.4–18.5 °C). Regarding maximum temperatures, these authors define the average maximum temperature of the warmest month at between 26.4 and 37.3 °C, and Manes et al. (1997) report significant depression in its photosynthetic capacity in response to hot summer days. In our study, however, we found that the maximum annual average temperature varied between 19.8 in the South MZ and 21.9 °C in the North MZ.



Node	Predictor variable	DBH (cm year^{-1})
1	TAT (<=14.3)	1.37
1.1	THI (<=-1104.7)	2.60
1.2	THI (>-1104.7)	1.34
1.2.1	Irrigation (NO)	1.25
1.2.1.1	TAR (<=781.6)	0.98
1.2.1.2	TAR (>781.6)	1.43
1.2.2	Irrigation (YES)	1.56
2	TAT (>14.3)	0.92

Node	Predictor variable	DBH (cm year^{-1})
1	TAT (<=5.9)	1.97
2	TAT (>5.9)	1.10
2.1	SHI (<=-492.5)	0.97
2.1.1	TNT (<=6.6)	0.58
2.1.2	TNT (>6.6)	1.02
2.2	SHI (>-492.5)	1.34

Node	Predictor variable	DBH (cm year^{-1})
1	TAT(<=12.8)	0.99
2	TAT(>12.8)	0.79
2.1	Pruning (NO)	0.82
2.1.1	TAR(<=790.8)	0.83
2.1.2	TAR(>790.8)	0.77
2.2	Pruning(YES)	0.71

Node	Predictor variable	DBH (cm year^{-1})
1	TAX(<=17.8)	1.23
2	TAX(>17.8)	1.53
2.1	TAX(<=19.6)	1.81
2.2	TAX(>19.6)	1.45

Fig. 5. (a) Climatic variables that best explain DBH annual growth along the stone pine distribution in Chile (all sites). Total growth data were first split into two subsets based on the predictor variable (TAT) and its threshold (14.3). Each subset, or node, was then analyzed independently using the same procedure. Variables close to top nodes are the most important to explain growth rates. Average DBH growth rates for each node are reported in the embedded table. TAT: annual average temperature; THI: annual hydric index; TAR: annual total rainfall. (b) Climatic variables that best explain DBH annual growth by stone pine macrozones in Chile. For each MZ, total growth data were first split into two subsets based on the predictor variable (TAT, TAT and TAX for North, Dry Coast and South MZs, respectively) and its thresholds (5.9; 12.8 and 17.8 °C, respectively). Each subset, or node, was then analyzed independently using the same procedure. Variables close to top nodes are the most important to explain growth rates. Average DBH growth rates for each node are reported in the embedded tables. TAT: annual average temperature; SHI: summer hydric index; TNT: annual minimum average temperature; TAR: annual total rainfall; TAX: annual average maximum temperature.

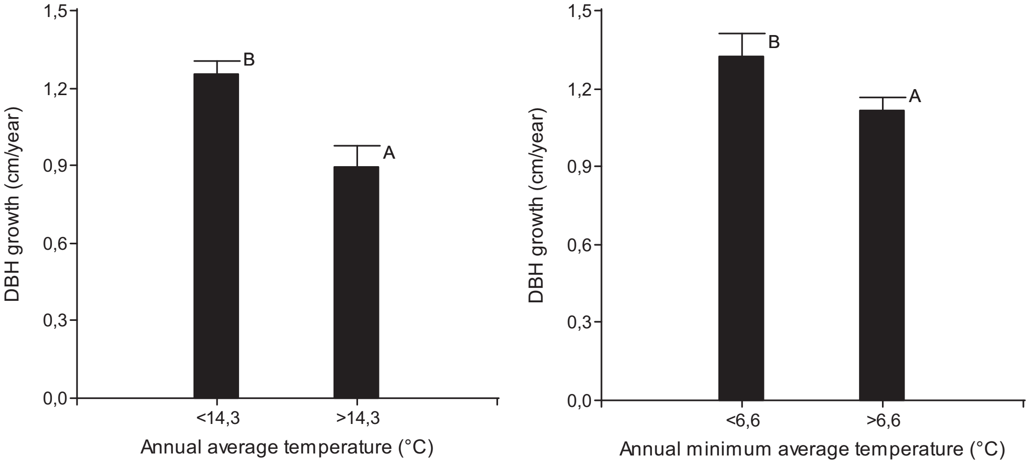


Fig. 6. Climatic variables impacting DBH growth. Each threshold was detected by means of CART analyses using data from all sites without conditioning upon other climatic variables. Different letters indicate statistically significant differences ($p < 0.05$).

For annual hydric deficits, Guzmán et al. (2013) set limits between 242 and 744 mm; however, in our study we found it to be 244 mm in the South MZ and 995 in the North MZ, being coincident in the south but much higher in the northern area where the species is also present. Those authors defined limits for accumulated annual rainfall between 284 and 1327 mm; in our study we found this value to be 384 mm in the North MZ, 648 mm in the intermediate MZ (Dry Coast) and 1047 in the South MZ. As for summer rainfall, they set limits between 15.6 and 64.4 mm, whereas in our study we found it to be considerably lower in the northern area (8.4 mm), 29.1 mm in the intermediate one, and 58.6 mm in the southern area.

We found different growth response patterns to climate for the three defined MZs, with different effects for xeric, mesic and intermediate environments (Figs. 3a, b and 5a, b), as described by Pasho et al. (2012). According to Castillo et al. (2002), the fact that almost no impact of summer drought was detected in our study, with the exception of height growth in the North MZ at TAT above 14.3 °C, can be due to the species adaptation to long drought periods in Mediterranean areas through a deep root system that allows it to reach deep water resources, as well as to some sites under irrigation in the northern area. Contrarily to our findings, Álvarez et al. (2013) found that maximum temperature in the growing season negatively affected *P. radiata* growth in Chile. They reported that sites with the highest productivities had the lowest annual water deficits, concluding that the most efficient use of water and light is found at sites with best rainfall distribution and highest soil water content, and that the most productive sites for this species are located on the western border of the coastal range, the piedmont of the Andes and the southernmost area, near 39–40° South latitude. Similar results were found for stone pine in our study.

Long and severe dry seasons and associated water shortages could seriously affect tree growth (Osborne et al., 2000) and particularly stone pine, as pointed out by Bussotti et al. (1995). Our results showed that with annual total rainfall above 1398 mm, height growth is 70% higher than that observed in sites with lower precipitation.

Accordingly, Mazza and Manetti (2013) reported the influence of low precipitation as the main factor driving tree diameter growth decline, an effect that was also found over longer periods, when stone pine can no longer obtain water from the soil by intensively exploring the ground at different levels. El-Khorchani et al. (2007) also stated the impact of hydric balance on diameter growth; and water stress can be intensified in sandy soils where water availability decreases drastically in dry years (Thabeet et al., 2007). In Chile, this was the case of the Dry Coast MZ. Mazza and Manetti (2013) concluded that a higher water stress induced by an increase in air temperature and a decrease in rainfall for successive years could seriously affect the species tree growth. Those results are in agreement with our findings on height growth, which showed differences above and below a spring hydric index threshold of −400 mm. Bjorn et al. (1997) explain this effect, stating that plants respond to summer water stress with extensive needle loss and photosynthetic capacity of the remaining needles.

Our study showed that annual average temperature is a relevant variable for DBH growth, with a threshold of 14.3 °C, being higher under that value. In Tunisia, Thabeet et al. (2007) report a negative correlation between average temperature and growth, but with a superior threshold (16 °C). In a study on the variation of stone pine productivity in relation to climate in Spain, Natalini et al. (2013) found that winter and spring rainfalls were positive to growth, whereas high spring temperature was negative. These authors found that stone pine growth is positively correlated to Palmer Drought Severity Index (PDSI) and with annual rainfall, and negatively correlated to maximum average annual temperature, which agrees with our findings for height growth in Chile. At a monthly and seasonal scale, they found a positive correlation of growth with winter, spring and October rainfall, as well as with winter average and minimum temperatures, and a negative correlation with spring and beginning of summer (June) temperatures. No significant correlations were found among growth and summer climatic variables, as in the present work. Similarly, Awada et al. (2003) found a significant height increase in response to shade in Greece.

Sánchez-Miranda et al. (2006) found in another conifer, *Abies alba*, that diameter growth is more dependent upon temperatures than rainfall, which is in agreement with our results. We found that the effect of annual minimum average temperature was relevant both for height and DBH, with thresholds of 6.3–6.6, respectively, with growth being significantly higher under those values. These results may exclude intensive frosts (−5 to −15 °C), since they cause root damage in the species, as reported by Oliet et al. (2014). Similarly, Galli et al. (1992) report a clear and consistent correlation among radial growth and winter severity (monthly minimum average temperature), establishing that a decrease of 1 °C would cause a 13% decrease in ring width.

Even though these findings are relevant to decide where to cultivate the species, it should be considered that functional processes, including the response to climatic conditions, are closely related to tree dimensions (physiological control) and that they undergo changes as the tree ages (genetic control) (De Luis et al., 2009). In fact, it has been shown that the size of the tree is more important than its age (Peñuelas, 2005).

This study did not include soil variables based on a previous study conducted in Chile (Ávila et al., 2012), which shows that the species grows well in different soil types, including clay ones, contrarily to findings reported by several authors, which indicate clay content as a limiting factor (Abellanas, 1990; Gandullo and Sánchez-Palomares, 1994; Gordo et al., 2009). Overall, the lowest growth was observed in the Dry Coast MZ where most of the soils are sandy and granitic, with lower water availability than in the remaining MZs.

The comparison of the environmental characteristics of the species' native and exotic habitats helps us to gain insights about the species behavior outside its normal environmental range. This comparison shows that in Chile, annual average temperature is lower than in its native habitat, whereas annual rainfall is higher and spring and summer rainfalls are lower. Our results highlight the relevance of temperature for the species, in such a way that a cooler habitat allows it to live with a lower hydric availability, which would explain the interesting performance it presents in Chile. Therefore, in light of climate change scenario with increasing temperature and decreasing rainfall, we should expect a reduction in growth rates, especially in the North and Dry Coast MZs. Natalini et al. (2013) also reported the species vulnerability under increases of temperature due to climate change. Consequently, heat tolerance should be considered a key breeding trait for increasing potential growth of stone pine.

Both pruning and irrigation, the two management practices evaluated, affected stone pine growth under some conditions, but were not the most influencing variables (Figs. 3a, b and 5a, b). The irrigation effect was positive for both height and DBH, as was reported by Pestaña (2000) in the evaluation of the impact of fertirrigation in a 75 year-old plantation of limited growth and no management established in a clay-sand soil. The author used a sprinkler irrigation system with 35 l/h during 5 years, with variable and growing doses ranging between 2460 and 5480 m^3 ha^{-1}; growth response was very positive, increasing from 2 to 15 mm diameter growth. Gordo (2010) stated that pruning negatively affects both height and diameter growth, whereas in our study we observed a positive effect on height growth, in agreement with findings reported by Loewe et al. (2012).

Given the observational nature of our study, the results for these management practices should not be taken as a conclusive, but as an indication that in a given site and under specific conditions, these interventions may be determinant for the species growth. The results suggest an interaction between these management practices and the local climatic conditions. Irrigation effect can increase up to 75% height growth rates in the North MZ, where temperatures and hydric deficit are high; even in the South MZ, irrigation increased this rate by 21% when total annual rainfall was lower than 1400 mm. Irrigation also increased DBH growth by 25%. For pruning, we observed height growth increases (18%) only in the Dry Coast MZ. Even though we do not have specific data on the costs of these management practices for this study, according to Loewe and Delard (2012), irrigation represents over 30% of the establishment costs whereas pruning represents a low fraction of the total annual management costs (5%). A preliminary relationship between costs and benefits suggest that the implementation of irrigation, when necessary due to climatic conditions, should be considered when intending to maximize stone pine growth.

5. Conclusions

Stone pine growth throughout Chile is high compared to the growth rates reported for its native habitat. We observed average growth of 0.32 m $year^{-1}$ in height and 1.24 cm $year^{-1}$ in DBH, showing marked differences among the three identified MZs. The highest height and DBH annual growth were found in the South MZ, with 0.35 m $year^{-1}$ and 1.50 cm $year^{-1}$ respectively, whereas in the Dry Coast MZ the species showed the lowest growth rates in height (0.23 m $year^{-1}$) and DBH (0.87 cm $year^{-1}$).

Average annual temperature and rainfall had a significant impact on height growth rate, which was favored by an average annual temperature below 14 °C, with high winter thermal oscillation (>14 °C), a spring water deficit lower than 400 mm and annual rainfall over 1400 mm $year^{-1}$. DBH growth was also favored by an average annual temperature below 14 °C. In sites that reach this temperature requirement, DBH growth was higher when annual water deficit was lower than 1100 mm $year^{-1}$. The study showed that temperature is the variable with the highest impact on stone pine growth in Chile; particularly, height growth was more than double in sites with low annual average temperature and high winter thermal oscillations. As practical applications of our results, we determined that a good selection of sites for the species cultivation in Chile should ensure annual average temperature below 14 °C. Moreover, in light of climate change, we should expect a reduction in growth rates especially in the North and Dry Coast MZs, where temperature is superior; therefore, heat tolerance should be handled as a key breeding trait for increasing growth of stone pine.

Pruning and irrigation also affected stone pine growth in Chile, but its average influence was lower in magnitude than the climatic impact; irrigation effect was positive for both DBH and height growth, and pruning for height growth in the Dry Coast MZ. Management practices oriented to enhance vegetative growth will depend upon the macrozone where the site is located.

Acknowledgements

The study was conducted as part of the R&D project "Development of techniques for producing Stone pine (*P. pinea* L.) pine nuts, an attractive commercial option for Chile" (D11I1134), funded by FONDEF (CONICYT), in execution between 2012 and 2016. The authors thank the private owners and companies that actively collaborated with this initiative. We also acknowledge the support from University of Córdoba-Campus de Excelencia CEIA3 (Spain).

We are grateful for the interesting comments and suggestions from three anonymous reviewers, which improved the quality of this communication.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2015.08.248.

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