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Research article

Nutrient status of mahogany and soil fertility with management of *Sesbania herbacea* (Mill.) McVaugh

Estado nutrimental de caoba y fertilidad del suelo con manejo de *Sesbania herbacea* (Mill.) McVaugh

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Abstract

Mahogany, due to the beauty of its wood and its high economic value, has been heavily harvested for centuries, leading to its listing as an endangered species under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (Cites). The objective of this study was to evaluate the nutritional status of mahogany plants in the early stages of growth and soil fertility patterns, in both cases using *Sesbania herbacea* as a green manure (GM). Two treatments were considered: T1: mahogany with *S. herbacea* (MGM) and T2: mahogany with chemical fertilization (Triple 17) (MCF). The nutritional status of the individuals was assessed at 10 and 15 months of age, two months after *S. herbacea* was incorporated into the soil, by determining the *N*, *P*, *K*, *Ca*, *Mg*, and *S* content in their leaves. With regard to soil fertility, two sampling sessions were conducted: the first at the beginning of the study, after soil tillage, and the second at the conclusion of the research. No statistically significant differences were found between treatments in any case, nor in the parameters evaluated (p>0.05). However, the use of *Sesbania herbacea* as green manure is a good alternative for providing nutrients during the early stages of mahogany tree growth and development, and for maintaining the fertility of clay soil.

Kewords: Green manure, foliar analysis, soil fertility, legumes, nutrients, commercial forest plantations.

Resumen

La caoba, debido a la belleza de su madera y su alto valor económico ha sido intensamente explotada durante siglos, lo que la ha llevado a ser incluida en la lista de especies en peligro de extinción de la Convención sobre el Comercio Internacional de Especies Amenazadas de Flora y Fauna Silvestres (Cites). El objetivo de este trabajo fue evaluar el estado nutrimental de plantas de caoba en la etapa inicial de crecimiento y el comportamiento de la fertilidad del suelo, en ambos casos con el uso del abono verde (AV) *Sesbania herbacea.* Se consideraron dos tratamientos: T1: caoba con *S. herbacea* (CAV) y T2: caoba con fertilización química (Triple 17) (CFQ). Se evaluó el estado nutrimental de los individuos a los 10 y 15 meses de edad, dos meses después de la incorporación al suelo de *S. herbacea* mediante la determinación de su contenido de *N*, *P*, *K*, *Ca*, *Mg* y *S* en hojas. Respecto a la fertilidad del suelo, se realizaron dos muestreos; el primero al inicio del estudio, posterior a la mecanización del suelo y el segundo al concluir la investigación. No se obtuvieron diferencias estadísticas significativas entre tratamientos en ningún caso, ni en los elementos evaluados (p>0.05). No obstante, el uso de *Sesbania herbacea* como abono verde es una buena alternativa para la nutrición en etapas tempranas de crecimiento y desarrollo de las plantas de caoba, y para conservar la fertilidad de un suelo arcilloso.

Palabras clave: Abono verde, análisis foliar, fertilidad de suelo, leguminosas, nutrientes, plantaciones forestales comerciales.

Introduction

Swietenia macrophylla King (Meliaceae), commonly known as mahogany, has been one of the most important tropical tree species in Mexico and Central America since the 20th century and is considered one of the most important species for the development of the forestry industry in Latin America (Vester & Navarro-Martínez, 2007). Its range extends from Southern Mexico, along the Atlantic slope of Central America, to the Amazon Valley in Brazil and Peru (Danquah et al., 2019). Due to its high economic value, it has been heavily exploited for centuries, leading to its inclusion on the list of endangered species under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (Cites) and on the norm NOM-059-SEMARNAT-2010 (Carranza-Patiño et al., 2024; Secretaría de Medio Ambiente y Recursos Naturales [Semarnat], 2010).

In 2023, Mexico had approximately 241 744 ha of Commercial Forest Plantations (CFP), and mahogany was the eighth most commonly planted species, with 8 440 ha, distributed mainly across the states of *Campeche* (2 214 ha), *Puebla* (1 648 ha), *Tabasco* (1 268 ha), *Veracruz* (1 161 ha), *Chiapas* (809 ha), and *Oaxaca* (618 ha) (Comisión Nacional Forestal [Conafor], 2024a). *Tabasco* has a forest area of 817 154.130 ha (Conafor, 2024b).

Leaf analysis is a well-established method for diagnosing nutritional requirements that provides insight into nutritional needs in agriculture and horticulture (Alvarado-Hernández et al., 2022). This approach, however, is less commonly used in forestry, where it should be accompanied by other methods that allow determination of nutritional and, potentially, fertilizer status (Ávila-Arias et al., 2025). Fertilization affects the dynamics of soil microorganisms involved in humus formation, nutrient cycling, compound decomposition, and aggregate formation (Wu et al., 2011). According to Basave-Villalobos et al. (2020), fertilization is the most effective technique for accelerating growth and increasing plant survival in nurseries and established forest stands in the field.

One alternative in regenerative forestry is the use of green manure (GM), which consists of crop residues and plant parts that can be either incorporated into the soil or left in place as a cover crop (García-Hernández et al., 2010). Legumes are typically used as cover crops because they can supply nitrogen to the soil through biological nitrogen fixation (Li et al., 2015). Incorporating GM as a nutrient source into the soil can partially replace chemical fertilization, improving physical, chemical, and biological fertility and thereby contributing to better soil health (Obrador-Olán et al., 2019).

Sesbania herbacea (Mill.) McVaugh is a fast-growing legume native to North America that thrives in moist and waterlogged conditions (Krishnan et al., 2019). It adapts effectively to clay soils and can provide more than 200 kg N ha^{-1} by thriving and fixing N_2 under flooded conditions (Krishnan et al., 2019; Naranjo-Landero et al., 2020). Therefore, the objective of this study was to evaluate the effect of *Sesbania herbacea* green manure on the nutritional status of mahogany trees in their early stages and on soil fertility, based on the hypothesis that it is possible to replace chemical fertilizers with green manure during the initial growth stage of mahogany plantations, achieving statistically similar growth rates.

Materials and Methods

Study area

The research was conducted at the Experimental Field of *Colegio de Postgraduados* (College of Postgraduate Studies), *Tabasco* Campus, located at km 21 of Federal Highway 180 *Cárdenas-Coatzacoalcos* (18°01′ N and 93°03′ W), in the municipality of *Cárdenas*, *Tabasco*, Mexico. The soil is a Vertisol (Palma-López et al., 2017). The region has a climate typical of the humid tropics; according to the Köppen climate classification system, as modified by García, it is classified as (Am(g) "w"), a warm, humid climate with abundant rainfall in summer (Aceves-Navarro & Rivera-Hernández, 2019; García, 2004). The average annual temperature is 26 °C, with little variation; the annual precipitation is 2 324 mm during the dry months and approximately 4 000 mm during the rainiest months; the average evaporation is 1 400 mm of water (Rivera-Hernández et al., 2016).

Biological material

Mahogany seeds were collected from trees that had been selected in December 2022, based on their vigor and apparent health, in the area of the *Colegio de Postgraduados*, *Tabasco* Campus, located on *Periférico Carlos A. Molina* s/n, at km 3.5 of the *Cárdenas-Huimanguillo* highway, *Tabasco*, Mexico. The seedlings were produced in a nursery from untreated germinated seeds in 12×22 cm black polyethylene bags that contained a mixture of sand, Cosmopeat®, and agrolite (2:1:1), plus the controlled-release fertilizer (CRF) (Multicote™ Agri (8), 11.22.9+4 MgO+Boron). The experiment was set up on July 12, 2023, on land not used for agriculture; the mahogany plants were six months old. Triple 17 was applied at a rate of 50 g per plant 15 days after planting. Subsequently, two fertilizer applications were made, one every six months, using the same dose and formulation.

Experimental design and treatments

Two treatments were considered: T1, which consisted of mahogany treated with *S. herbacea* GM (MGM), and T2, which consisted of mahogany treated with chemical fertilizer (Triple 17) (MCF). The treatments were evaluated using a completely randomized block design with four replicates, for a total of eight experimental units, each measuring 8×12 m and containing 16 trees spaced 2×3 m apart, totaling 128 trees. To avoid the edge effect, the trees along the shore were not monitored. The usable area of the experimental plot was 768 m^2. Since the plantation was established, periodic manual weed control has been carried out in the MCF treatment.

In October 2023, *S. herbacea* was broadcast-sown at a density of 15 kg of seed per ha^{-1}; this was done when the mahogany plants were three months old; 60 days after the legume emerged, a 1 m^2 sample was collected from the central part of each replicate to determine its total dry weight, including its components: stems and leaves (Almeida-Santos et al., 2019). The plant samples were weighed fresh on an analytical balance (model AR0640 Ohaus®) with an accuracy of 0.001 g; they were then washed with distilled water, placed in paper bags, and dried in a model CE5F Shel® forced-air oven at 75 °C until they reached a constant weight; they were weighed and ground, and nutrient analyses were subsequently performed (Kalra, 1997).

Variables assessed and statistical analysis

To determine the nutritional status of mahogany plants, two leaf samplings were conducted at 10 and 15 months after planting in the field. The second recently matured leaf was collected from four randomly selected trees in each experimental plot. The leaf samples were stored in paper bags and dried at 65 °C for 72 hours in a forced-air oven (model CE5F Shel®), ground in a Wiley mill, and taken to the laboratory at the Center for Research and Innovation for Oil Palm Sustainability (*Ciispalma*) to perform nutrient analyses for *N*, *P*, *K*, *Ca*, *Mg*, *S*, *Cu*, *Fe*, *Mn*, *Zn*, and *B* (Sadzawka et al., 2007).

The effect of the mahogany-*S. herbacea* association on soil fertility was determined through two sampling events in the study area. The first was conducted after soil tillage, and the second at the conclusion of the study, when the plantation had been established in the field for 15 months. In both cases, a composite sample comprising 15 subsamples was collected using a Dutch-type auger at a depth of 0-30 cm, covering the entire area (Salgado-García et al., 2006). Soil analyses were conducted in accordance with NOM-021-RECNAT-2000 (Semarnat, 2002).

The data were analyzed using ANOVA in the Statistica (TIBCO Software Inc., 2023) software, version 14.1.0. When statistically significant differences were found, Tukey's test was performed at a significance level of $P \leq 0.05$. The assumptions of normality and homogeneity of variances were verified.

Results and Discussion

Effect of treatments on the nutritional status of mahogany plants

Based on the analysis of variance, no significant effects of the treatments on the foliar concentration of nutrients in mahogany plants were observed for any of the assessed elements (p>0.05), although the concentrations of *N* and *P* were higher in MGM than in MCF in both sampling periods (Table 1).

Table 1. Nutrient content in mahogany leaves 10 and 15 months after planting in the field.

Parameter	Unit	10 months		15 months	
		MGM	MCF	MGM	MCF
N	%	1.7±0.15	1.63±0.15	1.65±0.07	1.54±0.07
P		0.11±0.05	0.10±0.05	0.18±0.025	0.16±0.025
K		0.98±0.19	1.08±0.19	0.29±0.03	0.30±0.03
Ca		1.18±0.7	1.39±0.7	1.53±0.07	1.56±0.07
Mg		0.11±0.03	0.13±0.03	0.30±0.05	0.26±0.05
S		0.22±0.02	0.23±0.02	0.14±0.03	0.13±0.03
Cu	mg kg^{-1}	6±0.01	6±0.01	2.27±0.24	2.27±0.24
Fe		49±16.1	35±16.1	87.20±6.32	76.14±6.32
Mn		9±3.39	7±3.39	15.57±1.38	14.66±1.38
Zn		7±1.0	7±1.0	19.39±3.12	18.66±3.12
B		17±6.5	23±6.5	29.91±3.48	25.69±3.48

MGM = Mahogany with green manure; MCF = Mahogany with Chemical fertilizer (Triple 17). The values represent the averages±standard error. No significant effects of the evaluated treatments were observed in any of the variables.

Although no statistically significant differences were found in any of the elements analyzed, including micronutrients, at 15 months the plants with the MGM treatment had higher concentrations of *Mg*, *Fe*, *Mn*, and *Zn*; this suggests an improvement in nutrient availability and recycling associated with the use of *Sesbania herbacea* as green manure. Nutrient concentrations showed no statistically significant differences between treatments, nor were any differences observed between sampling times (10 and 15 months). The *N* concentration at 10 months was 1.7 % in MGM and 1.63 % in MCF, while at 15 months it was 1.65 % for MGM and 1.54 % for MCF. These values fall within the range of 1.59-1.81 % reported by Alvarado et al. (2015) for mahogany.

The *P* concentration at 10 months was 0.11 % in MGM and 0.10 % in MCF; at 15 months, it increased to 0.18 % and 0.16 %, respectively. These figures are consistent with those reported by Alvarado et al. (2015), who documented values of 0.18 to 0.19 %, as well as by Calvo-Alvarado et al. (2008), who cited 0.19 %. In this regard, low phosphorus concentrations in the aboveground biomass are common among tropical forest species (Blanco-Rojas et al., 2004).

The *K* concentrations at 10 months were 0.98 % in MGM and 1.08 % in MCF; they decreased significantly by 15 months, when they reached 0.29 and 0.30 %, respectively. The initial values were consistent with those reported by Drechsel and Zech (1991), who recorded an intermediate concentration of 0.97 %. However, the values for the 15-month mark were lower than those documented by Alvarado et al. (2015).

For *Ca*, concentrations of 1.18 % in MGM and 1.39 % in MCF were observed at 10 months, increasing to 1.53 % and 1.56 %, respectively, at 15 months. These values were higher than those reported by Alvarado et al. (2015), who found concentrations of 0.76-0.79 %, and than the value of 1.14 % cited by Calvo-Alvarado et al. (2008). Overall, the results show contrasting trends for the two nutrients: while *K* decreased markedly between 10 and 15 months, *Ca* increased during the same period.

In the assessment conducted at 10 months, the *Mg* concentration was 0.11 % in the MGM treatment and 0.13 % in the MCF treatment; at 15 months, these values increased to 0.30 % and 0.26 %, respectively. The percentages recorded at 15 months were higher than the 0.11-0.13 % range documented by Alvarado et al. (2015) and similar to the 0.20 % value reported by Calvo-Alvarado et al. (2008).

Regarding *S*, the results were lower than those reported by Calvo-Alvarado et al. (2008). Likewise, the concentrations of *Cu* and *Fe* were lower than those recorded by Alvarado et al. (2015), Calvo-Alvarado et al. (2008), and Drechsel and Zech (1991). However, at 15 months, the *Fe* concentration exceeded the intermediate values of 53-68 mg kg^{-1} reported by Drechsel and Zech (1991).

Mn and *Zn* concentrations were higher at 15 months. In particular, the *Zn* concentration exceeded the 15-16 mg kg^{-1} range indicated by Alvarado et al. (2015). *B* levels fell within the range of 25-30 mg kg^{-1} reported by Drechsel and Zech (1991) and were lower than the value of 674 mg kg^{-1} reported by Calvo-Alvarado et al. (2008).

Leaf nutrient concentration makes it possible to link growth variables to the nutrition and development of plantations (Telles-Antonio et al., 2022). On the other hand, Murillo et al. (2014) note that leaf nutrient levels vary with age, as in teak (*grandis grandis* L. f.) plantations, where concentrations of *Ca*, *Mg*, *Mn*, and *Fe* tend to increase over time, while those of *N*, *K*, and *Zn* decrease; however, there is little information on leaf nutrient concentrations in tropical forest species (Alvarado-Hernández et al., 2022).

Effect of treatments on soil fertility

Table 2 shows the results of the physical and chemical soil analyses conducted before (initial sampling) and after the application of the treatments (final sampling for the MGM and MCF treatments). The right-hand column includes the interpretation according to the norm NOM-021-RECNAT-2000 (Semarnat, 2002), which is the same for all three cases.

Table 2. Analysis of soil fertility at the Experimental Field of the *Colegio de Postgraduados*, *Tabasco* Campus.

Parameter	Unit	Initial sampling (0-30 cm)	Final sampling (0-30 cm)		Interpretation: NOM-021-RECNAT-2000		
					Initial sampling	Final sampling	
			MGM	MCF		MGM	MCF
pH (H_2O)	Rel. 1:2	5.98	6.2	5.6	Moderately acidic		
EC	dS m^{-1}	0.09	0.06	0.15	Negligible effects of salinity		
OM	%	4.03	3.78	4.58	High		
TN		0.15	0.19	0.23	High		
P-Olsen	mg kg^{-1}	9.64	10.05	10.11	Medium		
K	cmol($^+$) kg^{-1}	0.23	0.27	0.25	Low		
Ca		10.03	9.91	10.05	High		
Mg		1.94	1.94	1.95	Medium		
CEC		22.63	22.61	22.59	Medium		
Fe	mg kg^{-1}	12.58	16.1	16.0	Adequate		
Cu		2.96	4.7	7.4	Adequate		
Zn		2.01	3.7	2.0	Adequate		
Mn		1.87	16	8	Adequate		
Clay	%	45	46	45			
Silt		38	37	38			
Sand		17	17	17			
Textual classification: Clay							

*MGM = Mahogany with green manure; MCF = Mahogany with chemical fertilizer (Triple 17). *EC* = Electrical conductivity; *OM* = Organic matter; *TN* = Total nitrogen; *CEC* = Cation exchange capacity. Rel. = Ratio.

The soil is moderately acidic, with an initial *pH* of 5.98. In the MGM treatment, the final *pH* was 6.2, while in the MCF treatment it was 5.6 at the end of the study. Most nutrients were found in low to high levels; the chemical fertility of the analyzed soil supports the optimal growth and development of mahogany. Pérez-Vela (2017) points out that this species thrives in soils ranging from clay to clayey loam in texture, with good moisture retention but adequate drainage to prevent waterlogging—fertile soils with a slightly acidic to neutral *pH* (5.5-7.5) allowing for better nutrient uptake, a high organic matter (*OM*) content, and a high availability of nutrients such as calcium, magnesium, potassium, and phosphorus, as well as low aluminum saturation. These conditions promote its initial growth and the quality of the wood.

Based on the results of the chemical soil analyses, an estimate was made of the soil supply of the nutrients *N*, *P*, and *K* to the plants. For the MGM treatment, the values were 7.125, 37.6875, and 395.8875 kg ha^{-1}, respectively; and for the MCF treatment, the values were 8.625, 37.9125, and 366.5625 kg ha^{-1}, respectively.

Vertisols (VR) are clay soils that crack during dry seasons, which limits proper root development in plants. Although these soils are nutrient-rich, their use for agricultural crops is limited by the high water table and slow permeability, so only certain crops grow well there (Palma-López, 2019).

The nutrient status assessment indicated that the soil was moderately acidic, according to the norm NOM-021-RECNAT-2000 (Semarnat, 2002). With an initial *pH* of 5.98 and a final *pH* of 6.2 in the MGM treatment, and 5.6 in the MCF treatment. Soil *pH* is related to the dynamics of essential nutrients; thus, the values recorded in this study do not pose any problem for the growth and development of mahogany plants (Norghauer et al., 2008).

The initial *EC* for the MGM treatment was 0.09 dS m^{-1}, decreasing to 0.06 dS m^{-1} at the end, while for MCF it was 0.15 dS m^{-1}. This indicates that soil salinity had no negative effects on the plant growth and development, in accordance with the parameters of the norm NOM-021-RECNAT-2000 (Semarnat, 2002).

The *OM* and *TN* levels were high at both the beginning and end of the study, with values ranging from 3.78 to 4.58 % for *OM* and from 0.15 to 0.23 % for *TN*. It is important to note that the parameter with the greatest influence on soil fertility is organic matter (Nyamasoka-Magonziwa et al., 2020). The organic matter provided by plantations not only increases the soil's organic matter content and nutrient dynamics but also contributes to the spatial heterogeneity of soil properties (Zalamea et al., 2007).

The decrease in *OM* during green manure treatment may have been due to increased enzymatic activity among soil biota under this management practice, thereby increasing the rates of *C* and *N* mineralization (Liborio-Balota & Dias-Chaves, 2010). The use of green manure increases soil fertility and helps conserve soil; furthermore, trees in forested areas help improve soil organic carbon (*SOC*) reserves, and, due to its management practices and nature, green manure provides soluble nutrients in the short term (Singh et al., 2020).

The initial *P-Olsen* level was 9.64 mg kg^{-1}, while the final level was 10.05 mg kg^{-1} in MGM and 10.11 mg kg^{-1} in MCF. Of the three major elements, *P* is the least required by cultivated plants (Pérez-Camacho et al., 2024). However, this element plays a crucial role in acidic soils, where timely application at doses appropriate for forest species is essential for silvicultural management (Huang et al., 2023).

Regarding exchange bases, *Ca* levels were high at the beginning and end of the study. In the first sampling, a value of 10.03 $cmol(^{+})$ kg^{-1} was recorded, while at the end of the experiment, the MGM treatment reached a value of 9.91 $cmol(^{+})$ kg^{-1}, and the MCF treatment reached 10.05 $cmol(^{+})$ kg^{-1}. *K* levels were low in both assessments; the first measurement was 0.23 $cmol(^{+})$ kg^{-1}, and at the end of the study, the MGM treatment group had 0.27 $cmol(^{+})$ kg^{-1}, while the MCF treatment group had 0.25 $cmol(^{+})$ kg^{-1}. Similarly, the *Mg* content was moderate; at the beginning, it was 1.94 $cmol(^{+})$ kg^{-1}, remaining unaltered, and at the end in the MGM treatment and rising to 1.95 $cmol(^{+})$ kg^{-1} in the MCF treatment. The levels of *Ca*, *K*, and *Mg* are sufficient for the adequate growth of mahogany (Negreros-Castillo et al., 2018).

The cation exchange capacity (*CEC*) was classified as moderate at both the beginning and the end (Semarnat, 2002). The initial *CEC* was 22.63 $cmol(^{+})$ kg^{-1}, while the MGM treatment recorded a value of 22.61 $cmol(^{+})$ kg^{-1} and the MCF treatment recorded 22.59 $cmol(^{+})$ kg^{-1}, suggesting that this is a soil with a good clay content. Finally, the levels of the trace elements *Fe*, *Cu*, *Zn*, and *Mn* were found to be adequate, both at the beginning and at the end of the study (Semarnat, 2002).

The use of GMs is a rational way to improve soil fertility (García-Hernández et al., 2010). The long-term effects of GMs include significant improvements in organic matter levels and microbial activity, although early improvements in physical soil properties are difficult to observe (Martins-Costa et al., 2023). Fuentes-Molina et al. (2023) point out that the chemical properties of the soil in plantations are slightly more favorable, mainly in terms of organic matter and nutrient content, and that these conditions help control the presence of weeds.

In this context, research on *Crotalaria juncea* L., used as green manure, shows that its effects on the soil properties depend on the evaluation period. Almeida-Santos et al. (2019) did not detect any changes in the chemical properties of sugarcane soil during the first year following the incorporation of *C. juncea*, although they did observe a favorable response in terms of weed control. Similarly, Magaña-Valenzuela et al. (2020) found no significant differences in soil fertility between mineral fertilization and the use of *C. juncea* GM. For their part, Córdova-Sánchez et al. (2023) observed a decrease in root density associated with both increased chemical fertilization and the incorporation of the same type of organic fertilizer in a teak plantation. Recently, Jiménez-Pozo et al. (2025) found that one year after applying GM, there was no significant effect on the fertility of the soil where *T. grandis* grew. Taken together, these results suggest that changes in the soil's nutritional properties resulting from the use of *C. juncea* may require evaluation periods longer than one year to become consistently apparent.

Finally, it is clear that, in addition to providing nutrients, green manures help improve the soil's chemical environment, stabilize *pH*, promote microbial activity and nutrient availability, thereby increasing their agroecological and forestry potential (Hernández-Herrerías et al., 2022).

Conclusions

The use of *Sesbania herbacea* as green manure is an excellent option for providing nutrients during the early stages of mahogany tree growth and development, as well as for maintaining the fertility of clay soil. Green manure not only provides nitrogen but also improves soil fertility when used over an extended period.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contributions by author

Yesenia García Estrada: work in the nursery and in the field, data collection and analysis, interpretation of the results, and drafting of the manuscript; Eustolia García López: supervision of the research, verification of the results, and revision of the manuscript; José Jesús Obrador Olán: supervision of the research, verification and interpretation of the results, and revision of the manuscript; Saúl Sánchez Soto: supervision of the research and revision of the paper; Eugenio Carrillo Ávila: methodological design, statistical analysis, and revision of the manuscript; Francisco Rojas Pérez: work in the nursery and in the field, data collection and analysis.

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