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Meta-analysis of spineless cactus feeding to meat lambs: performance and development of mathematical models to predict dry matter intake and average daily gain

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Spineless cactus is a useful feed for various animal species in arid and semiarid regions due to its adaptability to dry and harsh soil, high efficiency of water use and carbohydrates storage. This meta-analysis was carried out to assess the effect of spineless cactus on animal performance, and develop and evaluate equations to predict dry matter intake (DMI) and average daily gain (ADG) in meat lambs. Equations for predicting DMI and ADG as a function of animal and diet characteristics were developed using data from eight experiments. The dataset was comprised of 40 treatment means from 289 meat lambs, in which cactus was included from 0 to 75% of the diet dry matter (DM). Accuracy and precision were evaluated by cross-validation using the mean square error of prediction (MSEP), which was decomposed into mean bias, systematic bias and random error; concordance correlation coefficient, which was decomposed into accuracy (C_b) and precision (ρ); and coefficient of determination (R^2). In addition, the data set was used to evaluate the predicting accuracy and precision of the main lamb feeding systems (Agricultural and Food Research Council, Small Ruminant Nutritional System, National Research Council and Institut National de la Recherche Agronomique) and also two Brazilian studies. The DMI, CP intake (CPI), metabolizable energy (ME) intake and ADG increased when cactus was included up to 499 g/kg DM ($P < 0.001$). In contrast, animals fed high levels of cactus (> 500 g/kg DM) had a decreased DMI, CPI and NDF intake, but increased feed efficiency ($P < 0.001$) and similar ADG compared with those without cactus addition. The DMI was positively correlated with initial BW, final BW, concentrate and ADG, while it was negatively correlated with cactus inclusion and ME of the diet. On other hand, ADG was positively correlated with DMI, initial and mean BW and concentrate, and it was negatively correlated with cactus inclusion. The two developed equations had high accuracy (C_b of 0.95 for DMI and 0.94 for ADG) and the random error of MSEP was 99% for both equations. The precision of both equations was moderate, with R^2 values of 0.53 and 0.50 and ρ values of 0.73 and 0.71 for DMI and ADG, respectively. In conclusion, the developed equation to predict DMI had moderate precision and high accuracy, nonetheless, it was more efficient than those reported in the literature. The proposed equations can be a useful alternative to estimate intake and performance of lambs fed cactus.

Keywords: nutrition models, nutritional requirements, *Opuntia ficus-indica*, semiarid, sheep

Implications

This study assessed the effect of dietary spineless cactus on performance, and developed and evaluated equations to predict dry matter intake (DMI) and average daily gain (ADG) in meat lambs. Lambs fed cactus at levels higher than 50% of the diet had lower DMI, CP intake (CPI) and NDF intake, but similar metabolizable energy (ME) intake and ADG, thus resulting in higher feed efficiency, than control animals. Equations to predict DMI and ADG developed in this study had high accuracy and should be preferred to those present in literature, which does not consider the particularities of cactus.

Introduction

The DMI of small ruminants, such as lambs, is usually predicted with the most widely used feeding systems, which are the British (Agricultural and Food Research Council (AFRC),

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1998), the North American (National Research Council (NRC), 2007; Small Ruminant Nutritional System (SRNS); Cannas *et al.*, 2004), the French (Institut National de la Recherche Agronomique (INRA), 2007) and the Australian (Commonwealth Scientific and Industrial Research Organization, 2007). In some countries like Brazil, several authors (Cabral *et al.*, 2008; Vieira *et al.*, 2013; Pereira *et al.*, 2017) reported that the equations proposed in these systems are not adequate to predict the DMI for sheep. This could be due to the influence of factors such as climate, genetics, neuroendocrine system, hormones, feeding management, diet composition and welfare (Pulina *et al.*, 2013), which are usually not accounted in predicting models.

In the semiarid areas of the Northeast of Brazil, where about 57% of the national sheep flock is raised (ANUALPEC, 2016), there are native plants used as feed like cacti (Santos *et al.*, 2010), which are not widely used in ruminant nutrition in other regions such as North America (except for Mexico), Europe and Oceania. Nevertheless, spineless cactus such as *Opuntia ficus-indica* and *Nopalea cochenillifera* are considered one of the most important feeds for sheep in arid and semiarid regions (Ben Salem *et al.*, 1996). As a result of its palatability, water content and adaptability to harsh soil and climatic conditions (Costa *et al.*, 2012), it has become a useful feed for ruminants in arid regions (Gebremariam *et al.*, 2006; Tegegne *et al.*, 2007; Costa et al., 2010), especially during the dry season, to compensate the lack of other forages and even water (Santos *et al.*, 2010).

Cactus has a particular chemical composition, characterized by a low concentration of dry matter (DM) about 70 g/kg as fed, CP and fiber (Santos *et al.*, 2001), but a high proportion of non-fibrous carbohydrates about 500 g/kg DM and high DM digestibility (Ben Salem *et al.*, 1996). Consequently, sheep fed high levels of cactus may have decreased DMI, mainly due to its high moisture content and high rumen filling (Gebremariam *et al.*, 2006). For these reasons, many authors attempted to define the level of cactus that could be more suitable for ruminants (Bispo *et al.*, 2007; Costa *et al.*, 2009; Vieira *et al.*, 2013). However, there are many differences among studies that should be taken into account to avoid a bias in the estimation of parameters (slopes and intercept) of regression models (Azevêdo *et al.*, 2010). The use of meta-analysis, which incorporates the study effect and its interaction as random components of a mixed model, should result in better prediction equations of biological systems and a more accurate description of prediction errors (St-Pierre, 2001). Thus, the aim of this study was to assess the effect of the inclusion of spineless cactus on the performance of meat lambs and to develop mathematical models to predict the DMI and ADG of meat lambs fed various amounts of spineless cactus.

Material and methods

Data used in the statistical analyses were obtained from eight different experiments that reported DMI and weight gain of lambs fed various amounts of spineless cactus in a semiarid region of Brazil. The main characteristics of each study are briefly described below.

Brief description of experiments used in the database

Experiment 1 – Cordova-Torres *et al.* (2017). The experiment was conducted using 42 non-castrated Santa Inês lambs at 100 days of age, averaging 18.8 ±0.46 kg of BW at the beginning of the trial. The animals were kept in individual pens and were fed *ad libitum*. Diets with forage to concentrate ratio of 70/30 were composed of spineless cactus (*N. cochenillifera*), Tifton (*Cynodon dactylon*) hay, soybean meal, corn meal, soybean oil and mineral salt. The trial was carried out in a completely randomized design in a $3 \times 2 + 1$ factorial arrangement. Treatments were three levels of substitution of low quality Tifton hay with spineless cactus (30%, 50% and 70% of diet DM), with or without access to water, and a control treatment with access to water and without cactus in the diet.

Experiment 2 – Cordeiro (2012). This experiment was conducted using 40 non-castrated Santa Inês lambs averaging 22.1 ± 0.25 kg of BW at the beginning of the trial. The animals kept in individual pens, and had *ad libitum* access to diets and water. The trial was carried out according to a completely randomized block design. Diets had forage to concentrate ratio of 70/30 and were composed by concentrate, and Buffel grass (*Cenchrus ciliaris*) hay replaced by spineless cactus (*O. ficus-indica* Mill) at 0%, 12.3%, 24.6%, 36.6% and 49.2% of diet DM.

Experiment 3 – Costa *et al.* (2012). The experiment was conducted using 45 non-castrated Santa Inês lambs, averaging 27.5 ± 0.48 kg of BW at the beginning of the trial. The animals were kept in individual pens and *ad libitum* access to diets and water. The trial was carried out according to a completely randomized block design. Diets were composed by Tifton-85 (*C. dactylon*) hay and corn meal was replaced by spineless cactus (*O. ficus-indica* Mill), at 0%, 7%, 14%, 21% and 28% of diet DM.

Experiment 4 – Porto Filho *et al.* (2015). The experiment was conducted using 42 non-castrated Santa Inês lambs at 180 days of age, averaging 21.6 ± 0.48 kg of BW at the beginning of the trial. The trial was carried out as a completely randomized design with a $3 \times 2 + 1$ factorial arrangement. Diets with forage to concentrate artio of 70/30 were fed *ad libitum* and composed by spineless cactus (*O. ficus-indica* Mill), Tifton (*C. dactylon*) hay, soybean meal, corn meal, soybean oil and mineral salt. The trial was carried out in a completely randomized design in a $3 \times 2 + 1$ factorial arrangement. Treatments were three levels of substitution of high quality Tifton hay with spineless cactus (30%, 50% and 70% of diet DM), with or without access to water, and a control treatment with access to water and without cactus in the diet.

Experiment 5 – Lima (2011). The experiment was conducted using 24 non-castrated Santa Inês lambs at 119 days of age, averaging 14.6 ± 2.28 kg of BW at the beginning of the trial, which lasted for 89 days. The trial was carried out according to a completely randomized block design. The animals kept in individual pens, and had *ad libitum* access to diets and water. Diets had forage to concentrate ratio of 70/30 and treatments were substitution of Tifton (*C. dactylon*) hay with cactus (*N. cochenillifera* Salm Dyck) at 0%, 6.5%, 16.6% and 35.1% of diet DM.

Experiment 6 – Bezerra (2015). The experiment was conducted using 32 non-castrated Santa Inês crossbred lambs averaging 20.4 ± 0.35 kg of BW at the beginning of the trial, which lasted for 70 days. The animals kept in individual pens, and had ad *libitum* access to diets and water. The trial was carried out according to a completely randomized block design. Diets had forage to concentrate ratio of 75/25 and treatments were replacement of Tifton (*C. dactylon*) hay by spineless cactus (*N. cochenillifera Salm Dyck*), at 0%, 25%, 50% and 75% of diet DM.

Experiment 7 – Moura (2013). This experiment was conducted using 32 non-castrated Santa Inês crossbred lambs averaging 20.8 ± 2.90 kg of BW at the beginning of the trial. The animals kept in individual pens, and had *ad libitum* access to diets and water. The trial was carried out according to a completely randomized block design. Diets had forage to concentrate ratio of 60/40 and treatments were replacement of maniçoba (*Manihot pseudoglaziovii* Muel Arg.) hay by spineless cactus (*N. cochenillifera* Salm Dyck) at 0%, 20%, 40% and 60% of diet DM.

Experiment 8 – Oliveira (2013). This experiment was conducted using 32 non-castrated Santa Inês lambs averaging 19.3 ± 1.65 kg of BW at the beginning of the trial, which lasted for 42 days. The animals kept in individual pens, and had *ad libitum* access to diets and water. The trial was carried out according to a completely randomized design. Diets had forage to concentrate ratio of 50/50 and treatments were replacement of Tifton-85 (*C. dactylon*) hay by spineless cactus (*O. ficus-indica*, Mill) at 0%, 16.7%, 33.3% and 50.0% of diet DM.

The data of animals with 30% of spineless cactus inclusion and without *ad libitum* access to water, from experiments 1 and 4, was not included in the database. Such decision was based in the information that there is a decrease in the DMI in this treatment, pattern that is not observed when the inclusion of spineless cactus was 50% or 70% (Cordova-Torres *et al*., 2017).

Data set

A data set (Supplementary Material S1) was composed using the eight publications cited above, which reported data on diet composition, intake and ADG. All data selected were from experiments that had at least 42 days of duration and an adaptation period to minimize the impact of compensatory growth on DMI and ADG. Overall, the data set was composed by 289 individual observations. Five of the experiments (experiments 2, 3, 4, 5 and 6) were carried out at the Universidade Federal da Paraíba (Bananeiras, Paraíba, Brazil), two (experiments 7 and 8) at the Universidade Federal Rural de Pernambuco (Recife, Pernambuco, Brazil) and one (experiment 1) at the Universidade Federal de Alagoas (Rio Largo, Alagoas, Brazil). Effects of breed were taken into the effect of study and were not evaluated as a fixed effect in the models. The mean, maximum, minimum, median and SEM of the variables included in the data set are shown in Table 1.

Statistical analysis

Pearson's coefficient of correlation between DMI or ADG with quantitative variables (i.e. initial BW, mean BW, level of

Table 1 *Descriptive statistics of animal and diet composition variables of the database used to develop dry matter intake (DMI) and average daily gain (ADG) prediction equations in meat lambs fed spineless cactus*

Items	Mean	Minimum	Maximum	Median	SEM
Diet composition					
Concentrate (% DM)	383.2	226.4	649.3	306.5	7.61
Cactus (g/kg DM)	295.9	0	750.0	280.0	1.35
CP (g/kg DM)	151.1	116.2	253.9	149	1.4
NDF (g/kg DM)	419.9	223.1	685.4	435.5	6.3
ME (Mcal/kg DM)	2.31	1.8	2.65	2.31	0.01
Intake					
DM (g/day)	1065.3	470.7	1618.5	1090.9	15.6
DM (% BW)	4.01	1.7	5.92	4.16	0.05
Cactus DM (g/day)	298.2	0	930.4	313.5	13.1
CP (g/day)	161.4	59.6	287.9	165.4	2.7
NDF (g/day)	444.6	146.2	776.7	448.5	9.4
ME (Mcal/day)	2.45	4.31	1.15	2.47	0.04
Animal performance					
iBW (kg)	20.8	10.6	28.6	20.8	0.21
fBW (kg)	32	18.2	44.4	32.2	0.22
mBW (kg)	26.4	15.5	32.8	26.5	0.19
ADG (g)	197.7	47.2	388.7	198.6	3.6
Feed efficiency (ADG/DMI)	0.194	0.095	0.325	0.189	0.003

DM = dry matter; ME = metabolizable energy; iBW = initial BW; fBW = final BW; mBW = mean BW.

cactus in the diet, square level of cactus in the diet, NDF concentration, ME of the diet and concentrate level in the diet). The ME was calculated by multiplying the digestible (0.82) energy to the factor of 0.82 and the digestible energy was calculated was calculated for each experiment using the values found in the digestibility trials.

Models for predicting DMI and ADG were developed according to the recommendations of St-Pierre (2001). A check for existing studies effect on the database was performed, being each experiment considered as a random sample of a large population. Subsequently, the inclusion of experimental effects in the model required the estimation of fixed effects, as well as random effects associated with the experiments. The equations were estimated using the MIXED procedure of SAS. Three variance–covariance matrix structures were tested: variance components (VC), composed symmetry (CS) and unstructured (UN). Initially, independent variables were adjusted to a model that included fixed effects for intercept and slope, and random effects of study on the intercept and slope through a covariance matrix with UN variation (option UN). When random covariance for intercept and slope was not significant ($P > 0.05$) or when models that included intercept or slope covariance did not converge, the option CS and VC from the PROC MIXED were used. The likelihood was evaluated using the criteria of Akaike's ($AICc_r$; Akaike, 1974) to define the best matrix covariance.

The dependent variables tested to develop the DMI equations were the following: level of cactus in the diet (CACT, in %), CACT square ($CACT^2$, in %), diet concentrate percentage (CON, in %), CONC square ($CONC^2$, in %), ADG (g/day), ADG square (ADG^2, g/day), NDF (% DM), NDF square (NDF^2, in % DM), initial BW (iBW, in kg), iBW square (iBW^2, in kg), mean BW (mBW, in kg) and mBW square (mBW^2, in kg). To develop the ADG equations, the variables tested were the same cited above, except for ADG and ADG^2, and including DMI (g/day). In order to identify the variables to be used in the regression equations, a REG procedure with the backward method of SAS was done.

A two-step analysis of outliers was performed in the database. First, the parameter of Cook's Distance >1 was used to determine studies that should removed from the database. Using this criterion, all studies were kept in the database. Subsequently, an analysis of outliers was performed to the individual observations using the studentized residuals as parameter and observations with values $> |2.5|$ were excluded from the database (Pell, 2000).

To evaluate the adequacy of the final model, a cross-validation technique (Efron and Tibshirani, 1998) was performed with 2000 simulations using the non-linear least squares function of R (R Development Core Team, 2015) and the packages 'boot' and 'mass'. Briefly, the original database was randomly divided into two new subsets of approximately the same size. The first subset (training subset) was used to obtain the equations, and the second subset (testing subset) was used to test the equations to obtain the adequacy statistics.

The cross-validation results were used to estimate the accuracy and precision of the developed empirical equations through the mean square error of prediction (MSEP) that was decomposed into: mean bias (MB), systematic bias (SB) and random error (RE), where RE represents the variation which is not explained by the regression (Tedeschi, 2006). The concordance correlation coefficient (CCC), which was decomposed into correlation coefficient estimate (ρ), which estimates model precision, and bias correction factor (C_b), which indicates model accuracy, and the R^2.

In addition, equations from the AFRC (1998), NRC (2007), INRA (2007), Cabral *et al*. (2008) and Vieira *et al*. (2013) were used for comparisons with the equation obtained in the present work to predict the DMI as follows:

(i) AFRC (1998):
$DMI\ (g/day) = (74.9 \times BW^{75}) \times [(-0.66 + 1.333 \times ME) - (0.266 \times ME^2)]$ equation (1)
(ii) SRNS (Cannas *et al*., 2004):
$DMI\ (g/day) = -0.124 + 0.0711 \times BW^{75} + 0.0015 \times ADG$ equation (2)
(iii) NRC (2007):
$DMI\ (g/day) = [0.04 \times ABW \times (BW/RSW) \times (1.7 - (BW/RSW))] \times 1000$ equation (3)
(iv) INRA, (2007):
$DMI\ (g/day) = (BCS_{adj} \times BW^{75}) \times 1000$ equation (4)
(v) Cabral *et al*. (2008):
$DMI\ (g/day) = [0.311 + ((0.0197 \times BW) + (0.682 \times ADG))] \times 1000$ equation (5)
(vi) Vieira *et al*. (2013):

$DMI\ (g/day) = 238.74 + 31.36 \times ALW + 1.26 \times ADG - 5.18 \times CON$ equation (6)

where BW^{75} = metabolic BW (kg); ME = metabolizable energy of diet (Mcal); ME^2 = metabolizable energy quadratic ($Mcal^2$); ADG = average daily gain (g/day); ABW = adult BW (assumed as 50 kg in this case); BW (kg); RSW = reference standard weight (assumed to be 45 kg), BCS_{adj} = adjustment for body condition score (0.081 for BCS 3 to 3.5); ALW = average live weight (kg); CON = concentrate percentage in the diet (%).

Aiming to evaluate the prediction bias of the six equations listed above, the observed DMI (dependent variable) values were regressed as a function its correspondent predicted DMI (independent variable). Linear regression parameters were tested for the independent null hypothesis according to Neter *et al*. (1996), using simultaneous *F*-test of the intercept and slope (H_0: intercept = 0 and slope = 1; $\alpha = 0.05$). When the null hypothesis was not rejected, the observed and predicted values were considered as similar. Evaluation of precision and accuracy of the described equations were performed according to Tedeschi (2006), using the Model Evaluation System software (available at http://nutritionmodels.com/mes.html, verified 26 April 2017).

Results

Effects of type of spineless cactus were also not observed in the models developed ($P > 0.05$). Thus, the term spineless cactus involves both, *O. ficus-indica* and *Nopalea cochenilifera*.

Table 2 *Pearson's coefficient of correlation and likelihood values of dependent variables of the dry matter intake (DMI) in lambs*

	DMI (g/day)		ADG (g)	
Variables	Coefficient of correlation	*P*-value	Coefficient of correlation	*P*-value
DMI (g/day)	1.00	–	0.60	< 0.0001
iBW (kg)	0.47	<0.0001	0.21	0.0003
mBW(kg)	0.60	<0.0001	0.50	<0.0001
Cactus (% diet)	−0.26	<0.0001	−0.12	0.0364
Cactus^2 (% diet)	−0.36	<0.0001	−0.24	<0.0001
NDF (g/kg DM)	0.04	0.4552	−0.11	0.0657
ME (Mcal/kg DM)	−0.26	<0.0001	0.05	0.4402
Concentrate	0.60	<0.0001	0.51	<0.0001
ADG (g)	0.36	<0.0001	1.00	–

ADG = average daily gain; iBW = initial BW; mBW = mean BW; Cactus^2 = cactus square; DM = dry matter; ME = metabolizable energy.

Correlations and equations to predict dry matter intake and average daily gain

In Table 2 it can be seen that initial ($r = 0.47$) and mean BW ($r = 0.60$) presented a positive correlation with DMI ($P < 0.001$). In contrast, the level of cactus, cactus quadratic and ME showed a negative correlation with DMI ($r = -0.26$, -0.36 and -0.26, respectively, $P < 0.001$). Diet concentrate level and ADG presented a positive correlation with DMI ($r = 0.60$ and 0.36, respectively), whereas there was no correlation between NDF of the diet and DMI ($P = 0.46$). Average daily gain was positively correlated with DMI, mean BW and concentrate level ($r = 0.60$, 0.50 and 0.51, $P < 0.0001$). However, a negative correlation between ADG and cactus or cactus quadratic was observed ($r = -0.12$ and -0.24, respectively). Finally, NDF and ME of the diet were not correlated with ADG ($P > 0.05$).

The meta-analysis approach fitted two equations, one to predict the DMI and another to predict ADG in meat lambs fed spineless cactus, as follows:

(1) $DMI = 53.453 + 3.3907 \times CACT - 0.09116 \times CACT^2 + 30.8033 \times mBW + 1.0797 \times ADG$

(2) $ADG = -58.0268 + 1.6404 \times CACT - 0.02655 \times CACT^2 + 0.1013 \times DMI + 3.4012 \times CONC$

where DMI = dry matter intake (g); CACT = cactus (% of diet DM); CACT^2 = cactus quadratic (% of diet DM); mBW = mean BW (kg); ADG = average daily gain (g); CONC = concentrate in the diet (% of DM).

The cross-validation indicated a high accuracy (Table 3) for both equations as demonstrated by the C_b values of 0.95 and 0.94 for DMI and ADG equations, respectively. In addition, the MSEP partition indicated a low prediction error directly associated with the fixed variables, because the majority of MSEP was associated with random error (99% for both equations) (Silva *et al.*, 2018). The equations presented a moderate coefficient of determination for DMI and ADG prediction equations ($R^2 = 0.53$ and 0.50, respectively).

Table 3 *Adequacy measures estimated by the cross-validation technique of the predicted equations for dry matter intake (DMI) and average daily gain (ADG) in lambs*

Items	DMI	ADG
Equation	(1)[1]	(2)[2]
Partition of MSEP (%)		
Mean bias	0.35	0.34
Systematic bias	0.29	0.32
Random error	99.36	99.34
CCC (ranging from 0 to 1)	0.69	0.67
ρ	0.73	0.71
C_b	0.95	0.94
Coefficient of determination	0.53	0.50

MSEP = mean square error of prediction; CCC = concordance correlation coefficient; ρ = correlation coefficient estimate; C_b = bias correction factor.
[1](1) $DMI = 53.453 + 3.3907 \times CACT - 0.09116 \times CACT^2 + 30.8033 \times mBW + 1.0797 \times ADG$.
[2](2) $ADG = -58.0268 + 1.6404 \times CACT - 0.02655 \times CACT^2 + 0.1013 \times DMI + 3.4012 \times CONC$, where CACT = cactus (% of diet); CACT^2 = cactus quadratic (% of diet); mBW = mean BW (kg); CONC = concentrate (%).

Comparisons with literature

Models suggested by the AFRC (1998), SRNS (Cannas *et al.*, 2004), INRA (2007), Cabral *et al.* (2008) and Vieira *et al.* (2013) presented different predicted DMI from those observed in this database (Table 4), when tested using regression statistics, with intercept different to 0 and slope different to 1. However, the equation proposed by the NRC (2007) presented an intercept equal to 0 ($P = 0.4967$) and a slope equal to 1 ($P = 0.8804$) and, for these reasons, equivalent to the observed DMI in practical feeding conditions. On other hand, the equation developed by Cannas *et al.* (SRNS, 2004)presented the highest coefficient of determination ($R^2 = 0.48$), accuracy ($C_b = 0.81$), CCC = 0.56 and the lowest root mean square error of prediction of 205.

Discussion

Santos *et al.* (2001) and Torres *et al.* (2009), studying dairy cows and steers, respectively, reported only few variations in the chemical composition between cactus cultivars *O. ficus-indica* and *N. cochenilifera*. These authors also not observed effects on DMI and animal's performance, what is in accordance with the present study. However, it is important to highlight that the use of equations presented in this study

Table 4 *Statistics for regression between observed and predicted dry matter intake (DMI) in lambs*

Equations	Intercept	*P-value*	Slope	*P-value*	R^2	MB	C_b	CCC	RMSEP	MB (%)	SB (%)	RE (%)
AFRC (1998)	−504.1	0.0004	1.82	0.0001	0.30	201.4	0.36	0.20	306.2	43.3	4.6	52.1
Small Ruminant Nutritional System (SRNS) (Cannas *et al.*, 2004)	−199.7	0.0109	1.26	0.0007	0.48	65.5	0.81	0.56	205.0	10.2	3.6	86.2
NRC (2007)	−86.1	0.4967	1.02	0.8804	0.23	−67.2	0.73	0.35	242.6	7.7	0.1	92.2
INRA (2007)	−664.5	0.0001	1.83	0.0001	0.36	122.8	0.50	0.30	255.0	23.2	8.2	68.6
Cabral *et al.* (2008)	543.0	0.0001	0.38	0.0001	0.37	−290.2	0.67	0.41	440.5	43.4	33.6	23.0
Vieira *et al.* (2013)	−396.2	0.0001	1.31	0.0010	0.41	−52.6	0.77	0.49	214.0	6.0	3.5	90.5

R^2 = coefficient of determination; MB = mean bias; C_b = bias correction factor; CCC = concordance correlation coefficient; RMSEP = root mean square error of prediction and its decomposition into MB; SB = systematic bias; RE = random error.

has to be done with care in case of differences in the chemical composition of these cultivars or even using of another cultivars.

The DMI was positively correlated with BW (initial and mean), level of concentrate and ADG and negatively with ME of the diet. Vieira *et al.* (2013), working with Santa Inês rams, found a very similar and positive correlation between DMI and BW ($r = 0.52$) and ADG ($r = 0.38$). However, the authors observed a negative correlation between DMI and concentrate ($r = -0.29$), implying that the highest diet concentrate proportions decrease DMI. The authors mentioned that negative correlations between DMI and diet concentrate percentage can be explained by the concentrate increment effect on ME input. In our study negative correlations were observed between DMI and proportions of cactus in the diet (linear and quadratic), and properly with the ME of the diet. Such pattern could be due to the fact that cactus is an excellent source of energy in the form rapidly fermentable nonstructural carbohydrates (Santos *et al.*, 2010).

In addition, DMI was negatively correlated with the level of cactus in the diet (linear and quadratic). Costa *et al.* (2012), Porto Filho *et al.* (2015) and Cordova-Torres *et al.* (2017) also observed a quadratic effect of cactus on DMI. These results suggest that the inclusion of cactus is beneficial for DMI up to a certain level, probably because of the low fiber content and high palatability and passage rate of this feed (Batista *et al.*, 2003). However, the decrease in total DMI as the proportion of cactus further increased may be explained by the high moisture content of cactus (approximately 880 g/kg fresh weight), which thus occupies a considerable volume in the rumen, leading subsequently to limited DMI.

The observed positive correlation between ADG and DMI is in agreement with the literature (AFRC, 1998; Cannas *et al.*, 2004; INRA, 2007; NRC, 2007; Vieira *et al.*, 2013) and allowed us to use DMI in the ADG predictive equation. Negative values of correlation between ADG and square of cactus in the diet indicate that there is an inflection point for ADG prediction models, which is affected directly by this variable. When this situation occurs, animals fed the highest cactus level would need higher levels of DMI to satisfy nutritional requirements, but it seems physiological effects on DMI regulation are observed when a high amount of spineless cactus is offered.

The cross-validation indicated that the estimated equations can perform accurate DMI and ADG prediction in lambs fed spineless cactus, through the C_b values of 0.95 and 0.94, respectively. In addition, the partition of MSEP indicated similar patterns in the errors of prediction between DMI and ADG predictive equations. In both cases, the lack of correlation of random error accounted for ~99% of the error and the coefficient of determination were 0.53 and 0.50, respectively. Azevêdo *et al.* (2010) reported lower precision to estimate DMI to zebu-crosses and Nellore cattle ($R^2 = 0.50$ and 0.35, respectively), similar partition of MSEP and bias correction for zebu-crosses (Random error = 99% and C_b = 0.96), but lower accuracy for Nellore cattle (Random error = 88% and C_b = 0.72). In both equations proposed in the present work to predict DMI and ADG, the intercept did not differ from 0 and the slope did not differ from 1, as recommended by Neter *et al.* (1996), indicating that models were reliable to predict DMI and ADG in diets using spineless cactus to meat lambs.

Models proposed by the AFRC (1998), SRNS (Cannas *et al.*, 2004), INRA (2007), Cabral *et al.* (2008) and Vieira *et al.* (2013) presented significant *P*-value for intercept and slope between the observed and predicted DMI. Thus, they were not able to predict the DMI of meat lambs fed spineless cactus efficiently. On other hand, the NRC (2007) was able, but had the smallest precision among tested models ($R^2 = 0.23$), moderate accuracy (C_b = 0.73) and the majority of the error of prediction was associated with random error (92%). The SRNS (Cannas *et al.*, 2004) model presented the most accurate equation to predict DMI, with the highest values of bias correction (0.81) and CCC (0.56), but the intercept was not different from 0 and the slope was not different from unity. In other words, this system presented predicted DMI different from those observed in the present dataset and, therefore, failed to predict DMI. Even equations developed under Brazilian conditions, such as those proposed by Cabral *et al.* (2008) and Vieira *et al.* (2013), were not able to predict the DMI in diets using spineless cactus. These findings suggest that cactus promotes a particular pattern of intake due to its palatability, chemical composition and digestibility (Bispo *et al.*, 2007; Costa *et al.*, 2009 and 2010) that should be considered when this feed is included in diets to meat lambs.

Conclusions

The meta-analysis revealed that spineless cactus has a significant effect on DMI and ADG in meat lambs. Although DMI, CPI and NDF intake decreased when feeding a high amount of cactus (>500 g/kg DM), ADG remained unaffected and feed efficiency even increased compared to animals without cactus in the diet. Nevertheless, DMI and ADG improved in animals fed low and medium amounts of cactus, meaning that spineless cactus could be offered to lambs up to 50% of the diet. Overall, the equation suggested in the present work was suitable and more efficient to predict DMI for meat lambs fed spineless cactus than those observed in the literature. Because of its moderate precision and very high accuracy, this equation is more efficient to be used for formulating diets. The developed equation took into account the level of cactus in the diet (linear and quadratic effect), mean BW and ADG.

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Declaration of interest

None.

Ethics statement

As this study was done using data of previous studies, no animal care and use protocol was needed. Therefore, the individual studies that composed the database were carried out following local guidelines for animal care and use.

Software and data repository resources

None of the data were deposited in an official repository.

Supplementary material

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