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PREDICTING BODY WEIGHT THROUGH BIOMETRIC MEASUREMENTS IN BOLIVIAN LLAMAS

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ABSTRACT

The objective of this study was to evaluate the relationship between body weight (BW) and different biometric measurements in llamas (*Lama glama*) from the Bolivian highlands and to generate prediction models of BW. A total of 515 individual records of BW and biometric measurements were used. The measurements were taken on 202 males and 313 females aged between 0.5 and 5 years, and included: neck length (NL), withers height (WH), rump height (RH), heart girth (HG), body length (BL), abdomen circumference (AC), rib depth (RD), hip width (HW), pin bone width (PBW), thoracic width (TW), and back length (BKL). The relationships between BW and biometric measurements were developed using simple linear and multiple regression. For the evaluation, the relationship between the observed and predicted values of BW was determined by linear regression, the mean squared error of prediction (MSEP) and root MSEP (RMSEP); concordance correlation coefficient analysis was also used. The BW ranged from 22 to 122 kg. Regression equations between BW, HG and RD had an r^2 of 0.94 and 0.92, respectively (RMSEP= 6.06 and 6.70 kg, respectively). The equations were highly precise (r^2 >0.86) and accurate (Cb>0.98), with a reproducibility index > 0.92. The model efficiency (MEF) indicated a higher efficiency of prediction (MEF ≥ 0.86). Using a single predictor, HG and RD accounted for more than 92% of the variation in BW. Overall, HG may be used as a single predictor to predict BW in llamas maintained under the conditions of the Bolivian highlands.

Keywords: Body weight, body measurement, heart girth, mathematical models.

INTRODUCTION

The South American camelids are represented by 4 families that include llama (*Lama glama*), alpaca (*Lama pacos*), guanaco (*Lama guanicoe*), and vicuña (*Vicugna vicugna*) (Zarrin et al., 2020). Because of their adaptation to harsh environments and high-altitude conditions, around 63% of the South American llama population is found in the Bolivian highlands (Treydte et al., 2011). The productive objectives of these animals are meat, fibre, work, and manure. Under high altitude conditions, llama productivity is higher than sheep (Wurzinger et al., 2005; Treydte et al., 2011; Canaza-Cayo et al., 2015). In addition, Rodriguez and Quispe (2007) and Treydte et al. (2011) reported on the positive contribution of llama production systems to the environmental protection of fragile ecosystems, such as Bolivian highlands, because these animals cause little damage to the sparse grasslands due to their feeding behaviour without affecting the soil.

Same as other livestock production systems, weight and growth data are of particular importance in llama farms because of their practical implications in improvement plans, genetic characterization, and flock management organization (Wangchuk et al., 2017; Ccora et al., 2019). Body weight (BW) is one of the most accurate measurements to determine the growth at the farm level. However, farmers and breeders do not often have the proper tools (animal weighing scale) under field conditions to take body weight measurements at different time points (Grund et al., 2018). Therefore, it is important to generate an alternative method to estimate BW. In this sense, biometric measurements, which have long been used to indicate animal type or to predict BW (Fisher, 1975), can be useful tools given the low-cost and ease in obtaining data. However, their main limitation is associated with the accuracy of measurements (Bautista-Diaz et al., 2017). Among biometric measurements, heart girth (HG), hip width (HW), body length (BL), withers height (WH) and rump height (RH), have been evaluated for the estimation of BW in different species (Tebug et al., 2016; Grund et al., 2018; Chay-Canul et al., 2019; Ccora et al., 2019).

Among those biometric measurements, heart girth (HG) is highly correlated with BW, being more frequently used on cattle, sheep, and goats to predict BW (Yilmaz et al., 2013; Tebug et al., 2016; Chay-Canul et al., 2019), and recently in alpacas and vicuñas (Grund et al., 2018; Ccora et al., 2019). In llamas, Leyva and Falcon (2007) and Zea et al. (2007) evaluated the hip area, chest circumference, thigh volume and size of the mammary gland, and indicated that these variables can be used as possible indicators for meat production. There are some scientific communications reporting on the relationship between BW and biometric measurements in llamas (Wurzinger et al., 2005; Riek and Gerken, 2007). However, to the best of the authors' knowledge, the evaluation of different biometric measurements to predict BW of llamas under field conditions is scarce. Thus, the objectives of this study are 1) to evaluate the relationships between the llama BW and the biometric information measured at the farm level, and 2) to develop predictive models for BW of Bolivian llamas raised under the Bolivian highlands.

MATERIALS AND METHODS

Location, animals, and handling

The study was conducted in the municipality of Santiago de Machaca, capital of the José Manuel Pando province of the Department of La Paz, Bolivia, located from 3890 to 5219 meters above sea level, between 16º 50′ and 17º 30′ south latitude and 69º 00′ and 69º 30′ western length. Temperatures vary between -14 and 21 ºC and rainfall reaches 180 mm/year.

The llamas used in the experiment were reared on native pastures of *Baccharis incanum*, *B. boliviensis*, *Parastrephia lepidophyla*, *Margiricarpus strictus*, *Festuca dolichophyla*, *F. orthophylla*, *Istipa ichu*, *Bouteloua simplex*, *Bromus unioloides*, *Trifolium amabile*, *Alchenilla pinnata*, *Muhlembergia fastigiata*, *Distichlis humilis*, *Adesmia spinosisima*, and *Hipochoeris taraxacoides* (Merlo et al., 2012).

A database was constructed based on the records of BW and biometric measurements from 515 llamas (*Lama glama*). Animals were classified by sex: 202 males (young: 182 and adults: 20) and 313 females (young: 226 and adults: 87); and age (< 2 years old for young animals and > 2 years old for adult animals (Laime-Huarcaya et al., 2016)). Before grazing, BW (kg) was recorded from each animal using a digital scale (Model EQB, Torrey, Mexico) and jointly to the following biometric measurements: 1) neck length (NL), 2) withers height (WH), 3) rump height (RH), 4) heart girth (HG), 5) body length (BL), 6) abdomen circumference (AC), 7) rib depth (RD); 8) hip width (HW); 9) pin bone width (PBW), 10) thoracic width (TW), and 11) back length (BKL) as described by Ccora *et al*. (2019). The biometric measurements were recorded while the animals were standing and fastened carefully, using a commercial flexible tape fiberglass.

Statistical analysis

Statistical analyses were performed using R software (R Core Team). The effect of sex and age on measured traits was analysed by a linear model using the *lm* function in R software. The means were compared using the Tukey's test, with a significance level of $P < 0.05$. A descriptive statistical analysis was performed using the *describe* function of psych package (Revelle, 2020). Simple regressions models were fitted using the *lm* function in R. To choose the best models, a stepwise selection procedure was carried out using the MASS package (Venables and Ripley, 2002). This procedure adds sequentially the most contributively predictor and removes any variable that no longer provides an improvement in the model fit. In this step of selection model procedure, Akaike information criteria (AIC) and Bayesian information criteria (BIC) were used to assess the goodness of each model. Outliers were tested by plotting the studentized residual against the statistical model-predicted values. Data points were removed if the studentized residual was outside the range of −2.5 to 2.5. The accuracy of the models was evaluated by the determination coefficient (R^2) and means square error (MSE).

Model evaluation

Model adequacy: The precision and the accuracy of models were evaluated based on the recommendations of Tedeschi (2006). For instance, several statistics were used to assess the predictability of the equations, including the coefficients of determination (R^2), standard deviation (SD), mean squared error of prediction (MSEP) and root of the MSEP (RMSEP), to account for the distance between predicted and true values. The mean bias (MB), as described by Cochran and Cox (1957), was used as a representation of the average inaccuracy of the model. The modelling efficiency factor (MEF), which represents the proportion of variation explained by the line Y = X, was used as an indicator of goodness of fit (Loague and Green, 1991; Mayer and Butler, 1993). The coefficient of model determination (CD) was used to assess variance in the predicted data. The bias correction factor (Cb), a component of the concordance correlation coefficient (CCC) (Lin 1989), was used as an indicator of deviation from the identity line, and the CCCs were also used as a reproducibility index to account for accuracy and precision. High accuracy and precision were assumed when the coefficients were > 0.80, and low accuracy and precision were assumed when the coefficients were < 0.50. Finally, all calculations were obtained using the Model Evaluation System (http://nutritionmodels.com/mes.html, last accessed January 1, 2019) (Tedeschi, 2006).

Model validation

The predictive ability of the three live weight prediction models was evaluated using *k*-folds validation (k = 10). This approach involves randomly dividing the set of observation into k non-overlapping folds of approximately equal size. The first fold is treated as a validation set, and the model is fit on the remanding k – 1-fold (training data). The ability of the fitted model in predict out the actual observations was evaluated by the root mean square prediction error (RMSPE), coefficient of determination (R^2) and mean absolute error (MAE). MAE is an alternative to the RMSPE that is less sensitive to outliers. It corresponds to the average absolute difference between the observed and predicted outcomes. The lower the values of RMSPE and MAE means a better model performance (predictivity). The *k*-folds validation was implemented in the *"caret"* package (Kuhn, 2019). This package allows comparing numerous validations of models under a unified framework. Data pre-processing, parameter tuning, cross-validation, and model performance evaluation are available in the users' guide package.

RESULTS

The average, maximum, and minimum values of the BW and all biometric measurements are presented in Table 1. It was observed that the BW ranged from 21.70 to 121.9 kg (39.8% Coefficient of variation, CV). The CV of explanatory variables HG, BL, AC, RD, HW TW and, BKL ranged from 15.61 to 21.35%; whilst CV of NL, WH, RH and, PBW was of 11%.

There were no significant interactions between sex × age on BW and body measurements (P >0.05). Furthermore, sex did not affect BW, while the abdomen circumference and pin bone width were higher in females than in males (P <0.001). However, there was an effect of age on BW and all biometric measurements (Table 2). Adult animals were heavier than young animals (P <0.05) and recorded higher values in the biometric measurements (P <0.05).

After analysis, the data from 16 young females were removed from the analyses due to the studentized residual was outside the range of −2.5 to 2.5. Although, all biometric measurements were positively correlated with BW (P < 0.001). The WH, RH, HG, BL, RD, HW, TW and BKL had the highest correlation with BW (r ≥ 0.90; P < 0.001); while PBW, NL and AC the correlation was 0.73 ≤ r ≤ 0.88 (Table 3).

For the prediction of BW of the llamas, simple regression models were developed using all biometric measurements obtained; but only models resulting in r^2≥ 0.85 and RMSEP <15% of observed mean, were used. Regression equations between BW, HG and RD had a determination coefficient (r^2) of 0.94 and 0.92, respectively (RMSEP= 6.06 and 6.70 kg, respectively); whereas, for the other biometric measurements the r^2 was 0.86 ≤ r ≤ 0.89 (Table 4). The addition of other biometric measurements as independent variables in a multiple regression improved slightly the r^2 by 1 to2% and reduce the RMSEP by 1.5% (Table 4).

Regarding the evaluation of equations (Table 5, Fig. 1), all equations (Eq. 1 to Eq. 7) yielded high precision (R^2 >0.86), high accuracy (bias correction factor ≥ 0.98; Table 5), confirming a good reproducibility index and good concordance with the observed data (concordance correlation coefficient, ≥0.92). In relation to MEF, all equations indicated high efficiency of prediction (MEF ≥ 0.869; Fig. 1). The CD ranged from 1.05 to 1.15, indicating high variability in the predicted data (Table 5), whereas, in Eq. 1 to 6, a random error was the main component of the MSEP partition (≥ 97.80 %). However, in Eq. 7, the partition of the MSEP showed that a considerable proportion (30.25 %; Table 4) of the component of the error that affected this equation prediction was mean bias. The test for intercept = 0 and slope = 1 was accepted in the equations 1 to 6; nonetheless, Eq. 7 had a problem because the intercept was different than zero and slope was different from 1 (P<0.05, Table 5; Fig. 1). Finally, the cross-validation reveals that all models showed adequate goodness of fit,

Table 1. Descriptive analyses of the of body weight and biometric measurements in Bolivian llamas.

Variable	Description	Mean ±SD	Maximum	Minimum
Biometric measurements				
BW	Body weight (kg)	61.1±24.3	121	21.7
NL	Neck length (cm)	47.9±6.06	64.2	33.0
WH	Withers height (cm)	88.8±10.1	108	64.0
RH	Rump height (cm)	91.4±10.4	119	67.4
HG	Heart girth (cm)	90.9±16.6	129	59.0
BL	Body length (cm)	84.2±13.1	111	56.4
AC	Abdomen circumference (cm)	70.8±14.4	98.0	43.0
RD	Rib depth (cm)	36.7±6.73	49.7	24.0
HW	Hip width (cm)	19.3±3.75	26.0	12.3
PBW	Pin bone width (cm)	7.35±1.06	9.50	4.90
TW	Thoracic width (cm)	27.1±5.80	43.3	18.1
BKL	Back length (BKL)	73.3±12.2	103	49.0

Table 2. The effect of sex and age on mean values of biometric measurements and body weight in Bolivian llamas.

	BW	NL	WH	RH	HG	BL	AC	RD	HW	PBW	TW	BKL
***Sex*[1]**												
Males	52.0	46.8	86.1	88.7	84.8	79.7	65.4	34.0	18.0	6.81	25.5	69.1
Females	66.2	48.5	90.4	92.9	94.3	86.8	73.9	38.2	20.1	7.65	28.0	75.7
P-value	0.383	0.664	0.613	0.378	0.075	0.299	0.0009	0.109	0.097	0.0001	0.398	0.094
***Age*[2]**												
Young	54.0	46.5	86.3	88.6	86.1	81.0	67.0	34.8	18.2	7.07	25.5	70.0
Adult	90.2	53.5	99.3	102	110	97.6	86.5	44.3	24.2	8.49	33.5	87.0
P-Value	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

[1]The variable sex combined both young and adult animals.
[2]The variable age combined both female and male animals.
BW: Body weight (kg); NL: Neck length (cm); WH: Withers height (cm); RH: Rump height (cm); HG: Heart girth (cm); BL: Body length (cm); AC: Abdomen circumference (cm); RD: Rib depth (cm); HW: Hip width (cm); PBW: Pin bone width (cm); TW: Thoracic width (cm); BKL: Back length (BKL).

with better performance of multiple regression models (Table 6).

DISCUSSION

In the current study, we evaluated the feasibility of using different biometric measurements to predict BW of llamas (*Lama glama)* raised under the conditions of the Bolivian highlands. Although some articles have been published on this topic in llamas (Wurzinger et al., 2005; Riek and Gerken, 2007; Grund et al., 2018; Ccora et al., 2019), there are no reports that evaluated these relationships in llamas with different age and raised under field conditions. Moreover, it has been reported that this type of models should be developed and evaluated for each breed under specific production systems (Chay-Canul et al. 2019).

Regarding South American camelids, some studies have evaluated the use of biometric measurements to predict BW and for morphometric characterization (Wurzinger et al., 2005; Riek and Gerken, 2007; Grund et al., 2018; Ccora et al., 2019). Riek and Gerken, (2007) found a moderate correlation (r=0.68) between BW and WH and BL; whilst, for HG the r was 0.77. In vicunas, Ccora et al. (2019) reported that the highest correlations (> 0.50) were between BW, HG and BL.

For the biometric prediction of BW, Wurzinger et al. (2005) found that HG (r^2=0.77) was the most suitable single variable for predicting BW in llamas from birth to one year of age, which agrees with the present study (r^2=0.94). Moreover, the authors also reported that the WH and BL gave reasonable estimates of BW in llamas (r^2= 0.83). Riek and Gerken (2007) found that the single or combined biometric measurements were good predictors of BW, and they reported that HG was the best predictor of BW (r^2=0·98), while the BL was also identified as another single predictor of BW (r^2=0·96) in llamas between birth and 27 weeks of age. For alpacas, Grund et al. (2018) reported that compared to other parameters, HG has the greatest r^2 = 0.97. In addition, the authors reported a strong relationship between BW and BKL (r^2 = 0.93). Recently, for vicuñas, Ccora et al. (2019) reported that HG as a simple linear regression accounted for 50.3 % of the variation in BW.

As previously described in other species, HG is particularly suitable for estimating BW, because there is a close relationship between this parameter and weight (Wurzinger et al., 2005; Yilmaz et al., 2013; Tebug et al., 2016; Grund et al., 2018; Chay-Canul et al., 2019; Ccora et al 2019). Furthermore, Wurzinger et al. (2005) concluded

Table 3. Correlation coefficients between biometric measurements and body weight in Bolivian llamas[1].

	BW	NL	WH	RH	HG	BL	AC	RD	HW	PBW	TW
NL	0.82										
WH	0.90	0.84									
RH	0.91	0.86	0.97								
HG	0.96	0.80	0.89	0.89							
BL	0.93	0.80	0.92	0.91	0.94						
AC	0.88	0.73	0.82	0.81	0.88	0.83					
RD	0.96	0.84	0.90	0.90	0.95	0.92	0.88				
HW	0.94	0.83	0.89	0.90	0.93	0.90	0.89	0.93			
PBW	0.73	0.57	0.63	0.66	0.71	0.64	0.73	0.71	0.71		
TW	0.93	0.79	0.89	0.97	0.92	0.87	0.90	0.90	0.90	0.68	
BKL	0.91	0.83	0.89	0.89	0.90	0.92	0.91	0.91	0.90	0.73	0.85

[1]Correlations followed by no superscript indicate $P < 0.001$; **P <0.01; *P <0.05; ns: non-significant.
BW: Body weight (kg); NL: Neck length (cm); WH: Withers height (cm); RH: Rump height (cm); HG: Heart girth (cm); BL: Body length (cm); AC: Abdomen circumference (cm); RD: Rib depth (cm); HW: Hip width (cm); PBW: Pin bone width (cm); TW: Thoracic width (cm); BKL: Back length (BKL).

Table 4. Regression equations to predict body weight in Bolivian llamas using biometric measurements.

No. Eq.	Equation	MSEP	RMSEP	r^2	P
	Simple regression				
1	BW (kg)= -57.52 (±1.89***)+6.11 (±0.09***)×WH	63.24	7.95	0.89	<.0001
2	BW (kg)= -68.08 (±1.55***)+1.42 (±0.01***)×HG	36.77	6.06	0.94	<.0001
3	BW (kg)= -44.84 (±1.92***)+3.89 (±0.06***)×TW	78.17	8.84	0.86	<.0001
4	BW (kg)= -65.84 (±1.69***)+3.45 (±0.04***)×RD	44.93	6.70	0.92	<.0001
5	BW (kg)= -84.42 (±2.45***)+1.72 (±0.02***)×BL	69.77	8.35	0.88	<.0001
	Multiple regressions				
6	BW (kg)=-70.04 (±1.36***)+0.84(±0.05***)×HG+1.47(±0.12***)×RD	27.49	5.24	0.95	<.0001
7	BW (kg)= -68.00 (±1.32***)+0.66(±0.05***)×HG +0.79(±0.10***)×TW+1.28(±0.11***)×RD	24.50	4.95	0.96	<.0001

Values within parentheses are S.E. of the parameter estimate. *: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$.
BW: Body weight (kg); WH: Withers height (cm); HG: Heart girth (cm); BL: Body length (cm); RD: Rib depth (cm); TW: Thoracic width (cm).

that HG shows a high correlation with BW and can easily be measured under field conditions. It seems that the HG plays a bigger role on the determination of BW, the practical implications are that the volume and weight of organs housed in the abdominal cavity may represent better determinants on body mass, which determines the bulk of nutrient requirements of maintenance (Chay-Canul et al., 2019).

Several authors agree that HG is the most practical, most reliable, and best repeatable biometric measurement. In fact, various studies have demonstrated that the measurement of HG in South American camelids enables precise estimation of BW (Wurzinger et al., 2005; Riek and Gerken, 2007; Grund et al., 2018; Ccora et al., 2019); for simplicity, a linear regression would be adequate for a quick and reliable method to estimate body weight.

The parameters for precision and accuracy showed that the proposed equation presented high precision (R^2 from 0.86 to 0.95%), accuracy (Cb =0.98 to 0.99), and reproducibility (CCC= from 0.92 to 0.97) to predict BW in llamas. The

Table 5. Mean and descriptive statistics of the accuracy and precision of the equations for predicting body weight in Bolivian llamas using biometric measurements.

Variable[1]	Obs	[Eq. 1]	[Eq. 2]	[Eq. 3]	[Eq. 4]	[Eq. 5]	[Eq. 6]	[Eq. 7]
Mean	61.13	61.00	61.02	60.82	60.78	60.56	60.16	57.45
SD	24.32	22.98	23.59	22.58	23.25	22.65	23.52	23.02
Maximum	121.90	101.34	115.09	123.60	105.63	106.80	111.40	106.84
Minimum	21.70	17.63	15.69	25.57	16.96	12.60	18.90	18.85
R^2		0.89	0.94	0.86	0.92	0.88	0.95	0.95
CCC		0.94	0.97	0.92	0.96	0.93	0.97	0.96
Cb		0.99	0.99	0.99	0.99	0.99	0.99	0.98
MEF		0.89	0.93	0.86	0.92	0.88	0.95	0.93
CD		1.12	1.06	1.15	1.08	1.14	1.05	1.07
Regression analysis								
Intercept (β_0)								
Estimate		0.06	0.14	0.03	0.07	0.28	0.55	1.74
SE		1.02	0.76	1.15	0.85	1.08	0.65	0.60
P-value ($\beta_0 = 0$)		0.95	0.85	0.97	0.93	0.79	0.48	0.004
Slope (β_1)								
Estimate		1.00	0.99	1.00	1.00	1.00	1.00	1.02
SE		0.02	0.01	0.01	0.01	0.01	0.01	0.009
P-value ($\beta_1 = 1$)		0.94	0.96	0.95	0.92	0.83	0.60	0.007
MSEP source, % MSEP								
Mean bias		0.02	0.03	0.01	0.05	0.36	2.139	30.25
Systematic bias		0.001	0.000	0.001	0.002	0.009	0.056	1.05
Random error		99.97	99.97	99.98	99.94	99.635	97.80	68.69
Root MSEP								
Estimate		7.93	6.05	8.82	6.69	8.35	5.29	5.94
% of the mean		12.98	9.90	14.48	10.98	13.67	8.68	9.79

[1]Obs: observed evaluation data set; CCC: concordance correlation coefficient; Cb: bias correction factor; MEF: modelling efficiency; CD: coefficient of model determination; MSEP: mean square error of the prediction.

Table 6. Validation of proposed models for equations for predicting body weight in Bolivian llamas using biometric measurements.

Model	RMSPE	r^2	MAE
[Eq. 1]	7.91	0.89	6.14
[Eq. 2]	6.04	0.93	4.82
[Eq. 3]	9.15	0.86	6.80
[Eq. 4]	7.36	0.91	5.57
[Eq. 5]	8.72	0.87	6.61
[Eq. 6]	5.43	0.95	4.35
[Eq. 7]	5.15	0.96	4.05

RMSPE, root mean square prediction error; r^2, coefficient of determination; MAE, mean absolute error.

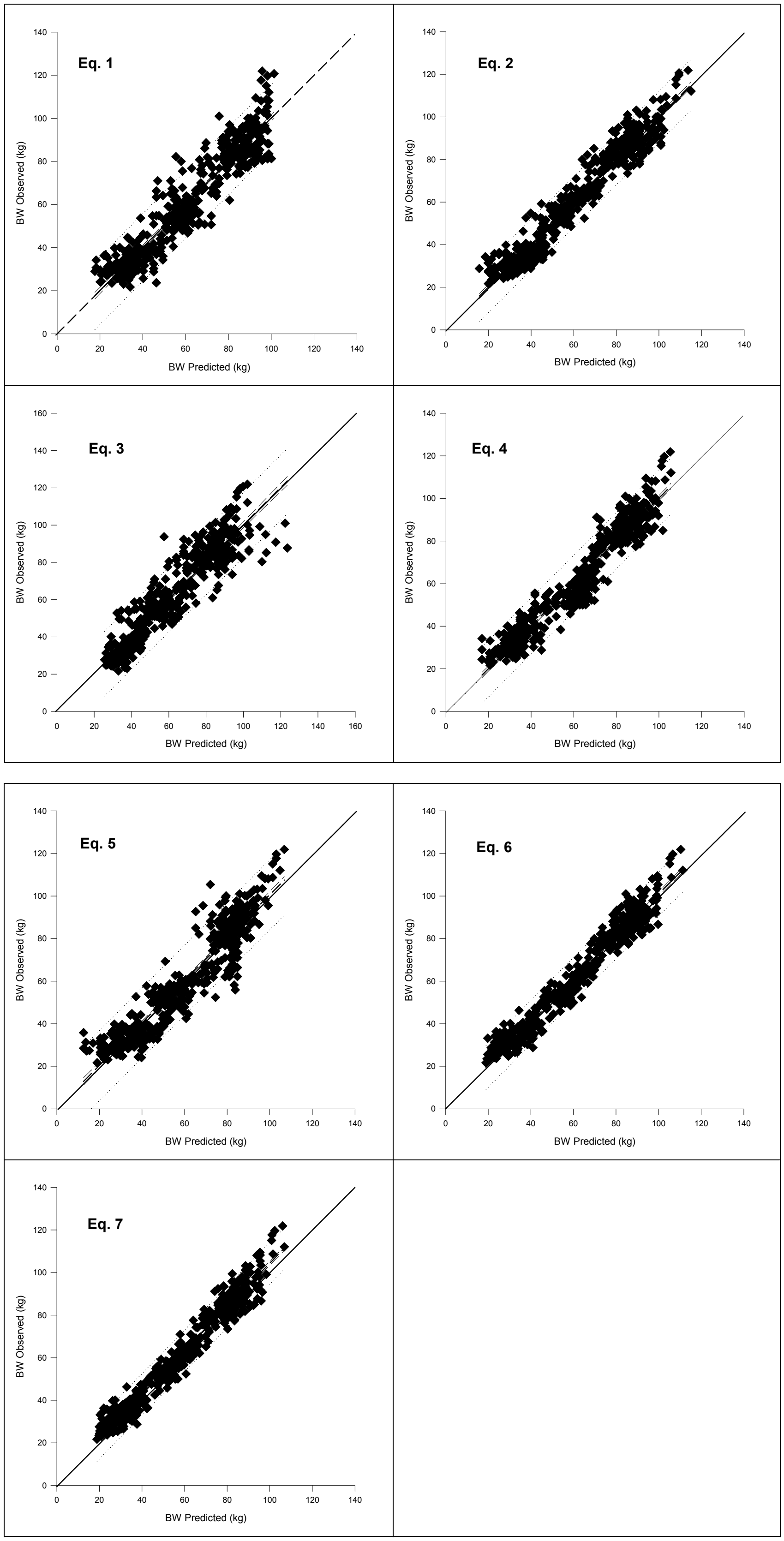

Fig. 1. Relationship between the observed and predicted values of body weight in Bolivian llamas. The solid line is Y = X, and the dotted line is the linear regression.

result of the model efficiency (MEF ≥ 0.86) indicated a relatively high value of concordance between the observed and predicted values. In a perfect fit, it might be one. MEF has been reported as the best measurement of concordance between the observed and predicted values. However, about CD, on a perfect fit would be worth one, if its value close to one indicates an improvement in the predictions of the model (CD > 1 indicates underprediction and CD < 1 indicates overprediction). The CD found in the present study ranged from 1.05 to 1.15, which indicates an underestimation of the BW with a variation of about 5 to 15 % (Tedeschi 2006). In Eq. (2), (4) and (6) the RMSEP accounted for 8.68 to 10.98% of the BW observed. Based on the results of the statistical evaluations, Eq. (2), (4) and (6) predicted the observed BW with good precision and accuracy. Eq. (2) and (4) accounted for more than 92 % of the variation in BW, HG and RD using a single predictor in simple linear regressions. For practicality, the use of HG as a single predictor may be used to predict BW in llamas.

CONCLUSIONS

Of the evaluated equations used to predict body weight in Bolivian llamas using biometric measurements, Eq. (2), (4) and (6), developed for BW estimation, predicted the observed BW suitably. HG and RD, using a single predictor in simple linear regressions, accounted for more than 92 % of the variation in BW. Therefore, HG may be used as a single predictor to predict BW in llamas under field conditions.

Conflict of interest

The authors declare that they have no conflicts of interest.

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Authors contributions

All authors were involved equally in the bibliographic review, the development of the methodology, the discussion of the results, and the final version of the article.

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