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Research article

Growth and stem quality of Southern black pine provenances in *Metepec*, State of Mexico

Crecimiento y calidad de fuste de procedencias del pino prieto austral en Metepec, Estado de México

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Abstract

In Mexico, the Southern black pine (*Pinus greggii* var. *australis*) is widely used for timber plantations and reforestation, but it is necessary to assess its performance at specific sites in order to select superior genotypes. The objective of this research study was to determine differences among provenances in terms of growth and stem quality, as well as to evaluate their relationship with environmental variables. The assessment was conducted in a provenance trial of eight sources of Southern black pine, established in *Metepec*, State of Mexico. All variables showed significant differences among provenances ($p \leq 0.0002$), except for branch angle and diameter ($p \geq 0.3558$). The provenances *El Madroño*, *El Cobre* and *El Pinalito* exhibited the highest survival rates (69.57 to 79.54 %). *La Parada*, *El Madroño*, *El Pinalito*, *El Cobre* and *La Cebada* showed higher stem volume (115.1 to 134.6 dm3), periodic annual increment in diameter at breast height (1.83 to 2.14 cm), and in height (0.80 to 0.84 m). *La Parada*, *Molango*, *El Madroño* and *La Cebada* produced the straightest stems, whereas *El Cobre*, *El Piñón* and *Ponthadó* showed fewer growth units and branches. Growth variables were positively correlated with latitude ($r \geq 0.711$, $p \leq 0.048$), while the number of growth units and stem straightness were correlated with precipitation ($r \geq 0.761$, $p \leq 0.028$) and branch diameter was correlated with latitude and altitude ($r \geq 0.714$, $p \leq 0.047$). *El Madroño* is recommended for both reforestation and timber plantations due to its high survival, growth performance, and stem quality.

Key words: *Agave angustifolia* Haw., species association, native tree species, Cultural Importance Index, prioritization of species, productive restoration.

Resumen

En México, el pino prieto austral (Pinus greggii var. australis) se usa ampliamente para plantaciones maderables y reforestaciones, pero es necesario evaluar su desempeño en sitios específicos para elegir los mejores genotipos. El objetivo de la presente investigación fue determinar las diferencias entre procedencias en función del crecimiento y calidad de fuste, así como evaluar su relación con variables ambientales. El estudio se realizó en un ensayo de ocho procedencias de pino prieto establecido en Metepec, Estado de México. Todas las variables tuvieron diferencias entre procedencias ($p \leq 0.0002$), excepto el ángulo y diámetro de ramas ($p \geq 0.3558$). Las procedencias El Madroño, El Cobre y El Pinalito registraron la supervivencia más alta (69.57 a 79.54 %). La Parada, El Madroño, El Pinalito, El Cobre y La Cebada alcanzaron mayor volumen (115.1 a 134.6 dm3), incremento periódico anual de diámetro normal (1.83 a 2.14 cm) y de altura (0.80 a 0.84 m). La Parada, Molango, El Madroño y La Cebada tuvieron los fustes más rectos; mientras que El Cobre, El Piñón y Ponthadó presentaron menores unidades de crecimiento y número de ramas. Las variables de crecimiento se correlacionaron con la latitud ($r \geq 0.711$, $p \leq 0.048$); las unidades de crecimiento y rectitud de fuste con la precipitación ($r \geq 0.761$, $p \leq 0.028$) y el diámetro de ramas con la latitud y altitud ($r \geq 0.714$, $p \leq 0.047$). El Madroño se recomienda tanto para reforestación, como para plantaciones maderables debido a su alta supervivencia, crecimiento y calidad de fuste.

Palabras clave: Correlación, incremento periódico anual, latitud, *Pinus greggii* Engelm. ex Parl. var. *australis* Donahue & Lopez Upton, rectitud de fuste, supervivencia.

Introduction

Forests are important for sustainable development because they provide multiple ecosystem goods and services (Food and Agriculture Organization of the United Nations [FAO], 2020; Pérez et al., 2008). At the global, national and local levels, forests are under pressure from stressors related to climate change, anthropogenic factors, and the increasing demand for forest products. Therefore, it is necessary to develop actions to protect, conserve, restore and sustainably use forest resources (FAO, 2024).

Among the alternatives to reduce pressure on natural forests is the establishment of productive and protective forest plantations (Carle & Holmgren, 2009; Carle et al., 2020). In Mexico, reforestation has been established in *ejidos* and communities with government support since 1970, with low survival rates (44 to 48 %) (Burney et al., 2015). Likewise, the federal government promoted commercial forest plantations between 1997 and 2008, establishing 117 479 ha, with an average growth of 10 m^3

ha^{-1} year^{-1} (Velázquez-Martínez et al., 2013). Reforestation efforts and commercial plantations in Mexico face multiple challenges, including increasing adaptation and productivity, as well as reducing mortality and the effects of climate change (Burney et al., 2015; Velázquez-Martínez et al., 2013).

In Mexico, the germplasm used is of low genetic quality (Burney et al., 2015; Velázquez-Martínez et al., 2013). Therefore, in reforestation programs and commercial plantations, forest genetic improvement (FGM) as a technological innovation is essential to address these challenges (FAO, 2024). Through FGM, provenances and families are selected, and varieties and clones are developed to increase productivity, improve adaptation, and increase tolerance to pests and diseases (Sánchez-Rosales et al., 2025; White et al., 2007; Zobel & Talbert, 1988). To establish plantations, it is necessary to select species and provenances that tolerate the conditions of specific sites (Sánchez-Rosales et al., 2025; Zobel & Talbert, 1988).

In the State of Mexico government, through the Forest Protection Agency (*Probosque*), 16 398.86 hectares of forest plantations were financed between 2012 and 2023 (*Protectora de Bosques del Estado de México* [*Probosque*], 2024). Between 1990 and 2002, this same productive entity initiated FGM programs, establishing 26 seed stands, 15 seed areas, 28 sexual seed orchards, and two asexual seed orchards, as well as multiple provenance and progeny trials with potential species for reforestation and commercial plantations (Azamar-Oviedo et al., 2000; Rojas-Vergara, 2023).

Among the species included in the FGM plans for the State of Mexico was *Pinus greggii* Engelm. *ex* Parl., which has shown good adaptation and growth in the region (Azamar-Oviedo et al., 2000). This species grows quickly and its wood is used in the sawmill industry, thus it is widely used in commercial plantations and in reforestation for the recovery of degraded soils (Gómez-Romero et al., 2012; Vásquez-García et al., 2016).

According to the above, *P. greggii* is the second most produced species in forest nurseries in Mexico, representing 10 % of national production (Burney et al., 2015). Both varieties of this species (var. *greggii* and var. *australis*) have been planted outside their natural distribution area, where their provenances show differential responses in terms of survival, growth and adaptation (Valencia-Manzo et al., 2006). For this reason, provenance and progeny trials were established in the State of Mexico to evaluate the performance of this species in the *Metepec* and *Almoloya de Juárez* regions. Of these trials, only one was evaluated and converted into a sexual seed orchard (Azamar-Oviedo et al., 2000); the rest lack scientifically rigorous evaluation, as is the case with a trial of *Pinus greggii* Engelm. *ex* Parl. var. *australis* Donahue & Lopez Upton, established in August 2012 in the Bicentennial Environmental Park in *Metepec*, State of Mexico.

In this context, the objective of this study was to determine the differences between provenances of *P. greggii* var. *australis* in terms of survival, growth characteristics and stem quality, as well as to evaluate the relationship of these characteristics with geographic and environmental factors. It was hypothesized that growth and stem quality would differ among provenances due to genetic variation and the influence of environmental and geographic factors of origin. A discussion was also provided on the use of provenances in the *Metepec* region, State of Mexico, Mexico.

Materials and Methods

Seed origin and trial establishment

The trial was established with eight provenances; the seed of two of them was collected from selected trees located in natural stands; while the seed source for the remaining provenances was the asexual seed orchard of *Pinus greggii* var. *australis*, located next to the *Probosque* greenhouses (19°14′27.9″ N, 99°35′06.1″ W, 2 600 masl) in the *Metepec* municipality, State of Mexico (Table 1). The plants were produced in the forest nursery of the *Colegio de Postgraduados* (Graduate studies School) at *Montecillo* Campus, with a peat moss (50 %), agrolite (25 %) and vermiculite (25 %) substrate. One kilogram of Multicote^{TM} was applied per cubic meter of substrate. The plants were six months old at the time of planting.

Table 1. Geographical and environmental characteristics of the evaluated provenances of *Pinus greggii* Engelm. *ex* Parl. var. *australis* Donahue & Lopez Upton.

Provenance	**Municipality, State**	**Latitude (N)**	**Longitude (O)**	**Altitude (m)**	**MAT (°C)**	**MAP (mm)**	**pH**
Ponthadó	*Metztitlán*, Hgo.	20°28′59.4″	98°53′59.3″	2 386	18	750	6.5
La Cebada	*Zimapán*, Hgo.	20°54′1.97″	99°11′54.5″	2 347	18	850	6.5
Molango¥	*Molango*, Hgo.	20°46′33.1″	98°43′18.9″	1 850	21	900	6.7
El Cobre¥	*Jacala*, Hgo.	21°02′39.8″	99°09′43.9″	1 840	20	700	6.2
El Madroño¥	*LDM*, Qro.	21°16′59.5″	99°08′25.5″	1 745	20	850	6.3
El Pinalito¥	*Jacala*, Hgo.	21°01′43.0″	99°09′35.8″	1 735	20	700	6.5
El Piñón¥	*Jacala*, Hgo.	21°02′47.6″	99°10′32.4″	1 700	20	650	6.2
La Parada¥	*LDM*, Qro.	21°15′36.1″	99°10′14.8″	1 638	20	850	6.3

¥Source: *Metepec* seed orchard. MAT = Mean annual temperature; MAP = Mean annual precipitation. Hgo. = State of *Hidalgo*; Qro. = State of *Querétaro*; LDM = *Landa de Matamoros*.

The provenance trial was planted in August 2012 in the Bicentennial Environmental Park (19°14’47.90” N, 99°35’26.20” W, 2 607 masl) in the *Sedagro* Complex, *Metepec*, State of Mexico, Mexico. The average annual rainfall is 800 mm, the average annual temperature is 12.7 °C, and there are 100 to 120 frost days per year (Azamar-Oviedo et al., 2000).

The water table is shallow, and the soil texture is sandy loam (57.84 % sand, 22.72 % silt, 19.44 % clay) with a depth of 1.20 m (Azamar-Oviedo et al., 2000). Prior to planting (April 2012), the soil was subsoiled (broken up the surface layer) every 3 m using heavy D7 machinery; the clods were then broken up and the soil leveled with a farm tractor harrow.

Spacing and experimental design

Planting was carried out on a 30×30 cm common stock using a true frame design with 3 m separation between plants. The experimental design was randomized complete blocks (23), with experimental units of one plant per family (60) corresponding to eight provenances. A total of 1 238 plants were planted for evaluation, in addition to a line of plants surrounding the experiment to eliminate the edge effect (Valencia-Manzo et al., 2006).

Growth variable measurement

The first height measurement was taken in early 2013, after the initial growth period; while the first normal diameter measurement (at 1.30 m height) was taken in early 2019, when all trees exceeded 1.30 m. Height and normal diameter were measured using a model MGA 725 Cadena® caliper and a model IP67 ABSOLUTE Miltutoyo® digital caliper, respectively. The second measurement of both variables was taken in early 2023, 10.5 years after the trial was established. For these measurements, normal diameter was determined using a model Mantax Blue 400 mm Haglöf® caliper, and height was determined using a model W-Germany Haga® hypsometer. Using the data from the first and second assessments, the Annual periodic increment in height (*APIH*) and normal diameter (*APIDN*) were calculated using the following Equation (Imaña & Encinas, 2008):

$$API = \frac{Second\ measurement - First\ measurement}{Years\ between\ the\ first\ and\ the\ second\ measurement} \qquad (1)$$

Using the normal diameter (*ND*) and height (*A*) data from 2023, the volume (*V*) of the trees was obtained using the Schumacher and Hall Equation (Muñoz-Flores et al., 2012):

$$V = 0.00013794(ND)^{1.671395792}(A)^{0.916603698} \qquad (2)$$

In early 2019, crown diameter was also measured using a model TP50ME Truper® measuring tape. Stem quality variables such as the number of growth units, stem straightness, and the number, diameter, and angle of branches were defined. Stem straightness was qualitatively assessed: 1 (very crooked or twisted), 2 (moderately crooked or twisted), 3 (slightly crooked or twisted), and 4 (straight). Branch diameter and angle were recorded on all branches in the first whorl of each tree, and the average was then calculated. Branch diameter was measured with a model VER-6PX Pretul® caliper, and angle with a model 01697 Faber Castell® 180° protractor.

Data analysis

Prior to analysis, the assumption of normality and homogeneity of variances were checked using the Shapiro-Wilk and Levene tests, respectively. All variables failed to meet both assumptions ($p \leq 0.0196$), except for the number of branches ($p \geq 0.165$). The number of branches was analyzed using parametric ANOVA and Tukey's mean comparisons; the remaining variables were analyzed using nonparametric RT4 tests and multiple range comparisons (Conover, 2012). The statistical model used was as follows:

$$Y_{ijk} = \mu + \beta_i + P_j + BP_{ij} + F_{k(j)} + \varepsilon_{ijk} \qquad (3)$$

Where:

Y_{ijk} = Observed value of the tree of the k^{th} family nested in the j^{th} provenance in the i^{th} block

μ = Population mean

β_i = Effect of the i^{th} block

P_j = Effect of the j^{th} provenance

BP_{ij} = Block-by-provenance interaction effect

$F_{k(j)}$ = Effect of the k^{th} family nested in the provenance

ε_{ijk} = Random error

To identify the best provenances based on the set of variables, a principal components analysis was performed for the growth variables, and another analysis for the stem quality variables that showed differences between provenances. Principal component 1 was used as a multidimensional index, which was combined with a rank comparison test to classify the provenances separately according to growth and stem quality.

To determine the relationship between the study variables and the geographic and environmental factors of the provenances, Spearman's correlation coefficients were obtained for the variables that did not meet the statistical assumptions, and Pearson's correlation coefficients were obtained for the number of branches.

Results

Survival and growth

Survival and all growth variables were significantly different among provenances ($p \leq 0.0011$), as *El Madroño* having the highest survival rate (75.54 %) while *Ponthadó* had the lowest (61.71 %) (Table 2). *La Parada* had the highest Annual periodic height increment (*APIH*), Annual periodic diameter increment (*APIDN*) and volume; *El Cobre* and *El Madroño* had the largest crown diameter; conversely, *Ponthadó* had the lowest growth rates (Table 2).

Table 2. Average values with range comparisons for survival and growth of *Pinus greggii* Engelm. *ex* Parl. var. *australis* Donahue & Lopez Upton provenances.

Provenance	**Survival (%)**	***APIH* (m)**	***APIDN* (cm)**	**Volume (dm^3)**	**Crown diámeter (m)**	**Principal component 1**
La Parada	64.38b	0.84a	2.08a	134.6a	2.94a	0.684a
El Madroño	75.54a	0.83ab	2.04ab	130.3ab	3.01a	0.328ab
El Pinalito	69.57ab	0.80ab	2.14a	119.0ab	2.72ab	0.126ab
El Cobre	74.81a	0.84a	1.86cd	121.3ab	3.05a	0.108ab
La Cebada	64.07b	0.83a	1.83bc	115.1bc	2.92a	0.060ab
Molango	68.12ab	0.80bc	1.87bc	111.1bc	2.80ab	-0.155abc
El Piñón	63.29b	0.78bc	1.84bcd	108.0bc	2.76ab	-0.368bc
Ponthadó	60.71b	0.75c	1.76d	99.1c	2.46b	-0.925c

APIH = Annual periodic height increment; *APIDN* = Annual periodic increment of base diameter. Different letters in the same column indicate a significant difference ($p \leq 0.05$) between provenances.

Principal component 1 of survival and growth variables (CPrin1) explained 71.95 % of the variation; volume had the greatest contribution (0.569), followed by *APIH*, *APIDN*, and crown diameter (0.481 to 0.469). CPrin1 showed differences between provenances (p<0.0001), with values ranging from -0.925 (*Ponthadó*) to 0.684 (*La Parada*). All the origins were the same as *La Parada*, except *El Piñón* and *Ponthadó* (Table 2).

Stem quality

The number of growth units, the number of branches, and stem straightness showed differences between provenances (p≤0.0002); conversely, branch angle and diameter did not differ significantly between provenances (p≥0.3558). *El Cobre*, *El Piñón* and *La Parada* showed a lower number of growth units (13.70) and branches (42.67) and greater stem straightness (2.48), respectively; while, for the same variables, *Molango*, *La Cebada*, and *El Piñón* had the most contrasting values (15.17, 46.16, and 1.78) compared to the values of the provenances mentioned above (Table 3). The angle and thickness of the stems ranged from 71.08° to 72.53° and from 1.61 to 2.12 cm (Table 3). Principal component 1 (CPrin1) of the stem quality variables explained 65.9 % of the variation; the largest contributions were made by the number of branches (0.619) and the number of growth units (0.613), followed by stem straightness (0.491). The CPrin1 of the stem quality variables showed significant differences among provenances (p≤0.0001); *La Parada* recorded the highest value and was statistically equal to all the others, except for *El Cobre*, *Ponthadó* and *El Piñón*, which obtained lower values (Table 3).

Table 3. Averages and comparison of variable ranges of stem quality in provenances of *Pinus greggii* Engelm. *ex* Parl. var. *australis* Donahue & Lopez Upton in *Metepe*c, State of Mexico, Mexico.

Provenance	**Growth units**	**Number of branches**	**Stem straightness**	**Branch angle (°)**	**Branch diameter (cm)**	**Principal component 1**
La Parada	15.14c	47.27b	2.48a	72.37a	2.09a	0.590a
Molango	15.17c	44.00ab	2.30ab	71.81a	1.98a	0.265ab
El Madroño	14.74bc	45.53ab	2.29ab	71.82a	2.08a	0.213ab
La Cebada	13.98abc	46.16b	2.32ab	71.08a	1.99a	0.206ab
El Pinalito	14.69bc	45.56ab	1.94bc	72.53a	2.12a	0.079ab
El Cobre	13.70a	45.20ab	1.98bc	72.52a	2.06a	-0.195b
Ponthadó	14.00ab	44.41ab	2.06bc	71.95a	1.61a	-0.274b
El Piñón	13.92ab	42.67a	1.78c	71.28a	2.05a	-0.421b

Different letters in the same column indicate a significant difference ($p \leq 0.05$) between provenances.

Relationship between growth and environmental variables

Latitude showed a high ($r \geq 0.711$) and significant ($p \leq 0.047$) positive correlation with the periodic Annual increase in height and normal diameter, volume, crown diameter, and branch diameter. Similarly, average annual precipitation registered a positive and significant correlation ($r \geq 0.761$, $p \leq 0.028$) with growth units and stem straightness; while altitude only had a negative and significant correlation ($r=-0.786$, $p=0.021$) with branch diameter; the remaining correlations between variables were not significant (Table 4).

Table 4. Correlation coefficient and significance between geographic and environmental variables and stem growth and quality variables.

	Sup	***APIH***	***APIDN***	***Vol***	***DC***	***UC***	***NR***	***RF***	***AR***	***DR***
Latitude	0.540	0.750	0.711	0.894	0.781	0.024	0.424	0.206	0.197	0.714
	0.167	0.032	0.048	0.003	0.022	0.955	0.295	0.625	0.640	0.047
Longitude	0.238	-0.352	0.143	-0.190	-0.238	0.548	-0.381	-0.024	0.286	-0.262
	0.570	0.393	0.736	0.651	0.570	0.160	0.352	0.955	0.493	0.531
Altitude	-0.238	-0.315	-0.690	-0.548	-0.214	-0.143	-0.214	0.143	-0.286	-0.786
	0.570	0.447	0.058	0.160	0.610	0.736	0.610	0.736	0.493	0.021
Average annual temperature	0.522	0.161	0.619	0.261	0.247	0.481	-0.302	-0.069	0.165	0.275
	0.184	0.703	0.102	0.532	0.555	0.227	0.467	0.872	0.696	0.510
Average annual precipitation	0.051	0.375	0.108	0.335	0.278	0.761	0.458	0.935	-0.176	-0.233
	0.905	0.361	0.800	0.417	0.505	0.028	0.254	0.001	0.676	0.578
pH	-0.257	-0.325	-0.105	-0.395	-0.451	0.593	-0.024	0.314	-0.118	-0.371
	0.538	0.433	0.805	0.333	0.262	0.121	0.956	0.448	0.780	0.366

Sup = Survival; *APIH* = Annual periodic increment in height; *APIDN* = Annual periodic increment of base diameter; *Vol* = Volume; *DC* = Crown diameter; *UC* = Growth units; *NR* = Number of branches; *RF* = Stem straightness; *AR* = Branch angle; *DR* = Branch diameter.

Discussion

The differences between provenances in growth traits and stem quality determined in this study are due to the influence of genetic factors, environmental factors, and the interaction of both (White et al., 2007; Zobel & Talbert, 1988). These differences indicated that provenances respond differentially to the environmental conditions of the planting site, which was reflected in their varying degrees of adaptability (Rodríguez Laguna et al., 2008).

For survival, branch number, and angle, genetic factors could have been crucial in the differences between provenances, as these variables were not associated with environmental variables; however, genetic control of branch angle is moderate (h_f^2= 0.21 to 0.35) in *P. greggii* var. *australis* (Reyes-Esteves et al., 2022). Another possibility is that environmental factors not considered in this study are playing a role. For example, minimum temperatures and photoperiod determine the differences between provenances of the *greggii* variety (Valencia-Manzo et al., 2017).

Differences in growth, growth units, stem straightness, angle, and branch diameter are possibly due to genetic adaptations of the provenances to environmental variations (López-Upton et al., 2004), shaped by longitude, altitude, and average annual rainfall. Genetic control for growth in diameter, height, and volume of the *australis* variety is moderate (h_f^2=0.21 to 0.47), as well as for growth units, stem straightness, and branch diameter (h_f^2=0.21 to 0.39) (Azamar-Oviedo et al., 2000; Reyes-Esteves et al., 2022). The positive relationship between growth variables and latitude indicated that more Northern provenances show greater growth; however, these also correspond to lower altitudes than the rest, so the general assumption of admitting the movement of provenances from high latitudes with low altitudes to low latitude sites with high altitudes is fulfilled (Zobel & Talbert, 1988).

Altitude only influenced branch diameter; the higher the provenance altitude, the thinner the branches. Similarly, height growth of the *greggii* variety was negatively associated with provenance altitude (Rodríguez-Laguna et al., 2008).

On the other hand, the contrasts between provenances in growth units and stem straightness were mainly due to differences in average annual precipitation, due to the high correlation between these variables. This indicated that provenances from wetter sites had straighter stems and larger growth units.

The survival of all the evaluated provenances was lower than that of both varieties in two 17-year trials (82.4 and 95.9 %) in degraded soils of the *Mixteca* Region of the state of *Oaxaca* (Ortiz-Mendoza et al., 2021); as well as the survival (92.6 %) in a six-year trial of the *australis* variety in the same area as the present study (Azamar-Oviedo et al., 2000). Other trials of the *australis* variety with a younger age (2.5 to 6.5 years) in different environments also showed higher survival rates (69.4 to 99.1 %) (Gómez-Romero et al., 2012; López-Upton et al., 2004; Reyes-Esteves et al., 2022; Valencia-Manzo et al., 2006). The lower survival rate in this study was expected because two blocks were affected by a forest fire in January 2015.

The Annual periodic increment in height (*APIH*), normal diameter (*APIDN*), and volume (*AVPI*) of the provenances was lower than the increments (*APIH*=1.36 to 1.54 m, *APIDN*=2.34 to 6.66 cm, *AVPI*=10.2 to 14.5 dm^3) in a 6-year trial of the *australis* variety assessed in the same area (Azamar-Oviedo et al., 2000). Other trials of var. *australis* (aged 2.5 and 6 years) established in sites with good environmental conditions also recorded higher *APIH* (1.23 to 2.45 m) and *APIDN* (2.10 to 2.40 cm), while the *AVPI* (7.9 to 12.1 dm^3) was similar (López-Upton et al., 2004; Salazar-García et al., 1999). In contrast, the increases in this study were higher than those of trials with the *australis* variety (*APIH*=0.40 to 0.76 m, *APIDN*=0.56 to 1.37 cm, *AVPI*=0.16 to 0.30 dm^3) established in degraded soils in the *Mixteca* of *Oaxaca* evaluated at different ages (2.5, 5 and 17 years) (Ortiz-Mendoza et al., 2021; Reyes-Esteves et al., 2022; Valencia-Manzo et al., 2006).

In regard to the growth units, the average per year was lower than that recorded (2.4 to 5.0 year^{-1}) in other trials of the same variety (Reyes-Esteves et al., 2022; Salazar-García et al., 1999; Valencia-Manzo et al., 2006; Velasco-Velasco et al., 2012). The *La Parada*, *El Cobre* and *La Cebada* provenances, which showed the greatest height growth, each followed a different strategy: the first formed more growth units, the second elongated these units more, and the third followed an intermediate strategy. The second strategy was previously recorded for the *australis* variety (Salazar-García et al., 1999).

Implications for the use of provenances

Provenance selection allows for the identification of those best suited for reforestation programs, but also allows for the determination of those with the greatest growth potential for timber plantation programs (Rodríguez-Laguna et al., 2008). In this sense, if germplasm is required for reforestation or restoration programs, survival and crown diameter are the most important variables (Rodríguez-Laguna et al., 2008); wider canopies protect and contribute more organic matter to the soil, which reduces erosion (Ortiz-Mendoza et al., 2021). Therefore, *El Madroño* and *El Cobre*, due to their higher survival and crown diameter, are the most suitable for reforestation purposes under conditions similar to the trial site.

On the contrary, if germplasm is required to establish timber plantations, stem growth and quality variables are the most relevant (White et al., 2007; Zobel & Talbert, 1988). To produce sawmill timber, germplasm from fast-growing trees and stems that produce good wood quality is required. Crooked stems, with bifurcations, abundant whorls, thick branches, and small insertion angles are undesirable because they reduce the quality of the sawn timber (Hernández-Hernández et al., 2019; Nocetti & Brunetti, 2024); they also reduce productivity and increase production costs (Cavassin-Diniz et al., 2020).

According to Principal component 1, *La Parada*, *Molango*, *El Madroño*, *El Pinalito*, *El Cobre* and *La Cebada*, due to their faster growth, are the most suitable provenances for timber plantations. This was expected because the seed sources for these provenances, except for *La Cebada*, came from the open-pollinated *Metepec* Seed Orchard; therefore, the genetic gain should be greater (White et al., 2007; Zobel & Talbert, 1988) compared to provenances whose germplasm came from superior trees selected in natural stands. *La Cebada* showed significant growth despite coming from natural stands; while *El Piñón* was expected to have high growth due to its origin in the Seed Orchard. This suggests that *La Cebada* and *El Piñón* are well and poorly adapted, respectively, to the *Metepec* area.

Provenances cannot be selected based on branch diameter and angle because they did not show differences in these variables. However, among the provenances with the greatest growth, *La Parada*, *La Cebada*, *El Madroño* and *Molango* had the specimens with the straightest stems. Furthermore, the latter two also had fewer branches, making them suitable for establishing timber plantations in the *Metepec* region.

Most of the provenances with the most notable growth recorded a higher number of growth units and crown diameter, possibly due to the positive correlation between these variables, as demonstrated in *P. greggii* var. *greggii* (Rodríguez-Laguna et al., 2008). This condition may be a strategy for achieving greater height (Salazar-García et al., 1999). Crown diameter, in turn, provides a larger area of light interception, resulting in greater potential for photosynthetic activity and, therefore, greater growth (Rodríguez-Laguna et al., 2008).

El Madroño was found to be the elite provenance from its high survival rate, broad crown, fast growth, and good stem quality, making it suitable for both reforestation programs and timber plantations in the *Metepec* region, State of Mexico. This provenance showed superior growth in diameter and height, and lower growth units, in several previous studies (Ortiz-Mendoza et al., 2021; Salazar-García et al., 1999; Valencia-Manzo et al., 2006; Velasco-Velasco et al., 2012).

Conclusions

Stem growth and quality vary among *P. greggii* var. *australis* provenances; these differences are due to genetic variation and the environmental impact associated with latitude, precipitation, and altitude of origin. Movement from high-latitude and low-elevation provenances to lower-latitude and higher-elevation sites favors the growth of *P. greggii* var. *australis*. The *El Madroño* provenance is recommended for both reforestation and timber plantations due to its superior survival, canopy, growth, and stem straightness.

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Conflict of interest

The authors declare that there is no conflict of interest. Mario Valerio Velasco García declares not having participated in any of the stages of the editorial process of the article.

Contribution by author

Gabriel Martínez-Cantera: fieldwork and preparation of the first version of the manuscript; Mario Valerio Velasco García: data analysis and manuscript writing; María Ascención Aguilar Morales: manuscript review. All authors participated in the research conception and approval of the final version.

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