The use of Artificial Neural Networks for modelling rumen fill in ruminants

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ABSTRACT:

Artificial Neural Network (ANN) and Random Forest models for predicting the weight of rumen fill of cattle and sheep were developed. Data on weight of rumen fill were collected from studies that reported body weights, measured rumen fill and stated diets fed to animals. Animal and feed factors that affected rumen fill were identified from each study and used to create a dataset. These factors were used as input variables for predicting the weight of rumen fill. For ANN modelling, a three-layer Levenberg-Marquardt Back Propagation Neural Network was adopted and achieved 96% accuracy in prediction of the weight of rumen fill. The precision of the ANN model's prediction of rumen fill was higher for cattle (80%) than sheep (56%). On validation, the ANN model achieved 95% accuracy in prediction of the weight of rumen fill. A Random Forest model was trained using a binary tree-based machine-learning algorithm and achieved 87% accuracy in prediction of rumen fill. The Random Forest model achieved 16% (cattle) and 57% (sheep) accuracy in validation of the prediction of rumen fill. In conclusion, the ANN model gave better predictions of the weight of rumen fill compared to the Random Forest model and should be used in predicting rumen fill of cattle and sheep.

Keywords: Artificial Neural Network model, cattle, Random Forest model, rumen fill, sheep.

INTRODUCTION

The weight of herbage or roughage in the rumen (rumen fill) is determined by total feed intake and the rate at which ingested feed leaves the rumen (Weston and Hogan 1971). Rumen fill regulates long term-term roughage intake through satiation, influences feeding behaviour and its prediction is crucial to planning feeding strategies to improve the productivity of livestock (Yearsley et al. 2001). Attempts (Sekine et al. 1991; Illius and Gordon 1992; Nsahlai and Apaloo 2007) have been made to predict rumen fill achieving moderate precision and accuracy in predictions. Several factors that affect rumen fill are not accounted for in existing rumen fill prediction models. Existing models for predicting rumen fill in ruminants are a function of body weight (Illius and Gordon 1992) and feed intake (Sekine et al. 1991) alone, making them structurally inadequate to predict rumen fill for nutritionally diverse classes of ruminants.

Few studies have considered predicting rumen fill in-cooperating both feed and animal characteristics to improve the predictive capacity of the model using Artificial Neural Networks. Artificial Neural Networks have been successfully used in simulation of milk production in goats (Fernandez et al. 2006), *in vitro* methane and carbon dioxide production in the rumen (Dong and Zhao 2014) and modelling of solid and liquid passage rate in ruminants (Moyo et al. 2017; Moyo et al. 2018a). Modelling of rumen fill will reduce the cost of cannulation of animals and use of invasive methods (fistulation) in ruminant nutrition, and find application in prediction of roughage intake and simulation of times spent ruminating. The objective of this study was to develop and compare Artificial Neural Network and Random Forest simulation models for predicting the weight of rumen fill. The study tested the hypothesis that Artificial Neural Networks would predict the weight of rumen fill better than Random Forest models.

MATERIALS AND METHODS

Creation of dataset

Data were collected from studies that reported average values or ranges for bodyweights of animals, measured rumen fill and stated the feeds and/or proportion of feeds in the diet given to animals. A dataset was created containing observations from cattle and sheep (Table 1). Studies used in the dataset had the weight of rumen fill measured by complete manual evacuation of the rumen through the fistulas or measured after slaughter, and had the rumen digesta homogenised, sub-sampled and at least analysed for dry matter. Qualitative and quantitative animal, feed and animal management factors that affect the weight of rumen fill were identified from each study and were included in a dataset.

Animal factors: The quantitative animal factors that affect rumen fill included in the dataset were age of animal (in years), body weight (LBW in kg), mature body weight (MBW in kg), time delay in measuring rumen fill after meal termination (TD in hours). Body weights reported in pounds or scaled to metabolic body weight were converted to actual body weight in kilograms. Time delay for measurement of fill after feeding was computed in hours, however, TD was assumed to be zero where no specification of TD was given. Qualitative animal factors that affect rumen fill were the physiological status of the animal and type of ruminant species. These qualitative factors were coded and given numerical weights. These were (i) physiological state (PHY) which classified animals as either growing (0), at maintenance (1), non-pregnant (2), pregnant (3) and as lactating (4); and (ii) species type (SPT) which categorised animals either as lambs (0), calves (1); wethers (3); steers (3), rams (4), bulls (5), ewes (6) or cows (7).

Feed factors: Diet properties that affect rumen fill were mainly the proximate chemical composition of feeds and diets fed to animals. These factors were dry matter (DM), crude protein (CP), neutral detergent fibre (NDF), acid detergent fibre (ADF), and non-fibre non-protein carbohydrate (CHO) of the feeds and diets all computed in g/kg DM. Where feed composition was not stated but feed name was given, chemical compositions of these feeds were obtained from Feedipedia (2015). The non-fibre non-protein carbohydrate (CHO) was calculated as CHO = 1000-CP-NDF.

Environmental factor: The only qualitative environmental management factor that affects rumen fill included in the dataset was animal management (MGT) which classified animals as either outdoor grazing (0) or indoor zero-grazing (1).

Thus, the 12 factors used as input variables for the prediction of rumen fill using Artificial Neural Networks and Random Forest models were; species type, age of animal, animals physiological state, body weight, mature body weight, dry matter content, crude protein content, neutral detergent fibre content, acid detergent fibre content, non-fibre non-protein carbohydrate content, time delay in measuring rumen fill after meal termination, and animal housing system. Although studies that qualified for creating the dataset might not include all published literature, the studies used were readily available. The final dataset comprised of 140 observations from 20 published experiments. The sources used to create the dataset are listed in the appendix.

Development of Artificial Neural Network model

One Artificial Neural Network model was programmed using the 32-bit Visual Basic version 6.0 to predict the rumen fill. Rumen fill was predicted using animal, feed and environmental factors as predictors as described above. Observations in the dataset were randomly separated into two sub-subsets: 75% of the dataset for model development and 25% for model validation. Since different variables span wide ranges, normalization (within the interval (−1, 1)) of input and output data were done. For modelling, a three-layer Levenberg–Marquardt BP Neural Network was adopted, which generally included one input layer, one hidden layer, and one output layer. Thus, network topologies of 12-7-1 were adopted, corresponding to the numbers of neurons of input, hidden and output layers for rumen fill (Figure 1). The training was carried out using a back-propagation algorithm. The models were trained for 2600 epochs at learning rate of 0.005, and momentum of 0.8 and the net error was reduced to 0.00251 for validation data for rumen fill.

Development of Random Forest model

One Random Forest model was programmed using the 64-bit Python version 3.0 Scikit-Learn package to predict the rumen fill. A Random Forest model was trained to predict rumen fill using animal, feed and animal management factors as predictors described previously above. The Random Forest algorithm intrinsically divided the dataset into 2 subsets, one for prediction and another for internal validation. To ensure a fair and conservative comparisons between Artificial Neural Network and Random Forest models, 75% of the dataset was for model development and 25% for model validation in both models. The Random Forest was trained as a binary tree-based machine-learning method to predict the weight of rumen fill.

Statistical analysis

A comparison of the accuracy and precision of the Artificial Neural Network and the Random Forest model was done by comparing the coefficients of determination achieved by the 2 models. After training and model development the Artificial Neural Network and Random Forest models were used to predict the weight of rumen fill using the training, validation and entire datasets. Linear regressions of the observed against the predicted weight of rumen fill was done and the coefficient of determination used to compare the accuracy of Artificial Neural Network and Random Forest models in the prediction of the weight of rumen fill. An independent dataset was created containing observations from domesticated and wild ruminants (Table 3). The dataset was used to test the performance of the Artificial Neural Network model's prediction of the weight of rumen fill. The sources used to create the datasets are listed in the appendix.

The linear regression analysis of observed against predicted rumen fill, and residuals against predicted and observed rumen fill were carried out. The coefficient of determination (R^2 value) was used to assess the precision of the model in approximating real data points, while the Root Mean Square Error (RMSE) was used to determine the accuracy of the model's prediction. The residuals (observed rumen fill minus predicted rumen fill) were regressed against predicted rumen fill to evaluate the linear and mean biases in the model prediction. The intercept and slope of the regression were tested to determine any linear or mean bias (St. Pierre 2003). To determine how close the predictions were from the datasets, the residuals were plotted against observed rumen fill. The Artificial Neural Network model has been deposited into the Repository of Intelligent Models (REDIM 2016) with accession number PRUV001134 as indicated at http://www.redim.org.za/?search=PRUV001134.

RESULTS

Description of the dataset used for model development and validation using ANN and Random Forests models

The database was characterized by large variations in dietary attributes (Table 1). The dataset included 140 observations from 20 studies (78 cattle and 62 sheep). There were thirty-five (35) lactating and seven (7) pregnant cows in the dataset. Fourteen (14) cattle were growing, while eight (8) cattle were at maintenance level. In sheep, one (1) was lactating, two (2) were non-pregnant, fifty-two (52) were at maintenance level and seven (7) were growing.

Description of the dataset used to test the performance of the ANN rumen fill model

The database was characterized by large variations in dietary attributes (Table 2). The dataset included 438 observations. The observations comprised of 396 grazing ruminants (viz. 2 addax antelope, 1 African buffalo, 10 black wildebeest, 9 swamp buffalo, 313 cattle, 2 muskoxen, 1 Oryx, 57 sheep and 1 waterbuck). There were only 19 observations from intermediate feeders (viz. 1 eland, 2 red deer and 16 goats). Only 3 species of browsing ruminants that made up 17 observations were present (viz. 1 giraffe, 1 gerenuk, and 15 white-tailed deer).

Comparison of the performance of ANN and Random Forest models

The precision and accuracy of prediction of rumen fill was high using the Artificial Neural Network compared to the Random Forest model (Table 4 and Figure 2a – g). The accuracy of the Random Forest (R^2 = 87%) model's prediction was 9% lower compared to the ANN model (R^2 = 96%) for prediction of rumen fill for both cattle and sheep combined. The precision of prediction of rumen fill in cattle was 60% lower for the Random Forest model compared to the ANN model.

Artificial Neural Network model: A function of residual against predicted rumen fill to assess the mean (intercept) and linear (slope) biases of the model's prediction of rumen fill is given in the equation: $Y = 0.0048 (\pm 0.1872) - 0.064 (\pm 0.0192) X$ (n=105, RMSE= 1.2087; SEM=0.118) (Figure 2c).

A function of residual rumen fill against observed rumen fill was $Y = -0.3086 (\pm 0.1934) - 0.0242 (\pm 0.021) X$ (n=105, RMSE = 1.2644) (Figure 2e).

Random Forest model: A function of residual rumen fill against predicted rumen fill to assess the mean (intercept) and linear (slope) biases of the model's prediction of rumen fill is given in the equation: $Y = 0.318(\pm 0.5777) - 0.120 (\pm 0.060) X$ (n=35, RMSE= 1.941) (Figure 2d).

A function of residual rumen fill against observed rumen fill was $Y = -0.744(\pm 0.5999) + 0.016 (\pm 0.0674) X$ (n=35, RMSE = 2.053) (Figure 2f).

Artificial Neural Network model validation and testing

The regression relationship between observed (Y) and predicted (X) rumen fill in model validation was $Y = 0.1889 (\pm 0.3544) + 0.9818 (\pm 0.0386) X$ (n=35, RMSE = 1.3306, SEM=0.225) accounting for 95% of the variation in the prediction (Figure 2g).

The regression relationship between observed (Y) and predicted (X) rumen fill for the combined dataset in modelling was $Y = 0.063 (\pm 0.1681) + 0.9453 (\pm 0.0.0175) X$ (n=140, RMSE = 1.2562, SEM=0.106) accounting for 96% of the variation in the prediction (Figure 3).

The regression relationship between observed (Y) and predicted (X) rumen fill in testing model performance was Y = 2.942 (±0.352) + 0.407 (±0.0446) X (n=433, RMSE = 3.731, SEM=0.1793) accounting for 15.98% of the variation (Figure 4).

DISCUSSION

ANN outperformed the Random Forest model by achieving 9% more accuracy, though both modelling strategies accounted for 96 and 87% of the overall variation, both of which are commendable for use. Because of this disparity, subsequent discussion focused on the ANN model. Rumen fill is a function of digesta passage rates (Illius and Gordon 1991), ruminant species (Gordon and Illius 1996), feed and/or diet quality (Nsahlai and Apaloo 2007), physiological state (Gunter et al. 1990), animal housing system (Kadzere et al. 2002), body weight and mature body weight (Illius and Gordon 1991), period of day and feed intake (Williams et al. 2014). The significant positive correlation of body weight and mature body weight with rumen fill observed in this study partly justifies Illius and Gordon's (1991) basing their prediction of rumen fill on body weight alone. Most studies have developed rumen fill prediction equations with good coefficients of determination (R^2 value) that accounted for a greater portion of the variation using intake as an input variable. Dry matter intake is one of the fundamental factors affecting rumen fill together with solid and liquid passage rates. Given that one application of rumen fill prediction models would be to predict dry matter intake, the inclusion of intake when developing rumen models may be questionable. To eliminate this bias, prediction model for rumen fill developed in this study did not incorporate feed intake as an input variable. Models developed in this study gave better predictions of rumen fill compared to the model of Nsahlai and Apaloo (2007), which achieved an accuracy of only 31%. Sekine et al. (1991) used feed intake alone to generate a regression equation that accounted for 65% of the variation in fresh rumen digesta weights, which is lower than the model developed in this study (for cattle); but higher than the amount of variation accounted for in sheep. Allometric regression of domestic and wild ruminants accounted for 97% of the variation in daytime rumen fill (Illius and Gordon 1992) suggesting that body weight alone can be an accurate predictor of daytime rumen fill load.

The rumen fill model developed in this study accounted for a large amount of variation for two (2) different ruminant species. However, there are a couple of limitations to the models developed in this study. Firstly, rumen fill observations used to develop models in this study were obtained for cattle and sheep, which are predominantly grazers. This limits the application of the models in predicting rumen fill for other ruminant species and feeding types. When tested using wild ruminant species (grazers, browsers, and intermediate feeders), model performance was fair. The model developed in this study gave good predictions of rumen fill for swamp buffalo ($R^2 = 0.55$), goats ($R^2 = 0.65$) and for some browsers (white-tailed deer) of body weights similar to sheep. However, the model underpredicted rumen fill for large ruminants namely the African buffalo (grazers) and giraffe (browsers); while it over predicted rumen fill for addax antelope, and cattle fed on diets of low dry matter content (279.38±131.582). Perhaps faster rates of passage of solid and liquid digesta played a significant role in lowering rumen fill levels in these cattle; rates of passage which were not accounted for in model development. Although competing activities in the rumen (degradation and passage), and their rates may apparently affect the rumen fill (Nsahlai 1991), the time delay (TD) before rumen fill measurement was not significant ($P > 0.05$). The lack of a significant correlation between time delay and rumen fill was unexpected. Evidence suggested that overnight starvation may have reduced rumen fill by approximately 45% (Moyo et al. 2018b) and 60% (Chilibroste et al. 1998) compared to rumen fill prior to starvation. Rumen fill included in this dataset correlates but are different from the actual rumen fill at slaughter (time zero hours), thus suggesting a need for this lapse to be determined from empirical trials and modelled. Finally, better predictions of rumen fill may be achieved by indexing for the effects of ambient temperature (climatic conditions), period of under nourishment (Nsahlai et al. 1996) and rates of passage of digesta in the rumen.

The models developed in this study achieved appreciable levels of precision and accuracy in prediction of rumen fill for cattle; while validation of predictions of rumen fill of sheep had low levels of precision. Low levels of precision in prediction and validation of rumen fill of sheep may be attributed to the relatively few observations available for modelling rumen fill in sheep and the narrow range of body weights of ruminant species used in modelling. Perhaps, the inclusion of observations from other ruminants (wild and domesticated) would allow model prediction to account for more variation in unused observations. Further investigation into input parameters, with the input of time delay and ambient temperature, and ANN models, especially what goes on in the hidden layers and specific built-in functions establishing the relationship, still need to be done to reduce noise in the datasets and achieve the best possible relationships between input variables and rumen fill.

CONCLUSION

The ANN model accounted for 9% more variation in prediction of the weight of rumen fill compared to the Random Forest model. The ANN model developed in this study accounted for 56% and 80% of the variation in prediction for sheep and cattle, respectively. The Random Forest model accounted for 16% (cattle) and 57% (sheep). During ANN model performance testing using an independent dataset, model accounted for only 14% of the variation in prediction of rumen fill for both domestic and wild ruminants.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest. We affirm that all the authors of this manuscript agree to the submission and the manuscript has not been submitted to, published in or considered for publication anywhere else. The authors affirm that the current study was conducted in compliance with ethical standards.

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Table 1 Summary statistics of diet quality and animal attributes used in the creation of database for rumen fill model development

	Diet quality attributes					Animal attributes			
Cattle	DM (g/kg)	CP (g/kg)	NDF (g/kg)	ADF (g/kg)	CHO (g/kg)	AGE	LBW (kg)	MBW (kg)	RF (kg DM)
N	78	78	78	78	78	78	78	78	78
Min	121	27	325	203	168	1	316	750	6.1
Max	911	259	778	480	489	6	749	900	21.9
Mean	581.0	129.7	565.2	331.1	305.1	4.0	556.7	788.5	11.8
S. D	317.4	67.3	128.9	101.0	77.3	1.8	122.2	65.9	3.4
Sheep									
N	62	62	62	62	62	62	62	62	62
Min	80	45	145	219	153.7	1	22.5	70	0.4
Max	921	345.6	768	530	710	5	71	90	2.3
Mean	692.7	130.5	556.3	341.0	313.2	2.9	54.0	78.7	1.2
S. D	315.5	63.2	148.6	72.6	113.8	1.1	12.2	10.0	0.5
Combined									
N	140	140	140	140	140	140	140	140	140
Min	80	27	145	203	153.7	1	22.5	70	0.4
Max	911	345.6	778	530	710	6	749	900	21.9
Mean	630.5	130.1	561.2	335.5	308.7	3.5	334.1	474.1	7.1
S. D	320.3	65.3	137.6	89.4	94.9	1.6	266.7	357.3	5.9

DM, dry matter; CP, crude protein; NDF, neutral detergent fibre; ADF, acid detergent fibre; CHO, non-fibre non-protein carbohydrate; SPT, species/type; PHY, physiological state; MGT, housing system; LBW, body weight; MBW, mature body weight; RF, rumen fill; N, number of observations; SD, standard deviation

Table 2 Summary statistics of diet quality and animal attributes used to test the predictive capacity of the rumen fill model (independent dataset not used in model development)

	Diet quality attributes					Animal attributes				
Grazers	DM (g/kg)	CP (g/kg)	NDF (g/kg)	ADF (g/kg)	CHO (g/kg)	AGE (yrs.)	LBW (kg)	MBW (kg)	RF (kg DM)	TD (h)
N	396	396	396	396	396	396	396	396	396	396
Min	159.7	16.5	129	38	44	1	30	45.3	0.264	0
Max	940	340	873	654	739.8	9	835	1200	47.5	24
Mean	597.5	146.1	521.5	324.5	332	4.89	416.5	608.1	6.23	1.61
S. D	311.2	64.18	163.8	106.3	134.4	1.61	205.03	292.9	4.72	4.50
Browsers										
N	17	17	17	17	17	17	17	17	17	17
Min	304	162	442	268.1	275	3	33.6	52	0.56	0
Max	600	209.4	515.2	337.2	396	8	702	1200	38.1	0
Mean	555.6	202	504.2	325.5	293.5	3.25	109	266.6	6.38	0
S. D	108.4	17.36	26.82	22.83	44.17	1.118	171.5	297.87	9.76	0
Intermediate feeder										
N	19	19	19	19	19	19	19	19	19	19
Min	540	20	355	231.5	194	0.5	15.3	36	0.394	0
Max	932	209.4	740.5	632	441	5	458.8	900	10.24	2.5
Mean	837.7	141.9	522.3	364.7	335.8	2.32	55.22	126.1	1.317	0.789
S. D	127.1	72.85	161.1	139.2	95.87	1.35	100.6	192.5	2.181	1.194
Combined										
N	433	433	433	433	433	433	433	433	433	433
Min	160	16.5	129	38	44	0.5	15.3	36	0.26	0
Max	940	340	873	654	739.8	9	835	1200	18.88	24
Mean	606	148.5	520.7	326.3	330.4	4.71	386.8	571.6	5.71	1.5
S. D	303.1	64.21	159.9	105.7	130.3	1.69	221.5	312.5	4.07	4.31

DM, dry matter; CP, crude protein; NDF, neutral detergent fibre; ADF, acid detergent fibre; CHO, non-fibre non-protein carbohydrate; SPT, species/type; PHY, physiological state; MGT, housing system; LBW, body weight; MBW, mature body weight; RF, rumen fill; N, number of observations; SD, standard deviation; TD, time delay

Table 3 Observed and predicted rumen fill (kg) of cattle and sheep in rumen fill model development

	Cattle Rumen Fill (kg DM)		Sheep Rumen Fill (kg DM)	
	Observed	Predicted	Observed	Predicted
Minimum	6.1	8.045	0.4	0.312
Maximum	21.9	21.916	2.3	2.881
Mean	11.737	12.547	1.172	1.231
S. D	3.589	3.382	0.459	0.531

Table 4 Comparison of the equations for linear regression between observed (Y) and predicted (X) rumen fill in Artificial Neural Network and Random Forest model development

Model type	Parameter estimates					
	Intercept	$P_{\text{intercept}}$	Slope	P_{slope}	RMSE	R^2 value
	Combined data					
Artificial Neural Network	0.005 ± 0.1872	*NS*	0.936 ± 0.0192	< 0.0001	1.209	0.96
Random Forest	0.318 ± 0.5777	*NS*	0.880 ± 0.0603	< 0.0001	1.842	0.87
	Cattle					
Artificial Neural Network	-0.216 ± 0.847	*NS*	0.953 ± 0.0622	*NS*	1.596	0.80
Random Forest	5.330 ± 2.964	*NS*	0.472 ± 0.2458	*NS*	2.319	0.16
	Sheep					
Artificial Neural Network	0.369 ± 0.1147	0.0002	0.652 ± 0.0857	0.0024	0.305	0.56
Random Forest	0.160 ± 0.2412	*NS*	0.789 ± 0.2078	0.0030	0.220	0.57

NS: not significant; RMSE: root mean square error

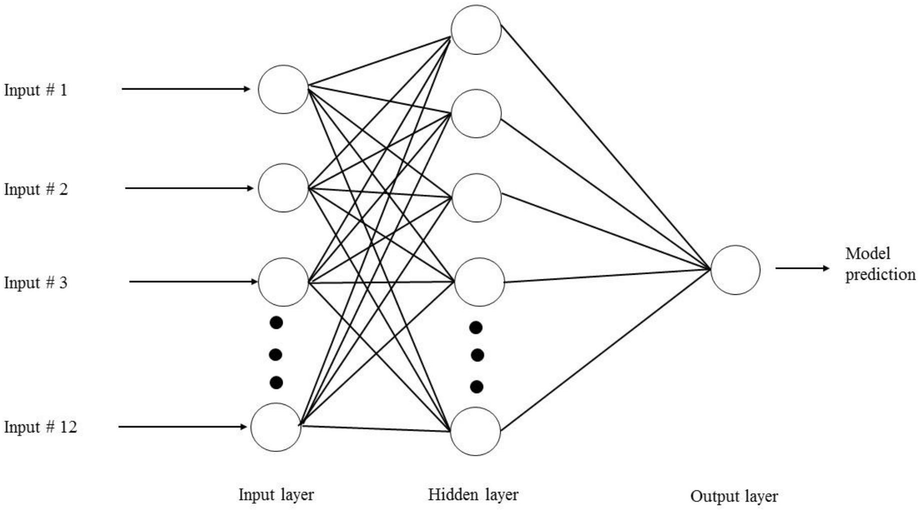

Figure 1 The basic structure of Levenberg–Marquardt back propagation (LM-BP) Neural Network for modelling.

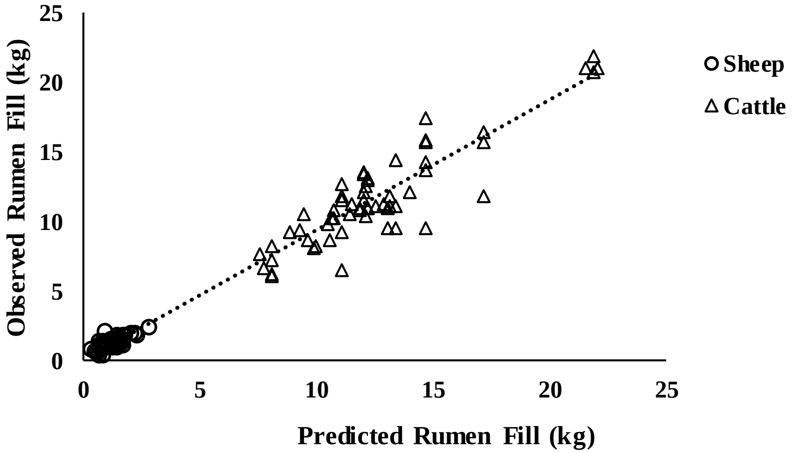

Figure 2a Relationship between the observed and predicted rumen fill for model development using Artificial Neural Networks.

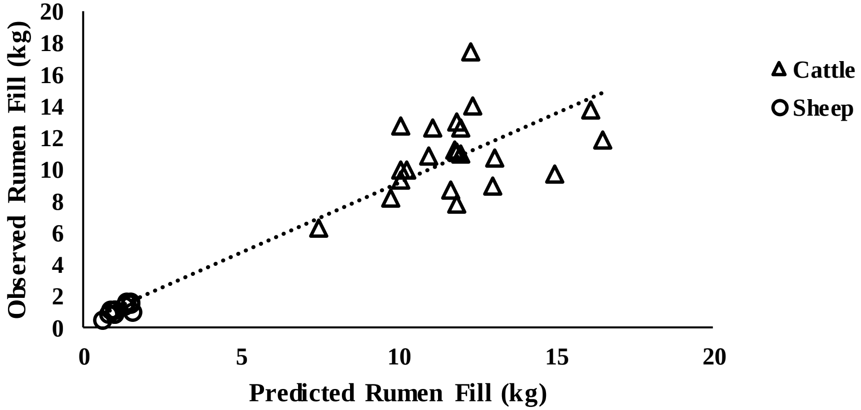

Figure 2b Relationship between the observed and predicted rumen fill for model development using the Random Forest model.

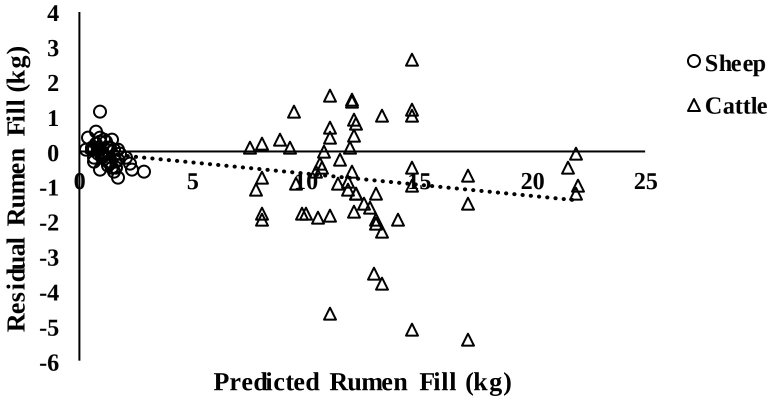

Figure 2c Residual (observed–predicted) plot against predicted rumen fill using Artificial Neural Networks.

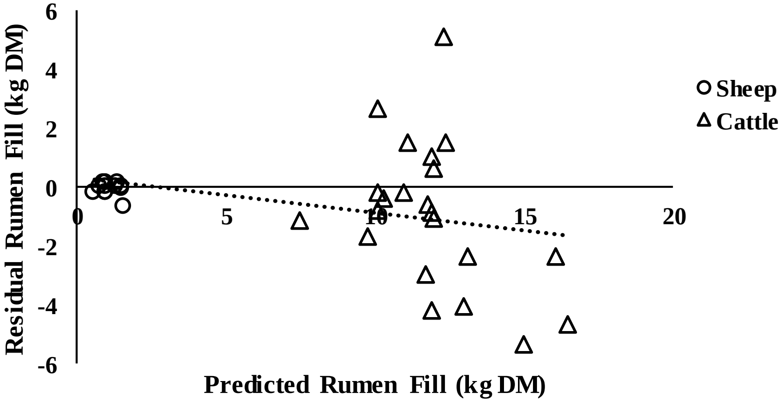

Figure 2d Residual (observed–predicted) plot against predicted rumen fill using the Random Forest model.

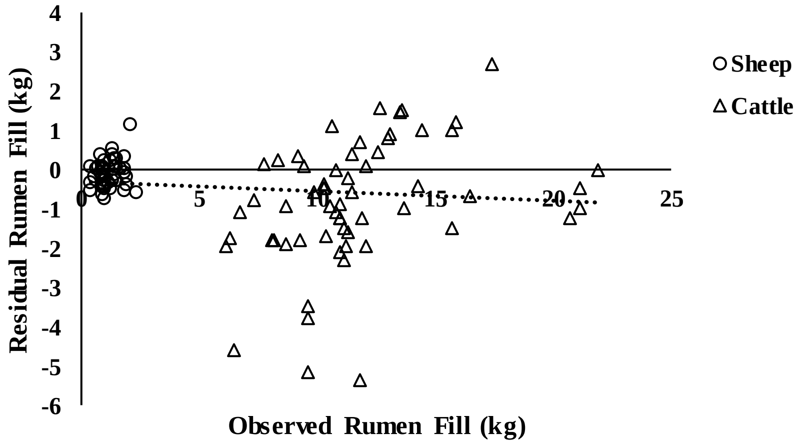

Figure 2e Residual (observed–predicted) plot against observed rumen fill using Artificial Neural Networks.

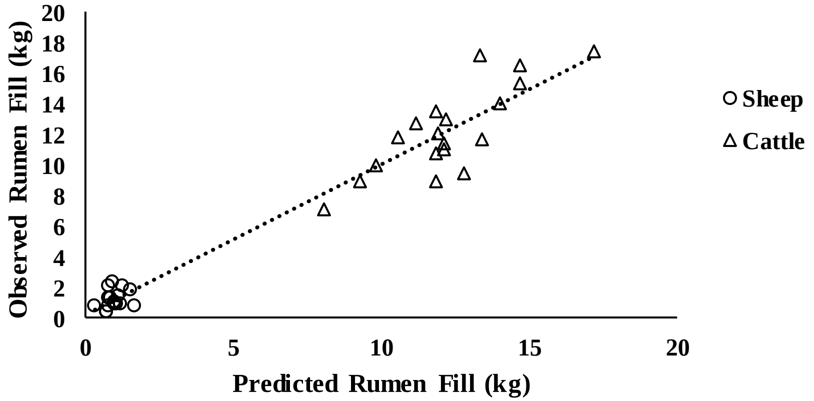

Figure 2g Relationship between the observed and predicted rumen fill for model validation using Artificial Neural Networks.

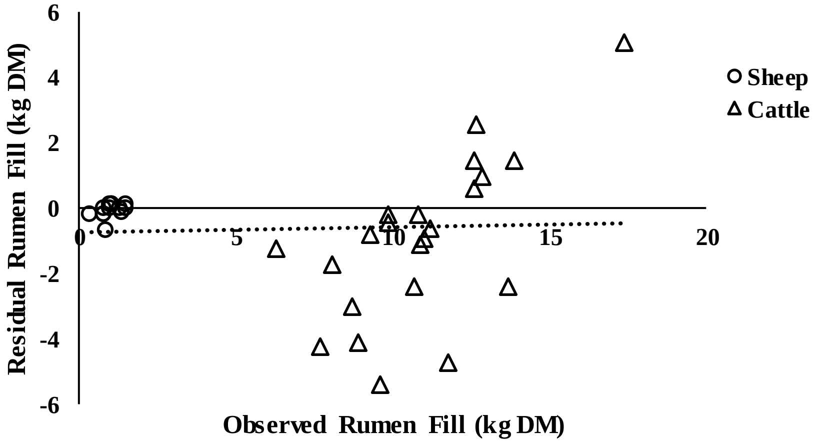

Figure 2f Residual (observed–predicted) plot against observed rumen fill using the Random Forest model.

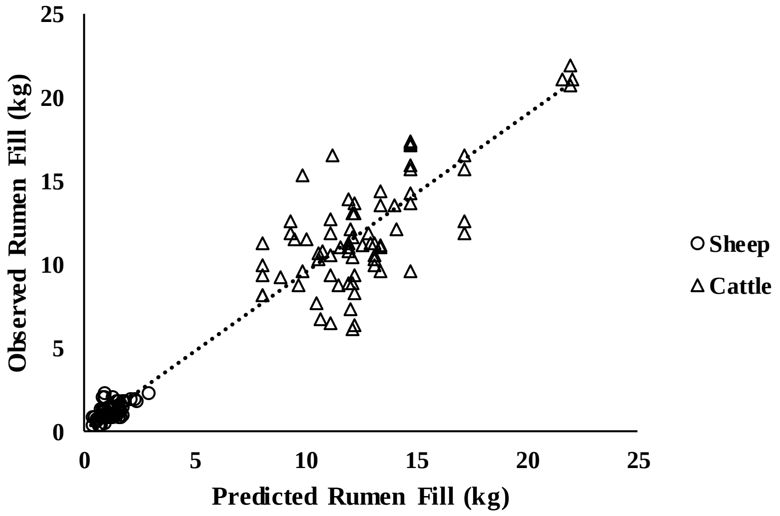

Figure 3 Relationship between the observed and predicted rumen fill for the entire dataset used for both model development and validation.

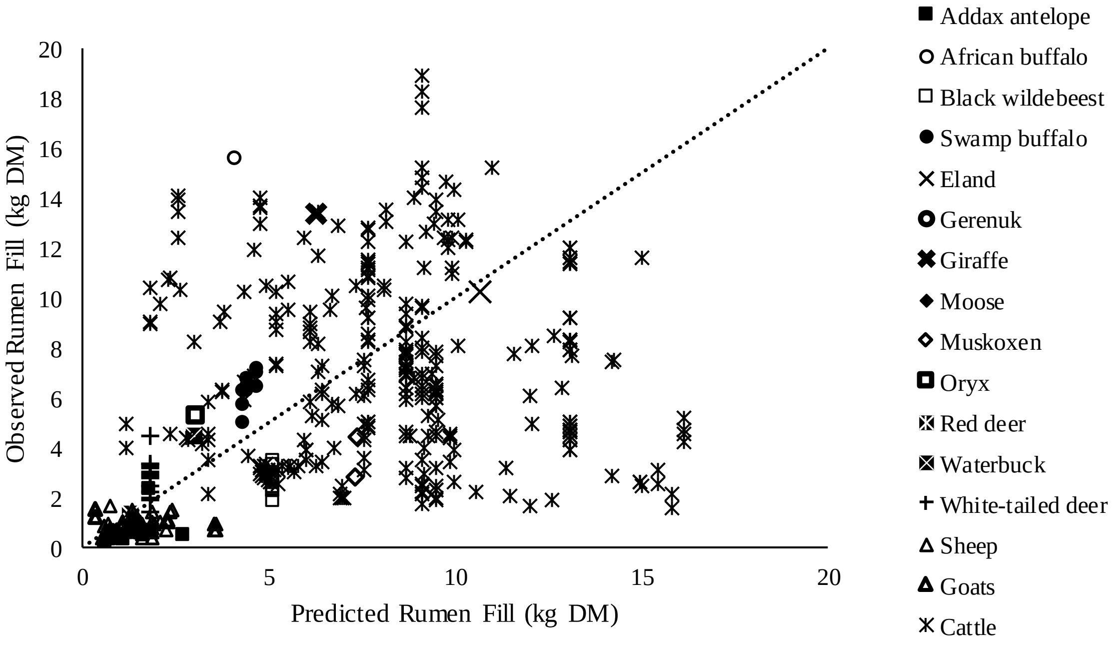

Figure 4 Relationship between the observed and predicted rumen fill for model performance test using observations from wild and domesticated ruminants.

APPENDIX

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