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Article

Estimación del rendimiento de biomasa y fibra de *Agave lechuguilla* Torr. en el norte de Zacatecas

Biomass and fiber estimation of *Agave lechuguilla* Torr. at north of *Zacatecas* State

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Abstract

Biomass and fiber yield tables were generated obtained from the bud of *Agave lechuguilla* at northern *Zacatecas*, Mexico. Regression models were evaluated to estimate green weight (*pv*, g) and dry weight of fiber (*ps*, g) by plant, respectively. The method of quadrants centered on a point was used as sampling to obtain information at 74 sites randomly located. In each plant it was measured, the smallest diameter (*smd*, cm), the largest aerial diameter (*lad*, cm), bud height (*h*, cm), *pv* (g) and *ps* (g). 296 buds were collected and they were manually carved to obtain the fiber, which was sun-dried in for 3-5 h. The average *pv* was 287.2 g bud^{-1}, *ps* 19.1 g bud^{-1}, average density was 2 149 plants ha^{-1}. The correlation showed high statistical significance (P<0.01) for *pv* with *lad* (R=0.968) and *ps* with *h* (R^2=0.945). The model pv=21.920(1.054)^h was selected to estimate the green biomass performance table for presenting better adjustment statistics (R^2_{aj}=0.960, *RCME*=0.095, *CV*=1.688 %, *Cp*=2.002, │*PRESS*│=0.012 and *PRESS*=0.0001). For the fiber dry weight the selected model was ps=0.0003(h)$^{2.812}$ (R^2_{aj}=0.921, *RCME*=0.164, *CV*=5.708 %, *Cp*=2.004, │*PRESS*│=0.123 y *PRESS*=0.015). The statistical criteria used gave certainty in the selection of models to generate biomass and fiber yield tables in the study area.

Keywords: *Agave lechuguilla* Torr., plant density, *ixtle*, *lechuguilla*, allometric model, biomass and fiber yield table.

Resumen

Se generaron tablas de rendimiento de biomasa y fibra del cogollo de *Agave lechuguilla* en el norte de Zacatecas, México. Se evaluaron modelos de regresión para estimar el peso verde (*pv*, g) y peso seco de fibra (*ps*, g) por planta, respectivamente. Se utilizó el método de muestreo de cuadrantes centrados en un punto para obtener información en 74 sitios ubicados al azar. En cada planta se midió el diámetro menor (*dme*, cm), el diámetro aéreo mayor (*dma*, cm), la altura del cogollo (*h*, cm), *pv* (g) y *ps* (g). Se recolectaron 296 cogollos, se tallaron manualmente para obtener la fibra y se secaron al sol por 3–5 horas. El *pv* promedio fue de 287.2 g cogollo^{-1}, el de *ps* de 19.1 g cogollo^{-1} y la densidad promedio de 2 149 plantas ha^{-1}. La correlación mostró alta significancia estadística (P<0.01) para *pv* con *dma* (R=0.968) y *ps* con *h* (R=0.945). Se seleccionó el modelo pv=21.920(1.054)^h para estimar la tabla de rendimiento de biomasa verde por presentar mejores estadísticos de ajuste (R^2_{aj}=0.960, *RCME*=0.095, *CV*=1.688 %, *Cp*=2.002, │*PRESS*│=0.012 y *PRESS*=0.0001). Para el peso seco de fibra se seleccionó el modelo $ps=0.0003(h)^{2.812}$ (R^2_{aj}=0.921, *RCME*=0.164, *CV*=5.708 %, *Cp*=2.004, │*PRESS*│=0.123 y *PRESS*=0.015). Los criterios estadísticos utilizados dieron certidumbre en la selección de los modelos para generar tablas de rendimiento de biomasa y fibra en el área de estudio.

Palabras clave: *Agave lechuguilla* Torr., densidad de plantas, ixtle, lechuguilla, modelo alométrico, tabla de rendimiento de biomasa y fibra.

Biomass and fiber estimation of *Agave lechuguilla* Torr. at north of *Zacatecas* State

Introduction

An economic activity carried out by the inhabitants of arid and semi-arid areas of Mexico is the use of natural resources, which provide raw materials, goods and additional services to satisfy their needs (Martínez, 2013). Non-woody products are known as non-timber forest resources, which would be, for example, lichens, mosses, fungi, resins, gums, seeds, fibers, waxes, rhizomes, leaves, stalks, stems; including also the soils of many wild lands; their harvest amounts to 32% of the country's production (Chandrasekharan *et al.*, 1996; Martínez, 2013). Of the 2 200 non-timber species, 450 are considered useful, 100 of them are marketed under official control and 25 are for commercial, domestic and regional use, however, changing market conditions influence their demand (Chandrasekharan *et al.*, 1996; Tapia-Tapia y Reyes-Chilpa, 2008; Semarnat, 2018).

The species of the *Agave genus* are relevant since they provide socioeconomic and agroecological benefits to the inhabitants of rural areas and to the environment where they grow; *Agave lechuguilla* Torr. in particular, is a plant from which a tight cone formed by the young leaves covered by the older ones located in the center of the plant is obtained, commonly known as the bud (Figure 1); there, high fiber contents are taken by cutting and carving or by manual-mechanical pulping where the parenchyma of the leaves is extracted (Martínez, 2013). This activity represents an important source of income and in many cases, the only one (Mayorga-Hernández *et al*., 2004). The lack of management plans has caused the decline of the natural populations of *A. lechuguilla*, mainly due to the type of harvest that is practiced, which does not consider the replacement of individuals and that, in general, plants of all sizes are extracted, which misleads the use of this natural resource (Semarnat, 1996; Mayorga-Hernández *et al*., 2004).

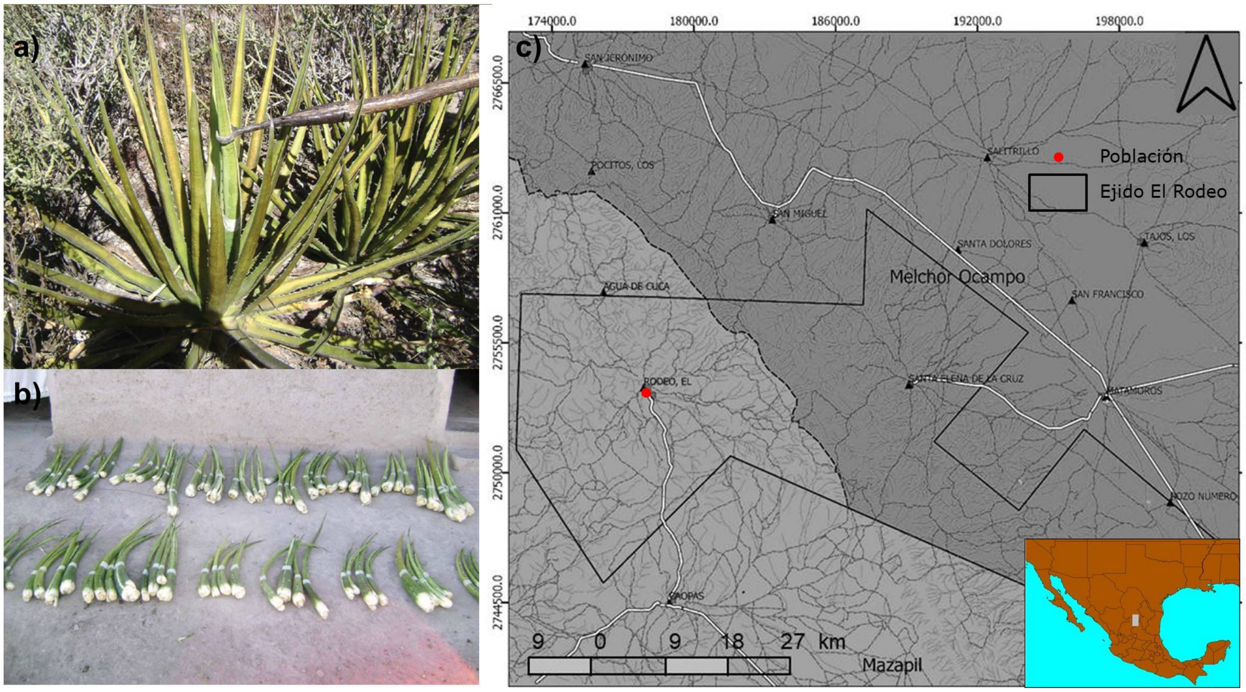


Figure 1. a) *Agave lechuguilla* Torr. plant. to the bud center; b) Storage yard; c) Location of the study area in the *El Rodeo ejido*, *Mazapil* municipality, *Zacatecas* State.

In Mexico, *A. lechuguilla* is distributed in the states of *Chihuahua*, *Coahuila*, *Nuevo León*, *Tamaulipas*, *Durango*, *Zacatecas*, *San Luis Potosí*, *Hidalgo* and *Oaxaca* (Sagarpa, 2009; Martínez, 2013). There are few studies to estimate the biomass and fiber production potential of the species, which can be known through statistical methodologies such as the evaluation of allometric models through regression. These models are fed with data from the field measurement of morphometric variables recommended in current regulations (Semarnat, 1996).

For the use of this type of species, the regulatory entity requests, previously, a technical study to have information on the real stocks of the natural population and then a use plan must be defined (Semarnat, 1996; Semarnat, 2018; Cano *et al*., 2005; Velasco *et al*., 2009; Martínez, 2013). This is useful to generate biomass and fiber yield tables for *A. lechuguilla*, because it is a tool that supports the description and conservation of the resource in arid and semi-arid zones (Cano *et al*., 2005; Velasco *et al*., 2009).

The objective of this study was to adjust models to predict the green weight (biomass) and dry weight (fiber) of *Agave lechuguilla* and, based on the selection of the best ones, develop performance tables that use morphometric variables that are easy to measure in wild populations. in the north of *Zacatecas*.

Materials and methods

Study area

The research was carried out in 2020 in the *El Rodeo ejido*, *Mazapil* municipality, located north of the state of *Zacatecas*, Mexico. Important natural populations of *A. lechuguilla* are found in this area. It is located between 23º08'00" North and 101º07'00" West (Figure 1), at an average altitude of 2 200 m (Conabio, 2014), with an area of 10 317.553 ha.

In order to cover the total variation of biological development of the plants and to know the fiber productivity due to altitudinal oscillations of the terrain and sampling sites, areas close to being exploited and also those that are not customary to harvest were considered (Semarnat, 1996).

Sampling design and assessed variables

For data collection in the field, 74 points were used as sampling units or sites (n=74), spaced at a distance of 100 m between them, randomly distributed. Starting from the center of the site, two axes were drawn, one north-south and the other east-west, which resulted in four quadrants centered on a point (Bonham, 2013; González *et al.*, 2022). There, measurements were taken of one plant per quadrant (the closest one) with usable characteristics, such as that they had not been harvested in previous years, that they were free of biological and mechanical damage. In addition, the current forest legislation was applied and those specimens whose minimum length or height of the top was 25 cm were collected (Berlanga *et al*., 1992; Semarnat, 1996; Velasco *et al*., 2009).

In each of the quadrats derived from each sampling point and aided by a tape measure 700 model MBZ®, the distance from the point to the closest plant (m) was taken, which was a total of 296 measured plants (r=296). To estimate the density of *lechuguilla* plants ha^{-1} (d) the unbiased estimators (1) and (2) were used (Bonham, 2013).

$$d = \frac{4(4n-1)}{\pi \sum_{i=1}^{n} \sum_{j=1}^{4} r_{ij}^{2}} \qquad (1)$$

$$s^2(d) = \frac{d^2}{4n-2} \qquad (2)$$

Where:

d = Estimator of plant density

n = Number of sampling points

r_{ij} = Individual distances in each quadrant

π = Value of pi (3.14159)

$s^2(d)$ = Variance of plant density

The confidence interval for the density (d) was determined by the expression:

$$d \pm \sqrt{(s^2(d)} \qquad (3)$$

Where:

$\sqrt{s^2(d)}$ = Square root of the variance of the density

The morphometric variables measured in each *A. lechuguilla* plant were the minor diameter (*dme*, cm) or bud base, which was measured with a tape measure after cutting the basal part of the plant. The greatest aerial diameter (*dma*, cm), which was obtained by putting a wooden ruler graduated in cm 5010 model Arly® over the widest part of the aerial cover of the plant. The height of the shoot (*h*, cm) was measured from the base to the tip of each of the leaves; the curved ones were fitted with a tape measure lengthwise.

Each bud was individually labeled to keep an orderly control and easy identification. The sample of collected specimens was transported to storage yards to obtain the green weight of the individual bud (*pv*, g) with a Torrey L-EQ 5/10 model digital scale 20 kg capacity. The dry weight of the fiber (*ps*, g) of each bud was determined after manual carving, labeling and direct exposure to the sun for 3 to 5 hours; to record the weight, the criteria that there was no moisture to the touch was applied. A SPX model portable scale with a 180×190 mm diameter plate and 2 000 g×0.01 g precision capacity was used.

Statistic analysis

The sample mean and intervals ($\bar{X} \pm s$), *s* the standard deviation, as well as the minimum and maximum values of each morphometric variable were calculated from the 296 individuals collected. In addition, the data normality test was performed with the Shapiro-Wilk W statistic in Excel® (Zar, 1999).

In order to know the linear relationship between the measured variables, the simple correlation coefficient (*R*) was estimated in Excel® (Pearson, $P<0.01$) for the pairs of variables in the data matrix (Zar, 1999). The associations of *pv* (g) and *ps* (g) with respect to *dme* (cm), *dma* (cm) and *h* (cm) were mainly considered, the highest value was selected to organize the information in ranges (Zar, 1999; Walpole *et al.*, 2012).

To predict biomass production in terms of *pv* and fiber yield given by *ps*, the regression adjustment of 18 linear and non-linear allometric models (9 for each dependent variable) was evaluated (Table 1), the method of least squares in Excel® was applied; for this end, the variables best correlated with the *pv* (g) and *ps* (g) were used. For the selection of the best models, the following criteria were used: Probability of committing the Type I Error ($P<0.01$) in the regression, the highest value of the adjusted coefficient of determination (R^2_{aj}), minimum values for the root of the Mean Square of the Error (*RCME*), Coefficient of Variation (*CV*), *Cp* Mallows statistic (*Cp*), absolute value of the prediction sum of squares ($|PRESS|$), and prediction sum of squares (*PRESS*) (Zar, 1999; Walpole *et al.*, 2012). Subsequently, the Breusch-Pagan (*BP*) test ($P<0.01$) for homoscedasticity was applied (Breusch and Pagan, 1979; Maldonado-Ortiz *et al*., 2022). It was sought that the model used included within its confidence bands (99 %) all the observations organized in intervals for new values of *pv* (g) and *ps* (g), respectively (Semarnat, 1996; Zar, 1999; Walpole *et al*., 2012).

Table 1. Tested models to estimate biomass yield *pv* (g) and fiber *ps* (g) of *Agave lechuguilla* Torr.

No.	Model	No.	Model
1	$pv=a+b(dme)$	10	$ps=a+b(dme)$
2	$pv=a+b(dma)$	11	$ps=a+b(dma)$
3	$pv=a+b(h)$	12	$ps=a+b(h)$
4	$pv=ab^{dme}$	13	$ps=ab^{dme}$
5	$pv=ab^{dma}$	14	$ps=ab^{dma}$
6	$pv=ab^{h}$	15	$ps=ab^{h}$
7	$pv=a(dme)^{b}$	16	$ps=a(dme)^{b}$
8	$pv=a(dma)^{b}$	17	$ps=a(dma)^{b}$
9	$pv=ah^{b}$	18	$ps=ah^{b}$

pv = Green weight of the bud (g); *ps* = Dry weight of the fiber (g); *a* and *b* = Estimators of the regression parameters; *dme* = Minor diameter (cm); *dma* = Major aerial diameter (cm); *h* = Bud height (cm).

Once the two regression models were selected (Table 1), a green biomass yield table for *pv* (g) and fiber for *ps* (g), respectively, was estimated.

Results and Discussion

Statistical analysis of the information

The average density of *A. lechuguilla* was 2 149±126 usable plants ha^{-1}, with an interval of 2 023-2 275 plants ha^{-1}, limits given by the unbiased estimators (1) and (2) of the quadrant sampling method centered on a point made in the field (Bonham, 2013) and that are only applicable to the study area.

The data analysis of *A. lechuguilla* resulted in the statistics presented in Table 2. The mean *pv* was 287.2±118.8 g bud^{-1}; for *ps* it was 19.1±10.0 g, which represented a yield of 6.65 % fiber, similar to that recorded by Berlanga *et al*. (1992) and Martínez (2013). It should be considered that the study areas were different, so the performance figures may differ. On the other hand, the morphometric variables *dme* (cm), *dma* (cm), *h* (cm), *pv* (g) and *ps* (g) showed a normal distribution *(W>P*) (Table 2).

Table 2. Data exploration analysis for the morphometric variables of *Agave lechuguilla* Torr.

Estimators	**Variables**				
	dme	***dma***	***h***	***pv***	***ps***
Mean	4.8±1.1	114.8±34.4	48.2±9.9	287.2±118.8	19.1±10.0
Minimum	2.3	36.8	27.0	81.0	4.0
Maximum	7.5	215.0	82.0	666.0	54.0
W>P	0.1373	0.6179	0.2666	0.3904	0.5815

dme = Minor diameter (cm); *dma* = Greatest aerial diameter (cm); *h* = Height of the bud (cm); *pv* = Green weight (g); *ps* = Dry weight (g); *W* = Shapiro-Wilk statistic.

Correlation between morphometric variables

The correlation between the variables (Table 3) was estimated with the averages of the 296 *A. lechuguilla* plants. It was determined that the linear relationship between pairs of variables was statistically significant at 99 % (P<0.01). Attention was focused on *pv* (g) and *ps* (g) as dependent variables with the morphometric variables; the highest values, with a positive and significant relationship (P<0.01), were for *pv* and *dma* (R=0.968), as well as *ps* and *h* (R=0.945), the intervals were ordered from 35-215 cm for *dma* and from 30–65 cm for *h*.

Table 3. Linear correlation coefficients (R) between the morphometric variables of *Agave lechuguilla* Torr.

	dme	***dma***	***h***	***pv***	***ps***
dme					
dma	0.878**				
h	0.936**	0.967**			
pv	0.895**	0.968**	0.952**		
ps	0.904**	0.919**	0.945**	0.965**	

dme = Minor diameter (cm); *dma* = Greatest aerial diameter (cm); *h* = Height of the bud (cm); *pv* = Green weight (g); *ps* = Dry weight (g); **P<0.01.

Table estimation of biomass yield of *pv* (g) and fiber *ps* (g) for *Agave lechuguilla* Torr.

The evaluation of the fitted models to estimate the biomass and fiber production of *A. lechuguilla* is shown in Table 4. The values of the regression estimators *a* and *b* are presented as exponential for the non-linear models of *pv* (4-6) and *ps* (13–15); only for a in *pv* (7-9) and *ps* (16-18) the selection criteria are shown in Table 5. The best were the non-linear ones for green biomass, $pv=21.920(1.054)^{h}$ (model 6, Table 1) and for fiber, $ps=0.0003(h)^{2.812}$ (model 18, Table 1), respectively. The choice of models was similar to what has been done for studies in other areas with the same species (Berlanga *et al.*, 1992; Pando *et al.*, 2004). They complied with homoscedasticity ($P>0.01$), that is, the selected models did not have the heteroscedasticity problem (Breusch and Pagan, 1979; Maldonado-Ortiz *et al.,* 2022). For the selected models, tables of biomass production *pv* (g) and fiber yield *ps* (g) were generated, respectively (Table 6); in addition, the confidence intervals (99 %) for the data are displayed (Figure 2), which gives the possibility of making estimates within the observed range of the data for the study area.

Table 4. Analysis of variance for the biomass models of *pv* (g) and fiber *ps* (g) for *Agave lechuguilla* Torr.

Model	*a*	*b*	*sa*	*sb*	*Pa*<0.01	*Pb*<0.01
1	-355.969	139.848	81.675	16.904	**	**

2	24.242	2.282	19.613	0.144	NS	**
3	-366.712	13.918	53.371	1.080	**	**
4	21.276	1.719	0.214	0.044	**	**
5	99.790	1.008	0.082	0.0005	**	**
6	21.920	1.054	0.124	0.002	**	**
7	8.334	2.279	0.326	0.209	**	**
8	4.042	0.899	0.214	0.045	**	**
9	0.320	2.351	0.470	0.121	**	**
10	-24.765	9.363	5.189	1.074	**	**
11	1.841	0.144	2.040	0.014	NS	**
12	-24.672	0.915	3.805	0.077	**	**
13	0.783	1.919	0.284	0.058	NS	**
14	5.528	1.009	0.168	0.001	**	**
15	0.881	1.063	0.256	0.005	NS	**
16	0.231	2.800	0.365	0.235	**	**
17	0.124	1.048	0.442	0.093	**	**
18	0.0003	2.812	0.749	0.194	**	**

sa = Standard error for *a*; *sb* = Standard error for *b*; ***Pa*<0.01; ***Pb*<0.01; NS = Non-significant.

Table 5. Regression models adjusted for the variables *pv* and *ps* based on morphometric variables of *Agave lechuguilla* Torr.

Model	*P*<0.01	R^2_{aj}	*RCME*	*CV (%)*	*Cp*	|*PRESS*|	*PRESS*	*BP*<0.01
1	**	0.789	59.896	19.315	599.919	48.445	2 346.959	NS
2	**	0.933	33.773	10.891	192.108	5.697	32.459	**
3	**	0.902	40.933	13.200	281.246	29.112	847.483	NS
4	**	0.892	0.158	2.780	2.004	0.049	0.0020	**
5	**	0.913	0.141	2.495	2.003	0.114	0.0130	NS

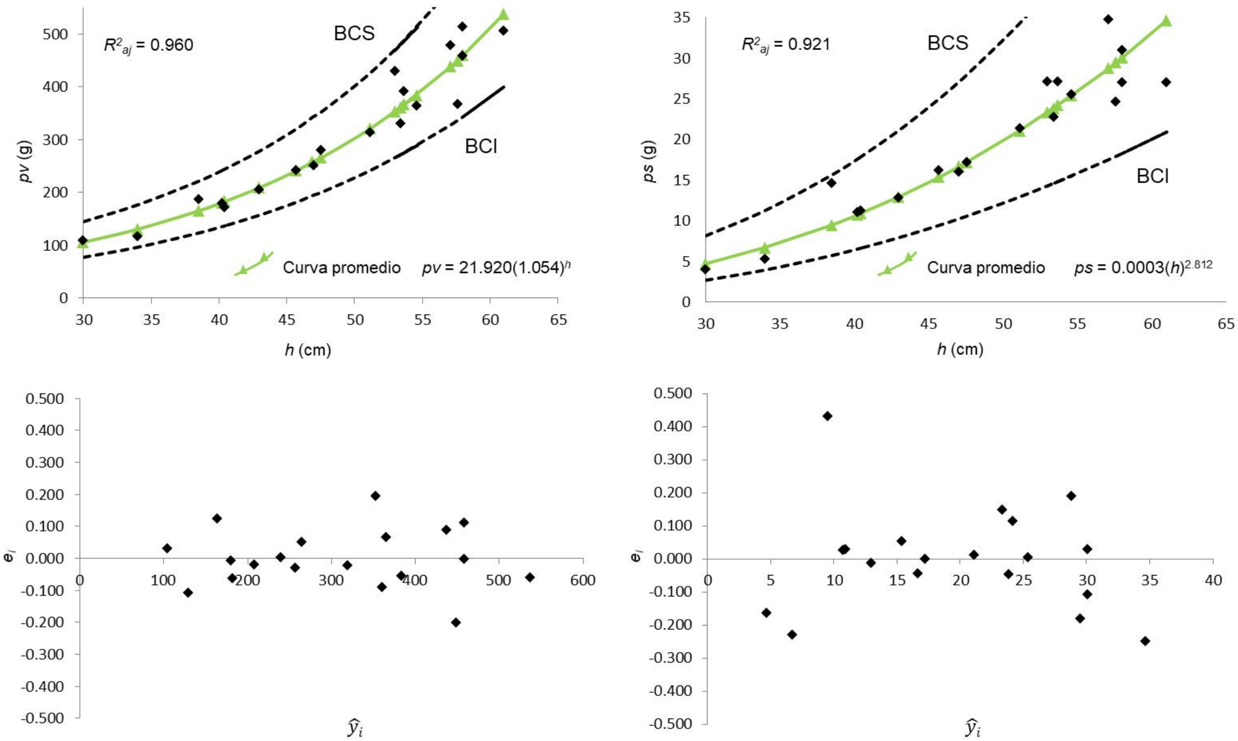
6	**	0.960	0.095	1.688	2.002	0.012	0.0001	NS
7	**	0.867	0.173	3.087	2.005	0.176	0.0310	NS
8	**	0.957	0.100	1.762	2.002	0.017	0.0003	NS
9	**	0.954	0.100	1.816	2.002	0.065	0.0040	NS
10	**	0.806	3.805	19.191	4.413	1.167	1.3620	NS
11	**	0.835	3.514	17.720	4.057	1.990	3.9580	NS
12	**	0.886	2.918	14.717	3.419	0.199	0.0390	NS
13	**	0.871	0.207	7.288	2.007	0.121	0.0150	NS
14	**	0.751	0.290	10.138	2.014	0.244	0.0590	NS
15	**	0.885	0.197	6.879	2.006	0.180	0.0320	NS
16	**	0.887	0.195	6.832	2.006	0.029	0.0010	NS
17	**	0.875	0.205	7.187	2.007	0.147	0.0220	NS
18	**	0.921	0.164	5.708	2.004	0.123	0.0150	NS

**$P<0.01$ in regression; **$BP<0.01$; NS = Non-significant.

Table 6. Yield tables for green biomass (g) and dry fiber (g) for *Agave lechuguilla* Torr. depending on the bud height (*h*).

***h* (cm)**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**
Green biomass (*pv*, g)	106.18	138.12	179.66	233.70	303.99	395.43	514.37	669.08
Dry fiber (*ps*, g)	4.27	6.59	9.59	13.36	17.97	23.49	30.01	37.58

h = Bud height (cm); *pv* = Green weight (g); *ps* = Dry weight (g).



BCI = Lower confidence band; *BCS* = Upper confidence band; *h* = Shoot height (cm); *pv* = Green weight (g); *ps* = Dry weight (g); e_i = Residual (y_i - $\hat{y}_i$); $\hat{y}_i$ = *i*-th estimated value of *y* (*pv* or *ps*).

Figure 2. Average curve, bands that reproduce the confidence intervals (P<0.01) and residual graphs for the selected models.

Conclusions

The morphometric variable height of the shoot (*h*) measured in wild populations of *A. lechuguilla* to the north of *Zacatecas* allowed to estimate the green biomass yield of the shoot (g) in terms of green weight (*pv*, g), as well as the fiber yield in terms of their respective dry weight (*ps*, g) using regression equations. For the first case the function $pv=21.920(1.054)^h$ was selected and in the second the expression $ps=0.0003(h)^{2.812}$, respectively. The statistical criteria used gave certainty in the selection of the best model for each variable of interest. Green biomass production and fiber yield tables were generated, which make up quantitative work tools that will contribute to the development of management plans for the species in areas with ecological-environmental characteristics similar to those studied.

Conflict of interest

The authors state no conflict of interests.

Contribution by author

Héctor Darío González López and Dino Ulises González Uribe: research planning and development, field sampling, data capture, data analysis and exploration, writing and review of the manuscript structure.

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