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Research article

Biomass and dry leaf yield of *Lippia graveolens* Kunth

Rendimiento de biomasa y hoja seca de *Lippia graveolens* Kunth

Hector Darío González López[1], Genaro Esteban García Mosqueda[1], Adriana Antonio Bautista[1], Rosalinda Cervantes Martínez[1], Dino Ulises González Uribe[1*]

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[1]Universidad Autónoma Agraria Antonio Narro. México.

*Autor para correspondencia; correo-e: digon_mx@yahoo.com
*Corresponding author; e-mail: digon_mx@yahoo.com

Abstract

Mexican oregano (*Lippia graveolens*) is a non-timber forest product of nutritional interest and pharmaceutical use. There is a lack of precise quantitative information on harvesting in natural populations and their response to exploitation. The objective of this study was to adjust regression models for estimating the fresh leaf weight (*flw*) and dry leaf weight (*dlw*) in order to generate biomass yield tables for fresh and dry leaves in wild populations of *Melchor Ocampo*, *Zacatecas*. In the field, the following morphometric variables were measured: height (*h*, cm) and average canopy diameter (*acd*, cm) per plant, fresh leaf weight (*flw*, g) and dry leaf weight (*dlw*, g). To estimate the *flw* and *dlw*, regression models were adjusted by the probability of committing a type I error (P<0.01) in the regression, the highest adjusted Coefficient of determination value (R^2_{aj}) and minimum values for the Root mean square error (*RMSE*) and Coefficient of variation (*CV*). On average, the *flw* per plant was 149.4±62.9 g and the *dlw* was 31.1±13.8 g. The density was 8 272 plants ha^{-1}. The fresh weight was estimated using the $flw = (22.063)(1.050)^{acd}$ model, which was highly significant (P<0.01) and exhibited very good fits (R^2_{aj}=0.979, *RMSE*=0.064, *CV*=1.29 %). The model utilized for the dry weight was $dlw = (10.933)(1.027)^{acd}$, with R^2_{aj}=0.909, *RMSE*=0.075 and *CV*=2.21 %. The selected models showed that the morphometric variable *acd* of *L. graveolens* predicts more than 90 % of the variation in *flw* and *dlw* in the study area.

Key words: Correlation analysis, nonlinear model, regression models, oregano, dry leaf yield table, morphometric variables.

Resumen

El orégano mexicano (*Lippia graveolens*) es un producto forestal no maderable de interés alimenticio y uso farmacéutico. Se carece de información cuantitativa precisa sobre la cosecha en poblaciones naturales y su respuesta al aprovechamiento. El objetivo del presente estudio fue ajustar modelos de regresión para estimar peso fresco (*pfr*) y seco de la hoja (*pse*) para generar tablas de rendimiento de biomasa de hojas frescas y secas en poblaciones silvestres de Melchor Ocampo, Zacatecas. En campo, se midieron las variables morfométricas: altura (*h*, cm) y diámetro promedio de cobertura (*dpc*, cm) por planta, peso fresco (*pfr*, g) y seco de las hojas (*pse*, g). Para estimar el *pfr* y *pse* se ajustaron modelos de regresión seleccionados por la probabilidad de cometer el error tipo I (P<0.01) en la regresión, el mayor valor de Coeficiente de determinación ajustado (R^2_{aj}) valores mínimos para la Raíz del cuadrado medio del error (*RCME*) y Coeficiente de variación (*CV*). En promedio, por planta el *pfr* fue de 149.4±62.9 g y el *pse* de 31.1±13.8 g. La densidad fue de 8 272 plantas ha^{-1}. El peso fresco se estimó con el modelo $pfr = (22.063)(1.050)^{dpc}$ el cual resultó altamente significativo (P<0.01) y presentó excelentes ajustes (R^2_{aj}=0.979, *RCME*=0.064, *CV*=1.29 %). El modelo para el peso seco fue $pse = (10.933)(1.027)^{dpc}$ con R^2_{aj}=0.909, *RCME*=0.075 y *CV*=2.21 %. Los modelos seleccionados mostraron que la variable morfométrica *dpc* de *L. graveolens* predice más de 90 % de la variación existente en el *pfr* y *pse* en el área de estudio.

Palabras clave: Análisis de correlación, modelo no lineal, modelos de regresión, orégano, tabla de rendimiento de hoja seca, variables morfométricas

Introduction

Lippia graveolens Kunth, known as Mexican oregano, is a shrubby and herbaceous plant of great importance in Mexico (Muñoz-Acevedo et al., 2007; Villavicencio-Gutiérrez et al., 2018). It is a non-timber forest product (NTFP) of nutritional, pharmaceutical, cosmetic, economic, and ecological interest, among others (Cortés-Chitala et al., 2021; Díaz-de León et al., 2020). Its importance has increased due to interest in its use as a natural antioxidant (Muñoz-Acevedo et al., 2007; Cortés-Chitala et al., 2021).

In Mexico, an average of 4 500 t of oregano are produced annually (García-Pérez et al., 2012; Orona-Castillo et al., 2017; Villavicencio-Gutiérrez et al., 2018); this species ranks second in global production, followed by Greece and Spain (García-Pérez et al., 2012; Villavicencio-Gutiérrez et al., 2018).

Currently, there is a lack of accurate quantitative information on leaf harvesting in natural populations; their response to high-intensity harvesting—a critical factor in the development of management and harvesting plans for this NTFP— is also unknown (Comisión Nacional Forestal [Conafor], 2011). This motivates the creation of a sustainable management plan for *L. graveolens*, which begins with an estimate of the actual available stocks (Conafor, 2011; Secretaría de Medio Ambiente y Recursos Naturales [Semarnat], 1997). This can be done by directly evaluating standing plants to determine their biomass or fresh leaf weight, or by applying estimation methodologies through simple measurements of the morphometry of individuals to determine the fresh weight of the leaves (Flores-Garnica, 1994; López-Serrano et al., 2021; Villavicencio-Gutiérrez et al., 2018).

This will make it possible to develop yield tables (González-López et al., 2022) for leaf weight and thus determine the respective dry weight once the water has been removed. These tables are a useful tool for estimating leaf production in *L. graveolens* (López-Serrano et al., 2021; Villavicencio-Gutiérrez et al., 2018). Their importance lies in the speed with which data can be obtained in the field and in their cost efficiency, as they require only morphometric measurements of variables without harvesting the plants (Ares et al., 2002; López-Serrano et al., 2021; Semarnat, 1997).

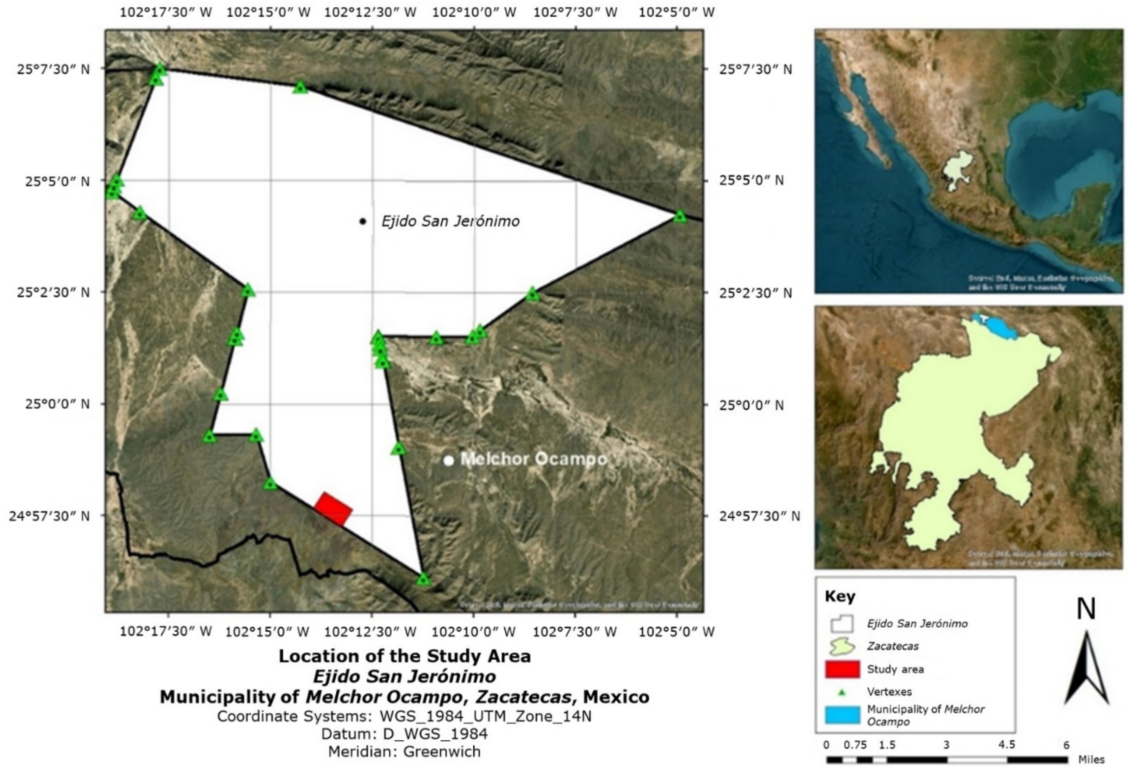
Estimates involve correlating the oregano leaf production with simple morphometric variables that can be measured in the field and adjusting regression models that estimate the standing biomass. In the case of *L. graveolens*, it can be the fresh and dry weight (Ares et al., 2002; López-Serrano et al., 2021). The results are the averages of oregano leaf production from plants of different sizes, based on one or more of their morphometric variables (López-Serrano et al., 2021; Villavicencio-Gutiérrez et al., 2018).

The objective of this study was to adjust regression models to estimate the fresh and dry weight of *L. graveolens* leaves in order to generate yield tables with morphometric variables in wild populations located in the municipality of *Melchor Ocampo*, *Zacatecas*, Mexico.

Materials and Methods

Study Area

The study area is located in the *ejido San Jerónimo* in the municipality of *Melchor Ocampo*, where natural *L. graveolens* populations are exploited. It is located in the North of the state of *Zacatecas* (24°59′6.00″ N and 102°13′2.00″ W), at an average altitude of 1 450 m (Figure 1). The area is located within the Chihuahuan Desert and belongs to the RH36 *Nazas Aguanaval* hydrological region, in the basin of the *Laguna de Mayrán y Viesca* and the sub-basin of the *Laguna de Viesca* (Sistema Nacional de Información sobre Biodiversidad [SNIB], 2025a, 2025b). The dominant vegetation is microphyll desert scrub and rosette desert scrub (SNIB, 2025c). The soils are of the Lithosol (dominant) and Solonchak types (SNIB, 2025d). The prevailing climate is very arid, semi-warm (BWhw), with temperatures ranging between 18 and 22 °C. The average annual precipitation is 200 to 400 mm with summer rains, equivalent to 5 and 10.2 % of annual rainfall (SNIB, 2025e).



Melchor Ocampo = Municipality of *Melchor Ocampo*.

Figure 1. Location of the study area.

Sampling and measurement of variables

In the *L. graveolens* collection area, a starting point was randomly selected, from which distances of 100 m were marked to define 22 sites (Martínez-Bencardino, 2019; Valdivieso-Serrano, 2021). At each site, a 25 m^2 (5×5 m) quadrant was marked out and subdivided into four equal quadrants (Bonham, 2013). The plants present at the site were counted; in the 25 m^2 quadrants, one plant was collected at random and its morphometric variables were measured: (a) plant height (*h*, cm); (b) smallest diameter (*sd*, cm), measured at ground level, considered the base of the plant; and (c) largest diameter (*ld*, cm) of the shrub cover, which corresponds to the widest part of the aerial cover of each plant. The above variables were obtained using a flexometer (model 5010 Arly®); the mean diameter was estimated to calculate the average cover diameter (*acd*, cm). Subsequently, the entire plants from each quadrant were collected, placed in paper bags, and labeled for proper identification and transfer to a storage center.

The leaves of each individual collected were separated and weighed using digital scale (model L-EQ 5/10 *Torrey*® with a capacity of 20 kg); this represented the fresh leaf weight (*flw*, g). Next, the leaves from each plant were placed on a plastic sheet and exposed to the sun for a week to dehydrate them. The samples were considered dry when the leaves felt semi-brittle to the touch. Once the process was complete, the dry weight of the leaves (*dlw*, g) was recorded using the same digital scale (Conafor, 2011; Orona-Castillo et al., 2017).

Statistical analysis

Twenty-two sites (m=22) were considered, and four plants were collected at each site, yielding a total of n=88 plants. The analyses were carried out in Excel®. A data exploration analysis was performed to estimate the sample mean ($\bar{x}$) and sample standard deviation (s), the interval $\bar{x}\pm s$, and the minimum and maximum values for each variable evaluated. The normality of the data was tested using the Kolmogorov-Smirnov test ($KS>P$) (Table 1) (Zar, 2014).

Table 1. Normality test for the morphometric variables and weight of *Lippia graveolens* Kunth.

Estimator	*h*	*acd*	*flw*	*dlw*
KS<*P*	0.2414	0.3039	0.3891	0.1431

KS = Kolmogorov-Smirnov test (*KS*>P); *h* = Height; *acd* = Average cover diameter; *flw* = Fresh leaf weight; *dlw* = Dry weight of the leaves.

Pearson's simple linear correlation coefficient (*R*) ($P<0.01$) was calculated for the variable pairs comprised in the field data matrix (Zar, 2014). Since the predictions of *flw* (g) and *dlw* (g) were an essential part of this research, the highest correlation was considered for the variables *h* (cm) and *acd* (cm). Once the highest value of the *R* correlation was identified, the 88 plants were grouped into intervals of that variable in the units of measurement (cm) (González-López et al., 2022; Zar, 2014).

Twelve linear and nonlinear regression models were evaluated using the Least squares method (Table 2) (Zar, 2014) to predict the leaf production in terms of fresh weight (*flw*, g) and leaf yield, given by its respective dry weight (*dlw*, g). The following criteria were used to select models: the probability of committing a type I error ($P<0.01$) in the regression, the highest Adjusted coefficient of determination value (R_{aj}^2), minimum values for the Root mean square error (*RMSE*), and the Coefficient of variation (*CV*) (Zar, 2014).

Table 2. Models evaluated to estimate fresh leaf weight (*flw*, g) and dry leaf yield (*dlw*, g) of *Lippia graveolens* Kunth.

No.	Model	No.	Model
1	$flw = a + b(h)$	7	$dlw = a + b(h)$
2	$flw = a + b(acd)$	8	$dlw = a + b(acp)$
3	$flw = (a)(b)^h$	9	$dlw = (a)(b)^h$
4	$flw = (a)(b)^{acd}$	10	$dlw = (a)(b)^{acd}$
5	$flw = (a)(h)^b$	11	$dlw = (a)(h)^b$
6	$flw = (a)(acd)^b$	12	$flw = (a)(acd)^b$

flw = Fresh leaf weight (g); *dlw* = Dry leaf weight (g); *a* and *b* = Regression parameter estimators; *h* = Plant height (cm); *acd* = Average cover diameter (cm).

In addition, the significance of the regression coefficients of the models was tested (Table 3) using Student's *t*-statistic. Homoscedasticity was verified in the selected models (Breusch & Pagan, 1979; Maldonado-Ortiz et al., 2022). Subsequently, *flw* tables for leaves and leaf yield were generated in terms of their *dlw*.

Table 3. Analysis of variance for the *flw* and *dlw* models of *Lippia graveolens* Kunth leaves.

Model	*a*	*b*	*sa*	*sb*	*Pa*<0.01	*Pb*<0.01
1	-444.234	8.510	108.642	1.529	**	**
2	-128.999	7.416	34.604	0.876	NS	**
3	3.279	1.055	0.8168	0.012	NS	**
4	22.063	1.050	0.124	0.003	**	**
5	0.00001	47.552	3.468	0.815	NS	**
6	0.197	1.819	0.468	0.129	NS	**
7	30.580	0.871	14.371	0.202	NS	NS
8	0.828	0.781	4.192	0.106	NS	**
9	3.935	1.029	0.527	0.007	NS	NS
10	10.933	1.027	0.145	0.003	**	**
11	0.004	2.096	2.167	0.509	NS	NS
12	0.814	0.995	0.417	0.115	NS	**

a = Intercept; *b* = Slope; *sa* = Standard error for *a*; *sb* = Standard error for *b*; ** = Highly significant; NS = Not significant; *Pa*<0.01 = Probability that *a* is not zero; *Pb*<0.01 = Probability that *b* is not zero.

Results and Discussion

Statiscal analysis

The average *flw* was 149.4±62.9 g per plant^{-1}, and the average *dlw* was 31.1±13.8 g plant^{-1} (Table 4). On average, the dry leaf yield was 22.18 %. The average density was 8 272 plants ha^{-1}. The average measurements of *h*, *acd*, and *dlw* of leaves were similar to those recorded in *Zacatecas* by López-Serrano et al. (2021). The values obtained comply with the standards that recommend using plants taller than 30 cm (Semarnat, 1997) and with coverage diameters of over 50 cm (Conafor, 2011). The results of this study meet these criteria.

Table 4. Estimators for the morphometric variables and biomass weight of *Lippia graveolens* Kunth.

Estimator	*h*	*acd*	*flw*	*dlw*
$\bar{x}$±*s*	69.7±15.8	38.1±7.2	149.4±62.9	31.1±13.8
Minimum	37	22.5	46	11
Maximum	115	52.5	342	79
CV (%)	22.67	18.90	42.10	44.37

h = Plant height (cm); *acd* = Average cover diameter (cm); *flw* = Fresh leaf weight (g); *dlw* = Dry leaf weight (g); $\bar{x}$ = Sample mean; *s* = Sample deviation; *CV* = Coefficient of variation.

During the drying process of *L. graveolens* leaves, a 79 % decrease in initial weight was quantified. The values cited for *Zacatecas* for *dlw* (López-Serrano et al., 2021) indicate that the variation is low; however, similar studies do not record the *flw* (Flores-Garnica, 1994; Villavicencio-Gutiérrez et al., 2018). The methodology utilized seeks to promote the sustainable use of *L. graveolens*; it was applied in accordance with current regulations, as only plants taller than 30 cm and with a diameter of over 50 cm were measured (Conafor, 2011), and at least 20 % of the specimens present at the site were left uncollected (Semarnat, 1997). This management allows plants to reach maturity, regenerate naturally, and help prevent soil erosion in their habitat. Together, these actions support the use of methods based on morphometric measurements and promote the sustainability and conservation of the resource (López-Serrano et al., 2021; Semarnat, 1997).

Correlation between the evaluated variables

The variable pairs with statistical significance at 99 % (P<0.01) were for *flw* and *acd* with R=0.753, and *dlw* and *acd* with R=0.472, which allowed us to order them into six 25-50 cm intervals for the independent variable *acd*. Similar studies determined relationships between the *dlw* and the variables *h* and *acd* (Flores-Garnica, 1994; López-Serrano et al., 2021; Villavicencio-Gutiérrez et al., 2018).

These results are important for estimating the biomass and dry leaf yield of the species (Flores-Garnica, 1994; Villavicencio-Gutiérrez et al., 2018). Correlation values support the creation of performance tables; however, such analysis is not always carried out (Flores-Garnica, 1994); however, their estimates prevent excessive harvesting of plants, ensuring their rational use (Ares et al., 2002; Semarnat, 1997).

Table of the fresh leaf biomass yield (*flw*) and the dry fiber yield (*dlw*) for *Lippia graveolens*

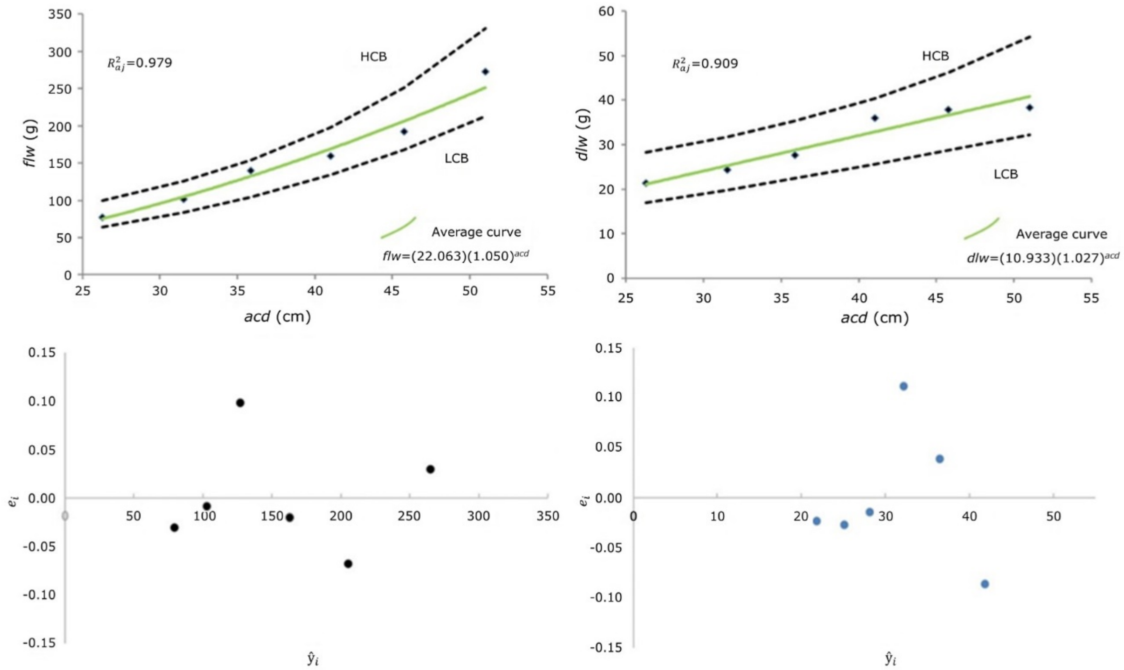
Table 3 shows the adjusted values for predicting the *flw* and *dlw* performance; also included is the significance test result for the regression coefficients of the models with Student's t-statistic. Table 5 shows the values of the model selection criteria. For the *flw*, the best result corresponded to the nonlinear model 4 ($flw = (22.063)(1.050)^{acd}$), while for the *dlw*, it corresponded to model 10 ($dlw =$

$(10.933)(1.027)^{acd}$). The selected models and their graphical behavior are shown in Figure 2, which shows the confidence bands (99 %) for the field data and the intervals for the average regression.

Table 5. Adjustment of regression models for the *flw* and *dlw* of the leaf based on the morphometric variables of *Lippia graveolens* Kunth.

Model	*P*<0.01	R^2_{aj}	*RMSE*	*CV* (%)	*BP*<0.01
1	**	0.857	26.400	16.80	NS
2	**	0.934	17.951	11.42	NS
3	**	0.805	0.198	3.99	NS
4	**	0.979	0.064	1.29	**
5	**	0.811	0.196	3.93	NS
6	**	0.975	0.070	1.42	NS
7	NS	0.778	3.492	11.28	NS
8	**	0.914	2.174	7.03	NS
9	NS	0.738	0.128	3.76	NS
10	**	0.909	0.077	2.21	**
11	NS	0.761	0.122	3.59	NS
12	**	0.934	0.062	1.84	**

R^2_{aj} = Adjusted coefficient of determination; *RMSE* = Root mean square error; *CV* = Coefficient of variation; ***P*<0.01 in the regression; **Breusch-Pagan test (*BP*<0.01); NS = Not significant.



LCB = Lower-confidence band; HCB = Higher-confidence band; *acd* = Average cover diameter of the plant (cm); *flw* = Fresh leaf weight (g); *dlw* = Dry leaf weight (g); e_i = Residuals.

Figure 2. Selected models with confidence bands (P<0.01) and residual plots.

The results are similar to a study of the dry leaf biomass of the same species in the state of *Coahuila*, in which regression models were adjusted without recording the coefficients, making it impossible to compare yields (Flores-Garnica, 1994; Villavicencio-Gutiérrez et al., 2018). The similarity lies in the fact that the best fits are also with nonlinear models between the variable *dlw* of the leaf and the canopy diameter; with the variable *h*, the fit was poor (R=0.08) (López-Serrano et al., 2021; Villavicencio-Gutiérrez et al., 2018). Furthermore, a good fit was obtained in the present study between the *flw* and the *acd* (R=0.979).

In the selected models, the residuals were shown to comply with homoscedasticity ($P<0.01$) (Breusch & Pagan, 1979; Maldonado-Ortiz et al., 2022). In research conducted with *L. graveolens* in the state of *Coahuila*, other adjusted models exhibited heteroscedasticity (Villavicencio-Gutiérrez et al., 2018).

The model selection criteria and the residuals' compliance with homoscedasticity allowed us to obtain the *flw* and *dlw* yield tables of *L. graveolens* in grams (Table 6).

Table 6. Yield tables for *flw* and *dlw* of *Lippia graveolens* Kunth in grams based on *acd* in cm.

***acd* (cm)**	**Fresh leaf weight (*flw*, g)**	**Dry leaf weight (*dlw*, g)**
25	74.6	21.1
30	95.2	24.1
35	121.5	27.5
40	155.0	31.3
45	197.7	35.7
50	252.3	40.8

acd = Average cover diameter of the plant (cm).

Conclusions

The morphometric and independent variable average diameter of coverage (*acd*) of *Lippia graveolens* explains leaf yield expressed in terms of its respective fresh weight (*flw*) and dry weight (*dlw*) by 97.9 and 90.9 %, respectively. The model selected to estimate the fresh weight of the leaf is $flw = (22.063)(1.050)^{acd}$ and for the dry leaf weight: $dlw = (10.933)(1.027)^{acd}$. With these nonlinear models, there is a 99 % reliability that the yield tables for leaves adequately represent the variables of interest, which is aimed at achieving sustainable use of *L. graveolens*, as well as their conservation, protection, and restoration in the natural habitat of their wild populations in *Melchor Ocampo*, *Zacatecas*, Mexico.

Conflict of interest

The authors declare that they have no conflict of interest.

Contributions by author

Héctor Darío González López and Dino Ulises González Uribe: research planning and development, field sampling, data collection, data analysis and exploration, drafting and revision of the final structure of the manuscript; Genaro Esteban García Mosqueda and Rosalinda Cervantes Martínez: final revision and editing of the manuscript; Adriana Antonio Bautista and Francisco Cruz García: field sampling, data collection, and revision of the structure of the final manuscript. All authors approved the final version of the document.

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