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Article

Generation of new equations to estimate aerial biomass based on morphological variables obtained from grasses in rangelands of Nuevo León, Mexico

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Abstract:

The estimation of aerial biomass of grasses contributes to carrying out efficient and sustainable management of rangelands. This study aimed to generate new equations to estimate the aerial biomass of grasses present in rangelands in Nuevo León, Mexico, based on data collected from the total number (n= 745) of individuals of the five species of grasses: *Cenchrus ciliaris* Linnaeus, *Pappophorum bicolor* Fourn, *Aristida purpurea* Nutt, *Tridens texanus* Watson and *Paspalum pubiflorum* Fourn present in the sampling plots. Using the maximum height and the height of the vegetative stems, the aerial, basal, and compressed diameters, and volumes measured in each of the collected individuals, linear (stepwise) and nonlinear equations were generated to estimate the aerial biomass (dry matter basis) of the grasses cut at ground level. Six general equations with the best statistical fit for the total species collected were selected. General equation III had the best values of R^2 =0.88 and AIC =3079, using the five variables evaluated. General equation IV had an R^2 =0.86 and AIC =3530, using only the variable compressed diameter. The selected specific equations estimated the aerial biomass of the grasses *Cenchrus ciliaris* (R^2=0.88, r=0.94), *Pappophorum bicolor* (R^2 =0.86, r =0.92), *Aristida purpurea* (R^2=0.92, r=0.96), *Tridens texanus* (R^2 =0.91, r =0.96), and *Paspalum pubiflorum* (R^2 =0.93, r = 0.97). The new equations are a reliable alternative to indirectly estimate the aerial biomass of the grasses of the rangelands of northeastern Mexico in a faster and less expensive manner than the traditional method.

Keywords: Allometric equations, *Cenchrus ciliaris*, Native grasses, Compressed diameter.

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Introduction

The rangelands distributed around the world cover more than 50 % of the earth's surface and provide biomass that supplies a fundamental ecosystem service on which wildlife, population, and livestock farming, the main economic activity in this ecosystem, depend(1,2). In the last century, rangelands have suffered degradation due to episodes of drought and overgrazing due to an excessive stocking rate(3,4), due to failures in efficient and sustainable use of the rangeland to cover the forage biomass requirements of the cattle herd(5). Therefore, it is essential to have reliable estimates of the amount of forage available for cattle that allow the proper use of forage, avoidance of overgrazing, and the satisfaction of the needs of animals(6,7).

The traditional method for estimating aerial biomass production is that of cutting and weighing grass; although this destructive method is accurate, it is usually expensive and time-consuming(8,9). In addition, the random distribution of vegetation makes it necessary to increase the recommended number of samples per site (15-20 samples(10)), ideally collected at each forage growing season(8).

Indirect methods (non-destructive, since they do not require cutting the grass present) arise as an alternative to the traditional one (destructive, which involves cutting and weighing the grass present) to determine the aerial biomass of forage in the rangeland since they have the advantage of achieving estimates of the biomass of large areas in a faster way[11,12]. Subjective empirical methods of visual estimation have the disadvantage of a high variation in results among people who perform them in different periods of time[13]. Graduated plates or sticks have been used in recent decades to estimate forage biomass in meadows with homogeneous vegetation[14,15]. New methodologies for biomass estimation have been developed through the use of satellite images[16], radar images[17], and unmanned vehicles[18]; however, these are mainly carried out in cultivated areas.

The rangelands have different types of vegetation with heterogeneous distribution. For example, in the Tamaulipan thornscrub (TTS), shrub and semi-shrub species predominate, sometimes constituting more than 80 % of the botanical composition, while grass species and other weeds hardly exceed 10 and 6 %, respectively[19,20]. Under these conditions, allometric models developed by relating the biomass production data obtained from the traditional method with the measurements made in morphological characteristics of the individual are a good option to estimate the biomass of grasses objectively. Once the model is generated, biomass estimation can only be done by measuring the necessary vegetative variables, without the need to cut the plants[5,9].

Studies prior to this work have been conducted in meadows under irrigated and monoculture conditions[15,21,22]. For rangeland conditions, results obtained under arid conditions in Arizona[23] and multispecies conditions in Argentina[9] have been published. There are reports of equations generated specifically for estimating the biomass of certain grass species, such as those reported based on 40 plants from *C. ciliaris* grass meadows in southern Arizona, relating biomass with basal diameter and plant height[24], as well as equations generated for *A. purpurea* in a previous study[25], using the diameter of the plant at different heights as variables.

In Europe, an indirect estimation methodology was developed for grass species[21], which used a measure called minimum volume, obtained by joining all the stems of the plant by applying a subjective, non-standardized force to form a minimum volume.

The present study aimed to generate new equations to estimate the aerial biomass of five species of grasses present in the rangelands of Nuevo León, Mexico, based on the measurement of their morphological variables, which could serve as an alternative to replace the need to cut grass as in the traditional method.

Material and methods

The study was conducted in an area of 132 ha of rangelands in the municipality of Marín, Nuevo León (25°52'28"N; 100°03'24"W), in which precipitation varies between 400 and 600 mm per year, and the average temperature ranges from 20 to 22 °C[26]. The primary vegetation type is Tamaulipan thornscrub (TTS), in addition to having areas of induced grassland and agriculture.

In January 2021, 31 sampling plots of 100 square meters (10 m x 10 m) were randomly established within the study area with vegetation typical of the Tamaulipan thornscrub, and five 1 m^2 subplots were delimited within each plot, in which was collected and weighed (dry matter basis) all the individuals of grasses present in each of the 155 subplots evaluated, in a design similar to that previously used in areas of rangeland[27]. A perimeter fence was placed around each plot to prevent disturbances. All plots were cut at 3 to 5 cm height at the beginning of the study and in each sampling. The first sampling was conducted from June 15 to July 15, 2021, and the second was conducted in the autumn from October 18 to November 8, 2021. In both cases, the sampling was carried out 30 to 40 d after a rainfall greater than 150 mm (in the first sampling) and 231 mm (in the case of the second sampling) since, according to previous studies[28], the flowering of the *Cenchrus ciliaris* grass occurs between 25 and 35 d after regrowth as a result of precipitation of 150 mm, which is considered as the threshold for the productivity of the species *Cenchrus ciliaris*[29] during the summer and autumn.

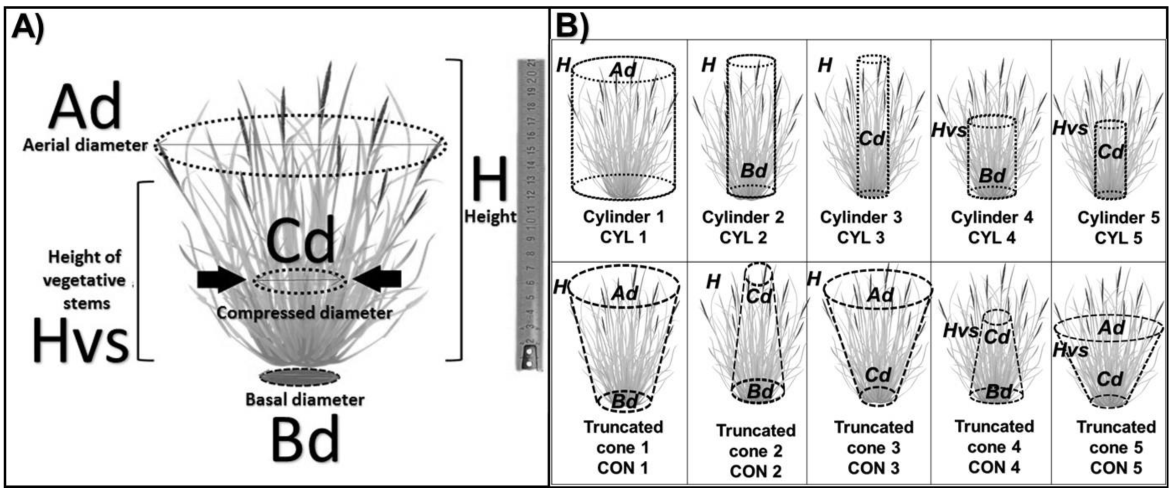
In each subplot, all plants of the grass species present were sampled and identified individually at the genus and species level. A Truper® pro-Lock FX-5M tape measure was used to measure the variables described below and shown in Figure 1A:

1. Maximum height (H): distance between the ground and the highest part of the stems and leaves.
2. Height of the vegetative stem (Hvs): distance between the ground and most vegetative leaves, usually those without a spike.
3. Basal diameter (Bd): of the circumference of the base of the plant.
4. Aerial diameter (Ad): at the height of the vegetative stems.
5. Using Traceable® model 6″ digital calipers, the compressed diameter (Cd, Figure 1) was measured at half the height of the grass using an experimental prototype that, through a retractable band, applies a graduated uniform pressure of 2 kg on the vegetative stems.
6. Using the morphological variables of Figure 1A, circular aerial cover (CACOV), ellipsoidal aerial cover (EACOV), circular basal cover (CBCOV), and ellipsoidal basal cover (EBCOV) were calculated. The volumes of the cylinder (in its CYL1 to CYL5 modalities)

and cone (in CON1 to CON5 modalities), indicated in Figure 1B, were based on previous proposals[30].

Each of the 745 plants sampled was identified, measured, and cut with hand scissors at ground level to record its fresh weight (g) in the field and stored in a Kraft paper bag. Subsequently, the samples were taken to the laboratory and dried in a forced air oven at 60 °C until reaching a constant weight in order to obtain their dry weight (g) by using a scale with a capacity of 500 g with a minimum division of 0.1 g (Torrey brand, model Lab-500).

Figure 1: Variables measured in grass plants (A) and shapes of estimated volumes (B)



H= height ; Hvs= height of vegetative stems ; Bd= basal diameter; Cd= compressed diameter; Ad= aerial diameter.

The 745 individuals found in the sampling subplots were identified, measured, and cut. The plants of the five grass species present in the study area: *Cenchrus ciliaris* (n= 424 individuals), *Pappophorum bicolor* (n= 125 individuals), *Aristida purpurea* (n= 107 individuals), *Tridens texanus* (n= 59 individuals) and *Paspalum pubiflorum* (n= 30 individuals) were collected for the generation of equations.

A total of 19 independent variables (aerial diameter, basal diameter, compressed diameter, height, vegetative stem height, circular basal cover, elliptical basal cover, circular aerial cover, elliptical aerial cover, volume of cylinder 1, volume of cylinder 2, volume of cylinder 3, volume of cylinder 4, volume of cylinder 5, volume of cone 1, volume of cone 2, volume of cone 3, volume of cone 4, volume of cone 5) and a dependent variable (measured biomass [g DM] per individual of the grass species) were subjected to linear regression, stepwise regression[9] and nonlinear regression (logarithmic, inverse, quadratic, cubic, power, exponential) analysis in the IBM SPSS software to generate biomass prediction equations both generally and specifically (for each of the five grass species found in the samplings).

To assess the quality of the biomass estimate achieved with the new general and specific equations, each of the values recorded in the destructive sampling was compared with the predicted values of each of the equations. The coefficient of determination of the regression (R^2)[27], the standard error (SE)[30]), Pearson's correlation (r)[18], the normalized root mean squared error (NRMSE)[21], and the Akaike information criterion (AIC)[27] were calculated.

The six general equations developed with the best statistical fits of AIC, NRMSE, R^2, SE, and r were selected to estimate the total species collected, and a specific equation was selected for each of the five recorded grass species.

Results

The grasses *Cenchrus ciliaris* and *Paspalum pubiflorum* presented values of aerial and basal cover, aerial and basal diameter, and fresh and dry weight (P<0.05) higher than the rest of the species (Table 1). *Cenchrus ciliaris* recorded an average value of dry weight per individual higher than that of *Aristida purpurea* and *Tridens texanus* (P<0.05), while *Paspalum pubiflorum* and *Pappophorum bicolor* obtained intermediate values.

The estimates of aerial biomass calculated with the six new general equations generated in the present study had coefficients of determination (R^2) that varied between 0.77 and 0.90, while Pearson's correlation coefficient (r) ranged from 0.88 to 0.94. The normalized root mean squared error (NRMSE) ranged from 0.68 to 0.48, and the Akaike information criterion (AIC) took values from 3553 to 3079 (Table 2).

Table 1: Average values of aerial cover, basal cover, aerial diameter, basal diameter, compressed diameter, maximum height, height of vegetative stems, fresh weight, and dry weight per individual of each species in 1 m^2 experimental subplots

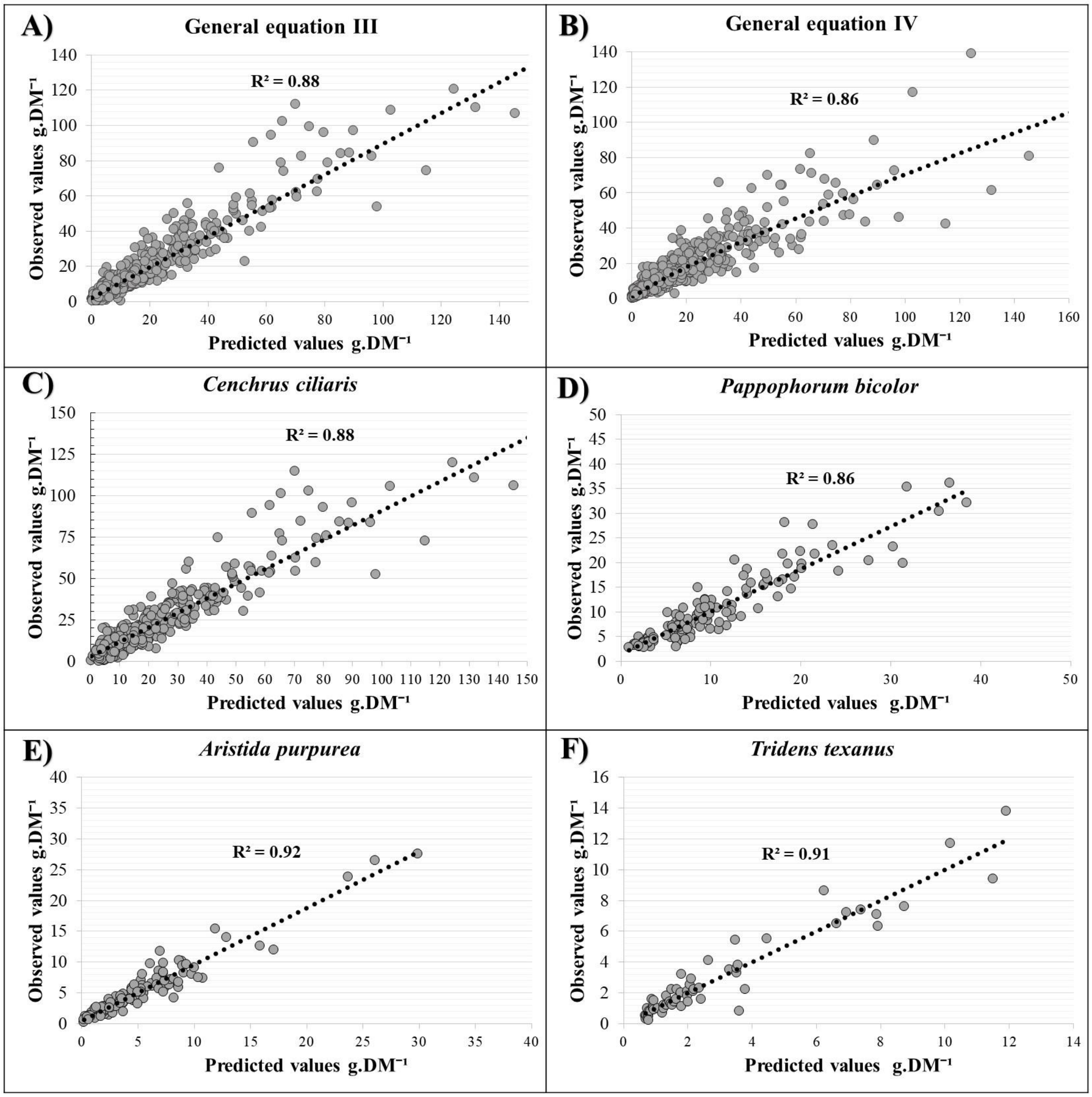
Species	Cover		Diameter			Height		Weight	
	AER (cm^2)	Basal (cm^2)	AER (cm)	Basal (cm)	Compressed (mm)	MAX (cm)	Vegetative stems (cm)	Fresh (g)	Dry (g)
Cenchrus ciliaris	729[ab]	190[a]	28[a]	14[a]	19[a]	52[a]	27[a]	53[a]	22[a]
Pappophorum bicolor	355[bc]	52[bc]	20[bc]	8[bc]	13[abc]	52[a]	23[ab]	15[bcd]	10[ab]
Aristida purpurea	277[bc]	29[c]	17[cd]	6[c]	9[bcd]	45[ab]	20[bc]	7[cd]	5[b]
Tridens texanus	208[c]	37[bc]	16[cd]	6[c]	6[d]	34[cd]	16[c]	5[d]	3[b]
Paspalum pubiflorum	799[a]	104[abc]	30[a]	11[ab]	13[ab]	40[bc]	23[ab]	48[ab]	13a[b]

AER= aerial; MAX= maximum.

[abcd] Different letters within the same column indicate a significant difference (P<0.05).

Equation I is a linear model that incorporates the measurement of cone 5 (Figure 1B), which is calculated based on three direct variables (aerial diameter, compressed diameter, and height of the vegetative stems), and whose estimates have an R^2 of 0.77, r=0.88, NRMSE=0.64, AIC=3469. The estimates calculated with equation II (linear) from the data generated by the variables aerial diameter, compressed diameter, height, and height of the vegetative stems have an R^2 of 0.87, r= 0.93, NRMSE= 0.49, and AIC= 3108. Equation III (linear) incorporates the data of the five measured variables to calculate estimates that have an R^2 of 0.88, r= 0.94, NRMSE= 0.48, AIC= 3079 (Figure 2A).

Figure 2: Regression of predicted values and observed values



A) General equation III (Table 2). **B)** General equation IV (compressed diameter). **C)** Specific equation for *Cenchrus ciliaris*. **D)** Specific equation for *Pappophorum bicolor* (Table 2). **E)** Specific equation of *Aristida purpurea*. **F)** Specific equation of *Tridens texanus* (Table 2). All graphs were set to zero.

Nonlinear equations IV (R^2= 0.86, r= 0.88, NRMSE= 0.67, AIC= 3530; Figure 2B), V (R^2= 0.89, r= 0.88, NRMSE= 0.68, AIC= 3553) and VI (0.90, r= 0.88, NRMSE= 0.67, AIC= 3530) are from the power model and use fewer variables. The estimates calculated using equation IV, which uses the compressed diameter as the only variable, have an R^2=0.86 (Figure 2B). Equation V uses cylinder 3, calculated from the compressed diameter and height of the plant, to estimate aerial grass biomass with R^2=0.89. Equation VI uses cylinder 5 (Figure 1B), calculated from the compressed diameter and height of the vegetative stems, to estimate aerial biomass with R^2= 0.90 (Table 2).

In the case of equations generated specifically for each of the grass species, comparisons between the estimated values and the results recorded directly from aerial biomass yielded R^2 values from 0.86 to 0.93. The values of r (Pearson) ranged from 0.92 to 0.97. For NRMSE, values from 0.40 to 0.24 were recorded, and AIC took values from 1603 to -18 (Table 2). In the specific case of the equation generated for *Cenchrus ciliaris*, a good fit of the estimated values of aerial biomass was achieved, with R^2 of 0.88, r= 0.94, NRMSE= 0.40, AIC= 1603, using the five variables measured (Figure 2C).

The results estimated using the five variables with the specific equation for the species *Pappophorum bicolor* (Table 2) had a fit of (R^2= 0.86, r =0.92, NRMSE= 0.29, AIC= 287) (Figure 2D).

The information collected from 107 individuals of *Aristida purpurea* allowed the generation of a specific equation for this grass species (Table 2), whose estimates, based on the five variables measured, had a fit with a coefficient of determination of 0.92, r=0.96, NRMSE= 0.27, AIC= 87. (Figure 2E).

Table 2: General and specific allometric equations generated based on morphological variables to indirectly estimate the aerial biomass of grasses (g DM^{-1})

Id	Equation	R^2	SE	r	NRMSE	AIC
General equations						
I	$Y= 0.9648 + 0.0026CON5$	0.77	10.1	0.88	0.64	3469
II	$Y= 2.5343 + 0.0027CON5 + 0.0139CYL3 - 0.0295CACOV +0.8253Cd - 0.2595Hvs + 0.0002CYL1$	0.87	7.8	0.93	0.49	3108
III	$Y= 1.2159 + 0.0032CON5 + 0.0447CYL3 - 0.0421CACOV + 0.8939Cd - 0.3478Hvs + 0.0003CYL1 - 0.0253CON2 + 0.5790Bd + 0.0084CYL2$	0.88	7.5	0.94	0.48	3079
IV	$Y= 0.1213 * Cd^{1.6818}$	0.86	0.4	0.88	0.67	3530
V	$Y= 0.4473 * CYL3^{0.7288}$	0.89	0.4	0.88	0.68	3553
VI	$Y= 0.8084 * CYL5^{0.7078}$	0.90	0.4	0.88	0.67	3530
Specific equations						
C.c.	$Y= 0.2862 + 0.0032CON5 - 0.0753CACOV + 1.4623Cd - 0.0767CON4 + 0.0279CYL4+ 0.0902CBCOV - 0.3257Hvs + 0.0022CYL1- 0.0032CON1 + 0.0931CYL5$	0.88	9.0	0.94	0.40	1603
P.b.	$Y= 2.1060 + 0.0490CYL3 + 0.0050CON4 + 0.0002CON3 - 0.0050EBCOV$	0.86	3.0	0.92	0.29	287

A.p.	*Y= -0.6641 + 0.1138CYL5 + 0.1257Ad + 0.0046CON2 - 0.0816CBCOV + 0.1951Cd*	0.92	1.5	0.96	0.27	87
T.t.	*Y= 0.5474 + (0.1672 * CYL3) + (-0.0012 * CYL3) + (1.18 × 10^{-5} * CYL3)*	0.91	0.9	0.96	0.30	-18
P.p.	*Y= -0.0371 +(0.2744 * CYL3) + (-0.0020 * CYL3) + (6 × 10-6 * CYL3)*	0.93	2.3	0.97	0.24	57

Linear model equations= I, II, III, C.c., P.b., and A.p.; Power model equations= IV, V and VI; Cubic model equations= T.t. and P.p.; Y= Aerial biomass (g DM^{-1}); R^2= Coefficient of determination; SE=Standard error; r= Pearson's correlation coefficient; NRMSE= Normalized root mean squared error; AIC= Akaike Information Criteria; C.c.= *Cenchrus ciliaris*; P.b.= *Pappophorum bicolor*; A.p.= *Aristida purpurea*; T.t.= *Tridens texanus*; P.p.= *Paspalum pubiflorum*. See Figure 1 for Bd, Ad, Cd, H, Hvs, EBCOV, CBCOV, CACOV, CYL1, CYL2, CYL3, CYL4, CYL5, CON1, CON2, CON3, CON4, CON5. All regression coefficients were significant (P<0.05).

The variable cylinder 3, calculated from the height of the plant and the compressed diameter, was the basis for generating the specific equations for *Tridens texanus* and *Paspalum pubiflorum* in the cubic model, whose estimates had a fit of R^2 of 0.91, r=0.96, NRMSE=0.30, AIC=-18 for *Tridens texanus* (Figure 2F) and R^2=0.93, r=0.97, NRMSE=0.24, AIC=57 for *P. pubiflorum*.

Discussion

The linear and polynomial equations generated in the present study based on the sampling of vegetative measurements and biomass weight records of grasses present in the rangeland allowed the estimation of the aerial biomass of grasses present in the rangeland with a high degree of precision.

The new general allometric equations established in the present study had values of R^2 (0.77 to 0.93) higher than those previously reported (R^2 from 0.25 to 0.85) for estimates of general equations for two grasses and two pseudo-grasses in the Peruvian Andes[27]. Allometric equations generated in Chubut, Argentina[23], by evaluating 50 individuals from three species of grasses, had R^2 values (between 0.72 and 0.86) similar to those obtained in the present study.

The number of plots established in the present study was similar to that previously used[27]; however, in the present study, there were plots of 100 m^2, while in the previous study[27], they had plots of 4 m^2. In addition, in each of the 31 plots of the present study, the values of botanical composition, vegetative measurements, and biomass of the grasses present in five subplots were recorded. With this, there was greater reliability of the recorded measurements and the calculated averages for the generation of the equations.

The species *C. ciliaris* had a significant presence in the grass vegetation observed in the rangeland evaluated since it represented 57 % of the total number (n= 745) of individuals collected and its biomass, calculated considering the number of individuals and the average weight of the individuals of the species shown in Table 1, represented 80 % of the biomass recorded in the rangeland evaluated. In the areas assessed in the present study, the *C. ciliaris* grass present was established by natural dispersion, evidencing its high potential to establish itself in the rangelands in Mexico[(31)]. The native species with the highest presence in the present study was *Pappophorum bicolor,* which had a record of 125 individuals, that is, 17 % of the total, whose biomass represented only 11 % of the total biomass (Table 1).

The compressed diameter was the variable included in 100 % of the general allometric equations and in 97 % of the specific equations, both for the linear and nonlinear model, generated in the present study for each grass species. The height of the vegetative stems was included in 87 % of the general equations. The variables vegetative stem height and plant height were included in 71 % of the specific equations. These variables have been directly related to forage density[(32)]. Some authors[(30)] reported that, in meadows with optimal conditions for their development, the variable vegetation cover is the one that can best indirectly estimate the biomass. Mahood *et al*[(22)] determined that vegetation cover is a good predictor for biomass estimation, with an R^2 of up to 0.89 in *Bromus tectorum* plant communities.

An indirect estimation methodology implemented for grass species in Western Europe[(21)] used a measure called minimum volume as a variable, consisting of manually joining all the stems of the plant until forming a minimum volume; nevertheless, the applied force was subjective, varying according to the person performing the measurement and it could even vary when the same person exerts different pressure due to fatigue when repeatedly making the sampling. By applying the same compression force, the compaction device used in the present work generated greater certainty of the results obtained.

The NRMSE values calculated in each of the new equations generated in the present study determine the dispersion of the estimated data with respect to the observed data, with 0 being the ideal fit[(33)]. In contrast, the Akaike criterion compares and selects from a group of prediction models that use the same experimental data the most appropriate to forecast the expected values compared to the observed values, which in this case should be the model with the lowest AIC value[(34,35)]. The values of NRMSE and AIC are very useful in the selection of the best models.

The specific equation generated in the present study for *Cenchrus ciliaris* had a value of R^2=0.87, and with it, an R^2 similar to that reported in a study (R^2 of 0.82[(24)]) to generate allometric equations relating biomass with the measurement of basal diameter and height of 40 plants of *C. ciliaris* grass meadows in southern Arizona. The equation generated in the present study for *A. purpurea* resulted in an R^2= 0.89, similar to those reported (R^2 from 0.82 to 0.90) in a previous study(25), for the species *A. purpurea*, using the diameter of the plant at different heights. Some authors(30) generated equations to estimate aerial biomass from the analysis of 93 plants of *Agropyron desertorum* and reported coefficients of variation (R^2 from 0.76 to 0.88) slightly lower than those of the present study. The new equations generated in this study are potential candidates to replace the cutting, drying, and weighing phases performed in the traditional method(36).

The development of allometric equations with application in rangelands is of utmost importance to achieve sustainable ecosystem management(27). These non-destructive vegetation samplings have advantages in terms of time and budget compared to traditional sampling and also allow growth monitoring at the individual level(21,37).

Conclusions and implications

The importance of 19 variables related to the morphological characteristics of grasses present in the rangeland was evaluated to estimate the production of aerial biomass per plant. This information was used to generate 6 new general equations for five grass species present in the study area and 5 new specific equations (one for each grass species *Cenchrus ciliaris*, *Pappophorum bicolor*, *Aristida purpurea*, *Tridens texanus*, and *Paspalum pubiflorum*), which reliably and practically estimate the production of biomass without destroying (cutting) the plant. The new equations generated in this study are a viable option to replace the cutting phase of the samples in the traditional method of estimating the production of aerial biomass of grasses in the rangeland. The development of general (multispecies) and specific (for a particular grass species) allometric equations is a reliable alternative to indirectly estimate the aerial biomass of the grasses of the rangelands of northeastern Mexico more quickly and less expensively than the traditional method.

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