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Variation in early growth and survival of *Pinus ponderosa* provenances established in Southern Chile

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Abstract

Pinus ponderosa P. & C. Lawson was introduced in Chile as a promising species for the diversification of the forest productivity and to optimize the soil productivity in areas where the traditional species have failed to develop satisfactorily; however, the introduction of exotic species in a new environment requires the selection of appropriate source of seeds as a first step for long-term breeding. In this study we assessed growth and survival on 30 *Pinus ponderosa* provenance seedlots from the Pacific and North Plateau races in the United States established in a common-garden experiment. The study included 3 seedlots from the coastal and inland regions of Washington State, 20 from Oregon, and 7 from California. Seedlings were planted in 2002 in a site characterized by high rainfall and snow. Tree height, root collar diameter, and survival were recorded, and a stem volume index calculated, at ages 1, 3, and 6 years since planting. At age 6 years, the best provenance seedlots from the Pacific race averaged 696 cm^3 $year^{-1}$ for stem volume index and 0.36 cm $year^{-1}$ for height. The slowest-growing seedlot, of the North Plateau race, averaged 197 cm^3 $year^{-1}$ for volume index and 0.22 cm $year^{-1}$ for height. Differences in survival were not large, ranging from 85% for a seedlot from interior Oregon to 98% for a Californian provenance. At age 6 years, the average survival across all seedlots was 91%, suggesting good adaptation of the species to the site conditions. The study suggests that provenances of the Pacific race could provide appropriate planting material for forest plantations in Southern Chile.

Keywords Seed origin · Provenance trial · Ponderosa pine · Pacific race · North plateau race

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Introduction

Pinus ponderosa P. & C. Lawson was introduced in Chile by the Instituto Forestal (INFOR) in 1962 as a strategy to diversify the forest productivity; due to the slow growth of the native conifers, and to utilize sub-optimal sites where *Pinus radiata* D. Don, the most widely planted exotic species in the country, exhibited slow growth and pest susceptibility (INFOR-CORFO 1986). *Pinus ponderosa* is an important commercial species found in the United States, Southern Canada, and Northern Mexico, where it covers over 11 million hectares (Ritchie et al. 2005). Some well-differentiated races have been reported, such as the Southern California, Pacific, North Plateau west of the Rocky Mountains and Southwestern east of the Rocky Mountains (Conkle and Critchfield 1988; Callaham 2013b). Most of the forests are located in the Inland northwestern United States and in northern California, where the species grows on a broad range of soil and climatic conditions, and elevations from near sea level to nearly 3300 m.a.s.l. (Oliver and Ryker 1990). Correspondingly, there is considerable provenance variation in growth and morphology (Squillace and Silen 1962; Hanover 1963; Burdon and Low 1991) associated with altitude, precipitation, and temperature (Rehfeldt et al. 1986a, b; Sorensen et al. 2001). Regarding the phenotypic plasticity and commercial potential for the species, it has been introduced at similar latitudes in the Southern Hemisphere in countries such as New Zealand, Australia, South Africa, Argentina, and Chile (INFOR-CORFO 1986; Burdon et al. 1991; Enricci et al. 2000; INFOR 2003).

Provenance tests are essential to select the best seed sources for further plantations at an operational scale, as they provide valuable information on the variation of both adaptive and growth traits. Some experiments with *P. ponderosa* in the Southern Hemisphere have shown significant provenance differences. For instance, in New Zealand, Burdon and Low (1991) found that provenances of the Pacific race had higher growth but lower resistance to *Dothistroma* needle blight than provenances of the North Plateau race. In Argentina, Enricci et al. (2000) found that in good-quality sites (latitude 41°S), provenances from Washington and Oregon (of North Plateau race) had the best growth, while provenances of the Pacific race had the best growth in poor-quality sites. In Chile, *P. ponderosa* was introduced on a moderate scale in the early 1960s by the Instituto Forestal (INFOR) (INFOR-CORFO 1986). Currently, there are ca. 12,000 hectares located in the southern part of the country i.e., from latitude 40° to 47°S, and established with planting material from known seed sources preliminarily selected by growth and survival. In this regard, Sanhueza (1998) in a 15-year-old trial testing 13 provenances located in Southern Chile (45°S, 72°W), in a site with mean annual temperature and precipitation of 4–8 °C and 1000–2000 mm, respectively, found significant variation in tree height and survival among provenances originating at similar longitude (close to the transition between Pacific and North Plateau races) but differing in 5° latitude. Both higher and lower growth rates were observed for provenances from interior Oregon. However, there is still little knowledge about the provenance variation and potential for the species in Chile. In this context, the aim of this study was to examine variation in growth and survival of *P. ponderosa* provenances established in Southern Chile and to test if the ecological resemblance between the provenances origin and the test site conditions is related with provenance performance. A common-garden experiment was established with 30 native provenance seedlots ('provenances'), and assessed for diameter, height, stem volume index, and survival at ages 1, 3, and 6 years since planting. The study also compared the Pacific and North Plateau races because they are the most important racial subdivisions for the well-defined *P. ponderosa* var. *ponderosa* (Burdon et al. 1991; Callaham 2013b). We expect that provenances belonging to the Pacific race with ecological resemblance to the common-garden experiment exhibit a greater performance.

Materials and methods

Plant material

The 30 provenance seedlots of *P. ponderosa* (seed origins) came from areas in coastal and inland Washington, Oregon, and California (United States). The seeds for this study were supplied by Silvaseed Company (http://www.silvaseed.com/index.html) and included three provenances from Washington State, 20 from Oregon State, and seven from California State (Table 1). A probable limitation of the study is that numbers of seed parents and their percentage contributions of seed to individual provenances were unrecorded, but the INFOR took care that each provenance was represented by an appropriated number of seed parents. The provenances were grouped in the races Pacific and North Plateau following Callaham (2013b) and according to the seed zone provided by Silvaseed Company. As there are no records of the exact location of each collection site, we estimated coordinates and altitudes using GoogleEarth. Estimated altitudes ranged from ca. 600–900 m above sea level in Washington, 750–1500 m in Oregon, and 400–1000 m in California, but were not used for statistical analysis.

Raising planting stock

Seeds were soaked in distilled water for 72 h and stratified at 4 °C for 60 days. Seedlings were initially raised by the Instituto Forestal (INFOR) in a coastal nursery (Concepción, central Chile, 36°53′S, 73°07W, 200 m.a.s.l.), under conditions of natural light and temperature. In October 2000, the seeds were sown in pots with 100-mL tray compartments (84 compartments per tray and cultivation density of 441 seedlings m^{-2}) filled with composted bark of radiata pine (*Pinus radiata* D. Don) and then grown until August 2001. Seedlings were fertilized with a commercial foliar fertilizer containing N, P, K (Champion™), and sprayed with fungicide benomyl (Benlate™). At the end of the first growing season (September 2001), the potted seedlings were shipped to a different nursery in the city of Valdivia, Southern Chile (39°47′S, 73°15′W, 18 m.a.s.l.), and cultivated as bare-root stock in 50 m-long transplant beds until May 2002 (i.e., stock type 1 + 1) at a cultivation density of *ca* 100–140 seedlings m^{-2}. During this period, seedlings of all provenances were root pruned to control shoot height and to obtain planting stock of ca 20 cm height (H) and 4 mm in root collar diameter (D). At both nurseries, provenances were randomly allocated to trays and transplant beds.

Trial establishment

In May 2002 a 3.9-ha common-garden experiment was established at the Rucañaco locality (Lonquimay, Southern Chile, 38°44′S, 71°16W, 1,050 m.a.s.l). According to the Köeppen climatic classes, the climate of the region where the trial was installed corresponds to Cfb (temperate oceanic climate with no marked dry season and warm summer). The study site

Table 1 Geographic race and aproximate location for the 30 provenances (seed origins) of *P. ponderosa*

State	Region	Geographic race	Provenance code	Latitude (°N)	Longitude (°W)
Washington	Interior	North Plateau	651-20	46°01′	121°17′
			652-20	45°59′	121°31′
			652-25	45°59′	121°31′
Oregon	Southwestern	Pacific	270-35	42°59′	123°23′
			502-25	42°20′	122°45′
			511-20	42°12′	123°22′
			511-30	42°12′	123°22′
			511-35	42°12′	123°22′
	Interior	North Plateau	673-35	44°23′	120°57′
			673-40	44°23′	120°57′
			675-35	44°22′	121°48′
			675-40	44°22′	121°48′
			675-45	44°22′	121°48′
			681-45	43°27′	121°41′
			682-45	43°38′	121°11′
			701-45	42°41′	121°57′
			702-40	42°37′	120°50′
			721-45	42°05′	121°34′
			863-35	45°23″	117°46′
			882-40	44°36′	117°50′
			922-50	44°17′	119°08′
			930-50	43°58′	118°21′
			941-50	43°54′	119°00′
California	Northwestern	Pacific	303-05	41°03′	123°40′
	Northern interior		521-40	41°15′	121°57′
			741-40	41°16′	121°31′
			741-45	41°16′	121°31′
			741-50	41°16′	121°31′
			742-40	41°08′	120°40′
			742-45	41°08′	120°40′

has a high precipitation (average 2380 mm year^{-1}), and mean, daily maximum, and daily minimum annual temperatures are 8.6 °C, 14.6 °C, and 3.3 °C, respectively (INFOR 2003). The average frost period is 97 days per year, and the dry period is 2 months. The coldest winter months (June and July) receive precipitation as snow. After establishment i.e., July 2002, snow was 25 cm in depth but in severe winters can reach up to 1 m in depth. The site is flat, and soils are derived from volcanic andesitic ash (INIA 1985). The soil texture is loam at 0–11 cm depth, sandy clay loam at 43–98 cm, and clay loam at 98–140 cm (INFOR 2003).

The layout was a randomized complete block design with the 30 provenances and 7 blocks. The experimental unit was a block-plot of 49 trees in a 7 × 7 tree arrangement (i.e., 10,290 seedlings in total), but the analysis considered only the 5 × 5 inner trees, in order to avoid edge effects (i.e., 5250 seedlings in total). Before planting, the site was covered by species of both the montane matorral shrub and Andean grasslands. Site preparation was done manually and consisted of weed control and fencing. Seedlings were hand planted in 40×40×30 cm planting holes at a spacing of 3×2 m (i.e., tree stocking of 1667 stems ha^{-1}). To prevent desiccation around the roots, a superabsorbent polymer (HIDROSORB Forte G^{TM}) was applied by hand at the plantation hole at a dose of 2 g seedling^{-1}. Seedlings were protected from animal damage with a sturdy plastic fence (80 cm tall×20 cm wide) secured with bamboo poles.

Growth and survival assessments

Tree height (H), root collar diameter at the ground line (D), and survival (SUR) were measured on each tree at the ages of 1, 3, and 6 years since planting (i.e., 2003, 2005, and 2008, respectively). A tree-volume index (VOL) was derived as $VOL = D^2H$. H and D were measured in June, during the winter, using a height pole and digital calipers respectively. SUR was recorded as a categoric trait (i.e., live tree = 1, dead tree = 0). Those trees scored as dead in 2003, 2005, and 2008 were replanted but not considered in the data analyses.

Data analysis

The analyses of variance for each single variable were carried out on a plot-mean basis, and were done both separately for each year and across all years. The effects of block, provenance, year, and provenance by year interaction were considered fixed. For each growth variable we also calculated Pearson correlation coefficients between simple provenance means at different ages (i.e., provenance×by time interaction). The analyses were performed using PROC MIXED of SAS 9.2 (SAS Institute, Cary, North Carolina, USA). To meet the assumption of normality and constant variances, growth traits were transformed according to the Box-Cox transformation when appropriate. Analysis of survival data was done unsig a generalized lineal model, using the PROC GLIMMIX of SAS 9.2., and assuming a binomial distribution. Post-hoc mean comparisons of seedlots overall for individual variables were based on the Tukey test. Orthogonal contrast analysis was used to test for differences between races (Pacific vs. North Plateau race). Significant differences were deemed significant at a probability level of < 0.05. Because the repeated measurements were not equally spaced (i.e., years 2003, 2005, and 2008), we previously selected the exponential power structure to model the variance-covariance matrix.

In adition, we used an ecological distance analysis to check if ecological resemblance to the test site conditions was related with provenance performance. With the geographical coordinates of Table 1 we obtained climatic data for each provenance origin from the Worldclim (www.worldclim.org) high-resolution dataset (Hijmans et al. 2005) and calculated the Gower's distance (GD) (Rutter and Fenster 2007) as a measure of environmental distance from the planting site. The mean annual precipitation of the common-garden (2340 mm year^{-1}) is largerly superior to that in the native range of the species (240–740 mm year^{-1}) (Oliver and Ryker 1990; Howard 2003), we thus omitted this climate variable from the analysis and included annual mean temperature (T), maximum temperature of the warmest month (Tmax), minimum temperature of the coldest month (Tmin), temperature annual range (TAR), and summer precipitation (Ps). The same climatic variables were also obtanined for the common-garden experiment. This analysis was performed with INFOSTAT version 2018 (Group Infostat, Universidad Nacional de Córdoba, Argentina). After that, we calculated the Pearson's correlation coefficient between D, H, VOL, and SUR at age 6 years with Gower's environmental distance.

Table 2 Means, standard errors (in parentheses) and F-values for the estimated contrast on growth traits and survival at year 2008 between Pacific and North Plateau races

Trait	Pacific	North plateau	F value
D	6.92 (0.15)	6.02 (0.09)	43.63***
H	186.7 (4.46)	167.0 (3.05)	24.15***
VOL	2959.6 (163.3)	1981.2 (89.6)	41.31***
SUR	92.1 (1.01)	91.3 (0.8)	0.64 ns

***$p < 0.0001$, ns = non-significant ($p > 0.05$)

Table 3 F-values from the analysis of variance on diameter (D), height (H), volume (VOL), and survival (SUR) of *Pinus ponderosa* established in a site in Southern Chile, and assessed from 2003 to 2008

Effect	Traits			
	D	H	VOL	SUR
Provenance (P)	8.51***	7.74***	8.75***	7.47***
Year (Y)	20.22***	14.96***	25.42***	36.30***
P ⊆ Y	1.50*	1.49*	1.70**	0.51ns

***$p < 0.0001$, **$p < 0.001$, *$p < 0.05$, *ns* non-significant ($p > 0.05$)

Results

One year after outplanting, some rabbit damage was evident, with 143 seedlings (2.2% of the trial) showing moderate chlorosis and some exposed roots out of the ground. Continued damage by rabbits was moderate and affected 187 trees (3.5%) in 2003 and 522 trees in 2005 (10%). By the year 2008, 592 trees were forked (11.2% of the trial) with no damage by rabbits. No visual symptoms of fungal attack were observed during the study period.

Differences in growth and survival between geographical races

With the exception of survival, the geographic race samples differed in the growth traits at all ages since planting, with main differences in tree volume index (Table 2). Growth in the Pacific race material was 13, 11, and 33% superior for D, H, and VOL respectively in comparison to that in the North Plateau race.

Provenance variation in growth and survival

Based on Tukey tests, provenances varied in all growth traits by year (Table 3; Fig. 1). At age 6 years, provenances of southwestern Oregon averaged 6.8 cm, 191 cm, and 3,051 dm^3 of D, H, and VOL respectively; while for interior Oregon these traits averaged 5.8 cm, 158 cm and 1768 dm^3, respectively. Provenances 502-25 and 270-35 from southwestern Oregon, and 521-40 and 303-05 from northwestern California (all of Pacific race) had the highest growth. The lowest growth was for the provenance 673-35 from interior Oregon of the North Plateau race. The provenances by time interaction was more related to changes in the level of expression of provenances than in changes in ranking. This is supported by the high age-to-age phenotypic correlations in all the growth traits ($r > 0.88$, Table 4), which suggest a high ranking stability across the study period. A minor exception was provenance

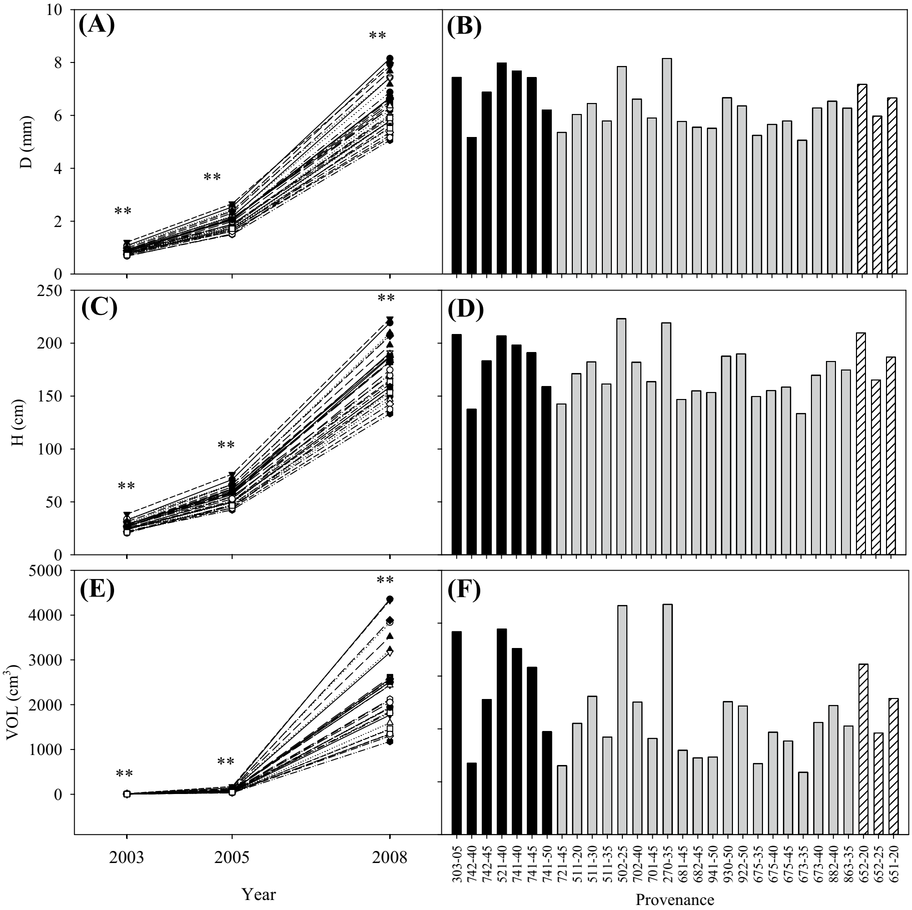

Fig. 1 Means for D, H and VOL for the 30 provenances of *P. ponderosa* from 2003 to 2008 (**a**, **c**, **e**) and by provenances at year 2008 (**b**, **d**, **f**). Provenances are ordered from left to right by latitude of origin. Black bars = Provenances from California; Grey bars = Provenances from Oregon; Dashed bars = Provenances from Washington State. **Differences among provenances by year at $p < 0.001$

Table 4 Age-age phenotypic correlations for simple provenance means for each growth variable (28 degrees of freedom, $p < 0.001$ throughout)

Age (years)	D		H		VOL	
	3 years	6 years	3 years	6 years	3 years	6 years
1	0.94	0.88	0.93	0.89	0.96	0.90
3	–	0.90	–	0.97	–	0.96

D diameter, *H* height, *VOL* volume

675-40 (from interior Oregon and close to the transition zone between the races), which was at the bottom of the ranking for D, H, and VOL among the 30 provenances in 2003 and 2005, but it changed to rankings 24th, 23th, and 19th in 2008 for D, H, and VOL, respectively.

There was no provenance by year interaction for SUR (Table 3). This trait decreased from 96% in 2003 to 91% in 2008 (Fig. 2a). At age 6 years, high survival rates (close to 98%) were found in provenances 741-40 from northearn interior California and provenances 922-50 and 930-50 from interior Oregon. SUR lower than 90% were mainly found in provenances from interior Oregon, i.e., provenances 721-45, 702-40, 681-45, and 673-35 (Fig. 2b).

Relationship between growth traits and ecological distance

Provenances 502-25 and 270-35 of Pacific race were among the provenances with the shortest Gower's distance ($0.24 < GD < 0.34$), whereas the opposite was true for provenance 673-35 of the North Plateau race ($GD = 0.85$). We found no significant correlation between GD and SUR ($r = 0.02$; $p = 0.902$), but there were moderate correlations between GD with growth traits. The Pearson correlation coefficient was -0.52 ($p = 0.015$), -0.45 ($p = 0.038$), and -0.53 ($p = 0.014$), for D, H, and VOL, respectively, confirming that closer ecological distances between provenances origin and the common-garden experiment were related to greater growth.

Discussion

We observed differences in growth among provenances from the Pacific versus North Plateau races, which may be associated to specific differences in altitude, precipitation, and temperature in the sites of origin and that of the planting site (Rehfeldt et al. 1986a, b; Sorensen et al. 2001). The temperate oceanic climate with abundant precipitation, no extended dry season and warm summer experienced in our planting site; located at 1050 m.a.s.l., favored growth in provenances of the Pacific race over those of the North Plateau race, which is best adapted to sites with dry summers and cold winters (Burdon et al. 1991). The Pacific and the North Plateau races are morphologically different (Callaham 2013a, b) and have distinct climate niches (Willyard et al. 2017). The Pacific race has fast growth but a low cold tolerance, while the North Plateau race is cold- and drought tolerant (Burdon et al. 1991). In our study, provenances 502-25, 270-35, and 303-05 (all of the Pacific race, representing the southwest of the Cascade crest and northwestern

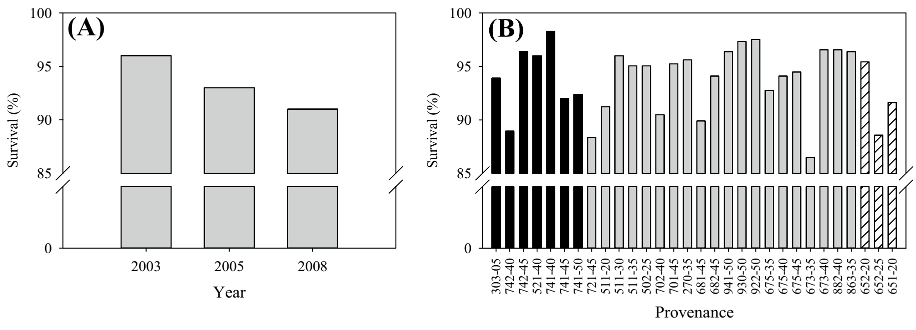

Fig. 2 Average survival for 30 provenances of *P. ponderosa* from years 2003 to 2008 (**a**) and by provenances (**b**). Provenances are ordered from left to right by latitude of origin. Black bars = Provenances from California; Grey bars= Provenances from Oregon; Dashed bars = Provenances from Whashington State

California); from altitudes of ca. 420–900 m.a.s.l., had higher growth than the other provenances. Mirov et al. (1952) observed that provenances from altitudes of 450–1066 m.a.s.l. grew best. In contrast, the provenance 673-35 from interior Oregon (of the North Plateau race and from altitude of ca.. 1,500 m.a.s.l.), exhibited the lowest growth. Burdon and Low (1991) in a large provenance trial with *P. ponderosa* in New Zealand found that in sites with altitude and precipitation levels up to 500 m.a.s.l. and 1450 mm year^{-1}, respectively, height was higher in provenances of the Pacific race, while provenances of the Northern Plateau race exhibited smaller diameters. Enricci et al. (2000) in a provenance trial located in Southern Argentina; where the site was at a similar longitude to our study but with less precipitation, found that provenances from Oregon and Washington were the tallest. Although those authors did not evaluate any Pacific race provenances, the Washington provenances come from west of the Cascade crest and probably from a transition zone between the two races.

In our survival results the Pacific and North Plateau races did not differ from each other ($p > 0.05$), but provenances did so. At age 6 years, the differences in SUR between provenance 742-45 (latitude 41°08′) and provenance 651-20 (latitude 46°01′) (95 v. 88%, respectively) suggests genotypic control of this trait as an adaptation at their respective seed sources (cf. Kitzmiller 2005). However, at age 6 years the difference in SUR between the best and worst provenance was small, being only 14.8%, and likely reflects high soil moisture at the planting site. The common-garden was established in a site with a mean annual precipitation of 2340 mm and a dry period of 2 months, whereas the ecological requirement of *P. ponderosa* on its native habitat are 250–750 mm year^{-1} of precipitation and a dry period of 4 months (Oliver and Ryker 1990; Howard 2003). On the other hand, some *P. ponderosa* provenances grows in sites with extreme low temperatures ($< -$ 40 °C) (Oliver and Ryker 1990), and the absence of this extreme temperatures in our planting site may have also favored survival. However, the results of this study are still limited because it included only one site, and cannot be extrapolated to sites receiving low precipitation. In this regard, Dome and Gartner (2003) found a height growth rate of 0.09 m year^{-1} at the age 31 years in natural stands growing in a site with 645 mm year^{-1} of precipitation. Squillace and Silen (1962) in a provenance trial replicated at different sites found the same height growth rate at the age 30 years old, i.e., 0.09 m year^{-1}, in provenances belonging to the Pacific race established at high altitude with little rainfall and cooler temperatures (1150 m.a.s.l., 422 mm year^{-1}, 8 °C of mean annual temperature). The same provenances established at a low altitude site with high rainfall and warm temperatures (290 m.a.s.l., 1017 mm year^{-1}, 11.3 °C of mean annual temperature) exhibited a mean height growth rate of 0.37 m year^{-1}. According to Kitzmiller (2005) growth of *P. ponderosa* is inversely associated with elevation. Similarly, Burdon and Low (1991) found a height growth rate of 0.58 m year^{-1} at 22–24 years for provenances established in a site with annual precipitation of 1,050 mm and a value of 0.34 m year^{-1} for provenances established in a site with precipitation of 360 mm year^{-1}. Our trial remains to be assessed at older ages, but average height growth rate of 0.26–0.32 m year^{-1} for all provenances at 6 years compares well with those recorded by Enricci et al. (2000) and Jovanovski et al. (2002) at 11 years, who reported values from 0.18 to 0.39 m year^{-1} depending on precipitation and the site quality. This corroborates the potential growth of the provenances tested in Southern Chile.

Temperature- and precipitation-based variables are typically used in common-garden experiments to relate provenance growth to climate at provenance origin (Akalusi and Bourque 2018). Compared to precipitation, it has been reported that temperature is a better determinant of plant population variations (Thomson et al. 2009). Kitzmiller (2005) pointed out that the growth potential of *P. ponderosa* is strongly influenced by the temperature at seed origin, and Callaham (2013b) found a positive correlation between needle growth with the temperature of the growing season. In our study, average annual temperature at the planting site is 8.6 °C; which is higher than that reported by Squillace and Silen (1962) and Callaham (2013b) for some provenance origins, and must have favored growth and survival. Our ecological distance analysis indicated that growth was inversely related with GD. Provenances 270-35 and 502-25, with short GD, tended to grow more than those provenances from sites with larger GDs, e.g., provenance 673-35, which had the large difference in annual temperature with the common-garden experiment and corroborates the importance of temperature in the ecology of the species. Martínez-Berdeja et al. (2019) found a mean survival rate of 67% for four provenances of *P. ponderosa* planted in a site with a mean annual temperature of 6.7 °C, but the same provenaces planted in a site with mean annual temperature of 13.5 °C had survival up to 98%. However, our results of ecological distance must be viewed with caution because the geographical coordinates to obtain climatic data from the WorldClim dataset were an approximation of the exact location of each provenance origin and not the exact location at which seed was collected.

In Chile, the potential of *P. ponderosa* was recognized by the Instituto Forestal (INFOR) in the early 1960s. However, the phases in the development of new plantations in Chile i.e., discovery, acceptance, domestication, consolidation, and full industry adoption, may take over 50 years, as was experienced with the radiata pine (*P. radiata*) industry in Chile, and after the implementation of government subsidies (Mead 2013). Radiata pine is the most extensive and profitable conifer planted in Chile but our results would support the adaptation of *P. ponderosa* to Southern Chile in sites with climatic limitations for radiata pine plantations. Usually, sites with very low temperature, heavy snow, and above 1000 m.a.s.l. are avoided for *P. radiata* (Mead 2013), while *P. ponderosa* grows naturally up to 3280 m.a.s.l. and in climates where much of the precipitation is snow (Jones 1972). Our planting site is characterized by high rainfall and snow in winter (INFOR 2003), similar to some soils where *P. ponderosa* grows naturally in western United States. Snow can cause toppling in young trees and crown breakage in older trees. Although trees in this common-garden trial must have suffered some snow damage and winter injury, the average survival at age 6 years was 91%, which compares with the 92% survival found by Enricci et al. (2000) in an 11-year-old stand. Thus, the potential growth of *P. ponderosa* in Southern Chile might be positively influenced by the effect of a combination of climate variables that resemble some of those of their native origins, i.e., mean annual temperature of 8.6 °C, frost-free period of 268 days, elevation of 1050 m.a.s.l., and rainfall of 2380 mm year^{-1}. Altough rainfall over 2000 mm year^{-1} incresases the occurrence of *Dothistroma* needle blight (Mead 2013) in *P. ponderosa* outside its native range (Bingham et al. 1971), this disease was absent in our experiment and may be explained by minimal summer precipitation (Rack 1986). However, in the context of climate change, it is expected that seed sources for future plantations have adaptations for the predicted changes in the patterns of temperature and precipitation (Jacobs et al. 2015). This is particularly important in Central Chile (30°–38°S), a natural region that has experienced a succession of dry years since 2010 i.e., the so called "Mega Drought" (Garreaud et al. 2019), and highlights the necessity to replicate provenance trials to test the adaptation of new introduced species across a range of environmental conditions.

Conclusions

Our results of growth and survival suggest great adaptability of the provenances under study to the test site characterised by high rainfall and snow and confirms that the provenances origin with closer ecological distances to the common-garden experiment were related to greater performance. Provenances of the Pacific race, from southwestern of the Cascade crest and northwestern California might be considered as a valuable source for planting material in Southern Chile as they were the fastest-growing origins.

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References

Akalusi ME, Bourque CP (2018) Effect of climatic variation on the morphological characteristics of 37-year-old balsam fir provenances planted in a common garden in New Brunswick, Canada. Ecol Evol 8(6):3208–3218

Bingham RT, Hoff RJ, Mcdonald GI (1971) Disease resistance in forest trees. Annu Revi Phytopathol 9:433–452. https://doi.org/10.1146/annurev.py.09.090171.002245

Burdon RD, Low CB (1991) Performance of *Pinus ponderosa* and *Pinus jeffreyi* provenances in New Zealand. Can J For Res 21:1401–1414. https://doi.org/10.1139/x91-197

Burdon RD, Miller JT, Knowles FB (1991) Introduced forest trees in New Zealand: recognition, role, and seed source. 10. Ponderosa and Jeffrey Pines. FRI Bulletin No 124. Forest Research Institute, Rotorua, 23 p

Callaham RZ (2013a) *Pinus ponderosa*: a taxonomic review with five subspecies in the United States. Research Paper PSW-RP-264. USDA Forest Service, Albany, 52 p

Callaham RZ (2013b) *Pinus ponderosa*: geographic races and subspecies based on morphological variation. Research Paper PSW-RP-265. USDA Forest Service, Albany, 53 p

Conkle MT, Critchfield WB (1988) Genetic variation and hybridization of *Ponderosa pine*. General Technical Report. USDA Forest Service, Berkeley, CA, 17 p

Dome JC, Gartner BL (2003) Relationship between growth rates and xylem hydraulic characteristics in young, mature and old-growth ponderosa pine trees. Plant Cell Environ 26:471–483. https://doi.org/10.1046/j.1365-3040.2003.00978.x

Enricci R, Pasquini N, Picco OY, Mondino V (2000) Ensayos de procedencia de *Pinus ponderos*a Dougl. ex Laws. en la Patagonia de los Andes de Argentina. FAO. http://www.fao.org/docrep/008/x9662s/X9662S07.htm. Accessed 30 June 2020

Garreaud RD, Boisier JP, Rondanelli R, Montecinos A, Sepúlveda HH, Veloso-Aguila D (2019) The central Chile mega drought (2010–2018): a climate dynamics perspective. Int J Climatol 40:421–439. https://doi.org/10.1002/joc.6219

Hanover JW (1963) Geographic variation in ponderosa pine leader growth. For Sci 9:86–95. https://doi.org/10.1093/forestscience/9.1.86

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. Int J Climatol 25:1965–1978. https://doi.org/10.1002/joc.1276

Howard JL (2003) *Pinus ponderosa* var. brachyptera, P. p. var. scopulorum. USDA Forest Service. https://www.fs.fed.us/database/feis/plants/tree/pinpons/all.html. Accessed 30 June 2020

INFOR (2003) Pino ponderosa and Pino oregón. Coníferas para el sur de Chile. INFOR, Valdivia

INFOR-CORFO (1986) Especies forestales exóticas de interés económico para Chile. Instituto Forestal, Corporación de Fomento de la Producción. http://bosques.ciren.cl/handle/123456789/14794. Accessed 19 Nov 2020

INIA (1985) Suelos volcánicos de Chile. Instituto de Investigaciones Agropecuarias, Santiago

Jacobs DF, Oliet JA, Aronson J, Bolte A, Bullock JM, Donoso PJ, Landhäusser SM, Madsen P, Peng S, Rey-Benayas JMR, Weber JC (2015) Restoring forests: What constitutes success in the 21st century? New For 46:601–614. https://doi.org/10.1007/s11056-015-9513-5

Jones JR (1972) Moisture stresses in Arizona mixed conifer seedlings. Research Paper RM-86. USDA Forest Service, Fort Collins, CO, p 8

Jovanovski A, Jaramillo M, Loguercio G, Antequera S (2002) Densidad de la madera de Pinus ponderosa (Dougl. Ex Laws) en tres localidades de Argentina. Bosque (Valdivia) 23(2):57–67

Kitzmiller J (2005) Provenance trials of ponderosa pine in northern California. For Sci 51(6):595–607. https://doi.org/10.1093/forestscience/51.6.595

Martínez-Berdeja A, Hamilton JA, Bontemps A, Schmitt J, Wright JW (2019) Evidence for population differentiation among Jeffrey and Ponderosa pines in survival, growth and phenology. For Ecol Manag 434:40–48. https://doi.org/10.1016/j.foreco.2018.12.009

Mead DJ (2013) Sustainable management of *Pinus radiata* plantations. FAO, Rome

Mirov NT, Duffield JW, Liddicoet AR (1952) Altitudinal races of *Pinus ponderosa*-a 12-year progress report. J For 50:825–831. https://doi.org/10.1093/jof/50.11.825

Oliver W, Ryker R (1990) Ponderosa pine (*Pinus ponderosa* Laws.). In: Fowells HA (ed) Silvics of forest trees of the United States. Volume 1: Conifers. USDA Forest Service, Washington, DC, pp 417–431

Rack K (1986) Über die jahreszeitliche Entlassung der Konidien von Dothistroma pini in Pinus radiata Kulturen des südlichen Chile. Eur J For Pathol 16:6–10. https://doi.org/10.1111/j.1439-0329.1986.tb01046.x

Rehfeldt GE (1986a) Adaptations in *Pinus ponderosa* from Intermountain regions. I. Snake and Salmon river basins. For Sci 32:79–92. https://doi.org/10.1093/forestscience/32.1.79

Rehfeldt GE (1986b) Adaptations in *Pinus ponderosa* from Intermountain regions. II. Middle Columbia river System. Research paper INT-373. USDA Forest Service, Ogden, p 9

Ritchie MW, Maguire DA, Youngblood A (2005) Proceedings of the symposium on ponderosa pine: issues, trends, and management. Geneneral technical report PSW-GTR-1982004. USDA Forest Service, Klamath Falls, OR, p 281

Rutter MT, Fenster CB (2007) Testing for adaptation to climate in *Arabidopsis thaliana*: a calibrated common garden approach. Ann Bot 99:529–536. https://doi.org/10.1093/aob/mcl282

Sanhueza O (1998) Evaluación de un ensayo de procedencias de *Pinus ponderosa* Laws en el sector de Río Claro, XI Región. Dissertation, Universidad Austral de Chile

Sorensen FC, Mandel NL, Aagaard JE (2001) Role of selection versus historical isolation in racial differentiation of ponderosa pine in southern Oregon: an investigation of alternative hypotheses. Can J For Res 31:1127–1139. https://doi.org/10.1139/x01-039

Squillace AE, Silen RR (1962) Racial variation in ponderosa pine. For Sci Monogr 2:1–27. https://doi.org/10.1093/forestscience/8.s1.a0001

Thomson AM, Riddell CL, Parker WH (2009) Boreal forest provenance tests used to predict optimal growth and response to climate change: 2. Black spruce. Can J For Res 39:143–153. https://doi.org/10.1139/X08-167

Willyard A, Gernandt DS, Potter K, Hipkins V, Marquardt P, Mahalovich MF, Langer SK, Telewski FW, Cooper B, Douglas C, Finch K, Karemera HH, Lefler J, Lea P, Wofford A (2017) *Pinus ponderosa*: a checkered past obscured four species. Amer J Bot 104(1):161–181