Plant Soil
https://doi.org/10.1007/s11104-024-06682-y

RESEARCH ARTICLE

Effects of climate and soil properties on growth of *Pinus pinea* young plantations

**Verónica Loewe-Muñoz · Claudia Bonomelli ·
Rodrigo del Río · Claudia Delard ·
Mónica Balzarini**

Received: 30 November 2023 / Accepted: 15 April 2024

Abstract
Background and aims Growth of *Pinus pinea* forests and plantations in native countries is known to be affected by soil and climate characteristics. However, edaphoclimatic drivers of growth and fruiting have been scarcely studied outside the species' native range; in addition, the role of soil nutrients, particularly in juvenile trees' development, has been poorly explored.
Methods Relationships between edaphoclimatic variables and the performance of 54 young plantations were studied in Chile. Vegetative growth and fruiting were measured in 100 randomly selected trees per plantation. Composite soil samples were taken from each site to analyze soil chemical characteristics and texture. A principal component analysis was performed including climatic, soil data, and growth and fruiting variables.
Results Annual growth was 1.3 cm year^{-1} for stem diameter, 28.3 cm year^{-1} for crown diameter, and 38.9 cm year^{-1} for height; cone production per crown area was 0.07 cones m^{-2}. Negative correlation of height growth, crown growth and cone production with EC, Na, and pH were found, along with positive correlations with OM, PP and the index PP × AT. Stem diameter growth was favored by less acidic soils with high sand content, and showed no correlation with cone production. Furthermore, vegetative growth was positively correlated with N, P, Mg and clay content. In young plantations, vegetative growth was higher than in the species' native habitat.
Conclusion Soil properties, in particular low EC and Na were identified as favorable for growth of young stone pine trees, along with high content of soil N, P and Mg, and PP.

Keywords Climate impact · Early growth and fruiting · Electrical conductivity · Nitrogen · Phosphorus · Stone pine · Sodium

Introduction

Stone pine (*Pinus pinea* L.) is a Mediterranean species that produces highly priced pine nuts (Lonja

Responsible Editor: Michel-Pierre Faucon.

V. Loewe-Muñoz (✉) · C. Delard
Chilean Forest Institute (INFOR), Metropolitan Office,
Sucre 2397, Santiago, Chile
e-mail: vloewe@infor.cl

V. Loewe-Muñoz · C. Bonomelli · R. del Río
Centro Nacional de Excelencia Para La Industria de La
Madera (CENAMAD), Pontificia Universidad Católica de
Chile, Santiago, Chile

C. Bonomelli
Pontificia Universidad Católica de Chile, Av. Vicuña
Mackenna 4860, Macul, Santiago, Chile

M. Balzarini
CONICET - Universidad Nacional de Córdoba, Córdoba,
Argentina

de Reus 2020). Due to the socio-economic benefits of its cropping, the species is currently planted in several countries. In the native habitat, most natural stands grow on incipient soil types, such as arenosols, regosols, and lithosols (Mutke et al. 2012). However, the species has been reported to grow on better soils, such as mature cambisols or luvisols (Mutke et al. 2012); on well drained soils with low carbonate content, such as Lower Cretaceous sandstone or volcanic formations; on Cretaceous hard rock limestone (Masri et al. 1999); and on granite, volcanites, gneiss, flysch, quartzite, mica-schist and sand deposits (Bonari et al. 2020; IUSS 2022). Studies on growth variability (Court-Picon et al. 2004) and pine nut content (Evaristo et al. 2010; Vanhanen and Savage 2013) have revealed the species' sensitivity to soil. However, the main edaphic drivers of stone pine growth and fruiting outside the species native range have been scarcely studied.

An analysis of growth of adult stone pine trees along a climatic gradient in Chile (Loewe et al. 2015) showed marked differences in vegetative growth rates among zones, with the highest height and diameter at breast height (measured at 1.3 m height, DBH) growth rates (0.35 m year^{-1} and 1.50 cm year^{-1}, respectively) corresponding to the south of Chile (Loewe et al. 2015). Temperature and rainfall had a high and significant impact on height growth, which was favored by annual average temperature below 14 °C, a high winter thermal oscillation ($>$ 14 °C) and annual rainfall over 1,400 mm year^{-1}. DBH growth was also favored by an average annual temperature below 14 °C. The highest values of cone number (62 cones tree^{-1}), which were also recorded in the south of Chile, were favored by a spring minimum temperature above 7 °C and an annual thermal oscillation below 12 °C (Loewe et al. 2016).

Currently, most of the stone pine plantations in Chile (covering over 4,500 ha) are younger than 15 years, and their susceptibility to challenging environments might be greater than in native forests (Navarro-Cerrillo et al. 2018). Furthermore, it has been reported that bigger trees are more drought-tolerant than smaller, non-grafted ones (De Luis et al. 2009). Stone pine trees have a robust root system (Mutke et al. 2012; Jaouadi et al. 2021) that allows growth in many soil types (Cutini 2002), including poor habitats such as mobile dunes or limestone. However, some soil characteristics, like fertility, were found to affect growth (Montero et al. 2008; Bonari et al. 2020).

In young plantations, Loewe-Muñoz et al. (2019) reported that, altogether, climatic and edaphic variables could explain differences in stone pine growth across environments. In adult stone pine stands growth and cone production vary widely, depending on site quality and soil water availability (Mutke et al. 2012). The site index, which quantifies site quality, is defined as the height of trees that have always been dominant or codominant and healthy at a reference age (Piqué, 2003). Among the important soil variables in defining site quality for stone pine, Bravo-Oviedo and Montero (2005) mentioned soil texture, water holding capacity and altitude, particularly under developed acidic soils with loamy to sandy texture and limited chemical fertility. Mutke et al. (2012) indicated that soil properties are more important in defining tree growth than genetics (70% vs 15%).

The lack of knowledge about good management has been indicated as the main problem of the stone pine supply chain (Correia 2020). In fact, few studies have addressed how soil properties and available elements affect the performance of stone pine young plantations under different climatic conditions outside the species' native area (Ravazi et al. 2006; Tecimen et al. 2018; Loewe-Muñoz et al. 2020; Piraino et al. 2021). Non-mature forests may require different management strategies from those used for mature forests. Thinning was reported to improve growth response to drought for several pines (Navarro-Cerrillo et al. 2023), including stone pine trees (Del Río et al. 2011; Pardos et al. 2015).

Fertilization is commonly used to enhance growth and fruit production in several species. In pines, fertilization has been assessed in *Pinus pinaster* Aiton (Zas and Fernández-López 2005), *P. edulis* Engelm., *P. monophyla* Torr. & Frém. (McLain and Frazier 2008), *P. taeda* L. (Maggard et al. 2016), and *P. pinea* (Loewe et al. 2017). Studies on the impact of fertilization on adult *P. pinea* trees showed sensitivity to deficiency of the micronutrients boron (Bento and Coutinho 2011), and iron (Malchi and Shenker 2011). The latter authors reported that iron deficiency significantly decreases root growth and induces a reduction in chlorophyll in needles in soils with high soil pH. Similarly, the decline of the macronutrients nitrogen, phosphorus, potassium and calcium was found to increase cone loss (Kilci et al. 2013). Finally, calcium magnesium carbonate supply improved cone production and cone quality (Calama et al. 2007).

Nitrogen is a crucial macronutrient because it is a component of proteins and enzymes, and a vital part of chlorophyll (Ezeagu et al. 2002). A low N concentration per unit leaf mass was detected in adult stone pine trees growing in central-western Spain (Escudero and Mediavilla 2003). The effect of fertilization on growth and physiological characteristics was studied in seedlings and during the first years of plantation establishment both in stone pine (Delard et al. 2023) and in other pine species (Song et al. 2022). However, the role of soil nutrients on growth and development of juvenile trees has been less explored in stone pine.

The aim of this work was to study how soil texture, organic matter content and chemical properties (pH, EC, nutrient supply), and climatic variables (temperatures and rainfall) affect the performance of young stone pine plantations in Chile. We hypothesize that juvenile tree growth and fruiting would respond positively to the availability of some soil nutrients under different climatic conditions.

Materials and methods

Experimental design and study sites

The study was conducted in central Chile, between Valparaiso and Aysén regions (33.7°S to 46.6°S of latitude). A total of 54 stone pine plantations located in 19 sites were studied (Fig. 1). All plantations were younger than 15 years, with an average age of 6.6 ± 0.5 years. The planted area ranged from 0.5 to 3.0 hectares, with plantation spacing ranging from 5 × 5 to 7 × 7 m. In each plantation, 100 trees were randomly selected to measure vegetative growth and fruiting. Growth variables were recorded in winter, including root-collar diameter (RCD) and DBH, using a caliper; tree height was measured with a height pole and crown diameter was estimated as the distance between the crown projections of the longest living branches. All 3-year-old mature cones from each tree in the entire crown were counted. Growth rates were estimated for height, and for stem and crown diameters by dividing the observed value by tree age. Cone number was expressed as number of cones per crown area (# m^{-2}).

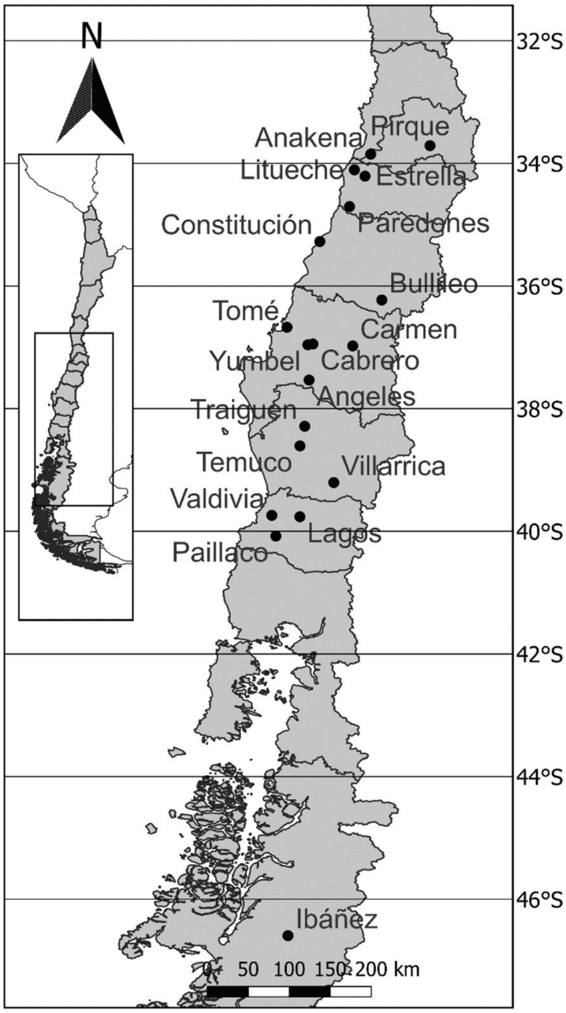


Fig. 1 Location of the studied stone pine plantations in Chile

Annual climate data were obtained from a 10-year climate series of the meteorological stations that were closest to the studied plantations (http://www.dga.cl). The following climatic variables were included: average temperature (AT); maximum average temperature (MXT); minimum average temperature (MNT); total annual rainfall (PP, expressed in mm); and thermal oscillation (TO = average maximum absolute temperature minus average minimum absolute temperature for a given period expressed in Celsius degrees). Climate indices were used to capture the interaction of rainfall and temperature along the studied latitudinal gradient. They were obtained by multiplying rainfall by temperature variables (PP × AT, PP × MNT and PP × MXT).

Composite soil samples were taken from the first 25 cm at each site. The following chemical characteristics were analyzed: pH (soil:water, 1:2.5); electrical conductivity (EC), measured in the same supernatant as the soil pH (1:2.5) analyzer (pH- EC meter Thermo Orion 3 Star); Organic Matter (OM) (Walky–Black wet oxidation method); nitrogen (N) concentration, determined using a LECO CNS-2000 Macro Elemental Analyzer (Leco Corporation, MI, US); and phosphorus (P), using the Olsen method. All exchangeable cations (K, Ca, Mg, Na) were also measured by extraction from the soil with 1 N ammonium acetate at pH 7.0; extractions were analyzed by ICP-Optical Emission Spectroscopy (Agilent 720 ES axial spectrometer, Varian Inc., Victoria, Australia). Texture (percentage of sand, silt and clay) was analyzed using the Bouyoucos method. Information on climate and some soil properties of each site is provided in Table 1.

Statistical analyses

A principal component analysis was performed including climatic, soil data, and growth and fruiting variables, generating a biplot (Johnson and Wichern 2015). Statistical analysis was performed using the software InfoStat (Di Rienzo et al. 2023) and its interface with R (http://www.r-project.org).

Results

Annual growth rate of stem diameter, crown diameter and height ranged from 0.2 to 2.7 cm year^{-1}, 5.5 to 54.8 cm year^{-1}, and 11.5 to 79.7 cm year^{-1}, respectively, with an average of 1.3 cm year^{-1}, 28.3 cm year^{-1}, and 38.9 cm year^{-1}, respectively. Cones per crown area ranged from 0.0 to 0.6 cones m^{-2} across the studied young stone pine plantations, with an average of 0.07 cones m^{-2}. Figure 2 represents the biplot of the three principal components by plantation, which explained 63.4% of the variability. The CP1 showed negative correlation of height growth, crown growth and cone production with EC, Na and pH, and positive correlations with OM, PP and the index PP×AT. The CP2 showed a different behavior of stem diameter, being favored by less acidic soils with high sand content; interestingly, DBH growth showed no correlation with cone production. Finally, the CP3 showed a positive correlation of vegetative growth (height and stem and crown diameter) with N, P, Mg and clay content.

Discussion

In our study, we confirmed high vegetative growth values in young stone pine plantations, with average values being higher than those reported by Correia et al. (2018) in the species' native habitat (1.3 vs 0.6 cm year^{-1} in stem diameter, 38.9 vs 22.5 cm year^{-1} in height). This result could be explained by a cooler climate (Loewe et al. 2015) and by the soil characteristics prevailing in the area where stone pine has been established in Chile. In this study, in sites where young plantations were successful, soil pH ranged from 5.2 to 6.8 and nutrients availability was enough. These soil characteristics are similar to those described by Bonari et al. (2020) for the primary habitat of natural stone pine dominant forests in terms of nutrient content (nitrogen and calcium) and a slightly acidic to acidic soil pH. Detecting differences in growth responses to site-specific soil patterns may allow us to select appropriate management strategies (Seifu et al. 2023).

Soil chemical and physical properties and growth

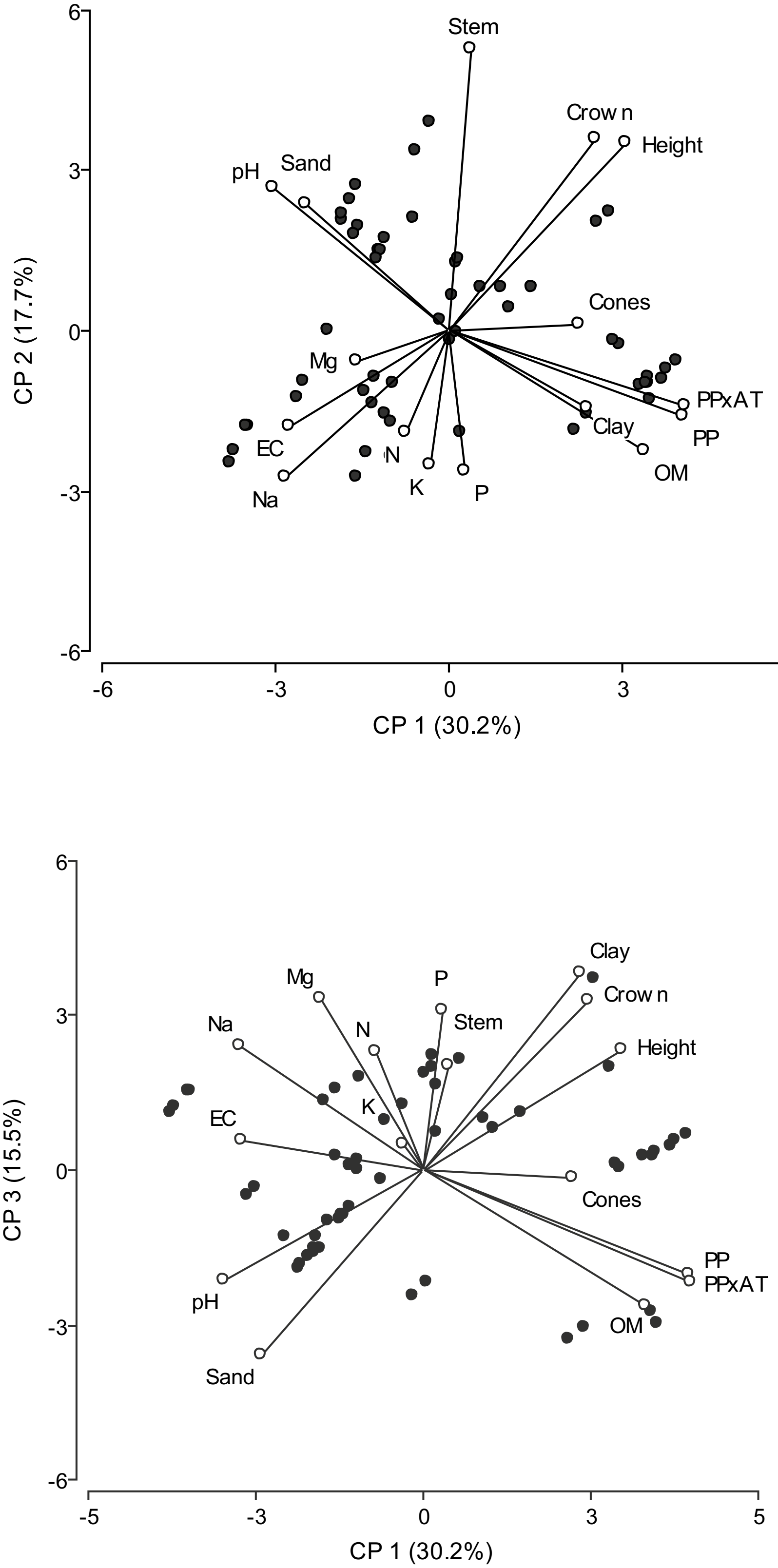
In our study, which covered a latitudinal range of 1,500 km, we found that soil properties, particularly N, P, Mg, Na, and EC, and climate are equally important for stone pine growth. Management techniques to enhance stem diameter growth have been proposed, since diameter was found to be positively correlated to cone production (Freire et al. 2019) and to total aboveground biomass (Correia et al. 2018). The systemic integration of pedoclimatic factors that affect crop production and cultural practices has been identified as key for a successful crop diversification (Hellou 2022). It is often assumed that nutrients are the main limiting resources and that light, water availability, salinity and temperature do not interfere with the response to removal of nutrient limitations (Goldstein et al. 2013).

Besides light and water, CO_2 and mineral elements are required for plant growth and development. Nitrogen is critical due to its role in synthesizing amino acids, proteins, nucleotides, chlorophyll, metabolites

Table 1 Average values of climate and soil properties of the sites where the studied stone pine plantations are located

Site	Annual rainfall (mm)	Annual average temperature (°C)	Thermal oscillation (°C)	Minimum average temperature (°C)	Maximum average temperature (°C)	Soil texture (sand, silt and clay in %)	pH	Organic matter (%)	N-P-K (mg kg^{-1})	Sodium (cmol + kg^{-1})	Calcium (cmol + kg^{-1})	Electrical conductivity (mmhos cm^{-1})
Pirque	206	13.8	19.6	4.6	24.2	68; 23; 9	6.2	1.7	65; 13; 150	0.30	11.7	0.28
Anakena	354	13.8	11.6	8.7	20.3	48; 22; 30	6.8	0.6	17; 2; 119	0.28	7.9	0.05
Litueche	449	12.9	12.6	6.9	19.5	34; 29; 37	5.9	1.3	12; 10; 71	0.16	3.5	0.03
Estrella	363	13.4	17.0	5.4	22.4	68; 16; 16	6.6	0.4	26; 3; 49	0.09	3.7	0.02
Paredones	512	12.8	15.4	5.6	21.0	51; 27; 22	5.6	3.6	3; 12; 164	0.06	1.5	0.25
Constitución	548	14.1	7.7	10.4	18.1	95; 4; 1	6.5	2.1	8; 6; 212	0.10	3.7	0.05
Bullileo	2,102	12.3	12.8	6.3	19.1	65; 24; 11	5.8	22.0	12; 4; 125	0.03	1.9	0.03
Tomé	711	13.0	8.6	8.7	17.3	38; 26; 36	5.3	3.0	6; 2; 186	0.06	1.1	0.05
Cabrero	498	14.0	13.6	7.8	21.3	95; 3; 2	6.7	0.7	3; 2; 73	0.07	2.5	0.10
Yumbel	498	14.0	13.6	7.8	21.3	73; 4; 23	6.2	5.4	48; 8; 165	0.05	3.8	0.07
Carmen	790	12.4	14.0	5.4	19.4	8; 49; 43	6.2	7.1	17; 11; 106	0.06	2.2	0.03
Angeles	407	13.8	14.5	7.0	21.6	74; 22; 4	6.3	1.0	2; 7; 178	0.05	2.0	0.04
Traiguen	827	11.7	11.7	5.8	17.5	34; 40; 26	5.8	4.5	13; 13; 345	0.12	7.0	0.05
Temuco	921	11.4	12.6	6.0	18.6	44; 39; 17	5.8	2.6	16; 5; 190	0.14	3.1	0.05
Villarrica	1,460	10.9	13.8	4.3	18.1	54; 40; 6	6.7	9.6	11; 2; 25	0.08	0.3	0.09
Valdivia	1,947	11.9	10.2	7.5	17.7	39; 36; 25	5.3	15.4	18; 19; 178	0.07	9.8	0.01
Lagos	2,006	11.4	11.2	6.4	17.6	42; 23; 35	5.8	9.3	53; 4; 109	0.06	0.4	0.03
Paillaco	1,947	11.9	10.2	7.5	17.7	12; 39; 49	5.2	7.3	9; 4; 89	0.09	5.2	0.01
Ibáñez	874	9.6	7.2	6.4	13.6	32; 60; 8	6.3	7.2	9; 6; 355	0.22	11.7	0.02

Fig. 2 Biplot for vegetative growth (height, and crown and stem diameter) and cone production, and climate and soil variables according to plantation. EC: electrical conductivity, PP: rainfall, PPxAT: annual rainfall × average temperature index, OM: organic matter



and cellular components, and it is required by plants in higher quantities than other nutrients (Nunes-Nesi et al. 2010). In this study, we found that vegetative growth is positively correlated to soil N content. This result agrees with a previous study performed in Chile, in which the three environments with the highest stone pine tree growth had a high soil N content (Loewe-Muñoz et al. 2019). A positive effect of fertilization with N, among other elements, on *P. pinea* stem diameter growth was reported in areas with Mediterranean climate in Turkey (Kilci et al. 2013), France (Rapp et al. 1979) and the central valley of Chile (Loewe-Muñoz et al. 2020; http://www.dga.cl). Similar results were found in young *Pinus taeda* L. plantations (5–7 years-old) established on acidic soils. Additionally, Thirukkumaran and Parkinson (2002) reported that N fertilization enhanced pine forest floor decay.

On the other hand, Balekoglu et al. (2021) found that a higher concentration of N in stone pine seeds provides higher water uptake, increasing mean germination percentage, whereas in seedlings, N may enhance survival and competitive amplitude. N fertilization in poplar plantations constrained by water and N deficiency resulted in improved drought adaptation and growth performance (Song et al. 2019); similar results were obtained in *Eucalyptus* by Bonomelli and Suarez (1999). Nitrogen addition under drought also increased leaf abscisic acid level, regulating stomata adjustment and promoting water use efficiency. Moreover, N fertilization increased levels of antioxidants in leaves of poplars, improving defense, drought tolerance and growth (Song et al. 2019). Felton et al. (2023) discussed the use of N fertilization as a strategy for climate change adaptation and mitigation, and indicated a positive growth response obtained when applying N. However, fertilizations with high N doses may not be sustained over time; indeed, the authors stated that the response may be regulated by the availability of other nutrients and water, and that when doses are not optimal, N fertilization could even induce deficiency of other nutrients.

Phosphorus is an essential element determining plants' growth and productivity, being a structural component of nucleic acids, sugars and lipids. Furthermore, it has a relevant role on seed germination, seedling establishment, root, shoot, flower and seed development, photosynthesis and respiration (Marschner 2012). In our study, we found a positive correlation of vegetative growth and P; in fact, numerous plantations have been established on andisols containing a clay fraction dominated by allophane which induces a strong retention of phosphorus, and consequently, a low availability of this essential nutrient for plant growth (Toneatti-Bastidas and Roger-Estrade 2015). Our findings agree with Consalter et al. (2021) who showed that fertilization with N and P led to volumetric gains of 100% and enhanced the volume of the most desirable log classes, adding economic value.

Magnesium is one of the essential macronutrients for plant growth, with functions including participation in photosynthesis, enzyme activation, and synthesis of nucleic acids and proteins (Chen et al. 2018). Mg deficiency reduced *P. radiata* D. Don growth through severe reductions in photosynthesis (Laing et al. 2000). Coincidently, in our study, we observed a positive correlation of soil Mg content with stone pine growth in young trees.

Salinity may be a problem in soils, disrupting productivity and affecting physical, chemical and biological soil properties (El-Ramady et al. 2024); i.e. high levels of Na affect soil structure, induce soil sealing, and reduce water infiltration and availability. In our study, we found negative correlations of height growth, crown diameter growth and cone production, with EC. EC values are highly correlated with both chemical and physical soil attributes, including soil water content (dos Santos et al. 2023). In soils where young stone pine plantations are grown in eastern Turkey, Tecimen et al. (2018) reported EC values from 0.094 to 0.097 mmhos cm^{-1}, lower than the ones observed in this study. Fernández-Caliani et al. (2021) reported that stone pine trees presented high survival (72%) and grew well in land reclaimed from a pyrite mine in Spain, with salinity varying from non-saline to moderately saline. In a stone pine plantation with slightly saline sandy soils in eastern Turkey, Kizildag et al. (2012) found that salt level had no effect on microbial activity. In a study on the EC of saline irrigation water, negative effects increased when there was no fresh water supply and stone pine trees used the underlying salty water (Teobaldelli et al. 2004). Drainage is therefore very important, and our results indeed showed that the higher the sand content, the better the stem diameter growth, which is related to salt leaching. Teobaldelli et al. (2004) observed reductions in productivity and health status linked to the persistent and periodic phenomena of combined drought and salt stress during summer; the authors confirmed the negative effects of salty water and prolonged soil drought on stone pine sap flow. The soils in which the studied stone pine plantations grow contain a relatively low soluble salt content in the soil solution, with values that classify them as non-saline (SDSHC 2023). However, it must be taken into account that in this study EC was measured in the supernatant of the soil: water, 1:2.5 instead of using the EC of saturated paste extract method, the most commonly used, with which higher values are obtained.

Regarding sodium, we found a negative correlation with vegetative growth, including height, and stem and crown diameter, as well as with cone production. Sidari et al. (2008) reported that a solution of NaCl of 50 mM caused a five-fold reduction in seed germination, and a solution of 100 mM inhibited germination; in addition, Barbolani et al. (1997) found small concentrations of $Na+$and $Cl-$ions in the needles and the woody tissues of stone pine trees, which indicates absorption of salts.

Soil texture is important for stone pine because its roots prefer well-aired and coarse-textured soils, such as sand, loamy sand, sandy loam, and soil with gravel (with water-holding capacity of at least 60 mm) (Gonçalves et al. 2023). In compact clay or silt soils (with less than 40% sand and more than 40% silt or more than 30% clay), root development is restricted, especially during the first phase of seedling establishment, and flowering can be delayed for many years, fixing the plant ontogeny in a stationary juvenile state (Mutke et al. 2012). However, stone pine can survive and thrive in heavy soils as long as they are not waterlogged (Gandullo and Sánchez-Palomares 1994).

Climate variables and growth

Some climate variables, including PP and the index PP×AT, were found to be positively correlated to height and crown diameter growth, and to cone production, in agreement with findings of Gonçalves et al. (2023), who indicated that the main limiting factor to the species growth is water availability, and with studies that report that the species optimum rainfall level ranges between 500 and 800 mm (Castaño et al. 2004; CABI 2022). In Turkey, rainfall (annual and of the wettest quarter), besides minimum temperature of the coldest month, is the most significant predictors of the potential distribution of the species (Bonari et al. 2020). In Italy, Tani (1991) attributed the diffuse and anomalous withering of the canopies to the occurrence of a marked drought period in autumn and spring, and Gandolfo (1999) reported that dendrochronological measurements were favored by the hydraulic supply from lateral runoff. Furthermore, Piussi and Torta (1994) found that needle length significantly declined after years of reduced rainfall. The severe continuous mega-drought that has affected Chile in the last decade, with rainfall drops of up to 40% (Garreaud et al. 2020), has reduced or even inhibited cone production in many plantations located in the central region. Furthermore, Loewe et al. (2016) reported that low rainfall reduces the species' growth, which was also reported by other studies (El Khorchani et al. 2007; Mazza and Manetti 2013; Natalini et al. 2016). A negative impact of warm conditions on growth was reported for *P. pinea* (Mechergui et al. 2021) and *P. pinaster* (Navarro-Cerrillo et al. 2018). On the other hand, Masri et al. (1999) indicated that cone production in Lebanon is significantly higher on the wetter slopes than on the drier ones.

In Chile, increased drought conditions with reduced rainfall and soil moisture, and increased temperatures since 1985 have affected both native species (Santelices-Moya et al. 2022) and exotic ones, including stone pine. One of the effects of drought on tree ecophysiology is the alteration of nutrient uptake and transport (Hu et al. 2023). Interestingly, these authors indicated that when nutrient uptake occurs during drought, high nutrient availability may increase water use efficiency, minimizing negative feedbacks between carbon and nutrient balances. Nutrients are released after the end of the drought period, which could promote a faster recovery, but the temporal dynamics of microbial immobilization and nutrient leaching significantly impact nutrient availability (Gessler et al. 2017). Therefore, climatic and edaphic variables together could be responsible for differences in stone pine growth across environments in Chile.

In a climate change scenario, the search for management alternatives to cope with these challenging conditions –adaptive forest management– is of high priority both for timber and cone production. First, adequate soil preparation is key; the addition of organic matter would improve soil structure and water and nutrient retention capacity (Mutke et al. 2012). Then, management practices that optimize tree growth and vigor are crucial for the species cropping (Mutke et al. 2012). Under limiting conditions for growth, tree thinning may be appropriate (Smith 1986), with positive effects on cone production having been reported (Moreno-Fernández et al. 2013).

Fertilization is another technique that deserves attention when the species is cropped for pine nut production. In fact, yield increments in cone number and size have been achieved by applying fertilizers and soil pH amendments, especially with dolomite (calcium-magnesium carbonate) on oligotrophic sands or gravels (Calama et al. 2007). Loewe-Muñoz et al. (2023) recently reported a boosting effect of fertilization on total pine nut weight per cone. Since nutrient uptake will depend on water availability, which is scarce in part of the stone pine's growing area, further studies combining fertilization and complementary irrigation (Lodolini et al. 2014) may be useful to allow tree survival and a minimum cone production. This study suggests that a targeted stone pine nutritional management might assist in enhancing growth and cone production, and that this management should be based on soil chemical and physical properties. These findings contribute to the understanding of different growing conditions of stone pine plantations and introduce original knowledge to boost this species cropping in environments exposed to new challenges.

Conclusions

In a wide latitudinal range, we found that soil properties are as important as climate for young stone pine tree growth. In particular, low soil EC and Na content were identified as favorable for growth, as well as high N, P and Mg concentrations. These results contribute to the understanding of the impacts of nutrients availability on stone pine performance under different climate conditions. In light of climate change, management techniques including fertilization could improve performance of the species cropping.

Acknowledgements The authors thank the plantation owners for maintaining the experimental plantations. Jorgelina Brasca edited the English style.

Author contributions All authors contributed to the study conception and design. Material preparation and data collection were performed by Rodrigo del Rio. Claudia Delard was in charge of trial maintenance. Claudia Bonomelli directed soil sampling, interpreted results, and contributed to the discussion. Mónica Balzarini led the statistical analysis. Verónica Loewe-Muñoz wrote the first draft of the manuscript and all authors commented on successive versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the project FONDEF [D11I1134]; Chilean Ministry of Agriculture [Development and contributions for the use of high value forest and fruit-forest species for Chile, INFOR]; and by ANID BASAL (CENAMAD) [FB210015].

Data availability The datasets generated and analyzed during the current study are not publicly available due to institutional guidelines, but are available from the corresponding author on reasonable request.

Declarations

Competing interest The authors have no relevant financial or non-financial interests to disclose.

References

Balekoglu S, Caliskan S, Makineci E, Dirik H (2021) Influence of seed nitrogen and carbon on germination in different populations of stone pine. Erwerbs-Obstbau 63:369–374. https://doi.org/10.1007/s10341-021-00593-3

Barbolani E, Gandolfo GP, Piussi P, Ramat G (1997) Influenza della salinità dell'acqua di falda sulle condizioni vegetative del pino domestico nel Parco Regionale della Maremma. In: la ricerca italiana per le foreste e la selvicoltura'. 1st Congress SISEF, Legnaro, Padua, Italy. pp 69–72

Bento J, Coutinho J (2011) Boron deficiency in Stone pine. In: Agropine 2011 International Meeting on Mediterranean Stone pine for Agroforestry 2011/11/17–19. Valladolid, Spain, p 25

Bonari G, Chytrý K, Çoban S, Chytrý M (2020) Natural forests of *Pinus pinea* in western Turkey: a priority for conservation. Biodivers Conserv 29:3877–3898. https://doi.org/10.1007/s10531-020-02052-z

Bonomelli C, Suarez D (1999) Fertilización del eucalipto. Efecto sobre la acumulación de biomasa. Cienc e Investig Agrar 26:1–10

Bravo-Oviedo A, Montero G (2005) Site index in relation to edaphic variables in stone pine (*Pinus pinea* L.) stands in south west Spain. Ann for Sci 62:61–72. https://doi.org/10.1051/forest:2004086

CABI (2022) *Pinus pinea* (stone pine). In: CABI Compend. https://www.cabidigitallibrary.org/doi/10.1079/cabicompendium.41689. Accessed 10 Nov 2023

Calama R, Madrigal G, Candela J, Montero G (2007) Effects of fertilization on the production of an edible forest fruit: stone pine (*Pinus pinea* L.) nuts in the south-west of Andalusia. For Syst 16:241–252. https://doi.org/10.5424/srf/2007163-01013

Castaño J, Estirado M, Abellanas B, Butler I, Cosano I, Luengo J, García J, Candela J (2004) Puesta en valor de los recursos forestales Mediterráneos. El injerto de pino piñonero (*Pinus pinea* L.). Manuales de Restauración Forestal No 9, 1st edn. Consejería de Medio Ambiente, Junta de Andalucía, Spain.

Chen ZC, Peng WT, Li J, Liao H (2018) Functional dissection and transport mechanism of magnesium in plants. Semin Cell Dev Biol 74:142–152. https://doi.org/10.1016/j.semcdb.2017.08.005

Consalter R, Motta ACV, Barbosa JZ, Vezzani FM, Rubilar RA, Prior SA, Nisgoski S, Bassaco MVM (2021) Fertilization of *Pinus taeda* L. on an acidic oxisol in southern Brazil: growth, litter accumulation, and root exploration. Eur J for Res 140:1095–1112. https://doi.org/10.1007/s10342-021-01390-z

Correia AC, Faias SP, Ruiz-Peinado R, Chianucci F, Cutini A, Fontes L, Manetti MC, Montero G, Soares P, Tomé M (2018) Generalized biomass equations for Stone pine (*Pinus pinea* L.) across the Mediterranean basin. For Ecol Manage 429:425–436. https://doi.org/10.1016/J.FORECO.2018.07.037

Correia A (2020) Threats and concerns in the management of stone pine in Portugal: insights from a survey among stakeholders. In: Incred. Innov. Netw. Cork, Resin Edibles, Factsheet 20705. https://oppla.eu/casestudy/20705. Accessed 10 Oct 2023

Court-Picon M, Gadbin-Henry C, Guibal F, Roux M (2004) Dendrometry and morphometry of *Pinus pinea* L. in Lower Provence (France): adaptability and variability of provenances. For Ecol Manage 194:319–333. https://doi.org/10.1016/j.foreco.2004.02.024

Cutini A (2002) Pines of silvicultural importance: *Pinus pinea* L. In: pines of silvicultural importance, 1st edn. CABI Publishing, New York, USA, pp 329–342

De Luis M, Novak K, Čufar K, Raventós J (2009) Size mediated climate–growth relationships in *Pinus halepensis* and *Pinus pinea*. Trees 23:1065–1073. https://doi.org/10.1007/s00468-009-0349-5

Delard C, Loewe V, Del RR, González M, Gregori G, Acevedo M, Cartes E, Balzarini M (2023) Effect of *Tuber borchii* inoculation on *Pinus pinea* seedling quality and initial growth in the field. New for. https://doi.org/10.1007/s11056-023-09992-8

Del Río M, Aguirre M, Calama R, Madrigal G, Gordo J, Finat L, Álvarez D, Montero G, Mutke S (2011) Early thinning for crown expansion and drought stress reduction. In: International meeting on mediterranean stone pine for agroforestry. AgroPine 2011, Valladolid-Spain, p 24

Di Rienzo J, Casanoves F, Balzarini M, Gonzalez L, Tablada M, Robledo C (2023) InfoStat Version 2023. https://www.infostat.com.ar. Accessed 10 Nov 2023

dos Santos FFL, de Queiroz DM, Valente DSM, Khorsandi F, de Moura AG (2023) Analysis of different electric current frequencies in soil apparent conductivity. J Biosyst Eng 48:269–282. https://doi.org/10.1007/s42853-023-00187-9

El Khorchani A, Gadbin-Henry C, Bouzid S, Khaldi A (2007) The impact of drought on the growth of three forest species in Tunisia (*Pinus halepensis* Mill., *Pinus pinea* L., and *Pinus pinaster* Sol.). Secheresse 18:113–121

El-Ramady H, Prokisch J, Mansour H, Bayoumi YA, Shalaby TA, Veres S, Brevik EC (2024) Review of crop response to soil salinity stress: possible approaches from leaching to nano-management. Soil Syst 8:11. https://doi.org/10.3390/soilsystems8010011

Escudero A, Mediavilla S (2003) Decline in photosynthetic nitrogen use efficiency with leaf age and nitrogen resorption as determinants of leaf life span. J Ecol 91:880–889. https://doi.org/10.1046/j.1365-2745.2003.00818.x

Evaristo I, Batista D, Correia I, Correia P, Costa R (2010) Chemical profiling of Portuguese *Pinus pinea* L. nuts. J Sci Food Agric 90:1041–1049. https://doi.org/10.1002/jsfa.3914

Ezeagu I, Petzke J, Metges C, Akinsoyinu A, Ologhobo A (2002) Seed protein contents and nitrogen-to-protein conversion factors for some uncultivated tropical plant seeds. Food Chem 78:105–109. https://doi.org/10.1016/S0308-8146(02)00105-X

Felton A, Belyazid S, Eggers J, Nordström E-M, Öhman K (2023) Climate change adaptation and mitigation strategies for production forests: Trade-offs, synergies, and uncertainties in biodiversity and ecosystem services delivery in Northern Europe. Ambio. https://doi.org/10.1007/s13280-023-01909-1

Fernández-Caliani JC, Giráldez MI, Waken WH, Del Río ZM, Córdoba F (2021) Soil quality changes in an Iberian pyrite mine site 15 years after land reclamation. CATENA 206:105538. https://doi.org/10.1016/j.catena.2021.105538

Freire J, Rodrigues G, Tomé M (2019) Climate change impacts on Pinus pinea L. silvicultural system for cone production and ways to contour those impacts: a review complemented with data from permanent plots. Forest 10:169. https://doi.org/10.3390/f10020169

Gandolfo G (1999) Fattori ambientali, relazioni idriche e dendroecologia del pino domestico (Pinus pinea L.) ad Alberese (GR). Università degli Studi di Padua, Italy

Gandullo J, Sánchez-Palomares O (1994) Estaciones ecológicas de los pinares españoles. Dirección General para la Conservación de la Naturaleza, Madrid, Spain

Garreaud RD, Boisier JP, Rondanelli R, Montecinos A, Sepúlveda HH, Veloso-Aguila D (2020) The central Chile mega drought (2010–2018): A climate dynamics perspective. Int J Climatol 40:421–439. https://doi.org/10.1002/joc.6219

Gessler A, Schaub M, McDowell NG (2017) The role of nutrients in drought-induced tree mortality and recovery. New Phytol 214:513–520. https://doi.org/10.1111/nph.14340

Goldstein G, Bucci SJ, Scholz FG (2013) Why do trees adjust water relations and hydraulic architecture in response to nutrient availability? Tree Physiol 33:238–240. https://doi.org/10.1093/treephys/tpt007

Gonçalves AC, Alexandre C, Andrade J, Pires R (2023) Effects of chemical soil characteristics, air temperature and precipitation on *Pinus pinea* Growth in Southern Inland Portugal. Forests 14:2160. https://doi.org/10.3390/f14112160

Hellou G (2022) DiverIMPACTS. In: Ingredients Success. Crop Diversif. https://www.diverimpacts.net/pl/service/news/ingredients-for-successful-crop-diversification.html. Accessed 10 Oct 2023

Hu Y, Sperotto RA, Koubouris G, Stojnić S, Bellaloui N (2023) Tree ecophysiology in the context of climate change. J for Res 34:1–5. https://doi.org/10.1007/s11676-023-01596-4

IUSS Working Group WRB (2022) World reference base for soil resources. International soil classification system for naming soils and creating legends for soil maps, 4th edn. International Union of Soil Sciences (IUSS), Vienna, Austria

Jaouadi W, Alsubeie M, Mechergui K, Naghmouchi S (2021) Silviculture of *Pinus pinea* L. in North Africa and the mediterranean areas: current potentiality and economic value. J Sustain for 40:656–674. https://doi.org/10.1080/10549811.2020.1798787

Johnson R, Wichern D (2015) Applied Multivariate Statistical Analysis, 6th edn. Pearson, India

Kilci M, Akbin G, Sayman M, Özçankaya M (2013) Determination of effect of fertilizing on cone yield of stone pine (*Pinus pinea* L.) in Kozak province. In: Mutke S, Correia A, Vila Verde C (eds) 2nd international meeting on mediterranean stone pine for agroforestry, pp 17

Kizildag N, Aka Sagliker H, Kutlay A, Cenkseven S, Darici C (2012) Some soil properties and microbial biomass of *Pinus maritima*, *Pinus pinea* and *Eucalyptus camaldulensis* from the Eastern Mediterranean coasts. EurAsian J Biosci 6:121–126. https://doi.org/10.5053/ejobios.2012.6.0.15

Laing W, Greer D, Sun O, Beets P, Lowe A, Payn T (2000) Physiological impacts of Mg deficiency in *Pinus radiata*: growth and photosynthesis. New Phytol 146:47–57. https://doi.org/10.1046/j.1469-8137.2000.00616.x

Lodolini E, Ali S, Mutawea M, Qutub M, Arabasi T, Pierini F, Neri D (2014) Complementary irrigation for sustainable production in olive groves in Palestine. Agric Water Manag 134:104–109. https://doi.org/10.1016/J.AGWAT.2013.12.006

Loewe V, Delard C, Balzarini M, Álvarez A, Navarro R (2015) Impact of climate and management variables on stone pine (*Pinus pinea* L.) growing in Chile. Agric for Meteorol 214–215:106–116. https://doi.org/10.1016/j.agrformet.2015.08.248

Loewe V, Balzarini M, Álvarez A, Delard C, Navarro-Cerrillo R (2016) Fruit productivity of Stone pine (*Pinus pinea* L.) along a climatic gradient in Chile. Agric for Meteorol 223:203–216. https://doi.org/10.1016/j.agrformet.2016.04.011

Loewe V, Alvarez A, Balzarini M, Delard C, Navarro-Cerrillo R (2017) Mineral fertilization and irrigation effects on fruiting and growth in stone pine (*Pinus pinea* L) crop. Fruits 72:281–287. https://doi.org/10.17660/th2017/72.5.3

Loewe-Muñoz V, Balzarini M, Del Río R, Delard C (2019) Effects of stone pine (*Pinus pinea* L.) plantation spacing on initial growth and conelet entry into production. New for 50:489–503. https://doi.org/10.1007/s11056-018-9672-2

Loewe-Muñoz V, Delard C, Del Río R, Balzarini M (2020) Long-term effect of fertilization on stone pine growth and cone production. Ann for Sci 77:69. https://doi.org/10.1007/s13595-020-00978-6

Loewe-Muñoz V, del Río R, Delard C, Balzarini M (2023) Effect of fertilization on *Pinus pinea* cone to seed and kernel yields. For Ecol Manage 545:121249. https://doi.org/10.1016/j.foreco.2023.121249

Lonja de Reus (2020) Histórico de precios. In: Histórico de precios. http://www.llotjadereus.org. Accessed 1 Apr 2020

Maggard AO, Will RE, Wilson DS, Meek CR, Vogel JG (2016) Fertilization reduced stomatal conductance but not photosynthesis of *Pinus taeda* which compensated for lower water availability in regards to growth. For Ecol Manage 381:37–47. https://doi.org/10.1016/j.foreco.2016.08.046

Malchi T, Shenker M (2011) Iron deficiency of *Pinus pinea*: evaluation of iron uptake mechanisms and comparison of different genetic lines. Thesis. The Hebrew University of Jerusalem, Israel

Marschner H (2012) Marschner's mineral nutrition of higher plants. 3rd edn. Elsevier, London. Academic Press, p 672

Masri T, Mousa Z, Routier J, Awad M (1999) A methodological approach for georeferenced phytosociological description of *Pinus pinea* forest. In: 5th annual Middle East GIS ESRI user conference. Beirut, Lebanon, pp 13.1–13.6

Mazza G, Manetti MC (2013) Growth rate and climate responses of *Pinus pinea* L. in Italian coastal stands over the last century. Clim Change 121:713–725. https://doi.org/10.1007/s10584-013-0933-y

McLain R, Frazier P (2008) Management Guidelines for Expanding Pinyon Nut Production in Colorado´s Pinyon-Juniper Woodlands. Portland, E.E.U.U. In: Pinon Nuts.org; a site for promoting the sustainable harvest of wild pinyon nuts. https://www.pinonnuts.org/PJE%20Mgmt%20Guidelines%203-18-08.pdf. Accessed 10 Jan 2024

Mechergui K, Saleh Altamimi A, Jaouadi W, Naghmouchi S (2021) Climate change impacts on spatial distribution, tree-ring growth, and water use of stone pine (*Pinus pinea* L.) forests in the Mediterranean region and silvicultural practices to limit those impacts. iForest – Biogeosci For 14:104–112. https://doi.org/10.3832/ifor3385-013

Montero G, Calama R, Ruiz R (2008) Selvicoltura de Pinus pinea L. In: Montero G, Serrada R, Reque J (eds) Compendio de selvicoltura de especies. INIA-Fundación Conde del Valle de Salazar, Madrid, Spain, pp 431–470

Moreno-Fernández D, Cañellas I, Calama R, Gordo J, Sánchez-González M (2013) Thinning increases cone production of stone pine (*Pinus pinea* L.) stands in the Northern Plateau (Spain). Ann for Sci 70:761–768. https://doi.org/10.1007/s13595-013-0319-3

Mutke S, Calama R, González S, Montero G, Gordo J, Bono D, Gil L (2012) Mediterranean stone pine: Botany and horticulture. In: Janick J (ed) Horticultural Reviews 39. Wiley-Blackwell, pp 153–201

Natalini F, Alejano R, Vázquez-Piqué J, Pardos M, Calama R, Büntgen U (2016) Spatiotemporal variability of stone pine (*Pinus pinea* L.) growth response to climate across the Iberian Peninsula. Dendrochronologia 40:72–84. https://doi.org/10.1016/j.dendro.2016.07.001

Navarro-Cerrillo R, Rodriguez-Vallejo C, Silveiro E, Hortal A, Palacios-Rodríguez G, Duque-Lazo J, Camarero J (2018) Cumulative drought stress leads to a loss of growth resilience and explains higher mortality in planted than in naturally regenerated *Pinus pinaster* Stands. Forests 9:358. https://doi.org/10.3390/f9060358

Navarro-Cerrillo RM, Cachinero-Vivar AM, Pérez-Priego Ó, Aspizua Cantón R, Begueria S, Julio Camarero J (2023) Developing alternatives to adaptive silviculture: Thinning and tree growth resistance to drought in a *Pinus* species on an elevated gradient in Southern Spain. For Ecol Manage 537:120936. https://doi.org/10.1016/j.foreco.2023.120936

Nunes-Nesi A, Fernie AR, Stitt M (2010) Metabolic and signaling aspects underpinning the regulation of plant carbon nitrogen interactions. Mol Plant 3:973–996. https://doi.org/10.1093/mp/ssq049

Pardos M, Calama R, Maroschek M, Rammer W, Lexer MJ (2015) A model-based analysis of climate change vulnerability of *Pinus pinea* stands under multiobjective management in the Northern Plateau of Spain. Ann for Sci 72:1009–1021. https://doi.org/10.1007/s13595-015-0520-7

Piqué M (2003) Modelos de producción para las masas de *Pinus pinea* L. en Catalunya: orientaciones para la gestión y aprovechamiento sostenible de madera y piña. Doctoral Thesis. Universitat de Lleida, Lleida, Spain, p 226

Piraino S, Cignoli FN, Robledo S, Pérez S (2021) Un pino mediterráneo en Sudamérica: situación actual y potencialidad de *Pinus pinea* L. en territorio argentino. Experticia 1:7–10

Piussi P, Torta G (1994) Osservazioni sulla lunghezza e sulla longevità degli aghi di pino domestico (*Pinus pinea* L.). G Bot Ital 128:887–902. https://doi.org/10.1080/11263509409430313

Rapp M, Leclerc M, Lossaint P (1979) The Nitrogen economy in a *Pinus pinea* L stand. For Ecol Manage 2:221–231. https://doi.org/10.1016/0378-1127(79)90048-3

Ravazi S, Azizi P, Rashidi R, Keivan F (2006) The effect of NPK fertilizers on hand planting *Pinus pinea* in coastal areas of Caspian Sea. Iran J Nat Resour Res 59:377–389

Santelices-Moya R, Gibson-Carpintero S, Cabrera-Ariza A, Santini-Junior L, Venegas-González A (2022) Reduced rainfall variability reduces growth of *Nothofagus alessandrii* Espinosa (*Nothofagaceae*) in the Maule Region. Chile Forests 13:1184. https://doi.org/10.3390/f13081184

Seifu W, Elias E, Gebresamuel G, Feyisa GL, Tefera W (2023) Characterization and mapping of soil-landscape for site-specific soil management in ayiba watershed, Northern Highlands of Ethiopia. Appl Environ Soil Sci 2023:1–21. https://doi.org/10.1155/2023/8899956

Sidari M, Mallamaci C, Muscolo A (2008) Drought, salinity and heat differently affect seed germination of *Pinus pinea*. J for Res 13:326–330. https://doi.org/10.1007/s10310-008-0086-4

Smith D (1986) The Practice of Silviculture, 8th edn. John Wiley & Sons, New York, EE.UU

Song J, Wang Y, Pan Y, Pang J, Zhang X, Fan J, Zhang Y (2019) The influence of nitrogen availability on anatomical and physiological responses of *Populus alba* × *P. glandulosa* to drought stress. BMC Plant Biol 19:63. https://doi.org/10.1186/s12870-019-1667-4

Song W, Lee B, Cho N, Jung S, Kim E, Lim J (2022) Effects of drought stress and nitrogen fertilization on growth and physiological characteristics of *Pinus densiflora* seedlings under elevated temperature and CO2 concentration. Korean J Agric for Meteorol 22:57–67. https://doi.org/10.5532/KJAFM.2020.22.2.57

South Dakota Soil Health Coalition (SDSHC) (2023) South Dakota Soil Health Coalition. In: Soil Electr. Conduct. https://www.sdsoilhealthcoalition.org/technical-resources/chemical-properties/soil-electrical-conductivity/. Accessed 10 Oct 2023

Tani A (1991) Note su possibili danni da siccità in *Pinus pinea* L. Monti e Boschi 42:10–12

Tecimen HB, Sevgi O, Akkaya M, Sevgi E, KizilarslanHançer Ç, AltundağÇakir E (2018) Some soil physical and chemical properties of natural stands and plantations at different ages of stone pine in Biga (Çanakkale-Turkey). Eurasian J For Sci 6:42–47. https://doi.org/10.31195/ejejfs.484866

Teobaldelli M, Mencuccini M, Piussi P (2004) Water table salinity, rainfall and water use by umbrella pine trees (*Pinus pinea* L.). Plant Ecol (formerly Veg) 171:23–33. https://doi.org/10.1023/B:VEGE.0000029384.40192.cc

Thirukkumaran CM, Parkinson D (2002) Microbial activity, nutrient dynamics and litter decomposition in a Canadian Rocky Mountain pine forest as affected by N and P fertilizers. For Ecol Manage 159:187–201. https://doi.org/10.1016/S0378-1127(01)00432-7

Toneatti-Bastidas M, Roger-Estrade J (2015) Recovering fertility of acidic volcanic ash soils in the Araucania Region (South Chile): impacts of liming, grassland composition, and p fertilisation. Agro Sur 43(2):3–9. https://doi.org/10.4206/agrosur.2015.v43n2-02

Vanhanen L, Savage G (2013) Mineral analysis of Pine nuts (*Pinus* spp.) grown in New Zealand. Foods 2:143–150. https://doi.org/10.3390/foods2020143

Zas R, Fernández-López J (2005) Juvenile genetic parameters and genotypic stability of *Pinus pinaster* Ait. Open-pollinated families under different water and nutrient regimes. For Sci 51:165–174. https://doi.org/10.1093/forestscience/51.2.165