DOI: 10.29298/rmcf.v17i97.1637

Research article

Equations for biomass estimation of *Tiquilia canescens* (DC.) A. T. Richardson in desert shrublands

Ecuaciones para la estimación de biomasa de *Tiquilia canescens* (DC.) A. T. Richardson en matorrales desérticos

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Fecha de recepción/Reception date: 8 de febrero de 2026.
Fecha de aceptación/Acceptance date: 4 de mayo de 2026.

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Abstract

Tiquilia canescens is a shrub found in the desert scrublands of northern Mexico; because it is so abundant, it may play an important role in carbon sequestration and storage. However, there are no allometric functions for estimating its biomass. The objective of this study was to design equations to estimate the aboveground, root and total biomass of *T. canescens*. Allometric measurements were taken on 49 plants found in desert scrublands in the *Aldama* and *Coyame del Sotol* municipalities, state of *Chihuahua*. The fit of the linear, linearized potential allometric, and linearized exponential models for predicting biomass was evaluated. Based on fit statistics such as higher adjusted R^2 values and lower Akaike Information Criteria (*AIC*) values, the variables with the greatest predictive power for total biomass were the long crown diameter (*LCD*, 47.9±18.0 cm), the short basal stem diameter (*SBSD*, 20.3±11.7 mm), and the canopy cover (*CC*, 1 754.4±1,342.8 cm^2). The linearized potential model provided the best fit (lower *RMSE* and higher *Pseudo-*R^2). Cross-validation was performed to test the predictive power of the equations. The final equations for estimating the aboveground, root, and total biomass of *T. canescens* included only the *LCD*, and these equations were robust and reliable for use in the Chihuahuan Desert scrubs and ecologically similar sites in North-central Mexico.

Keywords: Chihuahuan Desert, allometric equations, woody crinklemat, microphyllous scrub, rosette-forming scrub, linear models.

Resumen

Tiquilia canescens es una planta arbustiva de los matorrales desérticos del norte de México, debido a su abundancia puede desempeñar un papel importante en la captura y almacén de carbono. Sin embargo, no existen funciones alométricas para estimar su biomasa. El objetivo fue generar ecuaciones para estimar la biomasa aérea, radicular y total de *T. canescens*. Se realizaron mediciones alométricas en 49 plantas presentes en matorrales desérticos de los municipios Aldama y Coyame del Sotol, Chihuahua. Se evaluó el ajuste de los modelos lineal, alométrico potencial linealizado y exponencial linealizado para predecir la biomasa. Con base en estadísticos de ajuste como mayores R^2*ajustadas* y menores criterios de información de *Akaike* (*AIC*), las variables con mayor capacidad predictiva de la biomasa total fueron el diámetro largo de copa (*DLC*, 47.9±18.0 cm), el diámetro basal corto del tallo (*DCT*, 20.3±11.7 mm) y la cobertura aérea (*CA*, 1 754.4±1 342.8 cm^2). El modelo potencial linealizado presentó el mejor ajuste (menor *RECM* y mayor *Pseudo-R^2*). Se realizó una validación cruzada para probar la capacidad predictiva de las ecuaciones. Las expresiones finales para estimar la biomasa aérea, radicular y total de *T. canescens* incluyeron solamente el *DLC*, las cuales fueron robustas, y confiables para su uso en matorrales desérticos de Chihuahua y sitios ecológicamente similares del norte-centro de México.

Palabras Clave: Desierto Chihuahuense, ecuaciones alométricas, hierba de la virgen, matorral micrófilo, matorral rosetófilo, modelos lineales.

Introduction

The xerophytic scrubs of Northern Mexico are ecosystems of great economic and environmental importance; they represent the country's largest vegetation type, covering 40 % of the national territory (Rzedowsky, 2006). These scrublands, used primarily for livestock grazing, are characterized by their growth on poor soils, with low precipitation and a high degree of degradation (Secretaría de Medio Ambiente y Recursos Naturales [Semarnat], 2016). In these ecosystems, the main plant communities—based on the area they occupy—are the microphyllous scrubs, which are dominated by *Larrea tridentata* (DC.) Coville (creosote bush) and *Flourensia cernua* DC. (tarbush); in addition to rosette-forming shrubland, dominated by *Agave lechuguilla* Torr. (*lechuguilla*) and *Dasylirion wheeleri* S. Watson *ex* Rothr. (*sotol*) (Granados-Sánchez et al., 2011).

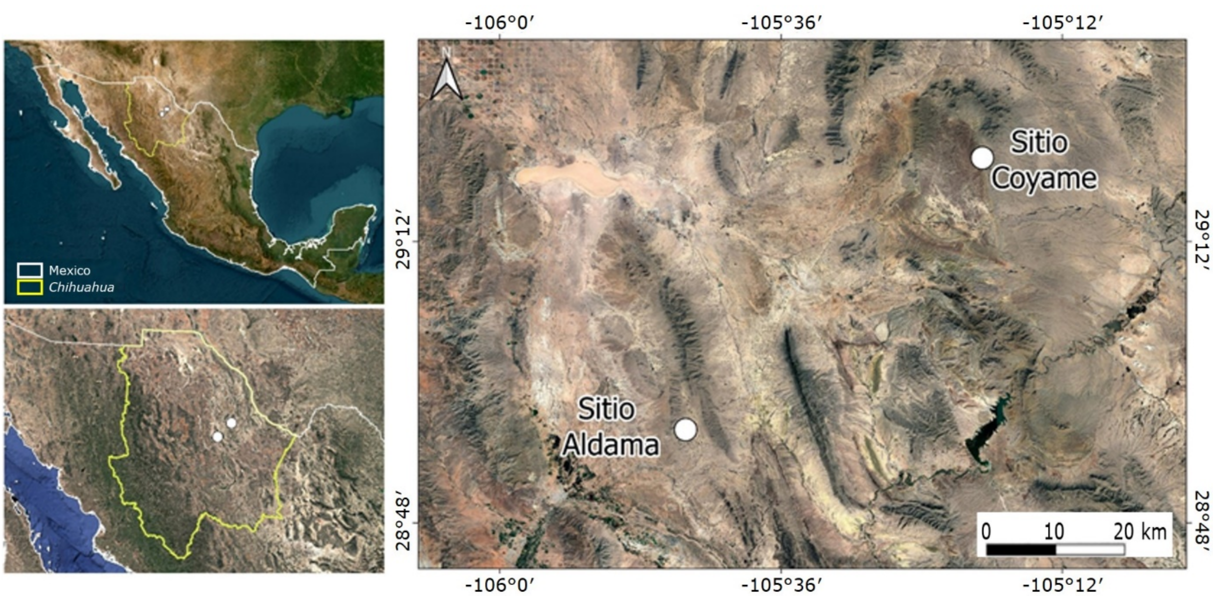
The multiple services provided by these desert ecosystems are essential to the well-being, health, livelihoods, and survival of nearly 60 % of Mexico's population (Briones et al., 2020). In the rosette-forming scrub, there are plants used for industrial purposes, such as *sotol* and *lechuguilla* (Rzedowski, 2006) and others, such as the woody crinklemat (*Tiquilia canescens* (DC.) A. T. Richardson), which, while not of great economic value, plays an important ecological role, especially in carbon storage and sequestration. However, the impact of desert scrubs in the context of climate change has been little studied in Northern Mexico (Briones et al., 2018).

The challenges in estimating carbon stocks in xerophytic vegetation stem from the high diversity of shrubs present and the limited research on the species found there. There are some general equations for calculating the biomass of shrubs (Conti et al., 2019; Paz-Pellat et al., 2021), as well as some specific allometric equations for determining the biomass of the creosote bush, *candelilla* (*Euphorbia antisyphilitica* Zucc.) and *lechuguilla* (Flores-Hernández et al., 2020; Hernández-Ramos et al., 2019; Ludwig et al., 1975). However, no similar studies have been reported for *T. canescens*. This perennial shrub, 0.25 to 0.5 m tall and heavily branched from the base, has moderate forage value (Melgoza-Castillo et al., 2016; Mellado et al., 2005), its high abundance in the Chihuahuan Desert (Moore & Jansen, 2007) could serve as a significant carbon sink. The objective of this study was to develop allometric equations to estimate the aboveground, root, and total biomass of *T. canescens* in desert scrublands in *Chihuahua*, Mexico.

Materials and Methods

Study area

The study was conducted at two sites, one in *Aldama* municipality and the other in *Coyame del Sotol* municipality, in the state of *Chihuahua*, Mexico (Figure 1). Both are located in the Central-eastern part of the state, within the region known as *Sierras y Llanuras del Norte* (Northern Plains and *Sierras*). The climate is dry and semi-warm, with a temperature of 18 °C and annual precipitation of 300 mm (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2010a, 2010b). The predominant soils are alluvial calcisols and leptosols, located within the *Bravo-Conchos* hydrological region. The vegetation in *Aldama* consists of microphyllous scrub (creosote bush and tarbush), while in *Coyame*, rosette-forming scrub (*lechuguilla* and *sotol*) predominates; both are found on low hillsides.



Sitio Coyame = *Coyame* site; *Sitio Aldama* = *Aldama* site.

Figure 1. Location of *Tiquilia canescens* (DC.) A. T. Richardson sampling sites in the desert scrubs of *Chihuahua*, Mexico.

Field sampling

In April 2023, 49 *T. canescens* plants of various sizes were selected to cover a wide range of heights and diameters. For each plant, the long crown diameter (*LCD*, cm), short crown diameter (*SCD*, cm) and total height (*H*, cm) from the ground to the top of the shrub were measured using a model ProLock Truper® 5 m measuring tape. Next, each plant was cut at ground level to obtain the aboveground biomass; the long base stem diameter (*LBSD*, mm) and the short base stem diameter (*SBSD*, mm) were measured using a model CAL-6MP Truper® digital caliper. Next, the root biomass was extracted; for this purpose, the area around the plant was dug up as deeply as possible to collect all visible roots. The aboveground and root biomass of 22 plants in *Aldama* and 27 in *Coyame del Sotol* were collected.

The biomass of each plant was washed to remove the dirt and dried for 30 days in a greenhouse at maximum temperatures of 50.9±0.5 °C. These materials were then transferred to a (model HS Riossa®) oven at 70 °C until they reached their anhydrous weight. Finally, the aboveground parts and roots of the plants were weighed on a model VE 5000 VELAB® digital scale, with an accuracy of 0.1 g. The total biomass per plant was calculated as the sum of aboveground and root biomass.

Based on the allometric variables measured in the field, the variables crown cover (*CC*), biovolume (*Bvol*) and Ludwig's volume (*LV*) were calculated. For the *CC*, it was assumed that the crown was elliptical in shape; the equations of Conti et al. (2013) were used:

$$CC = \pi \left(\frac{LCD}{2} \times \frac{SCD}{2} \right) \qquad (1)$$

$$Bvol = CC \times H \qquad (2)$$

$$LV = \frac{4}{3} \times \pi \times Cr^2 \times H \qquad (3)$$

Where:

CC = Crown cover area in cm^2

LCD = Long crown diameter in cm

SCD = Short crown diameter in cm

Bvol = Apparent biovolume in m^3

H = Plant height in cm

LV = Ludwig's spheroid volume in m^3

Cr = Crown radius in cm

The *Bvol* and *LV* variables imply an apparent volume when the shape of the shrub is assumed to be that of a specific solid body. For *Bvol*, a cylindrical morphotype was considered (Blanco-Oyonarte & Navarro-Cerrillo, 2003); for *LV*, that of a spheroid corresponding to the upper half of the crown (Ludwig et al., 1975). The variables obtained in the field and those data-derived variables served as predictors for estimating the aboveground biomass (*AB*), the root biomass (*RB*) and the total biomass (*TB*).

Statistical analysis

A Pearson correlation analysis and a collinearity assessment using the Variance Inflation Factor (*VIF*) were performed among the predictor variables (Neter et al., 1983). Collinearity was assessed by fitting a multiple linear model with *TB* as the independent variable; *AB* and *RB* were excluded because they are components of *TB*. Because high correlation and structural multicollinearity were observed among the predictor variables—particularly the composite variables—and given practical constraints in the field and the principle of parsimony, it was decided to use a simple equation with a single variable (Cayuela & de la Cruz, 2022). To select this variable, the following goodness-of-fit statistics were considered: Akaike Information Criterion (*AIC*), adjusted R^2 (R^2adj), and the Residual standard error (*RSE*).

After selecting the best predictor variable, the linear, exponential, and potential models for *TB* were evaluated. The ordinary least squares method was used; therefore, it was necessary to transform the last two models by applying logarithms. The predictions were converted to their original scale by applying a Correction factor (*CF*) to the constant in the equation (Baskerville, 1972). The selection of the best model was based on the Root mean square error (*RMSE*) and the *Pseudo*-R^2 on the original scale (Baty et al., 2015).

A graphical analysis of the residuals was also performed to evaluate the assumption of homoscedasticity. The best model selected was fitted to the *AB* and *RB* variables. The goodness of fit of the final equations was assessed using the Adjusted coefficient of determination (R^2aj), the *RMSE*, and the statistical significance ($p<0.05$).

To evaluate the predictive power of the models and rule out overfitting, given the small sample size ($n=49$), a leave-one-out cross-validation process was performed (James et al., 2021). During this process, the predictions were back-transformed and sequentially corrected to the original scale (g) to calculate the *RMSE*, the Mean absolute error (*MAE*), and a Validation coefficient of determination (R^2vc) (Parresol, 1999). All analyses were performed using *R*, version 4.2.1 (R Core Team, 2024).

Results and Discussion

Allometric variables and biomass

Table 1 shows the statistics for the predictor and independent variables of *T. canescens* biomass.

Table 1. Descriptive statistics for allometric and biomass measures of *Tiquilia canescens* (DC.) A. T. Richardson in the desert scrubs of *Chihuahua*, Mexico (*n*=49).

Statistic	*H*	*SCD*	*LCD*	*SBSD*	*LBSD*	*CC*	*Bvol*	*LV*	*AB*	*RB*	*TB*
Mean	34.7	40.8	47.9	20.3	24.2	1 754	0.073	0.098	161.9	35.1	197.0
St. Dev.	10.9	16.2	18.0	11.7	14.5	1 343	0.079	0.106	175.0	37.4	209.2
Min. value	16	13	21	4.2	5.3	224	0.004	0.007	10.5	1.6	12.1
Max value	61	82	91	52.6	60.4	5 789	0.335	0.449	620.3	183.4	748.9

H = Plant height (cm); *SCD* = Short crown diameter (cm); *LCD* = Long crown diameter (cm); *SBSD* = Short basal stem diameter (mm); *LBSD* = Long basal stem diameter (mm); *CC* = Crown cover area (cm^2); *Bvol* = Plant biovolume (m^3); *LV* = Ludwig's spheroid volume (m^3); *AB* = Aboveground biomass (g $plant^{-1}$); *RB* = Root biomass (g $plant^{-1}$); *TB* = Total biomass (g $plant^{-1}$).

The *T. canescens* population in the study area is stunted because the average height and crown diameter are less than 50 cm. These values are also lower than those of similar forage plants such as *mariola* (*Parthenium incanum* Kunth), for which the values cited by Villalobos (2007) are slightly higher (42.8 cm in height and 61.2 cm in *LCD*). The average *AB* and *RB* values in this study were higher than those reported for the same species by Hernández-Gómez et al. (2018) in desert scrubs of the states of *Nuevo*

León and *San Luis Potosí*, with averages of 63.2 g plant^{-1} and 4.4 g plant^{-1}, respectively; with an annual precipitation of 386 mm and a temperature of 17.2 °C. Hernández-Gómez et al. (2018) report a root-to-aboveground biomass ratio of 0.07, which is lower than the value of 0.216 obtained in the study documented herein. These differences can be attributed to the variability in ecological and edaphic conditions at each study site, since the growth of roots, stems, and leaves is influenced by various factors such as soil texture, structure, and compaction, as well as availability of moisture and nutrients (Barbour et al., 1987; Kramer, 1983).

Selection of predictor variables

The Pearson correlation coefficients among independent variables were significant ($P \leq 0.001$) and indicated a high correlation (Table 2). Most of the original and composite variables showed a high correlation with biomass (r=0.77 to 0.92; P<0.0001). The variable with the lowest correlation with biomass was height (r=0.70; P<0.0001), which suggests its low potential as a predictor variable.

Table 2. Correlation matrix of allometric variables and biomass of *Tiquilia canescens* (DC.) A. T. Richardson in Chihuahuan Desert scrubs (*n*=49).

Variable	H	SCD	LCD	SBSD	LBSD	CC	Bvol	LV
SCD	0.873							
LCD	0.881	0.963						
SBSD	0.677	0.757	0.798					
LBSD	0.669	0.749	0.789	0.982				
CC	0.868	0.979	0.963	0.768	0.770			
Bvol	0.876	0.935	0.903	0.713	0.719	0.977		
LV	0.878	0.935	0.906	0.715	0.722	0.978	0.999	
AB	0.764	0.867	0.892	0.851	0.854	0.912	0.884	0.886
RB	0.701	0.781	0.811	0.925	0.908	0.806	0.770	0.773
TB	0.764	0.865	0.892	0.878	0.877	0.908	0.878	0.880

H = Plant height; *SCD* = Short crown diameter; *LCD* = Long crown diameter; *SBSD* = Short basal stem diameter; *LBSD* = Long basal stem diameter; *CC* = Crown cover area; *Bvol* = Plant biovolume; *LV* = Ludwig's volume; *AB* = Aboveground biomass (g $plant^{-1}$); *RB* = Root biomass (g $plant^{-1}$); *TB* = Total biomass (g $plant^{-1}$).

The *VIF* values for all predictor variables were above 10, indicating high multicollinearity (Neter et al., 1983). The lowest value was for height (18); values above 632 were for crown cover area and both volumes, suggesting high structural multicollinearity, because these variables were calculated based on crown diameters (*SCD*, *LCD*) and height. The high correlation among the variables justified the decision to select a simple equation with a single predictor variable; Table 3 shows the statistics used in this selection.

Table 3. Fitting statistics for individual predictor variables with the total biomass of *Tiquilia canescens* (DC.) A. T. Richardson.

Variable	R^2adj	AIC	RSE
Long crown diameter (LCD)	0.862	57.57	0.4182
Short basal stem diameter (SBSD)	0.858	58.76	0.4233
Crown cover area (CC)	0.845	63.31	0.4434
Ludwig's volume (LV)	0.829	67.90	0.4647
Biovolume (Bvol)	0.827	68.56	0.4678
Long basal stem diameter (LBSD)	0.825	69.25	0.4711
Short crown diameter (SCD)	0.793	77.50	0.5125
Plant height (H)	0.636	105.11	0.6793

R^2adj = Adjusted coefficient of determination; *AIC* = Akaike Information Criterion; *RSE* = Residual standard error.

The *LCD* variable showed the best fit statistics. Although the *LCD* and the *SBSD* showed statistically equivalent goodness-of-fit criteria (ΔAIC<2), the *LCD* was selected as the sole predictor variable. In practice, measuring the crown is quick and non-destructive, whereas measuring the basal diameter of the stem is difficult due to the low-growing shape of *T*. *canescens*. The third-best variable was *CC*; however, two measurements (*LCD* and *SCD*) are required to estimate it, and this takes more time.

Similar studies in desert scrubs (Flores-Hernández et al., 2020; Hernández-Ramos et al., 2019; Maldonado-Ortiz et al., 2022) have pointed out that crown diameter is essential for predicting the biomass of species like *lechuguilla* and *candelilla*. However, in other taxa found in desert ecosystems, it has been observed that the most common variables used to estimate biomass are those derived from the crown diameter and plant height (Ludwig et al., 1975; Rojas-García et al., 2015).

In this study, the correlation analysis and the statistics in Table 3 reveal that height is not a significant predictor. This contrasts with studies aimed at estimating biomass in other species of desert shrubs (Flores-Hernández et al., 2020; Hernández-Ramos et al., 2019; Ludwig et al., 1975; Maldonado-Ortiz et al., 2022), in which the height, either on its own or combined to form a composite variable (such as volume), has demonstrated strong predictive power.

Hernández-Gómez et al. (2018) analyzed the biomass of *T. canescens* and found that, in a quadratic model, height (R^2adj=0.73) was the most significant variable for this estimate, while the model using crown diameter showed a moderate fit (R^2adj=0.51). The low influence of height on biomass in this study can be explained, in part, by the limited vertical growth (Table 1), as the height measurements were similar for both younger specimens—identified by their small stem diameters—and adult specimens with larger stem diameters, which was reflected in a low correlation between the two variables.

Model fitting

The fit statistics for the three models evaluated are presented in Table 4; the relationship between *TB* and *LCD* is shown in Figure 2. The evaluation of the models showed that the potential (linearized using logarithms) provided the best fit for estimating *TB*. When the predictions were backtransformed to the original scale and *CF* was applied, the potential model had the lowest prediction error (*RMSE*=75.963) and the highest proportion of explained variance (*Pseudo*-R^2=0.865). Although the linear model produced consistent statistics, its error was nearly 18 units higher than that of the linearized potential; furthermore, the linear model exhibited heteroscedasticity (Figure 3).

Table 4. Model structure and goodness-of-fit statistics for the models evaluated to predict total biomass (*TB*) based on the long crown diameter (*LCD*).

Model	Equation	*Pseudo-R^2*	*RMSE*
Linear	$TB = b_0 + b_1 \times LCD$	0.796	93.499
Potential (Log)	$ln(TB) = ln(a) + b \times ln(LCD)$	0.865	75.963
Exponential	$ln(TB) = ln(a) + b \times LCD$	0.498	146.734

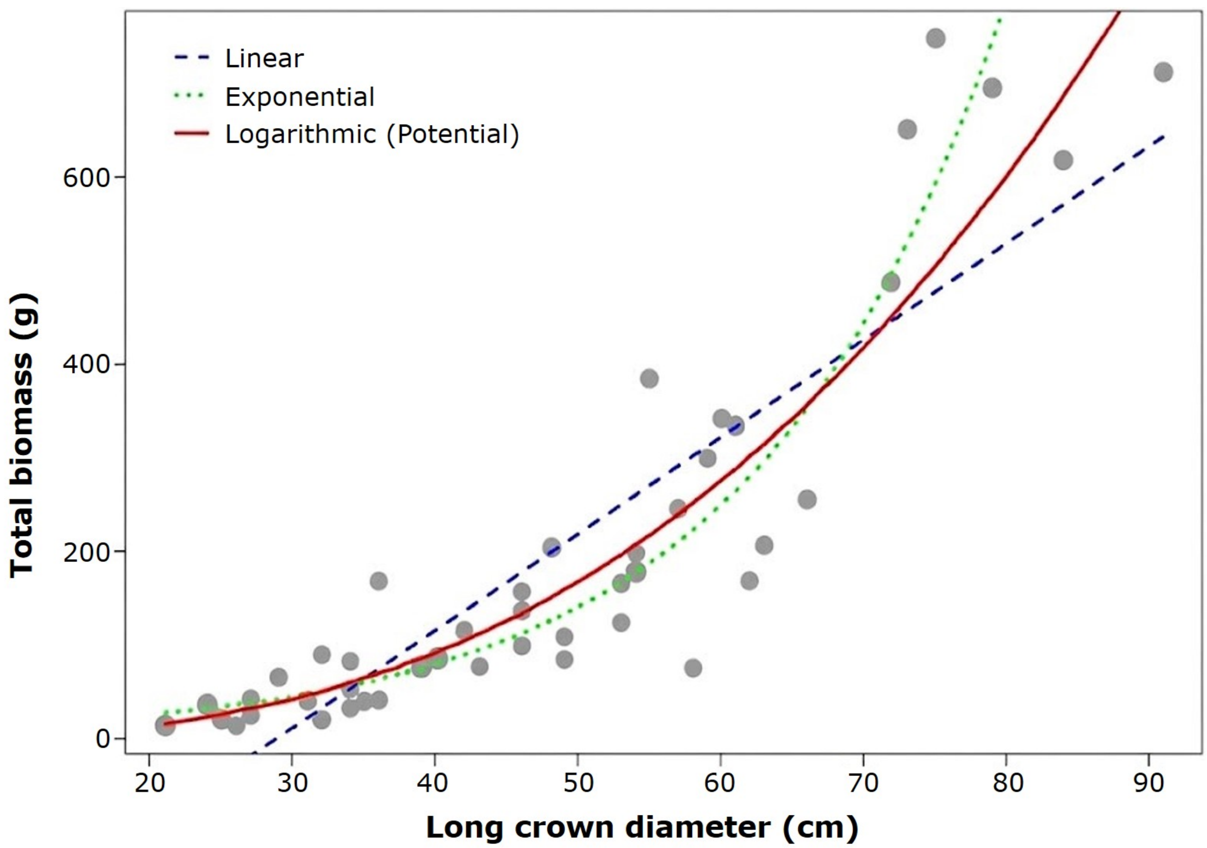


Figure 2. Relationship between the total biomass and the long crown diameter of *Tiquilia canescens* (DC.) A. T. Richardson using linear, potential (logarithmic), and exponential models (*n*=49).

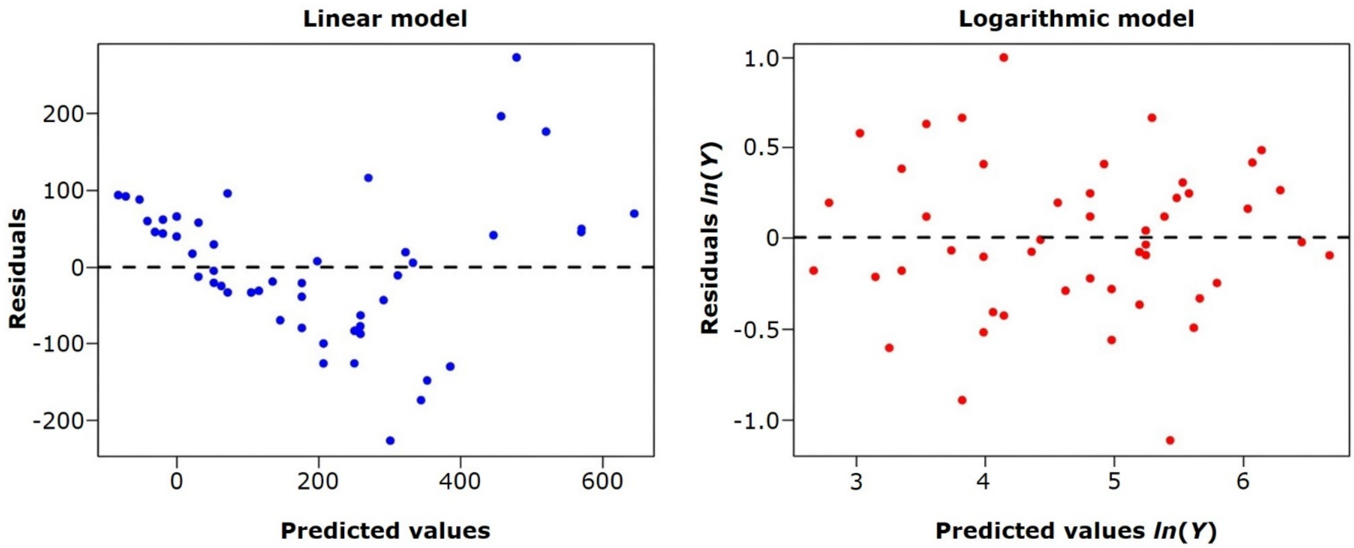


Figure 3. Comparison of observed *versus* predicted residuals for the linear and linearized potential models using logarithms.

The linear model was inadequate for predicting the *TB* in very large or very small plants. The exponential model showed a very high error, which demonstrated that the biomass of *T. canescens* does not grow at an exponential rate relative to long crown diameter; therefore, it was also ruled out. Therefore, the linearized potential model was selected to generate the final equations as a function of the *LCD*, which predict *TB*, *AB*, and *RB* (Table 5).

Table 5. Equations for estimating the aboveground, root and total biomass of *Tiquilia canescens* (DC.) A. T. Richardson in the Chihuahuan Desert scrubs.

Equation	R^2adj	CF	RMSE
$AB = 0.0028 \times LCD^{2.7566}$	0.866	1.090	75.96
$RB = 0.0014 \times LCD^{2.5596}$	0.797	1.130	21.29
$\mathrm{TB} = 0.0039 \times LCD^{2.7235}$	0.862	1.091	60.76

AB = Aboveground biomass (g plant^{-1}); *RB* = Root biomass (g plant^{-1}); *TB* = Total biomass (g plant^{-1}); *LCD* = Long crown diameter (cm); R^2adj = Adjusted coefficient of determination; *CF* = Correction factor in the backtransformation; *RMSE* = Root of the mean square error.

The *LCD*-based equations were highly significant (p<0.001) for the biomass components of *Tiquilia canescens* (Table 5). The equations for *TB* and *AB* have adequate predictive power, as they account for more than 86 % of the observed variance, while the equation for root biomass has slightly lower predictive power (R^2adj=0.79). The correction factors ranged between 1.090 and 1.130, indicating low back-transformation bias in all three components. The allometric exponents ranged between 2.55 and 2.75, indicating accelerated biomass accumulation (positive allometry) with increasing canopy.

The results are consistent with a study on *Parthenium incanum* (Villalobos, 2007), whose *LCD* is highly significant in explaining aboveground biomass, compared to height. Other studies to estimate the aboveground biomass of desert plants such as *candelilla* and *lechuguilla* (Flores-Hernández et al., 2020; Hernández-Ramos et al., 2019) point out that the best models include at least the variables crown diameter and plant height as predictor variables. The model of Ludwig (Ludwig et al., 1975) for the broom snakeweed (*Gutierrezia sarothrae* (Pursh) Britton & Rusby), a shrub of similar size in the Chihuahuan Desert, was the only one that provided an acceptable fit and estimate of the aboveground biomass of *T. canescens* when using the crown cover area as an allometric variable.

In the case of root biomass, the findings contrast with those reported by Hernández-Gómez et al. (2018), who observed that crown diameter, when modeled using an exponential function, was an effective method for estimating the root biomass of *T. canescens* in the scrubs of the Southern Chihuahuan Desert. They also report that, using exponential models, root biomass can be estimated when height is combined with crown diameter, with an R^2 ranging from 0.91 to 0.95.

Few studies have estimated the *TB* for desert shrubs; generally, only aboveground or root biomass is recorded (Hernández-Gómez et al., 2018; Ludwig et al., 1975). However, the *TB* is important for estimating carbon stocks and their contribution to climate change mitigation (Briones et al., 2018).

Cross-validation confirmed the high robustness and generalizability of the proposed equations, although there was a slight underestimation for large plants, particularly in the *RB* (Figure 4). These equations should be used only within the evaluated range, since they may lead to underestimating the biomass of individuals with larger crown diameters.

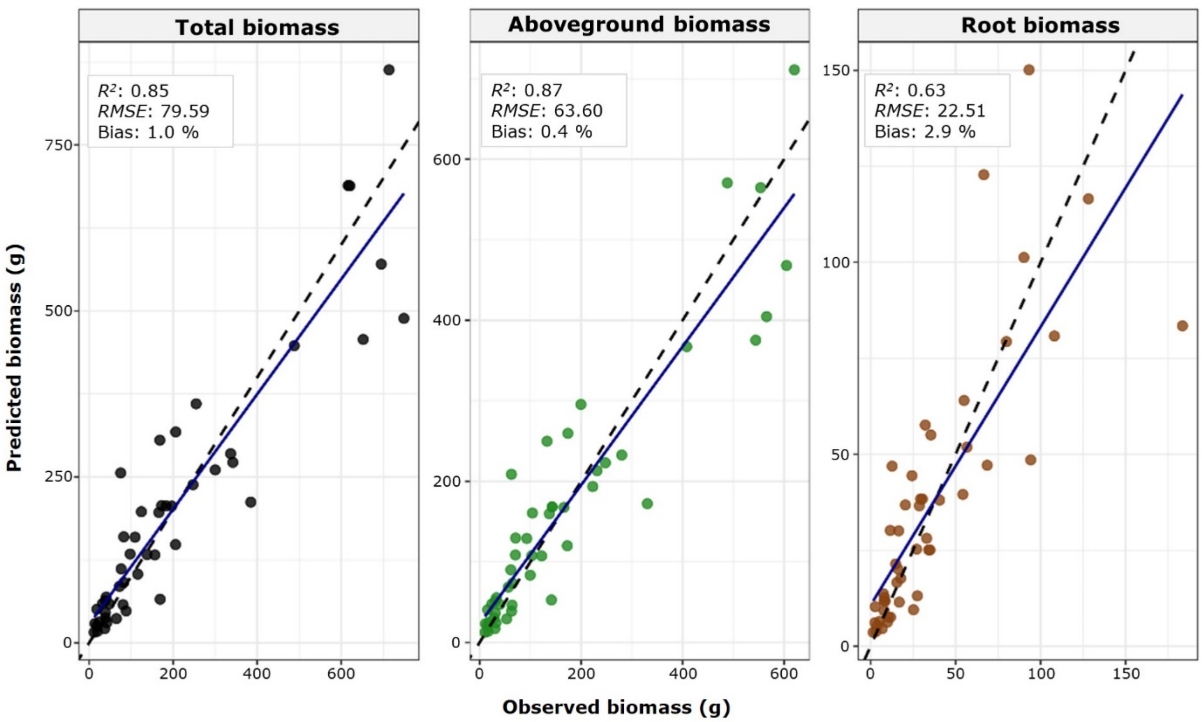


Figure 4. Observed and predicted values from cross-validation for total, aboveground and root biomass.

For the *TB* equation, the R^2 value of 0.852 showed a minimal deviation (<1 %) from the fit reported in Table 5 (R^2=0.862). On the original scale, the equation had an *RMSE* of 79.5 g and a *MAE* of 54.4 g. These predictive parameters were similar for aboveground biomass (R^2=0.865, *RMSE*=63.5 g) and root biomass (R^2=0.632, *RMSE*=22.505 g), with *MAE* values of 43.4 g and 13.3 g, respectively. In general, the predictive power of the equations is adequate because the biases are less than 2.9 % (Figure 4); this confirms that the *LCD* is a reliable variable for estimating biomass in *T. canescens*.

Conclusions

The linearized potential allometric equation provides the best predictive performance for estimating the aboveground, root, and total biomass of *Tiquilia canescens* when the long crown diameter, which is easy to measure, is used as the predictor variable. The derived biomass equations have practical implications for quantifying the carbon stock and forage availability of this taxon in the Chihuahuan Desert scrubs and similar ecological sites in north-central Mexico.

Acknowledgements

Thanks are due to the National Institute of Forestry, Agricultural and Livestock (*Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias*) *La Campana* Experimental Field (*Campo Experimental La Campana*), for the facilities to carry out the study.

Conflict of interest

The authors declare that they have no conflicts of interest.

Contributions by author

All authors participated in the study design, fieldwork, and sample handling, as well as in the drafting, revision and final version of the manuscript. Gabriel Sosa Pérez and José Luis García Pérez: statistical analysis.

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