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Research article

Allometric model for estimating the leaf biomass of *Poliomintha longiflora* A. Gray

Modelo alométrico para estimar la biomasa foliar de *Poliomintha longiflora* A. Gray

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Abstract

Poliomintha longiflora, commonly known as Mexican oregano, is a wild aromatic species of high economic value, utilized in the food, pharmaceutical, and cosmetic industries. In arid and semi-arid regions of Northeastern Mexico, it represents a non-timber forest resource of relevance for the rural localities where it grows. In order to contribute to its technical and sustainable management, allometric models were developed to estimate leaf biomass (*LB*) based on structural dendrometric variables. Destructive sampling was applied to 271 individuals distributed in seven natural sites in the states of Coahuila and San Luis Potosí. For each shrub, the total height (*H*) and largest (*LCD*) and smallest crown diameters (*SCD*) were recorded, from which the mean crown diameter (*MCD*) was calculated. The collected leaves were dried and weighed to obtain the dependent variable (*LB*). Eight allometric models were evaluated by means of ordinary least squares regression in R. The potency model $LB = 0.047028(MCD)^{1.347942}$ exhibited the best fit, with an Adjusted coefficient of determination of 0.833, a low standard error (0.710 g), and no inconsistencies with respect to the classical statistical assumptions of the model. These results confirm that the *MCD* is a reliable predictor of *LB* in *P. longiflora*. The implementation of this model enables non-destructive estimations, reducing costs and sampling times, and thereby strengthening forest inventories. Additionally, it constitutes a valuable technical contribution to the rational and sustainable use of smooth oregano in microphyllous desert scrub ecosystems.

Keywords: Leaf biomass, allometric models, non-timber, Mexican oregano, shrubby plants, aromatic plants.

Resumen

Poliomintha longiflora, conocida como orégano liso, es una especie aromática silvestre de alto valor económico, utilizada en las industrias alimentaria, farmacéutica y cosmética. En regiones áridas y semiáridas del noreste de México representa un recurso forestal no maderable de relevancia para las localidades rurales donde crece. Con el objetivo de contribuir a su manejo técnico y sustentable, se desarrollaron modelos alométricos para estimar la biomasa foliar (*Bf*) a partir de variables dendrométricas estructurales. Se aplicó un muestreo destructivo de 271 individuos distribuidos en siete sitios naturales en los estados de Coahuila y San Luis Potosí. Para cada arbusto se registró la altura total (*H*), diámetro mayor (*DM*) y menor (*Dm*) de copa, con los cuales se calculó el diámetro promedio de copa (*Dp*). Las hojas recolectadas fueron secadas y pesadas para obtener la variable dependiente (*Bf*). Se evaluaron ocho modelos alométricos mediante regresión por mínimos cuadrados ordinarios en el

programa R. El modelo de potencia $Bf = 0.047028(Dp)^{1.347942}$ presentó el mejor ajuste, con un Coeficiente de determinación ajustado de 0.833, bajo error estándar (0.710 g) y sin inconsistencias respecto a los supuestos estadísticos clásicos del modelo. Estos resultados confirman que el Dp es un predictor confiable de la Bf en *P. longiflora*. La implementación de este modelo permite realizar estimaciones no destructivas, reducir costos y tiempos de muestreo y fortalecer los inventarios forestales. Además, constituye un aporte técnico valioso para el aprovechamiento racional y sostenible del orégano liso en ecosistemas de matorral desértico micrófilo.

Palabras clave: Biomasa foliar, modelos alométricos, no maderable, orégano liso, plantas arbustivas, plantas aromáticas.

Introduction

In the arid and semi-arid regions of Mexico, approximately 2 200 species that provide non-timber forest products (NTFPs) have been identified, of which 450 have current applications in the economy of rural localities (Tapia-Tapia & Reyes-Chilpa, 2008). 95 % of these taxa are for domestic use, while 25 % have significant commercial importance in the food, industrial, and pharmaceutical sectors (Villavicencio-Gutiérrez et al., 2021).

Oregano is a scrub of great aromatic value widely recognized for its diverse uses, its economic importance comes from its attributes as a culinary condiment, medicinal plant, and source of essential oils (Rivero-Cruz et al., 2011). In particular, its essential oil is of great importance in the industrial and pharmaceutical sectors, and is used in the production of cosmetics, soaps, perfumes, flavors, among other products (Koksal et al., 2010).

Poliomintha longiflora A. Gray, commonly known as Mexican *oregano*, is a wild aromatic plant that grows in Northeastern Mexico, with distribution in the states of *Coahuila*, *San Luis Potosí*, *Nuevo León*, *Tamaulipas*, as well as in the limits of *Querétaro* and *Hidalgo* (Aranda Ruiz et al., 2009). It is a shrub up to 1 m high, with slender ascending or decumbent shoots and 7-15 mm elliptic leaves, pubescent on the underside and glabrous on the upper side. The flowers are axillary, with a 7-to-12.5 mm calyx and a 27-to-35 mm tubular corolla (Díaz-de León et al., 2020). It exhibits a phenological pattern of annual regrowth after the first significant rainfall

event. The leaves are mainly used as a spice, in the extraction of oils and as a culinary herb in regional gastronomy (Zheng & Wang, 2001).

Aranda Ruiz et al. (2009) conducted a research to estimate the biomass production of *P. longiflora*, which they valued in 66 kg ha⁻¹ per year; in addition, the phytochemical analysis of the essential oil identified 11 compounds, among which thymol and carvacrol were the most important. Several studies have pointed out that the compounds carvacrol and thymol, abundant in the essential oil of *P. longiflora*, are the key agents behind its antimicrobial effect. This property highlights its potential application as a natural preservative in the food industry (Paredes-Aguilar et al., 2007).

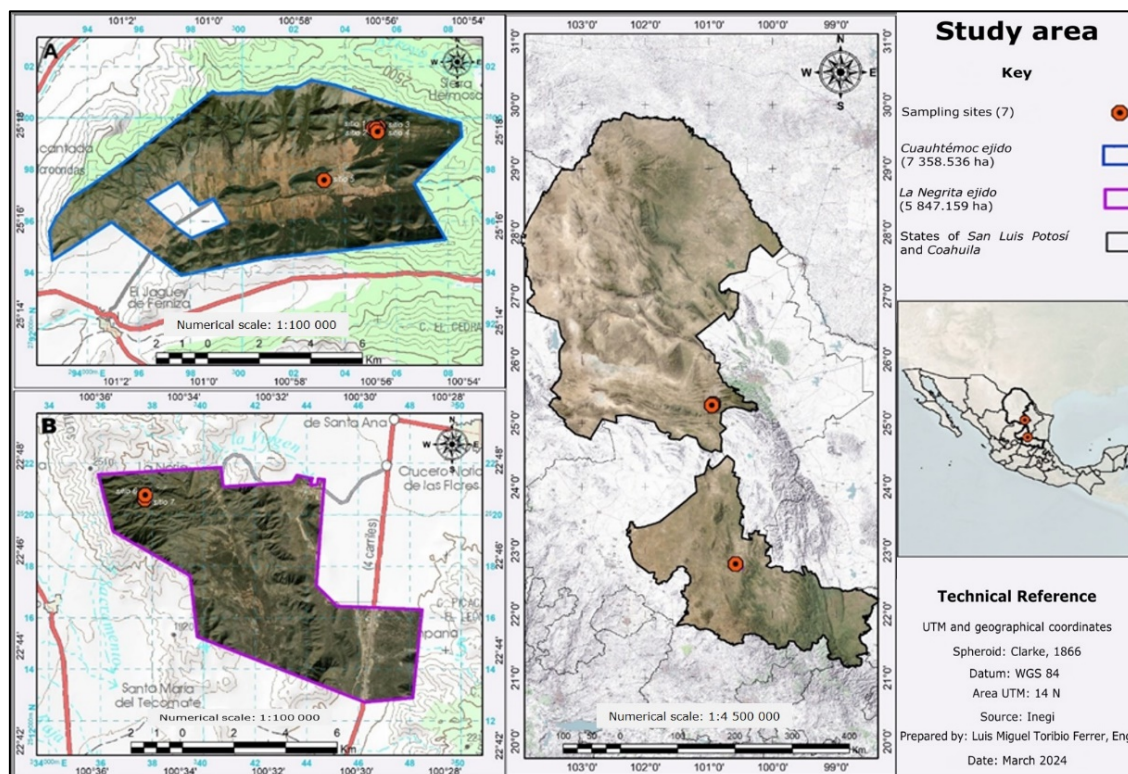
Allometric models are very useful indirect tools for calculating variables such as volume, biomass, carbon content, and fresh weight in both woody and herbaceous taxa (Acosta-Mireles et al., 2002; Velasco Bautista et al., 2009). In the case of non-timber species, they have been used to assess the leaf biomass of bay *laurel* and *oregano* (Villavicencio-Gutiérrez et al., 2018, 2020), the green biomass of *candelilla* (Hernández-Ramos et al., 2019), and the biomass of tree species (Acosta-Mireles et al., 2002; Ares et al., 2002; Marroquín-Morales et al., 2023). Implementing this type of model in plant resource planning facilitates cost and time reduction, while also enabling the anticipation of growth or development patterns. However, the models must meet certain criteria to ensure the accuracy and reliability of the estimated values.

In order to achieve sustainable management of wild *oregano* populations, it is essential to have accurate estimates of the amount of dry leaf produced by the taxon of interest. In this regard, the present study aimed to develop allometric models based on structural variables such as height, average crown diameter, and dry weight of the foliage, in order to predict the leaf biomass of *P. longiflora*. This tool aims to support foresters in managing the species, especially in regions with similar ecological conditions.

Materials and Methods

Study area

The research was carried out in natural populations of *P. longiflora* located in sites with similar ecological conditions, located in *Cuahtémoc ejido*, *Saltillo* municipality, *Coahuila*, at 25°17'3.61" N and 100°56'57.99" W (Registro Agrario Nacional [RAN], 2023a), and in *La Negrita ejido*, *Guadalcázar* municipality, *San Luis Potosí*, at 25°46'55.4" N and 100°34'58.6" W (RAN, 2023b) (Figure 1). Both locations have Litosol (I) and haplic Xerosol (Xh) soils (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2007a, 2007b). The climate is classified as semi-arid temperate (BS1kw), with 26 °C average temperature varying between 12 and 30 °C and 500 to 800 mm annual rainfall (INEGI, 2008). The dominant vegetation is microphyllous desert scrubland (Instituto Nacional de Estadística y Geografía [Inegi], 2018).



A = Site 1, site 2, site 3, site 4, and site 5; B = Site 6 and Site 7.

Figure 1. Location of the study area of *Poliomintha longiflora* A. Gray in the states of Coahuila and San Luis Potosí.

Field data

A targeted sampling was carried out during the period corresponding to the harvesting of the species, between July and October. The locations of the populations were recorded by georeferencing for subsequent spatial analysis (Figure 1). A total of 271 specimens of smooth *oregano* were collected, of which 160 came from two sites in Guadalcázar, San Luis Potosí and 111 from five sites in Saltillo, Coahuila.

Independent variables

The independent dendrometric variables measured for each *oregano* bush in the field were total height (H , cm) from ground level to the top of the plant, the largest crown diameter (LCD , cm), and the smallest crown diameter (SCD , cm) measured with a model 12696 Truper® flexometer. The mean crown diameters (MCD , cm) were calculated from the LCD and SCD values.

Dependent variables

Leaf biomass (LB , g) was estimated using a destructive method applied to selected individuals, which consisted of cutting leaves and stems from each scrub; the samples

were stored in brown paper envelopes, labeled for identification. Subsequently, they were dried in the greenhouse of the *Saltillo* CIRNE-INIFAP Experimental Field at room temperature for five days, following the protocol used by the local producer. After drying, the leaves and branches were separated manually. The weight of the dry leaves was determined using a model H-9885 ADAM® high-precision digital balance scale, with a sensitivity of 0.001 g. This process enabled the estimation of the dependent variable (*LB*, g), which corresponds to the usable material.

Stem cutting, although a destructive practice, is justified because it is the most accurate standard method for directly estimating leaf biomass in herbaceous-shrub species (Corella-Bernal & Ortega-Nieblas, 2013; Granados-Sánchez et al., 2013). It also reflects the traditional system of local harvesting, in which producers manually extract the leaves and stems for drying and subsequent commercialization (Llamas-Torres et al., 2022). Therefore, their inclusion responds to both methodological criteria and the representativeness of field management practices (Benavides Solorio et al., 2021; Villavicencio-Gutiérrez et al., 2018). In the case of *P. longiflora*, a perennial and deciduous species (Díaz-de León et al., 2020), its regrowth capacity allows it to recover and even surpass its coverage and productivity after pruning, especially after rain events (Aranda Ruiz et al., 2009).

Statistical analyses

In order to estimate the *LB* of the Mexican *oregano* (Table 1), a set of allometric models was fitted in the R statistical package version 4.3.2 (R Core Team, 2023) that have been assessed in similar studies for bay *laurel* (Villavicencio-Gutiérrez et al., 2020), *oregano* (Villavicencio-Gutiérrez et al., 2018), *candelilla* (Hernández-Ramos et al., 2019) and *lechuguilla* (Velasco Bautista et al., 2009). The mean diameter, total

height, and leaf biomass variables were analyzed using ordinary least squares regression (OLS).

Table 1. Allometric models used to estimate the leaf biomass of *Poliomintha longiflora* A. Gray in *Cuauhtémoc ejido* (Saltillo, Coahuila) and *La Negrita ejido* (Guadalcázar, San Luis Potosí).

Model	Name	Equation
1	Allometric	$LB = \beta_0(MCDH)^{\beta_1}$
2	Constant morphic coefficient	$LB = \beta_1(MCD^2H)$
3	Australian model	$LB = \beta_0 + \beta_1MCD^2 + \beta_2H + \beta_3MCD^2H$
4	Spurr's combined variable	$LB = \beta_0 + \beta_1(MCD^2H)$
5	Salas	$LB = \beta_0 + \beta_1(MCDH)$
6	Schumacher-Hall	$LB = \beta_0(MCD)^{\beta_1}(H)^{\beta_2}$
7	Potency	$LB = \beta_0(MCD)^{\beta_1}$
8	Takata	$LB = \frac{(MCD^2H)}{(\beta_0 + \beta_1MCD)}$

LB = Leaf biomass (g); MCD = Mean crown diameter (cm); H = Total height (cm); $\beta_0, \dots, \beta_n$ = Coefficients of regression. Source: Segura and Andrade (2008).

It was decided to adjust the allometric models jointly for both sampling locations, as the ecological conditions of the *Cuauhtémoc* and *La Negrita ejidos* are similar in terms of soil type, climate and dominant vegetation, which reduces environmental variability between locations. Furthermore, preliminary analysis showed no statistically significant differences in key dendrometric variables between sites, which supports the integration of data into a single dataset to improve the explanatory power and stability of the model (Segura & Andrade, 2008). This methodological strategy is consistent with approaches adopted in previous studies that have modeled species with wide ecological distribution and high phenotypic plasticity (Benavides Solorio et al., 2021; Hernández-Ramos et al., 2019; Villavicencio-Gutiérrez et al., 2018).

Allometric equation selection criteria

The choice of allometric equation was based on the following regression fit statistics: priority was given to the highest Adjusted coefficient of determination (R^2_{adj}), together with a lower Standard error (S_{xy}), low Sum of squared residuals (SSR) and reduced value in the Coefficient of variation ($CV\%$), in addition to the significance of its parameters ($p \leq 0.05$). The regression assumptions were verified using specific model validation tests; the autocorrelation in the residuals was assessed with the Durbin-Watson ($D-W$) test (Durbin & Watson, 1950); the normality of the errors, with the Kolmogorov-Smirnov ($K-S$) test (Massey, 1951); and the heteroscedasticity, with the White test (White, 1980). All analyses were performed using the statistical package R version 4.3.2 (R Core Team, 2023).

Results and Discussion

The study included the entire observed range of heights and crown sizes of *P. longiflora* shrubs within the study area (Table 2). *P. longiflora* plants in the study area had a maximum H of 60 cm, while their LCD reached 74 cm, with an MCD of 14.806 cm and an average LB of 1.907 g per individual, with a variation ranging between 0.086 and 9.777 g. These values align with those cited by Díaz-de León *et al.* (2020), who point out that the species can reach up to 100 cm in both H and LCD .

Table 2. Descriptive statistics of *Poliomintha longiflora* A. Gray in *Cuahtémoc ejido* in *Saltillo* municipality, *Coahuila* and *La Negrita ejido* in *Guadalcázar* municipality, *San Luis Potosí*.

Variables and components	Mean	S. D.	CV	Maximum	Minimum
<i>H</i> (cm)	31.974	11.124	2.874	60.000	10.000
<i>LCD</i> (cm)	17.303	9.552	1.811	74.000	4.000
<i>SCD</i> (cm)	10.074	6.386	1.577	48.000	2.000
<i>MCD</i> (cm)	14.806	8.701	1.702	50.500	3.000
<i>LB</i> (g)	1.907	1.739	1.097	9.777	0.086

H = Total height; *LCD* = Largest crown diameter; *SCD* = Smallest crown diameter; *MCD* = Mean crown diameter; *LB* = Leaf biomass; *S. D.* = Standard deviation (g); *CV* = Coefficient of variation (%).

At present, there is a lack of specific information on the optimal harvest dimensions for *P. longiflora*. However, studies conducted on species of the same family (Lamiaceae) have shown that pruning at a height of 10 to 15 cm promotes vigorous regrowth, increases aerial biomass yield, and improves the concentration of secondary metabolites such as essential oils (Kimera et al., 2021; Soltanbeigi et al., 2021). Similarly, Carlen et al. (2009) reported that in perennial herbs such as *Salvia officinalis* L., cuts below 10 cm negatively affected the recovery capacity and reduced the yield in successive harvests. In contrast, maintaining a remaining height of 10 to 15 cm promotes the structural and functional regeneration of the plant, which ensures greater accumulation of useful biomass in subsequent harvest cycles.

Poliomintha longiflora flowers even at early vegetative stages and at reduced heights (Aranda Ruiz et al., 2009; Díaz-de León et al., 2020); however, maximum *LB* production is observed after rainfall events, similarly to the behavior observed in *Origanum syriacum* L. (Al-Tawaha et al., 2016). Because it is a perennial shrub, harvesting at low *H* does not compromise its regeneration; on the contrary, it stimulates the development of basal woody tissue and the thickening of the stems, which increases its structural robustness and regrowth capacity in each pruning cycle.

This adaptive response pattern has also been described in other Lamiaceae managed under sustainable use schemes (Kimera et al., 2021; Soltanbeigi et al., 2021).

The relationship between *LB* and the variables *H* and *MCD* exhibited a linear behavior. Both variables have been widely recognized as reliable indicators for estimating biomass in shrub species, as documented in previous studies on *oregano* and *laurel* (Villavicencio-Gutiérrez et al., 2018, 2020). It is important to note that, as these predictor variables increase, so does the dispersion observed in the *LB* data (Figure 2).

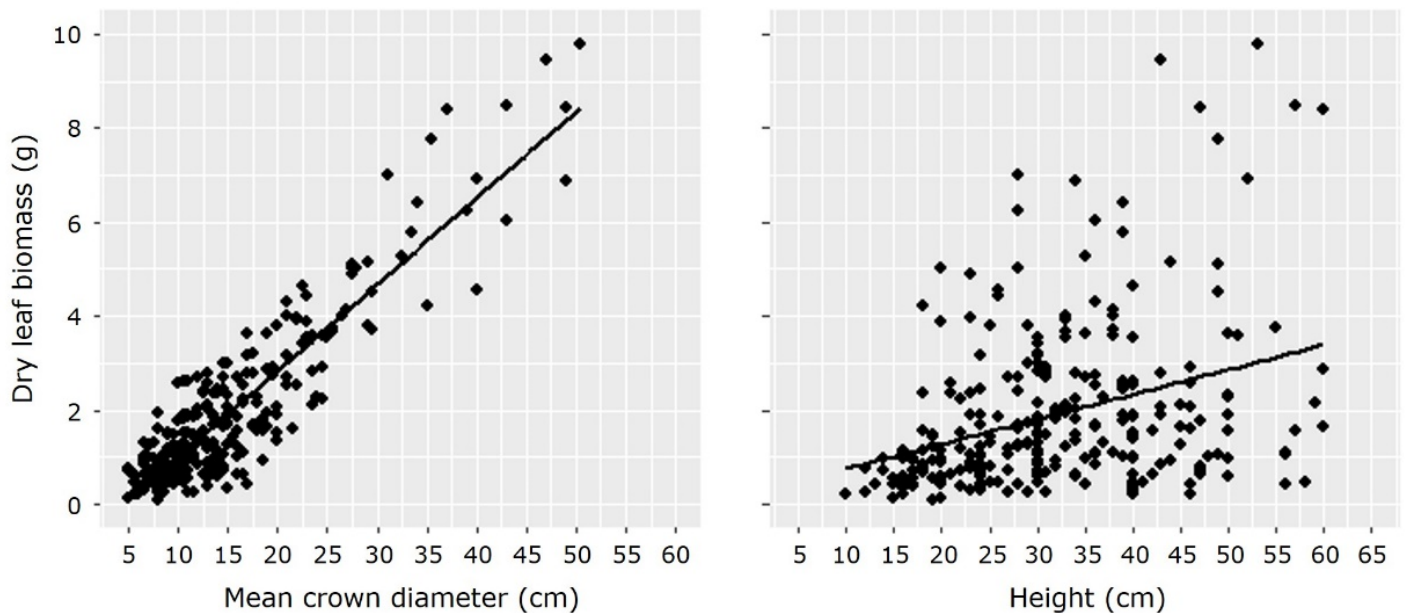


Figure 2. Distribution of the leaf biomass in relation to the mean crown diameter and height of *Poliomintha longiflora* A. Gray in *Cuauhtémoc ejido* in *Saltillo* municipality, *Coahuila* and *La Negrita ejido* in *Guadalcázar* municipality, *San Luis Potosí*.

Statistical analyses performed for the different allometric models revealed a high explanatory power; seven of the eight models evaluated registered a R^2_{adj} above 70 %. This level of adjustment is consistent with what has been documented in models for shrub species, where sample sizes ranging from 4 to 784 individuals have been used, with R^2_{adj} values of 0.65 to 0.95 (Rojas-García et al., 2015). The results confirm that the plant's *MCD* and *H* are robust predictors of *oregano's LB*

(Villavicencio-Gutiérrez et al., 2018, 2020). However, considerable variation was observed in the accuracy of the models, with standard errors ranging between 0.696 and 1.212 g and a maximum Coefficient of variation of 70.03 %.

In this study, the Australian (3) and *Salas* (5) models presented insignificant coefficient values for determining *LB* and were therefore discarded. As for the Schumacher-Hall model (6), although it initially showed an acceptable fit ($R^2_{adj}=0.82$), it failed to pass the validation tests due to heteroscedasticity issues ($\chi^2=34.24$, $p=0.0001$) in its residuals. The non-linear potency model (7) proved to be superior in estimating the *LB* of *P. longiflora*, as it explained 83.3 % of the total variability, with an *Sxy* of 0.710 g and a *CV* of 37.26 % (Table 3). Model (7) has been used in previous studies to quantify aboveground biomass and carbon content in species such as cedar and oak (Benavides Solorio et al., 2021; Gómez-Díaz et al., 2011), to predict forage biomass and firewood production in *Acacia* sp. (López-Merlín et al., 2003), and even to estimate the dry weight of palm heart shoots (*Euterpe edulis* Mart.) within sustainable production systems (Ares et al., 2002).

Table 3. Regression statistics for estimating the leaf biomass of *Poliomintha longiflora* A. Gray at the study sites.

Model	Coefficient	Estimate	$Pr> t $	R^2_{adj}	S_{xy}	SSR	CV	$K-S$	$D-W$	White	Order
1	B_0	0.004308	<0.0001	0.733	0.898	216.995	47.09	0.0771	1.772	21.44	7
	B_1	0.977942	<0.0001					0.0793*	0.0301*	0.0108*	
2	B_1	0.000194	<0.0001	0.514	1.212	396.586	70.03	0.1182	1.754	188.93	8
								0.0010*	0.021*	<0.0001*	
3	B_0	0.4307	0.0132	0.806	0.765	156.333	40.12	0.0809	1.561	64.68	3
	B_1	0.003615	<0.0001								
	B_2	0.01157	0.0255					0.0576*	<0.0001*	<0.0001*	
	B_3	0.00000387	0.7075								
4	B_0	0.9979	<0.0001	0.755	0.859	198.555	45.04	0.1176	1.538	34.24	4
	B_1	0.00008471	<0.0001					0.0011*	<0.0001*	<0.0001*	
5	B_0	0.097111	0.259	0.734	0.896	216.285	47.01	0.0781	1.762	21.1	6
	B_1	0.00358	<0.0001					0.0731*	0.025*	0.0121*	
6	B_0	0.026488	<0.0001	0.829	0.696	129.998	36.45	0.0543	1.736	37.32	2
	B_1	1.300898	<0.0001					0.4000*	0.0147*	<0.0001*	
	B_2	0.202887	<0.0001								
7	B_0	0.047028	<0.0001	0.833	0.710	135.816	37.26	0.0559	1.736	13.41	1
	B_1	1.347942	<0.0001					0.3640*	0.0547*	0.1564*	
8	B_0	991.5	<0.0001	0.745	0.0877	207.018	46.00	0.06823	1.8000	19.34	5
	B_1	228.7	<0.0001					0.1603*	0.0497*	0.0224*	

* = $Pr>|t|$ = Statistical significances at 95 %; R^2_{adj} = Adjusted coefficient of determination; S_{xy} = Standard error; SSR = Sum of squared residuals; CV = Coefficient of variation (%); $K-S$ = Kolmogorov-Smirnov normality test; $D-W$ = Durbin-Watson autocorrelation statistic; White = White's heteroscedasticity test; Order = Order of model selection.

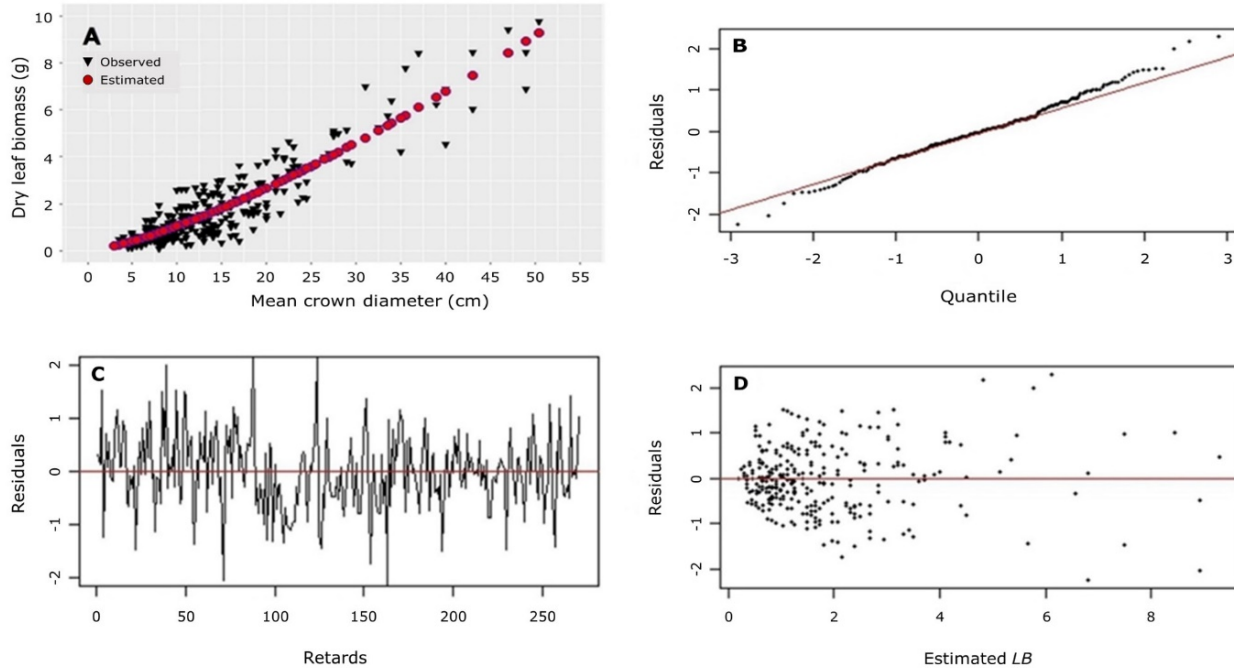
Diagnostic tests were performed to evaluate the adequacy of the potency model (7). The Durbin-Watson test ($D-W=1.736$, $p>0.05$) did not indicate the presence of serial autocorrelation in the residuals (Durbin & Watson, 1950). Furthermore, the Kolmogorov-Smirnov test ($D=0.0559$, $p=0.3640$) did not reject the null hypothesis of normality of the residuals, which supports the application of parametric statistical inference (Massey, 1951). Finally, White's test ($\chi^2=13.41$, $p=0.1564$) did not reveal heteroscedasticity, suggesting that the variance of the errors is constant across the predicted values (White, 1980).

To estimate biomass in forests, Rodríguez-Laguna et al. (2007) used the potency model and obtained a R^2_{adj} above 0.97 to determine the biomass of oak components. In a similar way, Acosta-Mireles et al. (2002) used the same model on six species from the mesophyllic forest in the state of *Oaxaca* and estimated a R^2_{adj} above 0.97. To estimate the biomass in oak components, Rodríguez-Laguna et al. (2007) used the potency model in its linear form and also registered a R^2_{adj} above 0.97.

Villavicencio-Gutiérrez et al. (2018) assessed 10 allometric models in *oregano* (*Lippia graveolens* Kunth) and noted that the potency model provided a solid fit ($R^2_{adj}=0.80$). This makes this model one of the best options for estimating biomass in this type of species. In *laurel* (*Litsea parvifolia* (Hemsl.) Mez) with the potency model, a R^2_{adj} of 0.82 was calculated (Villavicencio-Gutiérrez et al., 2020); while in teak plantations (*Tectona grandis* L. f.), the potency model was used to estimate the biomass by components of the harvested tree, reaching a R^2_{adj} of 0.92 for the leaves (Marroquín-Morales et al., 2023).

The findings derived from the regression model indicated a significant correlation between the mean *MCD* value and *LB* in *oregano* individuals, suggesting that the *MCD* can be accurately used for *LB* estimates (Benavides Solorio et al., 2021; Gómez-Díaz et al., 2011; Marroquín-Morales et al., 2023). Forest technicians or specialized service providers could use this relationship as a tool for making accurate estimates. The validation graphs support the robustness of the model, as they show

adequate dispersion of the points, a normal distribution of errors, and no autocorrelation (Figure 3).



A = Observed and estimated values; B = Q-Plot; C = Autocorrelation; D = Homoscedasticity.

Figure 3. Results of validation tests of the assumptions of the potency model for *Poliominta longiflora* A. Gray at the study sites.

The potency model (7) for estimating the leaf biomass of *P. longiflora* was structured as follows:

$$LB = 0.047028(MCD)^{1.347942}$$

Where:

LB = Leaf biomass

MCD = Mean crown diameter

Conclusions

The allometric potency model developed enables the estimation of the leaf biomass of *P. longiflora* and constitutes a significant contribution to the technical and sustainable management of non-timber forest products in arid and semi-arid ecosystems. The model utilizes the mean crown diameter as the primary dendrometric variable and exhibits a high predictive capacity ($R^2_{adj}=0.833$). It also strictly complies with the statistical assumptions of normality, homoscedasticity, and independence of errors, which guarantees its reliability and applicability in field conditions. Its implementation will help optimize forest inventories, reduce operating costs, and avoid destructive methods, thereby promoting the rational use of natural populations of Mexican *oregano*. This type of model represents a key tool for supporting forestry and resource assessment activities, facilitating more accurate decision-making in regard to the sustainable use of native aromatic species with commercial value.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contributions by author

Luis Miguel Toribio-Ferrer: methodological design, modeling and statistical analysis, drafting of the manuscript, and bibliographic research; Eulalia Edith Villavicencio-Gutiérrez: research design and supervision, fieldwork, interpretation of results, revision and editing of the document; Antonio Cano-Pineda: analysis of results, revision and editing of the document.

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