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Research article

Evaluación de ensayos de progenie de *Cedrela odorata* L. en distintas regiones de México

Evaluation of progeny tests of *Cedrela odorata* L. in different regions of Mexico

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Abstract

Progeny trials provide information on genotype performance, stability and adaptation in different environments, with the aim of refining and converting them into seed orchards that produce high-quality seed and genetic diversity. In three *Cedrela odorata* progeny trials established in *Venustiano Carranza*, state of *Puebla*, *Tihuatlán*, state of *Veracruz* and *Tamazunchale,* state of *San Luis Potosí*, the objective of this study was to evaluate the morphological variation between sites and families, and to identify the families with the best development and growth. The trials were established with the same families, in 16 complete randomized blocks with 64 families per block. After three years, the survival percentage, height, normal diameter, clean stem height, stem shape, bifurcation and incidence of *Hypsipyla grandella* were recorded; using these variables, the families were ordinally classified. Significant differences were observed between sites in survival, height and diameter. Survival rates were 80 % in *Tamazunchale*, 77 % in *Venustiano Carranza* and 35 % in *Tihuatlán*. Regarding height and normal diameter, *Tamazunchale* had the best averages (5.8 m and 7.1 cm, respectively), followed by *Venustiano Carranza* (3.5 m and 4.2 cm) and *Tihuatlán* (2.5 m and 2.5 cm). Within sites, families 7, 45, and 62 had outstanding and stable performance in the three environments tested. Although no variation was detected between families, the conditions of each site influenced the performance of the trees, with the *Tamazunchale* trial standing out with the best performance and commercial characteristics.

Keywords: Red cedar, ordinal ranking, progeny trials, families, environmental variation, morphological variation.

Resumen

Los ensayos de progenie proporcionan información sobre el desempeño de los genotipos, estabilidad y adaptación en diferentes ambientes, con la finalidad de depurar y convertirlos en huertos semilleros que produzcan semilla de alta calidad y diversidad genética. En tres ensayos de progenie de *Cedrela odorata* establecidos en Venustiano Carranza, Puebla, Tihuatlán, Veracruz y Tamazunchale, San Luis Potosí se planteó evaluar la variación morfológica entre sitios y familias, e identificar las familias con mejor desarrollo y crecimiento. Los ensayos se establecieron con las mismas familias, en 16 bloques completos al azar con 64 familias por bloque. A los tres años se registró el porcentaje de supervivencia, la altura, diámetro normal, altura de fuste limpio, forma de fuste, bifurcación e incidencia de *Hypsipyla grandella*; con estas variables se clasificó ordinalmente a las familias. Diferencias significativas se observaron entre sitios en supervivencia, altura y diámetro. Los porcentajes de supervivencia fueron 80 % en Tamazunchale, 77 % en Venustiano Carranza y 35 % en Tihuatlán. Respecto a la altura y diámetro normal, Tamazunchale tuvo los mejores promedios (5.8 m y 7.1 cm, respectivamente), seguido por Venustiano Carranza (3.5 m y 4.2 cm) y Tihuatlán (2.5 m y 2.5 cm). Dentro de los sitios, las familias 7, 45 y 62 presentaron desempeño sobresaliente y estable en los tres ambientes probados. Aunque no se detectó variación entre familias, las condiciones de cada sitio influyeron sobre el rendimiento de los árboles, destacó el ensayo de Tamazunchale con el mejor desempeño y características comerciales.

Palabras clave: Cedro rojo, clasificación ordinal, ensayos de progenie, familias, variación ambiental, variación morfológica.

Introduction

In the field of genetic improvement of forest species, the main objective of provenance and progeny trials is to obtain genetic gains based on the selection of the best phenotypes and genotypes (White et al., 2007). These trials begin with the selection of superior trees based on their phenotype, that is, those that show outstanding performance in evaluated traits of commercial interest compared to the average of the natural population (Zobel & Talbert, 1988). Phenotypic selection allows for the selection of traits of interest and the prediction of genetic gains for subsequent use in the formation of more productive and better-adapted forests (White et al., 2007). These traits are not limited solely to rapid growth but also encompass relevant aspects such as survival, resistance to adverse environmental factors, wood quality, and seed production (Flores Flores et al., 2014). The quantification of trait variability, estimation of genetic parameters, and heritability through differential selection are key elements in the genetic improvement process of forest species (Flores Flores et al., 2014). Furthermore, they provide valuable information for the management of seed orchards and guide forest genetic improvement programs (White et al., 2007). The evaluation of morphological variation in progeny trials is relevant for identifying individuals with desirable phenotypic characteristics and understanding their adaptability to different conditions (Quijada, 1984; White et al., 2007). The genotype-environment interaction is especially important in species with a wide natural distribution, such as *Cedrela odorata* L., since progenies and/or provenances can behave differently in different environments (Flores Flores et al., 2014). Therefore, it is desirable for genotypes to maintain stability in morphological traits across different environments, since their relatively good and predictable performance demonstrates the potential to respond favorably to different sites considered for establishing more productive plantations (Falconer & Mackay, 1996; Quijada, 1984; Zobel & Talbert, 1988). However, finding genotypes that are stable across different environments is complicated. To cite one study, in progeny trials conducted under two contrasting conditions with more than 40 families of *Pinus elliottii* Engelm. var. *elliottii*, only four families were identified with high stability in morphological traits of interest, which indicates the level of adaptation of the families to their environment and limits their productive potential to the conditions of the plantation site (Pagliarini et al., 2016).

Family performance in progeny trials during the first years reflects the variation in the expression of various traits, which are influenced by site quality, management, and interaction with biotic and abiotic factors (Rodríguez-Vásquez et al., 2021). In tropical and subtropical areas, *C. odorata* has a high economic value due to the quality of its wood (Olvera-Moreno et al., 2022). In Mexico, it ranks second in terms of the establishment of commercial forest plantations, after the genus *Eucalyptus* spp., with an area of 20 705 hectares (Velázquez Martínez et al., 2011). Together, they represent 60 % of the planted area in the country, especially in the states of *Veracruz*, *Tabasco* and *Campeche* (Palma-López et al., 2007). Therefore, the objectives of the present study were: (1) To evaluate the variation in morphological and growth characteristics among families established in three *C. odorata* progeny trials under different environmental conditions, and (2) To identify the families with the best performance.

Materials and Methods

The trials were established in the localities of *Tamazunchale*, in the state of *San Luis Potosí*; *Tihuatlán*, in the state of *Veracruz*; and *Venustiano Carranz*a, in the state of *Puebla*, in 2018 (Table 1). These are places with contrasting characteristics (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2010a, 2010b, 2010c). Sixty-four families from *Veracruz* (23 families), *Puebla* (17 families), *San Luis Potosí* (11 families), *Tamaulipas* (3 families), and *Hidalgo* (10 families) were included in each trial.

Table 1. Geographic location and characteristics of the establishment sites of the *Cedrela odorata* L. progeny trials.

Location	Latitude N and Longitude W	Altitude (masl)	Mean annual temperature (°C)	Mean annual precipitation (mm)	Soil type	Exposure
Venustiano Carranza, *Puebla*	20°28'26.3" 97°41'59.0"	330	22-26	1 400 a 1 600	Vertisol	Zenithal
Tihuatlán, *Veracruz*	20°33'44.9" 97°29'6.2"	164	24-26	1 100 a 1 300	Regosol	Zenithal
Tamazunchale, *San Luis Potosí*	21°28'39" 98°58'45"	140	20-24	1 500 a 3 000	Leptosol	Zenithal-North

Between March and May 2018, three trials were established with plants from the 64 families, each between 6 and 8 months old, with a height of 30 to 40 cm and a root collar diameter of 35 to 50 mm.

The plants were grown in 680 mL plastic tubes filled with a mixture of Peat moss® (60 %), vermiculite (20 %), perlite (20 %), and Osmocote® 9-45-15 (3 g per 680 g of substrate). Irrigation was applied every three or four days using a robotic irrigation system, with scheduled fertilization once a week with Peters® 20-10-20 fertilizer (3 g L^{-1}). The trials were established under a randomized complete block (RCB) experimental design, with one plant per family per block as the experimental unit, spaced 4×4 m in 16 blocks. Therefore, 64 plants were incorporated into each block, and a total of 1 024 specimens were included in each trial.

Assessed variables

At the time of the evaluation, only 57 of the 64 families were considered in the analysis, as seven were discarded due to their 100 % dead trees.

In each trial, survival percentage (*SUP*) (alive: standing trees with green leaves and growing shoots in the crowns, dead: trees without living tissue standing or felled with absence of leaves and shoots in the crowns), total height (*ALT*; m) (telescopic pole±1 cm, no trademark), clean stem height (*AFL*; cm) (telescopic pole±1 cm, no trademark) and normal diameter (*ND*; mm) (model 573-282 Mitutoyo®, digital vernier±0.05 mm) were determined. Stem shape (*SSS*) was determined based on four categories: (1) Very twisted, (2) Twisted, (3) Slightly twisted, and (4) Straight; bifurcations (*BIF*): (1) Bifurcated from the lower third, (2) Bifurcated from the middle third, (3) Bifurcated only in the upper third, and (4) Not bifurcated; and incidence of attack by *Hypsipyla grandella* (Zeller) (*NIV*) based on the number of perforations in the tree: (1) High: in the entire trunk, shoots and branches, (2) Medium: in shoots and branches, and (3) Low: only in shoots.

Statistical analysis

The assumptions of normality and homogeneity of variance were verified using the Shapiro-Wilk test using the UNIVARIATE procedure in SAS© version 9.1 (SAS Institute Inc., 2004) for the variables *SUP* (p=0.9342), *ALT* (p=0.9556), and *ND* (p=0.9678). An analysis of variance (α<0.05) was performed using the GLM procedure in SAS© (SAS Institute Inc., 2004). The statistical model used was:

$$Y_{ijk} = \mu + S_i + \beta_{j(i)} + F_k + SF_{ik} + e_{ijk}$$

Where:

Y_{ijk} = Observed value in the individual of the k^{th} family, in the j^{th} block nested in the i^{th} site

μ = General mean

S_i = i^{th} site fixed effect

$\beta_{j(i)}$ = Fixed effect of the j^{th} block nested in the i^{th} site

F_k = Random effect of the k^{th} family $\sim NID(0, \sigma^2_f)$

SF_{ik} = Random effect of the site×family interaction $\sim NID(0, \sigma^2_{sf})$

e_{ijk} = Experimental error $\sim NID(0, \sigma^2_e)$

i = 1, 2 and 3 (sites)

i = 1, 2, and 3 (sites)

j = 1, …16 (blocks)

k = 1, …57 (families)

Subsequently, the means were separated using the Tukey test (α<0.05) (SAS Institute Inc., 2004). The families were classified using the procedure suggested by Dlamini et al. (2017) and Edward et al. (2014) and each variable evaluated (*SUP*, *ALT*, *AFL*, *ND*, *FOR*, *BIF* and *NIV*) was assigned a continuous categorical value, which varied from the best (with 1 point assigned) and successively to the worst (with 57 points assigned) for each family. Then, the data were averaged for each variable, to obtain the general average (*MEAN*) of the 7 variables in each family. Subsequently, the families were grouped and classified (CLAS) based on the averages (*MEAN*), in descending order, using the SAS© PROC RANK procedure (SAS Institute Inc., 2004).

Results and Discussion

The site factor significantly influenced (p<0.0001) survival, height, and diameter; however, no significance was found between families or in the interaction between the two factors (Table 2).

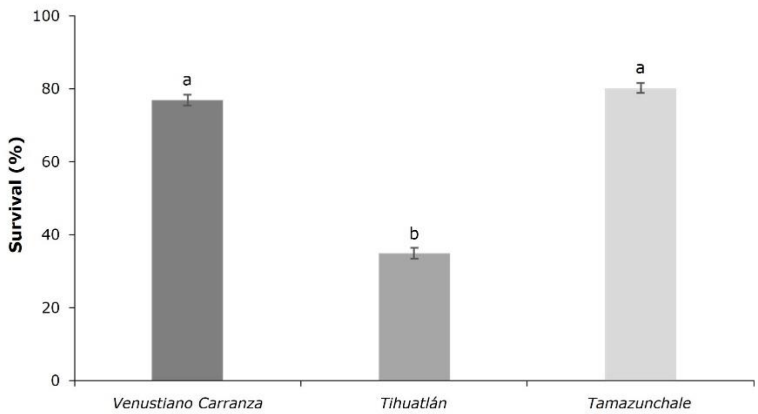
Table 2. Probability (*P*) values obtained in the analysis of variance for the survival, height, and diameter variables of *Cedrela odorata* L. families.

SV	DF	Survival	*ALT*	*ND*
Site	2	<0.0001	<0.0001	<0.0001
Family	56	0.3297	0.6775	0.9572
Site×Family	112	0.1106	0.9364	0.9897

SV = Source of variation; DF = Degrees of freedom; *ALT* = Total height; *ND* = Normal diameter.

Effect of site on survival

The average survival percentage across the three trials was greater than 60 %. Trees from the *Venustiano Carranza* and *Tamazunchale* trials had higher survival rates (>70 %) than those from *Tihuatlán* (35 %) (Figure 1). Previous studies have observed that mortality in plantations is primarily associated with the environmental conditions and silvicultural practices at each site, as well as with the lack of adequate protection (Grignola et al., 2014).



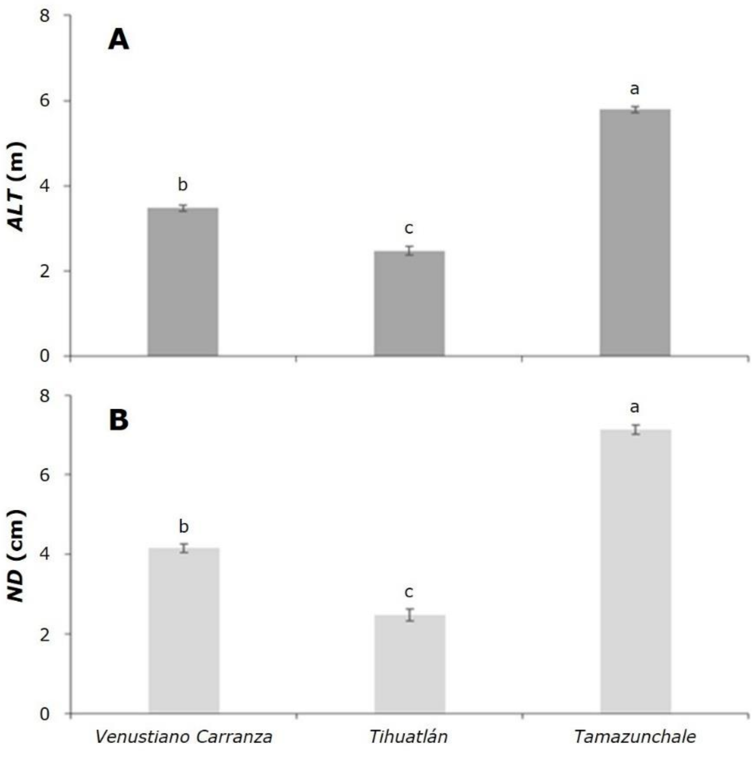
Means with different letters are statistically different, with $p \leq 0.05$. Standard error represented by the lines above the bars.

Figure 1. Effect of site on survival rates of *Cedrela odorata* L. trees.

In the *Tihuatlán* trial, survival was only 35 % due to the soil conditions, which included excessive waterlogging, causing hypoxia and anoxia, which negatively affected plant functions, including photosynthesis (Lee et al., 2011; Peña-Castro, 2014). Other associated factors were competition with weeds and the presence of climbing plants, which suppressed the growth of *C. odorata* trees, and once weakened, they were more susceptible to pests and diseases (Da Ponte Canova & Salas, 2009).

Effect of site on height and diameter

Trees established in *Tamazunchale* reached significantly greater heights than those in *Venustiano Carranza* and *Tihuatlán*, with a difference of approximately 2.3 and 3.3 m, respectively (Figure 2A). Regarding *ND*, the trees in the *Tamazunchale* trial exhibited diameters greater than 5.5 cm, and were more than 2.8 and 4.6 cm taller than those in *Venustiano Carranza* and *Tihuatlán*, respectively (Figure 2B).



A = Total height (*ALT*; m); B = Normal diameter (*ND*; cm). Means with different letters are statistically different, with $\alpha \leq 0.05$. The lines above the bars represent the standard error.

Figure 2. Effect of site on total height and normal diameter of *Cedrela odorata* L. trees.

The lower altitude, higher annual rainfall, well-drained soil (Leptosol), and Northern exposure in *Tamazunchale* favored tree height (*ALT*) and diameter (*ND*) growth, in contrast to those in *Venustiano Carranza* and *Tihuatlán*. Under optimal rainfall conditions (1 200 to 3 000 mm), the species experiences high height growth rates (Alonso-Báez et al., 2020).

Tree growth and adaptation to environmental conditions are important aspects for understanding their response to climate and genetic adaptation strategies (Mondino, 2014). Furthermore, in this same trial, cultural work was carried out regarding weed control and pruning, unlike the other two trials. Regular weed control practices are recommended to avoid competition between individuals during the first three years of plantation establishment (Toro Vergara, 2004).

The presence of the borer *Hypsipyla grandella* represents a significant risk to plantations, affecting tree growth and wood quality (Cornelius & Watt, 2003; Santos Murgas et al., 2015). Regular monitoring and the implementation of control measures such as cultural practices are essential to mitigate this problem. In *Tihuatlán* in particular, lower rainfall, limited cultural practices, and some areas of the plantation with poor drainage, allowing frequent flooding during the rainy season, created stressful conditions for the trees. Although *C. odorata* can grow in different environments, soil characteristics are known to determine its establishment, growth, and development; the best growth of the species has been recorded in soils with good drainage and fertility (Cintron, 1990).

Ordinal classification of families

In the overall classification, 39 % of the families are found within the top five (Table 3). This indicates a significant and positive response from most families to the three sites, despite the fact that phenotypic selection for superior trees was carried out using what remains of the natural populations of *C. odorata*, sometimes with reduced tree densities and in other cases, only with relicts where there were not enough individuals to perform a better selection.

Table 3. Ordinal classification of families in the three progeny trials of *Cedrela odorata* L.

Family	*SUP*	*ALT*	*AFL*	*ND*	*FOR*	*BIF*	*NIV*	*MEAN*	CLAS
62	11	2	9	3	11	7	7	7	1
7	21	4	5	6	5	5	5	7	1
45	27	1	6	2	1	9	6	7	1
20	24	4	3	8	5	5	5	8	2
37	14	5	10	6	7	5	9	8	2
71	39	1	4	2	6	5	2	8	2
26	10	3	19	5	11	6	5	8	2
48	3	6	21	6	8	6	9	8	2
18	25	6	1	7	15	1	9	9	3
51	19	6	12	7	9	6	5	9	3
63	35	7	7	10	2	2	2	9	3
34	1	6	14	10	18	5	11	9	3
77	29	3	17	3	2	4	9	10	4
59	3	8	31	8	8	3	7	10	4
65	23	8	8	10	9	5	5	10	4
72	17	7	29	6	5	2	3	10	4
80	25	7	11	9	9	3	9	10	4
8	46	5	2	4	10	4	4	11	5

10	6	6	25	13	9	6	11	11	5
3	2	8	35	13	7	8	5	11	5
61	16	7	28	8	9	1	9	11	5
55	25	6	15	9	12	3	9	11	5
33	13	8	20	10	16	7	9	12	6
78	4	9	33	14	16	5	4	12	6
19	18	4	36	10	10	7	1	12	6
46	20	7	22	8	10	8	11	12	6
29	9	5	39	8	8	9	10	13	7
54	8	7	40	12	10	9	2	13	7
13	7	8	45	12	7	5	5	13	7
5	15	8	32	10	9	4	11	13	7
12	22	8	23	14	9	4	11	13	7
42	35	7	13	9	10	10	8	13	7
36	38	5	26	1	14	5	7	14	8
58	26	11	26	14	13	3	5	14	8
69	44	9	18	9	12	3	4	14	8
23	35	11	16	16	11	1	11	14	8
60	5	6	52	7	13	7	11	14	8
39	30	7	30	13	7	4	11	15	9
76	43	5	27	6	13	4	4	15	9
70	35	10	24	13	8	7	6	15	9
66	12	9	56	12	8	11	5	16	10
35	28	5	42	11	11	7	11	16	10
28	39	9	34	7	17	6	4	17	11
43	34	9	49	11	7	6	4	17	11
79	25	10	46	15	12	8	4	17	11
68	37	9	41	11	12	9	5	18	12
22	33	10	44	11	14	7	7	18	12
11	40	10	43	12	11	4	8	18	12
47	41	9	38	15	11	8	7	18	12
21	49	6	47	10	3	6	10	19	13
49	31	10	48	17	9	6	11	19	13
32	42	9	51	14	6	7	5	19	13
64	32	9	50	13	15	10	5	19	13

50	47	5	55	4	12	8	4	19	13
41	45	7	37	13	18	11	4	19	13
25	48	4	54	8	4	7	11	19	13
24	36	9	53	16	5	8	11	20	14

SUP= Survival; *ALT* = Total height; *AFL* = Height of clean stem; *ND* = Normal diameter; *FOR* = Stem shape; *BIF* = Bifurcations; *NIV* = Incidence level of *Hypsipyla grandella*; *MEAN* = Average of the seven attributes; CLAS = Classification. The shading indicates the 22 best (top) and 17 worst (bottom) families, with no shading for intermediate families.

The results revealed that families 7, 45, and 62 exhibited remarkable stability across the three sites analyzed, primarily in *Venustiano Carranza* and *Tamazunchale*. Family 45 remained within the top five and showed consistency across each of the three sites. They excelled in *ALT*, *ND*, and *FOR* (ranked 1, 2, and 1, respectively), the variables of greatest commercial interest. Family 62 also stood out in *ALT* and *ND* (ranked 2 and 3, respectively) and maintained a prominent position in both. Family 7 exhibited the greatest consistency in growth characteristics, branching, stem form, and *Hypsipyla grandella* incidence, always ranging from 4 to 6 (Table 3).

The outstanding characteristics of these three families across the different sites evaluated indicate their ability to respond to the different conditions present at each site. However, these results need to be complemented with the estimation of genetic parameters and the evaluation of genotype-environment interactions. In similar studies involving *C. odorata* trials, but with grafted plants, it was reported that environmental heterogeneity between sites was the main cause of the low heritability of growth variables; in addition, the genotype-environment interaction was low to moderate (Olvera-Moreno et al., 2022).

These parameters help recommend management plans for trials and select superior genotypes for genetic improvement of the species at each site. The development and growth of genotypes is related to their genetics and all the environmental conditions present in each trial, particularly edaphic, climatic, and biotic factors (Kimmins, 2004). Therefore, the observed variability represents the diversity of genotypes present and is a fundamental parameter in genetic improvement programs (Murillo et al., 2017). This variability manifests itself at the morphological level in trees, affecting characteristics such as height, diameter, straightness, and stem quality.

In Mexico, studies such as this one are making significant progress in the field of genetic improvement of *C. odorata*, with the goal of developing improved materials that exhibit stable and distinctive characteristics in different locations (Rodríguez-Vásquez et al., 2021). In our study, the evaluations carried out at the three sites with contrasting environmental conditions allow us to understand the behavior and variation in growth and stem morphological characteristics within families. This will contribute to determining the adaptability and stability of the planted material (Olvera Moreno et al., 2022); however, studies of genetic variation will be necessary to carry out genetic thinning in trials and for transformation into seed orchards.

In the present study, three years after the plantations were established, at the family level, the *C. odorata* trees did not exhibit marked morphological differentiation.

Conclusions

Three years after the trials were established, the expected morphological variation among *C. odorata* families was not observed, despite the diverse conditions of their origin in the states of *Veracruz*, *Puebla*, *San Luis Potosí*, *Tamaulipas* and *Hidalgo*. However, the site factor influenced the survival and growth characteristics of the trees. In particular, the trees established in *Tamazunchale*, *San Luis Potosí*, stood out compared to the other two trials due to their high survival rate and commercial characteristics, such as height and normal diameter. The site is influenced by a much higher average annual rainfall than the other two, and has a Leptosol-type soil, different from the Vertisol and Regosol present in *Venustiano Carranza* and *Tihuatlán*, respectively. These factors influenced the variation described. Finally, families 7, 45, and 62 were identified as having the best development and growth, according to the classification based on the morphological attributes considered in this study.

Continued evaluation will be important to corroborate the results of this study in the medium and long term. Furthermore, it is recommended to study and analyze the degree of genetic control present in morphological traits, in order to understand the relevance of these traits in the adaptation and domestication of families in different environments.

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Conflict of interest

The authors declare no conflict of interest.

Contribution by author

Eliana Molar Peña: research development, data collection, statistical analysis, structure, and design of the manuscript; Marcos Jiménez Casas: design, supervision of the experiment, analysis of results, writing, and editing of the manuscript; Miguel Ángel López López: design, supervision of the experiment, and editing of the manuscript; José Pastor Parra Piedra: manuscript supervision and correction; José Vidal Cob Uicab: manuscript supervision and correction.

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