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Accepted Version

Angelidis, A. E., Crompton, L., Misselbrook, T., Yan, T., Reynolds, C. K. ORCID: https://orcid.org/0000-0002-4152-1190 and Stergiadis, S. ORCID: https://orcid.org/0000-0002-7293-182X (2021) Equations to predict nitrogen outputs in manure, urine and faeces from beef cattle fed diets with contrasting crude protein concentration. Journal of Environmental Management, 295. 113074. ISSN 0301-4797 doi: https://doi.org/10.1016/j.jenvman.2021.113074 Available at https://centaur.reading.ac.uk/98634/

To link to this article DOI: http://dx.doi.org/10.1016/j.jenvman.2021.113074

Publisher: Elsevier

Equations to predict nitrogen outputs in manure, urine and faeces from beef cattle fed diets with contrasting crude protein concentration

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ABSTRACT

Accurately predicting nitrogen (N) outputs in manure, urine and faeces from beef cattle is crucial for the realistic assessment of the environmental footprint of beef production and the development of sustainable N mitigation strategies. This study aimed to develop and validate equations for N outputs in manure, urine and faeces for animals under diets with contrasting crude protein (CP) concentrations. Measurements from individual animals (n=570), including bodyweight, feed intake and chemical composition, and N outputs were (i) analysed as a merged database and also (ii) split into three sub-sets, according to diet CP concentration (low CP, 84 -143 g/kg dry matter, n=190; medium CP, 144-162 g/kg dry matter, n=190; high CP, 163-217 g/kg dry matter, n=190). Prediction equations were developed and validated using residual maximum likelihood analysis and mean prediction error (MPE), respectively. In low CP diets the lowest MPE for N outputs in manure, urine and faeces was 0.244, 0.594 and 0.263, respectively; diet CP-specific equations improved accuracy in certain occasions, by 4.9% and 18.3% for manure N output and faeces N output respectively, while a reduction by 5.7% in the prediction accuracy for urinary N output was noticed. In medium CP diets the lowest MPE for N outputs in manure, urine and faeces was 0.227, 0.391 and 0.394, respectively; diet CP-specific equations improved accuracy by 13.2%, 41.2% and 16.8% respectively. In high CP diets the lowest MPE for N outputs in manure, urine and faeces was 0.120, 0.154 and 0.144, respectively; diet CP-specific equations improved accuracy in certain occasions by 5.8%, 9.1% and 6.3% respectively. This study demonstrated that for improved accuracy of N outputs in manure, urine and faeces from beef cattle, the use of dietary CP concentration is essential while dietary starch, fat, and metabolisable energy concentrations can be used to further improve accuracy. In beef cattle fed low N diets, using diet CP-specific equations improves prediction accuracy when feed intake or dietary CP concentration is not known. However, in beef cattle fed medium or high CP concentration diets, using equations that have been developed from animals fed similar CP concentration diets, substantially improves the prediction accuracy of N outputs in manure, urine and faeces in most cases.

Keywords

Nitrogen, efficiency, beef, urine, faeces, prediction

1. Introduction

Environmental issues arising from nitrogen (N) excretion in beef production systems are a concern for both the industry and for domestic and international regulation bodies, who increasingly seek improved calculation methods in order to promote more accurate reporting of greenhouse gas (GHG) and ammonia (NH_3) emission estimates, as well as to inform mitigation strategies (European Commission, 2010; DEFRA, 2017). Beef cattle often retain less than 20% of the total nutrients they ingest, with the rest being excreted mostly in faeces and urine as well as end products of various other metabolic processes (e.g. respiration, gastrointestinal gases) (NASEM, 2016). As regards N, the amount retained in the body can be as low as 10% of the N intake, with an upper limit of 20% (Satter *et al.*, 2002). Several studies involving beef and dairy cattle have reported an average N use efficiency (NUE) of nearly 25%, with measured values being between 15% and 40% (Kohn *et al.*, 2005; Huhtanen and Hristov, 2009; Calsamiglia *et al.*, 2010). Nevertheless, a large fraction of N in growing and finishing beef cattle rations comes from sources not suitable for human consumption, thereby reducing competition for food and transforming low human nutritional quality forages, grains and by-products into meat protein of higher value (Baber *et al.*, 2018).

A large proportion of dietary N which is excreted in faeces and urine contributes to atmospheric pollution and climate change by increasing volatilised NH_3 (an air quality concern) and nitrous oxide (N_2O; a potent GHG) emissions (Tamminga, 2006), eutrophication of terrestrial and aquatic habitats through subsequent N deposition and leaching of nitrates to groundwater (NASEM, 2016; Uwizeye *et al.*, 2020). However, faecal N is mostly present as organic compounds which typically exhibit slower mineralisation rates (Muck and Steenhuis, 1982), consequently producing less “reactive” N compared to urinary N; the latter is more labile and can have a more immediate impact on the environment as it swiftly cycles through it, taking different reactive N forms (Galloway *et al.*, 2003). Several studies conducted with beef cattle have shown that 40-80% of non-retained N is excreted in urine, and this amount increases with higher crude protein (CP) or rumen degradable protein (RDP) concentrations of the diet (Archibeque *et al.*, 2007; Vasconcelos *et al.*, 2009; Erickson and Klopfenstein, 2010; Koenig and Beauchemin, 2013a, b). Reynolds and Kristensen (2008) have also concluded that feeding N above requirements increases NH_3 absorption and subsequent urea production in the liver, therefore increasing urea excretion in urine. Most of the N excreted in urine is in the form of urea, especially at higher N intakes, and urea is a substance rapidly converted to ammonium and carbon dioxide once exposed to the action of microbial urease enzymes (Varel *et al.*, 1999; Monteny *et al.*, 2002). In feedlot operations, the production of ammonium and carbon dioxide might be greater than in pasture systems due to the high abundance of microbes (Cole *et al.*, 2009) and the reduced infiltration of urine (Rotz and Oenema, 2006; Hristov *et al.*, 2011) in feedlot surfaces compared to soil. An amount of infiltrated N at pasture may be further reduced by plant uptake to support growth (Petersen *et al.*, 1998), although excessive N infiltration will still result in groundwater pollution (NASEM, 2016).

Previously published studies on N excretion from beef cattle, did not either incorporate the diet chemical composition, nutrient digestibilities and energy values (Guo *et al.*, 2004; Guo and Zoccarato, 2005), or account for the different N amounts excreted in urine and faeces (Yan *et al.*, 2007) in their analyses. More recent studies have partitioned N excretion into urine and faeces (Hirooka, 2010; Waldrip *et al.*, 2013; Dong *et al.*, 2014; Reed *et al.*, 2015) with the latter also using fibre and energy related predictors for the first time. A recent study from Angelidis *et al.* (2019) was the first to include a wider set of explanatory variables for the prediction of N excretion in urine and faeces specifically by beef cattle, as well as the evaluation of NUE. The evaluation of the previously published models and the developed ones in the study of Angelidis *et al.* (2019), has shown a degree of under-prediction in N outputs for animals at the highest range of actual N excretion rates. The issue was partly, but not completely resolved with their equations, highlighting the potential risk of underpredicting the impact that intensive beef systems may have on atmospheric and water pollution. This could be attributed partly to the fact that all evaluated models were created using N excretion data obtained at a lower range of N intake than for the measurements in which under-prediction was noticed. In conjunction with the documented decrease in NUE with increasing dietary crude protein concentrations (Waldrip *et al.*, 2013; Dong *et al.*, 2014; Angelidis *et al.*, 2019), this finding emphasizes the necessity to create prediction models, potentially highly influenced by diet CP content and N intake, based on a N excretion range applicable to the one that the models will be used for.

Therefore, the aim of our study was to (i) develop diet CP-specific prediction equations for N output in total manure, faeces and urine from growing and finishing beef cattle which were fed diets with different protein concentrations, and (ii) compare their prediction accuracy with that of existing prediction equations.

2. Materials and methods

2.1 The database

The database used in the present study was constructed by merging three datasets of individual animal measurements from digestibility trials, conducted with beef cattle at Agri-Food and Biosciences Institute (AFBI, UK; n=286) Hillsborough (Yan *et al.*, 2007), Centre for Dairy Research, University of Reading, UK (CEDAR; n=48) (Hammond *et al.*, 2014; Hammond *et al.*, 2015) and Beltsville Agricultural Research Center (n=236), USDA ARS (Haaland *et al.*, 1981; Tyrrell and Reynolds, 1988; Reynolds *et al.*, 1991; Lapierre *et al.*, 1992; Reynolds *et al.*, 1992). All digestibility trials involved animals housed in individual stalls where feed intake and total collection of faeces and (acidified) urine was taking place over 5-7 days and the mean daily value for each measured parameter was used in the dataset. Composite samples were then analysed for N content by the macro Kjeldahl method (AOAC, 1995). The resulting database contained 570 observations from individual animals that included at least the following parameters: animal body weight (BW, kg); diet total forage content (TF, g/100g DM); diet concentrations of crude protein (CP, g/kg DM), N (g/kg DM) and metabolisable energy (ME, MJ/kg DM); intakes of dry matter (DMI, kg/d); and outputs (g/d) of N in manure (MNO), urine (UNO) or faeces (FNO). Where available, the following diet concentration parameters were also included in the database: neutral-detergent fibre (NDF, g/kg DM), acid-detergent fibre (ADF, g/kg DM), ether extract (EE, g/kg DM), starch (ST, g/kg DM), ash (g/kg DM), organic matter (OM, g/kg DM), gross energy (GE, MJ/kg DM). The mean values, standard deviation, number of observations, and minimum and maximum values for each parameter in the database are presented in Table 1 and a brief description is given in the supplementary material (Appendix; Summary of the data used). There was a wide variation in animal traits and production characteristics in this database, such as the animal breed (including Holstein, Hereford x Angus, Angus, and others), BW (153-631 kg), production stage (growing, ≤350 kg BW; and finishing, >350 kg BW), TF (20-100% of total DM), and various diet ingredients. All abbreviations used in this manuscript are introduced at their first instance in the text and also provided as a list following the Conclusion section.

2.2 Statistical analysis

The equations for the prediction of N excretion in manure, urine and faeces were produced using linear and multiple regression models in Genstat 17th edition (VSN International, 2015). The prediction equations were developed using residual maximum likelihood analysis, so that the potential random effects of experiment ID, animal ID, and treatment ID, experiment location and animal production stage (growing or finishing) were accounted for (Robinson, 1987; Searle *et al.*, 1992). The linear regression equations developed included MNO (g/d), UNO (g/d) and FNO (g/d) as response variables and (i) DMI, NI, BW in single linear relationships (Table 2), and (ii) DMI, NI, BW, TF, CP, NDF, ADF, ST, EE, ME in multiple linear relationships (Table 2), as explanatory variables. These two distinct approaches aimed to produce both (i) simple models for easier application in a commercial farm environment, where accurate feed intake measurements are challenging while BW is readily avilable and can serve as a proxy for DMI (because heavier animals consume more food), as well as (ii) higher complexity models with an improved prediction accuracy, to be used where relevant predictors are available (e.g. research environment). The method used in the present study to develop the prediction equations has been previously used in several studies (Stergiadis *et al.*, 2015a; Stergiadis *et al.*, 2015b; Stergiadis *et al.*, 2016). In brief, the optimum random model developed for each response variable was built by fitting the same fixed effect model and the prospective models of the random variation. The observed changes in deviance was the driver of whether to include a random factor in the model or not; and eventually the optimum random model included the individual experiment ID, animal ID, treatment ID. The Wald statistic was used in order to evaluate the significance of the various explanatory variables used in the single and multiple linear regressions. In the current study, the predictors comprising the prediction equations were statistically significant ($P<0.05$) according to the Wald statistic. The residual diagnostics of the final model were evaluated using normality plots. An approximate R^2 (pseudo correlation coefficient; squared correlation of the response and the fitted values) was generated to represent the proportion of variability explained.

In a recent study, Angelidis *et al.* (2019) showed that literature equations tend to under-predict N outputs in manure, urine and faeces, in animals with N excretions close to the highest end of the range. In order to provide an insight into how the prediction accuracy in specific N outputs ranges may be improved by using equations developed for animals with N intakes corresponding to those outputs, the database was split into three sub-sets, according to the diet CP concentrations (low CP, 84 -143 g/kg DM, n=190; medium CP, 144-162 g/kg DM, n=190; high CP, 163-217 g/kg DM, n=190), in line with the Agriculture and Horticulture Development Board (AHDB) recommendations for growing and finishing beef cattle dietary protein (AHDB, 2016). Three additional sets of equations for the prediction of MNO (g/d), UNO (g/d) and FNO (g/d) were developed, using the methods and explanatory variables described for the merged digestibility trials database (Tables 3, 4 and 5; for low CP, medium CP and high CP, respectively).

An external validation was performed to assess the prediction accuracy of all equations developed in the current study as well as of those previously published in literature. For this purpose, the literature database developed in a previously published study (Angelidis *et al.*, 2019) was used. Furthermore, this external database was also divided into three sub-sets representing low, medium and high dietary CP concentration (using the same range as described above). Evaluations were performed using the mean-square prediction error (MSPE) method:

$$\mathrm{MSPE} = 1/n\ \Sigma\ (P-A)^2$$

where P and A are the predicted and actual values respectively, and n represents the number of pairs of P and A values compared. Mean prediction error (MPE) was calculated to describe the prediction accuracy, using the following formula:

$$\mathrm{MPE} = \sqrt{(\mathrm{MSPE})}\ /\ (\Sigma A/n)$$

The quantification of agreement between actual and predicted values was derived from a Lin's Concordance Correlation Coefficient (Rc) analysis (Lawrence, 1989), with the results presented in Table 4 (for the equations produced from the merged digestibility trials database and the previously published models) and Table 5 (for the equations developed from the merged digestibility trials sub-sets). For the graphic representation of the agreement between predicted and actual values of MNO, UNO and FNO, Bland – Altman plots were used (Altman and Bland, 1983) including (i) equations presented previously from other authors, (ii) equations developed in the current study using the same explanatory variables, (iii) equations developed in the current study with higher prediction accuracy than the existing ones and (iv) equations developed in the current study from the partitions of the merged digestibility trials database. Rc with 95% confidence interval are also presented in the same graphs.

A total of 129 new equations, of which 51 were developed by the entire merged digestibility trials database, 24 by the low CP sub-set, 18 by the medium CP sub-set and 36 by the high CP sub-set, were validated against the literature database developed in the study by (Angelidis *et al.*, 2019) and its corresponding sub-sets. The models developed by the merged digestibility trials database were initially validated against the entire literature database (Table A2 for the prediction of MNO, UNO and FNO; Eq. 1a-1p, 2a-2s and 3a-3p, respectively), while the models developed from the sub-sets were validated against the corresponding CP sub-sets of the external validation database (Table A3 for the prediction of MNO, UNO and FNO; Eq. 4a-4i, 7a-7g and 10a-10p; Eq. 5a-5g, 8a-8f and 11a-11k; Eq. 6a-6h, 9a-9e and 12a-12i, respectively). In order to assess the potential benefit in prediction accuracy by using the models developed by corresponding sub-sets, the equations resulting from the entire merged digestibility trials database that included exactly the same predictors as the ones resulting from the sub-sets, were validated against the same external validation data (Table A4 for the prediction of MNO, UNO and FNO; Eq. 4a-4i, 7a-7g and 10a-10p; Eq. 5a-5g, 8a-8f and 11a-11k; Eq. 6a-6h, 9a-9e and 12a-12i, respectively). Finally, 23 external equations presented in the appendix (Table A1), for the prediction of MNO (Eq. E1-E9; Yan *et al.* (2007); Reed *et al.* (2015)), UNO (Eq. E10-E17; Hirooka (2010); Reed *et al.* (2015)); Waldrip *et al.* (2013); Dong *et al.* (2014)) and FNO (Eq. E18-E23; Hirooka (2010); Reed *et al.* (2015)); Waldrip *et al.* (2013); Dong *et al.* (2014)), were validated against the literature database developed in the study by Angelidis *et al.* (2019) (Table A2 for the prediction of MNO, UNO and FNO; Eq. E1-E9, E10-E17 and E18-E23, respectively).

3. Results

3.1 Prediction of N outputs using the entire merged digestibility trials database

The effects of DMI, CP, ME, TF, ADF, NDF, NI, ME, ST, EE, BW for the prediction of MNO, were significant according to the Wald statistic (Table 2; Eq. 1a-1p). MNO was positively correlated to DMI, CP, TF, ADF, NDF, ST and negatively correlated to EE and ME. When DMI and CP were used as predictors (Eq. 1b) the prediction accuracy was higher compared to using DMI alone in a single linear model (Eq. 1a), while adding ME to the former model, further reduced MPE (Eq. 1c). The use of NI instead of DMI as a sole predictor for the prediction of MNO (Eq. 1g), produced a lower MPE. Furthermore, the model including NI as the primary predictor and ME, ADF and ST as secondary predictors (Eq. 1j) showed the lowest MPE for the prediction of MNO. When BW was used as sole predictor (Eq. 1l), the prediction accuracy was low compared to the linear models using either DMI or NI as sole predictors. However, by using BW and CP in a multilinear model the MPE was slightly reduced (Eq. 1m), taking its lowest value when ME was added to the above model (Eq. 1n).

For the prediction of UNO, the effects of DMI, CP, TF, ADF, ME, EE, ADF, ST, NI, BW were significant according to the Wald statistic (Table 2; Eq. 2a-2s). UNO was positively correlated to DMI and CP, and negatively correlated to ME and EE. Prediction accuracy was higher when CP was used in combination with DMI for the prediction of UNO (Eq. 2b), compared to using DMI as sole predictor (Eq. 2a). The combination of DMI, CP and ADF produced a better MPE (Eq. 2d), while the addition of either EE or ST to the above model (Eq. 2g and 2h, respectively), further increased the prediction accuracy. The model including DMI as the primary predictor and CP, ADF, ST and ME as secondary predictors (Eq. 2i), produced the lowest MPE for the prediction of UNO. Using NI as a predictor in a single linear model (Eq. 2j) produced a better MPE compared to the respective single linear model with DMI. Furthermore, including ST and EE as secondary predictors (Eq. 2n) improved the prediction accuracy, yet only slightly. Equations including BW as the primary predictor and several secondary predictors in single and multiple linear models (Eq. 2o-2s) had similar MPEs, with the model including BW as a sole predictor (Eq. 2o) having a higher MPE compared to the previous single linear models with either DMI or NI, and the addition of CP to the above model (Eq. 2p) only marginally improving the prediction accuracy.

Finally for the prediction of FNO, the effects of DMI, CP, ME, TF, ADF, NI, NDF, ST, EE, BW were significant according to the Wald statistic (Table 2; Eq. 3a-3p). FNO was positively correlated to DMI, CP, ST and EE and negatively correlated to ME, TF and ADF. The prediction accuracy of the model using DMI as a sole predictor (Eq. 3a), was improved after the addition of CP in a multiple linear prediction model (Eq. 3b), with further improvement after TF was added to the above model (Eq. 3d). The model including NI as a sole predictor (Eq. 3g), had better prediction accuracy than adding any other secondary predictor (Eq. 3h-3k). Conversely, BW as a sole predictor (Eq. 3l) resulted in a high MPE, but when CP, ME and EE were added to the above model (Eq. 3o) the MPE was reduced, taking the lowest value in the equation including CP, ME and ST as secondary predictors (Eq. 3n).

3.2 Prediction of N outputs using the low dietary protein sub-set

The effects of DMI, CP, ME, ADF, NDF, NI, BW for the prediction of MNO, were significant according to the Wald statistic (Table 3; Eq. 4a-4i). MNO was positively correlated to DMI, CP, NDF, NI and BW and negatively correlated to ME and ADF. Prediction accuracy was improved when CP was used in combination with DMI for the prediction of MNO (Eq. 4b), compared to using DMI as sole predictor (Eq. 4a). The single linear model with NI (Eq. 4e) had the lowest MPE for the prediction of MNO.

Subsequently, for the prediction of UNO, the effects of DMI, CP, NI, BW, ME, TF were significant according to the Wald statistic (Table 3; Eq. 5a-5g). UNO was positively correlated to DMI, CP, NI, BW and TF and negatively correlated to ME. The multiple linear model including DMI and CP as predictors along with the single linear including NI as predictor (Eq.

5b and 5c, respectively) gave the best prediction accuracy among the group, yet the MPE values were high.

For the prediction of FNO, the effects of DMI, CP, ME, TF, NI, BW were significant according to the Wald statistic (Table 3; Eq. 6a-6h). MNO was positively correlated to DMI, CP, NI and BW and negatively correlated to ME and TF. The various models appeared to have similar prediction accuracy despite the primary predictor involved, with the exception of the multiple linear model including BW, CP and ME as predictors (Eq. 6h), which had a notably lower MPE.

3.3 Prediction of N outputs using the medium dietary protein sub-set

For the prediction of MNO, the effects of DMI, CP, ME, NI, ST, and BW were significant according to the Wald statistic (Table 4; Eq. 7a-7g). MNO was positively correlated to DMI, CP, NI, ST and BW and negatively correlated to ME. Prediction accuracy was improved when CP and ME was used in combination with DMI for the prediction of MNO (Eq. 7c), compared to using DMI as sole predictor (Eq. 7a). Similarly accurate was the single linear model with NI (Eq. 7d), while the model with BW as the primary predictor had low accuracy (Eq. 7g).

The effects of DMI, CP, NI, ADF, ST, and BW for the prediction of UNO were significant according to the Wald statistic (Table 4; Eq. 8a-8f). UNO was positively correlated to DMI, CP, NI, BW and TF and negatively correlated to ME. The single linear model including NI as predictor produced a low MPE (Eq. 8c), which was further improved after adding ADF and ST as secondary predictors (Eq. 8d).

For the prediction of FNO, the effects of DMI, NI, ME, BW, and CP were significant according to the Wald statistic (Table 4; Eq. 9a-9e). FNO was positively correlated to DMI, NI and BW and negatively correlated to CP and ME. The various models appeared to have similar prediction accuracy, as happened with the respective equations in the table 3 (Eq. 6a-6h), despite the primary predictor involved. In this case, the multiple linear model with NI and ME as predictors, had the lowest MPE among the models (Eq. 9c).

3.4 Prediction of N outputs using the high dietary protein sub-set

The effects of DMI, CP, TF, ME, EE, NI, ADF, and BW for the prediction of MNO were significant according to the Wald statistic (Table 5; Eq. 10a-10p). MNO was positively correlated to DMI, CP, NI and BW and negatively correlated to ME, EE and ADF. Prediction accuracy observed while using CP in conjunction with DMI for the prediction of MNO (Eq. 10b) was better than using DMI as sole predictor (Eq. 10a). Furthermore, adding ME as secondary predictor to the above model (Eq. 10e) further increased prediction accuracy. Similar results were observed in the model that included DMI as primary and CP, TF and ME as secondary predictors (Eq. 10f). When NI was used in combination with either ME alone or ME and TF (Eq. 10h and 10i) the MPE was in both cases lower compared to using NI as sole predictor (Eq. 10g). Furthermore, the substitution of TF with ADF in the above model produced an equation with similar prediction accuracy. When BW was used as a sole predictor (Eq. 10l), MPE appeared high in the single linear model, yet after the addition of CP and ME as secondary predictors (Eq. 10n), the prediction accuracy was notably improved.

For the prediction of UNO, the effects of DMI, CP, ME, NI, NDF, EE, BW, and TF were significant according to the Wald statistic (Table 5; Eq. 11a-11k). UNO was positively correlated to DMI, CP, NI, BW and TF and negatively correlated to ME, NDF and EE. The multiple linear model including DMI, CP and ME as predictors (Eq. 11c) displayed a notably lower MPE than using DMI as sole predictor (Eq. 11a). In the same manner, the multiple model including NI and ME as predictors (Eq. 11e) was more accurate than the one using NI as sole predictor (Eq. 11d). When BW was used as the primary predictor, only the model comprising CP and ME as secondary predictors showed a low MPE (Eq. 11j), with the model using the above predictors plus TF (Eq. 11k) showing similar, yet lower prediction accuracy.

Finally, for the prediction of FNO, the effects of DMI, CP, ME, TF, NI, and BW were significant according to the Wald statistic (Table 5; Eq. 12a-12i). FNO was positively correlated to DMI, CP, NI and BW and negatively correlated to ME. The model comprising DMI, CP and ME (Eq. 12c) had the highest prediction accuracy among the group of equations with DMI as primary predictor. When NI was used along with ME as a secondary predictor (Eq. 12f), the MPE was lower than using NI as sole predictor (Eq. 12e), while the addition of TF to the former model (Eq. 12g) did not improve the prediction accuracy. The model including BW as primary predictor (Eq. 12h) was only marginally improved when CP and ME were added as secondary predictors (Eq. 12i), however both MPE values were high compared to the rest in the FNO group.

3.5 External validation of the prediction equations

For the prediction of MNO in the merged digestibility trials database, (Fig. 1; plots a-c), the equation incorporating the most predictors (plot c), showed a higher Rc compared to both the existing (plot a) and new (plot b) equations which used NI as sole predictor. The Rc values for UNO and FNO (Fig.1; plots d-i) appeared similar. Rc and variation of the residual MNO, UNO and FNO was reduced when new models developed in the present study, including additional predictors (Eq. 1j, 2i and 3d), were applied. For the prediction of MNO, there was an over prediction in the equations including NI as sole predictor (Eq. E3 and 1g), when actual MNO was lower than 60 (g/d) and 67 (g/d), respectively; and under-prediction in the same equations, when actual MNO was higher than 168 (g/d) and 170 (g/d), respectively. For the prediction of UNO, there was an over prediction in the equations including NI as sole predictor (Eq. E10 and 2j) when actual UNO was lower than 49 (g/d) and 50 (g/d), respectively; and an under-prediction in the same models when actual UNO was higher than 121 (g/d) and 109 (g/d), respectively. In the case of FNO, there was no significant over- or under- prediction.

As regards the equations produced from the low CP sub-set compared to their identical ones from the full database (Fig. 2; plots a-f), the equation produced from the sub-set for the prediction of MNO showed a notably higher Rc compared to the identical equation produced from the full database, which also greatly over-predicted MNO, while the equations for the prediction of UNO and FNO showed similar Rc values. In the case of UNO, there was an under-prediction when actual UNO was higher than 93 (g/d) in both sets of equations. Furthermore, equations developed from the medium CP sub-set, when compared to the identical ones from the merged digestibility trials database (Fig. 3; plots a-f) showed higher Rc values for the prediction of MNO and FNO, with a similar variation across the zero line and no significant over- or under- prediction. For the prediction of UNO (Eq. 2j and 8c), there was a small overprediction when actual UNO was lower than 50 (g/d) and 54 (g/d); and an underprediction when actual UNO was higher than 99 (g/d) and 105 (g/d), respectively. Finally, equations developed from the high CP sub-set (Fig. 4) had in all cases similar or higher Rc values, when compared to their identical ones from the merged digestibility trials database. Variation of the residual MNO was reduced when the medium CP sub-set equation was used, while in the case of both UNO and FNO no significant differences were observed

4. Discussion

4.1 Prediction accuracy of equations developed using the merged digestibility trials database

The most accurate prediction of MNO was seen when NI, ME, ADF and ST were used as predictors, and this equation may be used when such data are available. Yan *et al.* (2007) found that adding predictors in a model already containing NI did not improve prediction accuracy, while Angelidis *et al.* (2019) there found a 67% improvement in prediction accuracy (MPE reduced from 0.440 to 0.162) when either dietary forage proportion, fibre concentration or nutrient digestibility data were used as additional predictors. In contrast to Angelidis *et al.* (2019), this study demonstrated that individually adding fibre or energy parameters in a model already containing NI may not beneficial to prediction accuracy but when these are added altogether, and in conjunction with ST the prediction accuracy may be increased up to 47% (MPE reduced from 0.242 to 0.129). The use of DMI alone as a predictor for MNO was expected to show low prediction accuracy, as it does not account for the level of dietary N. The addition of either fibre or forage proportion did not further improve the model, similarly to Yan *et al.* (2007), while the addition of ME improved the accuracy of combined model of DMI and CP by 13% (MPE reduced from 0.305 to 0.270). Energy values, such as the readily available at commercial farms as measured GE or calculated ME, are known to improve MNO prediction (Yan *et al.*, 2007; Reed *et al.*, 2015; Angelidis *et al.*, 2019), as they are both and useful indicators of microbial CP synthesis in the rumen (Hespell and Bryant, 1979). According to the Bland-Altman plots, the addition of diet energy and fibre concentration as predictors in equations already including NI improved the MNO underprediction, which was observed when NI was used as a sole predictor. Although NI is an accurate predictor for MNO, energy parameters, when added, may explain more variation in the data as they are profoundly affecting NUE (Angelidis *et al.*, 2019). As feed intake cannot be accurately measured in commercial farms, the readily available BW (which can serve as proxy for DMI because heavier animals eat higher amounts of feed), was also evaluated in the current study; the best performing model included BW, CP and ME as prediction, yet in the absence for DMI the overall prediction accuracy was relatively low.

The most accurate model to predict UNO included DMI, CP, ADF, ST and ME. DMI as sole predictor showed low prediction accuracy, a finding consistent with previous studies (Dong *et al.*, 2014; Angelidis *et al.*, 2019). However, prediction of UNO had an overall low accuracy, while the most accurate model relies on predictors that may be available in a research environment, but are unlikely to be recorded on commercial farms. Addition of ST and EE in the present work further improved prediction accuracy of models already containing NI as sole predictor. Dietary energy sources, such ST and EE may improve the energy supply in rumen microorganisms and enhance microbial protein synthesis, instead of ammonia, and therefore reduce UNO in the form of urea (Bach *et al.*, 2005). It is known that the addition of supplemental fat over 30 g/kg DM in the diet may disrupt ruminal fermentation and reduce the digestibility of structural carbohydrates, however amounts of up to 60 g/kg DM can be supplemented without problems, provided this is reached through a diet adaptation period (Hess *et al.*, 2008). Average fat intake was less than 30 g/kg DM in our database with a maximum of 63 g/kg DM, thus being unlikely that animals developed any adverse effects on digestibility. Models that did not account for NI had poor prediction accuracy give the strong positive correlation between NI and UNO (Archibeque *et al.*, 2001), and the fact that most excess dietary N is excreted in urine rather than faeces (Varel *et al.*, 1999). This is finding is in line with recent studies (Waldrip *et al.*, 2013; Dong *et al.*, 2014; Reed *et al.*, 2015; Angelidis *et al.*, 2019) showing NI to be an essential predictor for UNO. The equation from Hirooka (2010) was slightly more accurate when compared with its corresponding equation in the present study, while the under-prediction at the higher end of the range of actual N excretion as also observed by Angelidis *et al.* (2019), was common in both equations. The equation including DMI, CP, ADF, ST and ME as predictors, resolved this issue and can be recommended when such data are available.

Finally, FNO was accurately predicted when DMI, CP and TF were used together, yet excluding TF from the prediction model resulted in similar accuracy. When DMI is not available in practice, the equation including BW, CP, ME and ST could be used without compromising accuracy, although a detailed feed analysis is needed to obtain the additional parameters. The strong relationship between FNO and NI, as well as models of similar accuracy, were previously reported (Waldrip *et al.*, 2013; Dong *et al.*, 2014), . Microbial protein produced in the hindgut from the digestion of starch, increases N excretion through faeces, contributing to lower apparent N digestibility and a shift in N excretion from faeces to urine (Reynolds *et al.*, 2001); thus explaining the beneficial role of ST on increasing the explained variation and prediction accuracy. In case of FNO prediction, there were no significant over- or under-prediction issues.

4.2 Equations performance on the low range of diet CP concentration

The equation using DMI or BW as sole predictors and the low CP sub-set for the prediction of MNO, was markedly more accurate compared to the one produced from the merged digestibility trials database, when validated against the low CP range of the existing literature database by Angelidis *et al.* (2019). This suggests that when diet N concentration is not known, it becomes important that the equations used have been developed from animals at low diet CP. This is not necessary when diet CP is known because when CP was added to the above models, the prediction accuracy of the equations from the merged digestibility was higher than the diet CP-specific equations; and overall higher than the models without CP. The efficiency of microbial CP synthesis depends on the rumen N availability and the energy supply to ruminal microorganisms for growth, as mentioned above, and that explains why the addition of CP benefits the prediction accuracy (Bach *et al.*, 2005). Other combinations of NI, DMI or BW with CP and ME, or with CP, ADF and NDF led to similar prediction accuracy among the equations coming from both the merged database and the low CP dataset. However,adding these additional predictors did not improve prediction of MNO, which reveals that predictors describing diet and energy and fibre contents as not as important when we predict MNO from animals consuming low CP diets. Angelidis *et al.* (2019) have shown that the addition of dietary forage proportion can improve prediction accuracy by up to 20% in models already including DMI and CP, a fact demonstrated for the animals consuming low CP diets.

When DMI and BW were used as sole predictors for the prediction of UNO, prediction accuracy was expected to be low as this has been previously observed (Dong *et al.*, 2014;

Angelidis *et al.*, 2019). The combination of the above models with CP did not markedly improve the prediction accuracy, even when diet CP-specific equations were used. NI appeared to be the best sole predictor for the prediction of UNO, yet displaying an overall low accuracy compared to the equations available in literature (Waldrip *et al.*, 2013; Dong *et al.*, 2014; Angelidis *et al.*, 2019). ME was statistically significant in a single case, yet it did not benefit the accuracy, in the model including BW, CP and ME as predictors. Reynolds and Kristensen (2008) have concluded that feeding N above requirements raises NH_3 absorption and subsequent urea production, therefore increasing N excretion in urine. However, in cases of animals consuming low-CP diets, the excess dietary N is minimised and therefore ME does not play such an important role as a predictor as in animals at medium or high CP diets. Prediction of UNO is still challenging in low CP diets, and this has not been resolved by using diet CP-specific equations or additional predictors. Incorporating the metabolisable protein as predictor and accounting for all protein fractions reaching the duodenum (ruminally undegradable protein, microbial protein and endogenous protein), may further improve prediction accuracy of existing models but such data are scarce in literature.

Equations for the prediction of FNO including DMI either as sole predictor or in combination with CP, ME and TF, showed similar accuracy among the databases, confirming that DMI is a reliable sole predictor for FNO in low CP diets (Stergiadis *et al.*, 2015a; Angelidis *et al.*, 2019). The models originating from the merged digestibility trials database including NI as sole predictor or in combination with either ME or ME and TF, performed better than diet CP-specific equations for the prediction of FNO in animals under low-CP diets. However, the combination of BW with CP and ME developed from the low CP sub-set, improved prediction accuracy compared with its identical from the merged digestibility trials database, and its use can be recommended in the common commercial situation that DMI is not available but these predictors are.

4.3 Equations performance on the medium range of diet CP concentration

Equations for the prediction of MNO using the medium CP sub-set, showed similar prediction accuracy when they included DMI or BW as sole predictors, with their respective models from the merged digestibility trials database. In case of animals in medium CP diets, NI as a sole predictor can be used for small improvements in the accuracy of prediction of MNO than using DMI or BW, whendiet CP content is known. Incorporating additional predictors, such as CP, ME and ST, in all cases improved accuracy compared to their respective equations from the merged digestibility trials database; thus highlighting that, in contrast with low CP diets, there is a benefit of using diet-specific equations for animals in medium CP diets when these predictors are available. Several previous studies have suggested that dietary N concentration is negatively correlated with NUE in beef (Yan *et al.*, 2007; Waldrip *et al.*, 2013; Dong *et al.*, 2014). Therefore, using equations that have been developed using data from animals consuming diets of different N concentrations than the animals the equations are used to assess may deteriorate prediction accuracy; as the potential differences in kg N output per kg NI may not be as effectively accounted for.

As in low CP diets and previous work (Angelidis *et al.*, 2019), prediction equations for UNO from animals consuming medium CP diets, developed by using either DMI, NI or BW as sole predictors, showed low accuracy levels in all cases. The addition of CP as predictor benefited the prediction accuracy, as previously shown Angelidis *et al.* (2019), yet no benefit was seen by using diet-specific equations. Contrastingly, CP had no significant impact on the prediction accuracy of UNO when combined with BW, thus agreeing with Angelidis *et al.* (2019) that feed intakes are essential for the prediction of UNO. In contrast to low CP diets, the diet-specific equation combining of NI, ADF and ST, exhibited the highest prediction accuracy for UNO in animals under medium CP diets; thus revealing that energy and fibre variables, as well as diet-specific equations, are becoming more efficient on improving prediction accuracy as diet CP contents increase.

For the prediction of FNO, single or multiple linear models with DMI or BW as the main predictors, show similar and high MPE values in all cases; thus being in line with previous work (Angelidis *et al.*, 2019). This contrasts the finding for low CP diets and reveals that the need for additional predictors for FNO increases at diets with medium CP. The use of NI with ME improved prediction accuracy compared to the aforementioned models, especially when developed from the medium CP sub-set compared to the merged digestibility trials database. Therefore it is likely that the improvement in the prediction of MNO when using diet CP-specific equations in animals consuming medium CP diets, mainly comes from the improvement in the prediction of UNO, and at a lesser extent FNO, as the prediction error of the latter was still relatively high.

4.4 Equations performance on the high range of diet CP concentration

Diet-specific equations for the prediction of MNO, produced from the high CP sub-set, demonstrated in most cases higher prediction accuracy when compared to their merged digestibility trials database respective models. This finding emphasizes the need to use diet CP-specific equations in animals with increased NI (which are expected to have the highest N outputs; (Yan *et al.*, 2007; Waldrip *et al.*, 2013; Dong *et al.*, 2014)) in most cases. The addition of CP to the model including DMI as a sole predictor increased prediction accuracy, while the subsequent addition of TF did not affect it, which is in line with Yan *et al.* (2007). Further adding ME as secondary predictor offered a even higher accuracy for the prediction of MNO, thus further highlighting that CP and ME are key predictors for MNO, which is in line with Angelidis *et al.* (2019). When DMI, CP and ME are the only available predictors, then diet-specific equations are preferable. However, if TF or EE are also available the prediction accuracy can be maximised if the equations from the merged database are used. This may also demonstrate that for animals in extreme diet CP contents prediction accuracy is more likely to maximise by using more predictors rather than diet CP-specific equations; although the diet-specific equations can be used in cases that less predictors are available. Equations using BW as the main predictor did show a good prediction capacity only when CP and ME were added to produce a multiple linear prediction model; a need which to be higher with increasing dietary N.

In line with the findings for the low- and medium- CP datasets and previous work (Angelidis *et al.*, 2019), the single linear model using DMI or BW as the predictor and the model comprised of DMI or BW and CP, did not show good prediction accuracy for UNO. Conversely, the addition of ME to these models significantly increased the prediction accuracy, and the model developed from the high CP sub-set was slightly more accurate. As seen in the case of MNO from animals at high CP diets, more complex models, also including fibre data, were more accurate when developed from the merged digestibility trials database rather than its high CP sub-set, with the combination of NI, ME and NDF predicting UNO with the highest accuracy. The accurate prediction of UNO remains challenging and it seems that a combination of diet CP-specific equations, when DMI (or BW), CP and ME are available, or higher availability of predictors are necessary to maximise prediction accuracy; although the prediction accuracy of UNO has not appeared higher than 0.208 in any of the sub-sets in this study or previous work (Angelidis *et al.*, 2019). The fact that the influence of diet is higher on UNO than FNO (Vasconcelos *et al.*, 2009; Erickson and Klopfenstein, 2010) is possibly among the main reasons why UNO prediction is far more challenging than FNO or MNO (which partly consists of FNO).

Similar prediction accuracy was noticed when different combinations including DMI as the main and CP, ME and TF as the secondary predictors were produced using either the merged digestibility trials database or its high protein sub-set. Similarly, to animals under medium diets, the model including DMI, CP and ME showed the highest prediction accuracy for the prediction of FNO in the highest range of feed protein concentration. Differences in prediction accuracy among the models developed from the two databases, were seen only in the case of models using NI as the main predictors, favouring the specific equations developed by using the high CP sub-set. Therefore, there is no need for diet-specific equations for the prediction of FNO in animals at high CP diets when DMI, CP and ME are known but the prediction accuracy will be favoured by diet-specific equations when ME is not available. The improvement in the prediction of MNO when using diet CP-specific equations in animals with high diet CP concentration comes from the improvement in the prediction of FNO and UNO collectively, as the prediction both parts of N outputs is benefited. Finally, in contrast with animals at low-CP diets, using BW as the main predictor, cannot predict FNO satisfactorily.

5. Conclusions

The equations developed in the current study using a large database explore the relationships between N output in manure, urine and faeces from beef cattle with various dietary factors and animal body weight. This study confirmed previous results that for a higher prediction accuracy of nitrogen outputs, recording and using dietary nitrogen concentration is essential while energy-related parameters (dietary starch, fibre, fat, metabolisable energy) can further improve the accuracy of prediction models across the spectra of dieary protein concentrations. Diet crude protein-specific equation improved prediction accuracy of nitrogen outputs in several occasions across the spectra of diet protein concentration (84-217 g/kg dry matter) and this was more pronounced in diets with crude contents over 143 g/kg dry matter; and in particular when feed intake and diet nitrogen, and energy concetrations were available. However, the accurate prediction of urine nitrogen outputs, remains a challenge and it is likely predictors that account for protein utilisation (metabolisale protein, undegradable protein) could improve prediction accuracy in future.

Acknowledgements

The authors would like to acknowledge funding support from the University of Reading, Rothamsted Research, and UK Biotechnology and Biological Sciences Research Council (BBS/E/C/000I0320).

Abbreviations

ADF: Acid detergent fibre; AFBI: Agri-Food and Biosciences Institute; BW: animal body weight; CEDAR: The Centre for Dairy Research; CP: Crude protein; DM: Dry matter; DMI: Dry Matter intake; EE: Ether extract; FNO: Faecal nitrogen output; GE: Gross energy; GHG: Green House Gases; ID: Identity; LinCCC: Lin's concordance correlation coefficient; ME: Metabolisable energy; MNO: Manure nitrogen output; MPE: Mean prediction error; MSPE: Mean squared prediction error; N: Nitrogen; N2O: Nitrous oxide; NDF: Neutral detergent fibre; NH3: Ammonia; NI: Nitrogen intake; NUE: Nitrogen Use Efficiency; OM: Organic matter; RDP: Rumen-Degradable Protein; ST: Starch; TF: Total forage; UNO: Urinary nitrogen output.

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Figure captions

Figure 1 Bland-Altman plots showing the agreement between actual manure nitrogen output (MNO), urine nitrogen output (UNO) and faeces nitrogen output (FNO) and predicted from equations shown by Yan *et al.* (2007), Hirooka (2010) and Dong *et al.* (2014) (panels a, d and g, respectively) or developed in the current study by using exactly the same variables (panels b, e and h, respectively) or newly introduced ones (panels c, f and i). In order to predict (i) MNO, (ii) UNO and (iii) FNO, the following were used as predictors: (i) nitrogen intake (NI) for panels a, b, d, e, g and h (ii) NI, metabolisable energy (ME), acid detergent fibre (ADF) and starch (ST) for panel c, (iii) dry matter intake (DMI), crude protein (CP), ADF, ST, ME for panel f and (iv) DMI, CP and forage proportion for panel i. Prediction equations are shown in Table A1 (for panels a, d and g), Table 2 (for panels b, c, e, f, h and i). Residual represents the difference between predicted minus actual value. Rc is Lin's concordance correlation coefficient with 95% confidence interval given in square brackets.

Figure 2 Bland-Altman plots showing the agreement between actual manure nitrogen (N) output (MNO), urine N output (UNO) and faeces N output (FNO) and predicted from equations developed in the current study by using either the merged animal trials database (panels a, c and e, respectively) or the low crude protein sub-set (panels b, d and f). In order to predict (i) MNO, (ii) UNO and (iii) FNO, the following were used as predictors: (i) dry matter intake (DMI), crude protein (CP), acid detergent fibre and neutral detergent fibre for panels a and b, (ii) DMI and CP for panels c and d and (iii) bodyweight, CP and metabolisable energy for panels e and f. Prediction equations are shown in Table 2 (for panels a, c and e) and Table 3 (for panels b, d and f). Residual represents the difference between predicted minus actual value. Rc is Lin's concordance correlation coefficient with 95% confidence interval given in square brackets.

Figure 3. Bland-Altman plots showing the agreement between actual manure nitrogen (N) output (MNO), urine N output (UNO) and faeces N output (FNO) and predicted from equations developed in the current study by using either the merged animal trials database (panels a, c and e, respectively) or the medium crude protein sub-set (panels b, d and f). In order to predict (i) MNO, (ii) UNO and (iii) FNO, the following were used as predictors: (i) dry matter intake (DMI), crude protein (CP) and metabolisable energy (ME) for panels a and b, (ii) N intake (NI) for panels c and d and (iii) NI and ME for panels e and f. Prediction equations are shown in Table 2 (for panels a, c and e) and Table 4 (for panels b, d and f). Residual represents the difference between predicted minus actual value. Rc is Lin's concordance correlation coefficient with 95% confidence interval given in square brackets.

Figure 4. Bland-Altman plots showing the agreement between actual manure nitrogen (N) output (MNO), urine N output (UNO) and faeces N output (FNO) and predicted from equations developed in the current study by using either the the merged animal trials database (panels a, c and e, respectively) or the high crude protein sub-set (panels b, d and f). In order to predict (i) MNO, (ii) UNO and (iii) FNO, the following were used as predictors: (i_a), N intake (NI), metabolisable energy (ME), acid detergent fibre (ADF) and starch for panel a, (i_b) NI, ME and ADF for panel b, (ii) dry matter intake, crude protein and ME for panels c and d, (iii) NI and ME for panels e and f. Prediction equations are shown in Table 2 (for panels a, c and e) and Table 5 (for panels b, d and f). Residual represents the difference between predicted minus actual value. Rc is Lin's concordance correlation coefficient with 95% confidence interval given in square brackets.

Figure 1

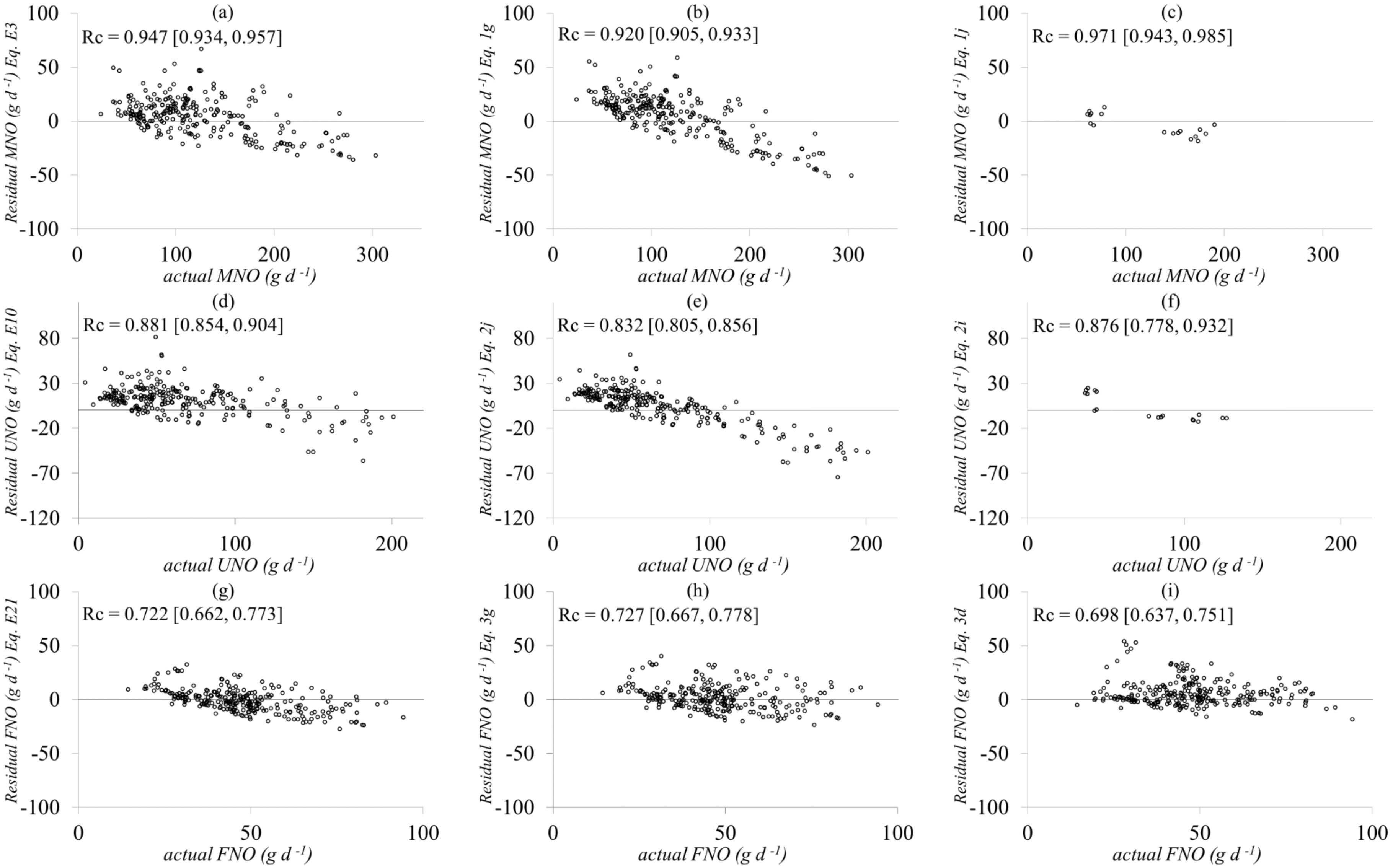

(a)
Rc = 0.947 [0.934, 0.957]
Residual MNO (g d -1) Eq. E3
actual MNO (g d -1)
(b)
Rc = 0.920 [0.905, 0.933]
Residual MNO (g d -1) Eq. 1g
actual MNO (g d -1)
(c)
Rc = 0.971 [0.943, 0.985]
Residual MNO (g d -1) Eq. 1j
actual MNO (g d -1)
100
50
0
-50
-100
0
100
200
300
(d)
Rc = 0.881 [0.854, 0.904]
Residual UNO (g d -1) Eq. E10
actual UNO (g d -1)
(e)
Rc = 0.832 [0.805, 0.856]
Residual UNO (g d -1) Eq. 2j
actual UNO (g d -1)
(f)
Rc = 0.876 [0.778, 0.932]
Residual UNO (g d -1) Eq. 2i
actual UNO (g d -1)
80
30
-20
-70
-120
0
100
200
(g)
Rc = 0.722 [0.662, 0.773]
Residual FNO (g d -1) Eq. E21
actual FNO (g d -1)
(h)
Rc = 0.727 [0.667, 0.778]
Residual FNO (g d -1) Eq. 3g
actual FNO (g d -1)
(i)
Rc = 0.698 [0.637, 0.751]
Residual FNO (g d -1) Eq. 3d
actual FNO (g d -1)
100
50
0
-50
-100
0
50
100

Figure 2

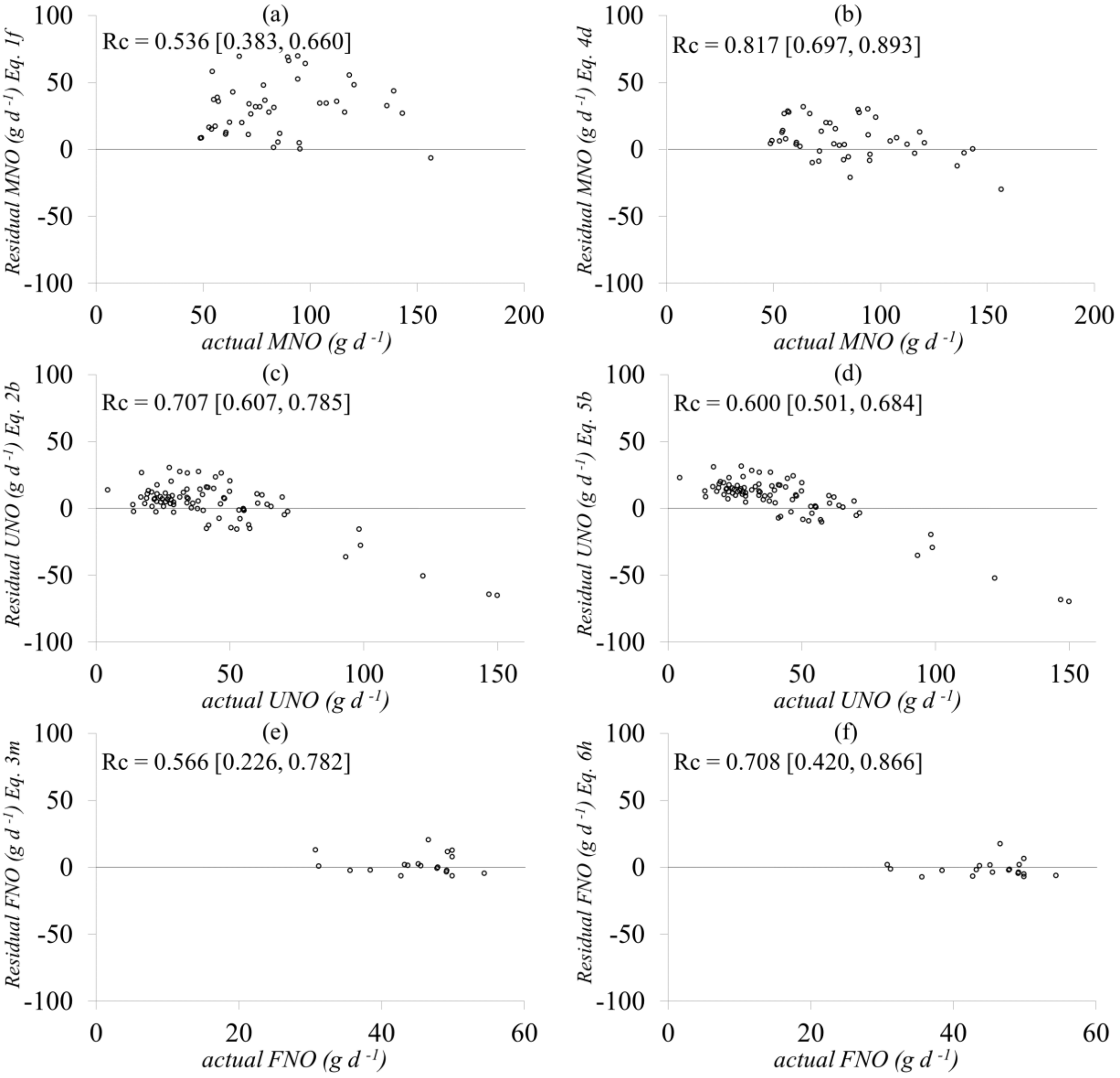

(a)
Rc = 0.536 [0.383, 0.660]
Residual MNO (g d -1) Eq. 1f
actual MNO (g d -1)
(b)
Rc = 0.817 [0.697, 0.893]
Residual MNO (g d -1) Eq. 4d
actual MNO (g d -1)
(c)
Rc = 0.707 [0.607, 0.785]
Residual UNO (g d -1) Eq. 2b
actual UNO (g d -1)
(d)
Rc = 0.600 [0.501, 0.684]
Residual UNO (g d -1) Eq. 5b
actual UNO (g d -1)
(e)
Rc = 0.566 [0.226, 0.782]
Residual FNO (g d -1) Eq. 3m
actual FNO (g d -1)
(f)
Rc = 0.708 [0.420, 0.866]
Residual FNO (g d -1) Eq. 6h
actual FNO (g d -1)
100
50
0
-50
-100
0
50
100
150
200
20
40
60

Figure 3

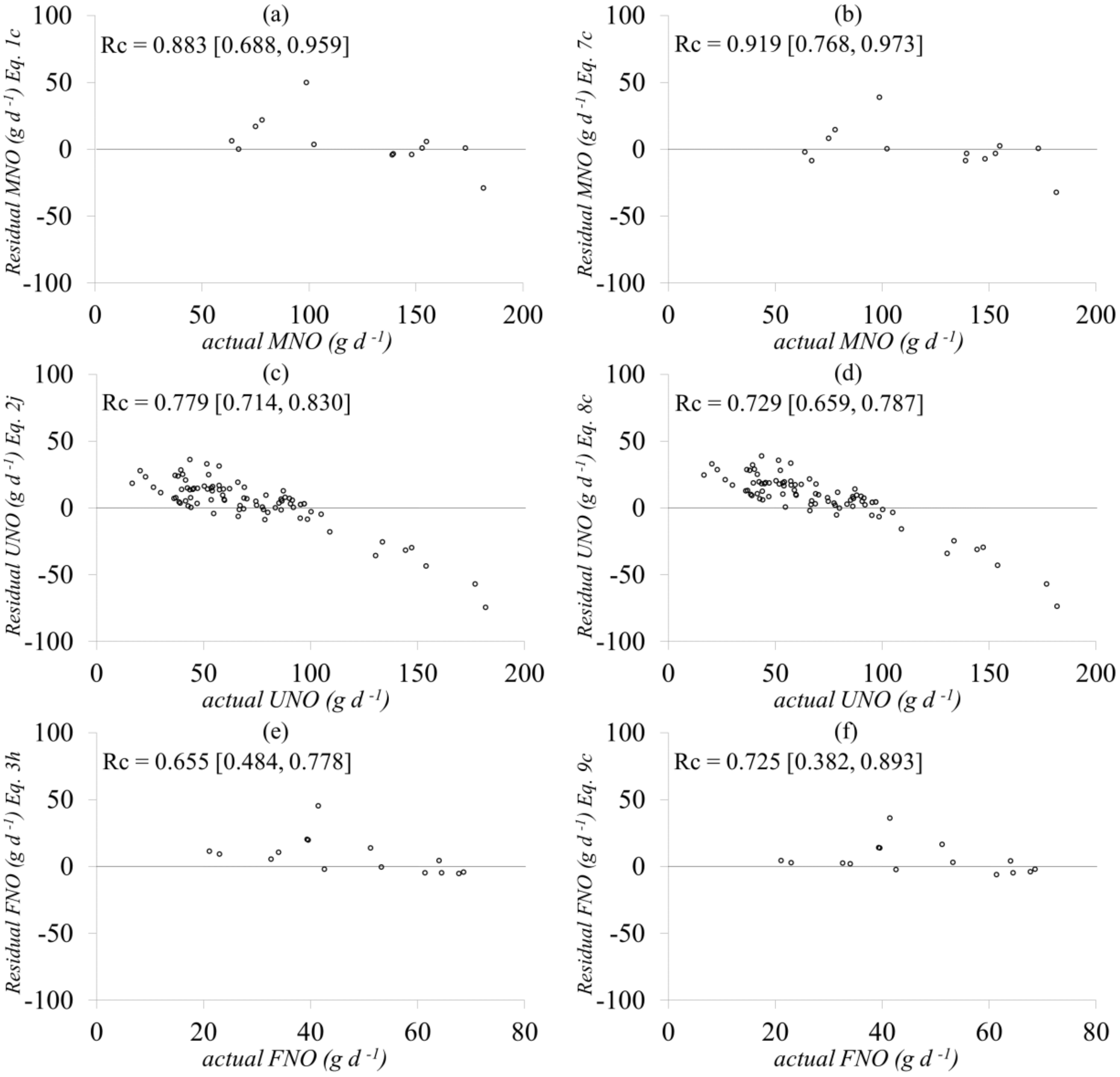
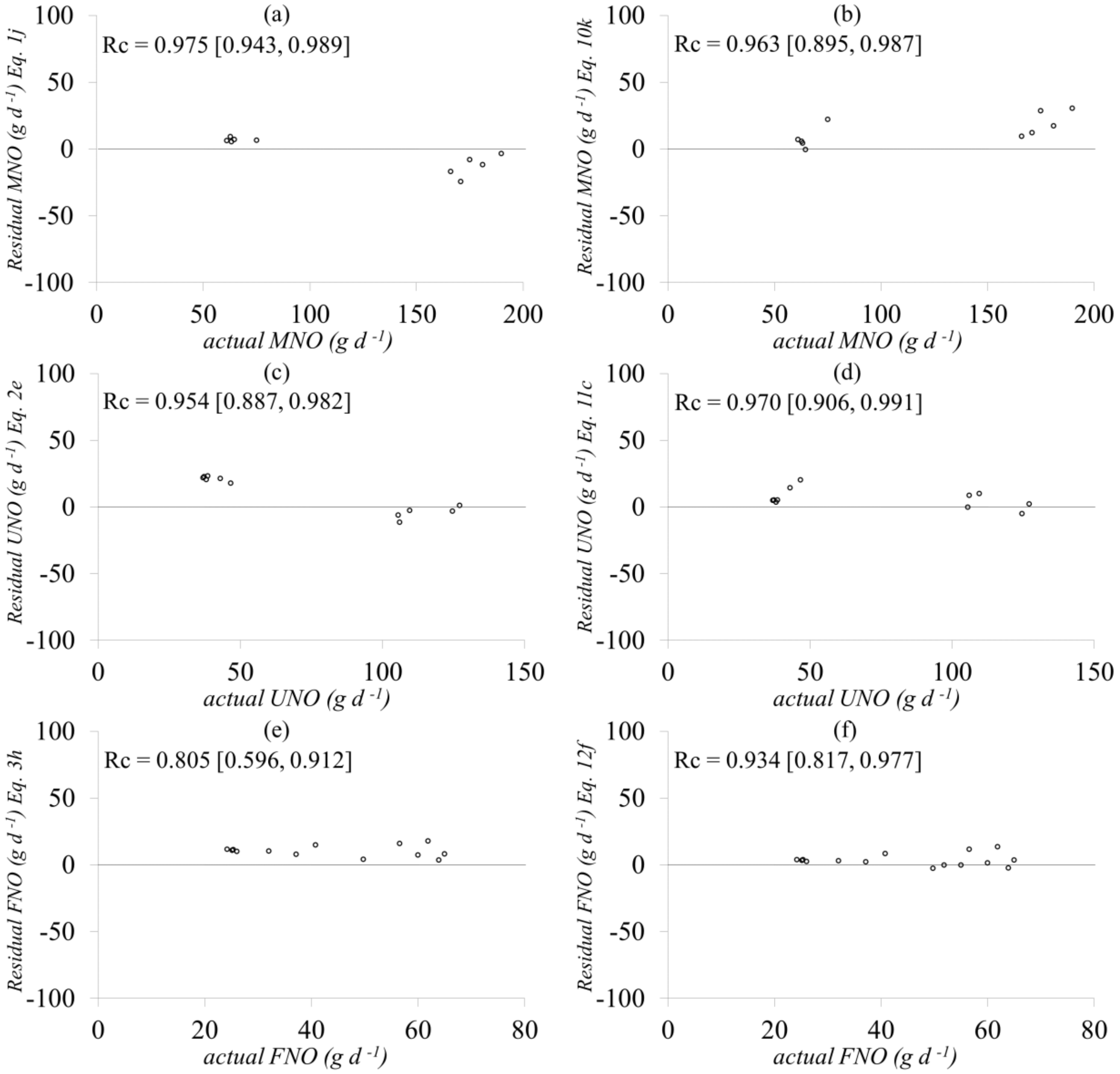

(a)
Rc = 0.883 [0.688, 0.959]
Residual MNO (g d -1) Eq. 1c
actual MNO (g d -1)
(b)
Rc = 0.919 [0.768, 0.973]
Residual MNO (g d -1) Eq. 7c
actual MNO (g d -1)
(c)
Rc = 0.779 [0.714, 0.830]
Residual UNO (g d -1) Eq. 2j
actual UNO (g d -1)
(d)
Rc = 0.729 [0.659, 0.787]
Residual UNO (g d -1) Eq. 8c
actual UNO (g d -1)
(e)
Rc = 0.655 [0.484, 0.778]
Residual FNO (g d -1) Eq. 3h
actual FNO (g d -1)
(f)
Rc = 0.725 [0.382, 0.893]
Residual FNO (g d -1) Eq. 9c
actual FNO (g d -1)
100
50
0
-50
-100
0
50
100
150
200
20
40
60
80

Figure 4


(a)
Rc = 0.975 [0.943, 0.989]
Residual MNO (g d -1) Eq. 1j
actual MNO (g d -1)
100
50
0
-50
-100
0
50
100
150
200
(b)
Rc = 0.963 [0.895, 0.987]
Residual MNO (g d -1) Eq. 10k
actual MNO (g d -1)
(c)
Rc = 0.954 [0.887, 0.982]
Residual UNO (g d -1) Eq. 2e
actual UNO (g d -1)
150
(d)
Rc = 0.970 [0.906, 0.991]
Residual UNO (g d -1) Eq. 11c
actual UNO (g d -1)
(e)
Rc = 0.805 [0.596, 0.912]
Residual FNO (g d -1) Eq. 3h
actual FNO (g d -1)
20
40
60
80
(f)
Rc = 0.934 [0.817, 0.977]
Residual FNO (g d -1) Eq. 12f
actual FNO (g d -1)

Tables

Table 1 Description of the data derived from the merged digestibility trials database, used to predict N excretion, including body weight, diet chemical composition and energy concentrations, nutrient and energy intakes and N outputs in manure, urine and faeces.

Parameters assessed	Mean ±SD	Min	Max	CV	n
Animal data					
Bodyweight (kg)	379 ±105.9	153	631	0.28	570
Diet chemical composition (g/kg DM)					
Total forage (g/100g DM)	56.6 ±25.40	20.00	100.0	0.45	570
OM	940.5 ±21.88	862.6	971.9	0.02	284
CP	153.6 ±24.67	84.90	217.3	0.16	570
N	24.57 ±3.948	13.60	34.80	0.16	570
EE	28.44 ±9.863	6.700	63.20	0.35	284
NDF	298.6 ±93.20	174.6	655.4	0.31	284
ADF	157.7 ±76.17	75.00	367.2	0.48	284
Starch	427 ±158.8	23.50	641.1	0.37	284
Ash	59.5 ±21.87	28.10	137.4	0.37	284
Diet energy concentration (MJ/kg DM)					
GE	18.4 ±0.510	17.00	19.70	0.03	284
ME	11.5 ±1.190	6.500	14.40	0.10	564
Nutrient (kg/d) and energy (MJ/d) intakes					
DM intake	6.36 ±2.006	2.090	11.30	0.32	570
OM intake	5.58 ±1.902	1.990	10.70	0.34	284
CP intake	0.97 ±0.332	0.270	1.970	0.34	570
N intake (g/d)	155.4 ±53.14	43.40	316.1	0.34	570
NDF intake	1.83 ±0.969	0.420	5.320	0.53	284
ADF intake	0.99 ±0.687	0.190	3.480	0.69	284
Starch intake	2.42 ±1.174	0.180	6.050	0.49	284
GE intake	109.3 ±36.99	39.50	210.1	0.34	284
ME intake	73.0 ±24.38	26.80	137.9	0.33	564
Diet digestibility					
N apparent digestibility (g/kg)	677.5 ±66.52	354.2	814.3	0.10	570
Nitrogen output and retention (g/d)					
Manure N output	123.3 ±42.37	26.90	261.4	0.34	570
Urine N output	74.1 ±29.71	11.90	179.2	0.40	566
Faeces N output	49.8 ±18.09	11.00	105.3	0.36	570

N = nitrogen; SD = standard deviation; Min = minimum value observed; Max = maximum value observed; CV = coefficient of variation; n = number of observations; DM = dry matter; OM = organic matter; CP = crude protein; EE = ether extract; NDF = neutral-detergent fibre; ADF = acid-detergent fibre; GE = gross energy; ME = metabolisable energy.

Table 2 Single and multiple linear prediction of nitrogen excretion in manure, urine and faeces using (i) intakes of feed, nutrients, or body weight, diet chemical composition, energy concentrations, and forage proportion and (ii) data representing feed protein concentrations across the whole available crude protein range.

Equations^a			n	R^2	MPE	Eq.
MNO =	$22.28_{(7.364)}$	$+ 15.64_{(0.742)}\ \text{DMI}$	570	0.92	0.460	(1a)
	$–92.42_{(8.632)}$	$+ 16.61_{(0.491)}\ \text{DMI} + 0.704_{(0.0317)}\ \text{CP}$	570	0.94	0.305	(1b)
	$–42.60_{(10.382)}$	$+ 16.60_{(0.463)}\ \text{DMI} + 0.759_{(0.0294)}\ \text{CP} – 5.048_{(0.5811)}\ \text{ME}$	564	0.94	0.270	(1c)
	$–97.54_{(9.017)}$	$+ 16.62_{(0.505)}\ \text{DMI} + 0.691_{(0.0322)}\ \text{CP} + 11.38_{(3.901)}\ \text{TF}$	570	0.94	0.303	(1d)
	$–94.90_{(12.508)}$	$+ 16.32_{(0.798)}\ \text{DMI} + 4.183_{(0.3640)}\ \text{CP} + 0.073_{(0.0245)}\ \text{ADF}$	284	0.93	0.336	(1e)
	$–108.4_{(13.37)}$	$+ 18.28_{(0.872)}\ \text{DMI} + 0.642_{(0.0679)}\ \text{CP} + 0.068_{(0.0422)}\ \text{ADF} + 0.019_{(0.0271)}\ \text{NDF}$	278	0.96	0.297	(1f)
	$17.34_{(6.208)}$	$+ 0.673_{(0.0167)}\ \text{NI}$	570	0.94	0.242	(1g)
	$9.299_{(6.9250)}$	$+ 0.668_{(0.0171)}\ \text{NI} + 13.89_{(3.750)}\ \text{TF}$	570	0.94	0.241	(1h)
	$82.79_{(8.538)}$	$+ 0.691_{(0.0148)}\ \text{NI} – 5.922_{(0.5297)}\ \text{ME}$	564	0.94	0.317	(1i)
	$60.60_{(19.802)}$	$+ 0.697_{(0.0229)}\ \text{NI} – 6.564_{(1.1004)}\ \text{ME} + 0.074_{(0.0350)}\ \text{ADF} + 0.044_{(0.0166)}\ \text{ST}$	278	0.94	0.129	(1j)
	$19.71_{(8.253)}$	$+ 0.709_{(0.0241)}\ \text{NI} – 0.250_{(0.1128)}\ \text{EE}$	284	0.94	0.262	(1k)
	$73.14_{(7.646)}$	$+ 0.134_{(0.0166)}\ \text{BW}$	570	0.88	0.569	(1l)
	$–33.50_{(10.633)}$	$+ 0.166_{(0.0146)}\ \text{BW} + 0.615_{(0.0516)}\ \text{CP}$	570	0.89	0.472	(1m)
	$39.71_{(11.775)}$	$+ 0.187_{(0.0099)}\ \text{BW} + 0.782_{(0.0485)}\ \text{CP} – 9.203_{(0.9168)}\ \text{ME}$	564	0.89	0.456	(1n)
	$–57.33_{(11.096)}$	$+ 0.169_{(0.0145)}\ \text{BW} + 0.593_{(0.0500)}\ \text{CP} + 42.16_{(6.824)}\ \text{TF}$	570	0.88	0.541	(1o)
	$13.37_{(13.759)}$	$+ 0.182_{(0.0118)}\ \text{BW} + 0.750_{(0.0490)}\ \text{CP} – 7.787_{(0.9782)}\ \text{ME} + 27.02_{(6.722)}\ \text{TF}$	564	0.88	0.484	(1p)
UNO =	$25.40_{(7.484)}$	$+ 7.254_{(0.6927)}\ \text{DMI}$	566	0.84	0.695	(2a)
	$–78.14_{(8.864)}$	$+ 8.287_{(0.4863)}\ \text{DMI} + 0.630_{(0.0305)}\ \text{CP}$	566	0.86	0.536	(2b)
	$–83.60_{(9.223)}$	$+ 8.222_{(0.5006)}\ \text{DMI} + 0.617_{(0.0308)}\ \text{CP} – 12.75_{(3.759)}\ \text{TF}$	566	0.86	0.555	(2c)
	$–86.54_{(12.136)}$	$+ 7.792_{(0.7806)}\ \text{DMI} + 3.976_{(0.3405)}\ \text{CP} + 0.079_{(0.0204)}\ \text{ADF}$	280	0.86	0.489	(2d)
	$–29.13_{(15.673)}$	$+ 7.287_{(0.7887)}\ \text{DMI} + 4.258_{(0.3471)}\ \text{CP} – 4.246_{(0.9276)}\ \text{ME}$	278	0.87	0.616	(2e)
	$–74.01_{(11.642)}$	$+ 8.471_{(0.7485)}\ \text{DMI} + 4.145_{(0.3456)}\ \text{CP} – 0.313_{(0.1179)}\ \text{EE}$	280	0.86	0.504	(2f)
	$–83.48_{(11.819)}$	$+ 7.987_{(0.7702)}\ \text{DMI} + 4.207_{(0.3409)}\ \text{CP} + 0.076_{(0.0199)}\ \text{ADF} – 0.321_{(0.1160)}\ \text{EE}$	280	0.86	0.476	(2g)
	$–124.5_{(18.510)}$	$+ 7.601_{(0.7515)}\ \text{DMI} + 4.216_{(0.3358)}\ \text{CP} + 0.154_{(0.0359)}\ \text{ADF} + 0.049_{(0.0188)}\ \text{ST}$	280	0.85	0.443	(2h)
	$–78.82_{(23.925)}$	$+ 7.140_{(0.7707)}\ \text{DMI} + 4.437_{(0.3472)}\ \text{CP} + 0.104_{(0.0400)}\ \text{ADF} + 0.048_{(0.0188)}\ \text{ST} – 3.428_{(1.1796)}\ \text{ME}$	278	0.86	0.289	(2i)
	$5.173_{(5.7226)}$	$+ 0.426_{(0.0181)}\ \text{NI}$	566	0.87	0.424	(2j)
	$–4.725_{(6.5358)}$	$+ 0.419_{(0.0181)}\ \text{NI} + 17.58_{(4.058)}\ \text{TF}$	566	0.87	0.474	(2k)
	$22.88_{(9.039)}$	$+ 0.429_{(0.0180)}\ \text{NI} – 1.582_{(0.6178)}\ \text{ME}$	564	0.87	0.518	(2l)
	$–7.764_{(9.4770)}$	$+ 0.431_{(0.0266)}\ \text{NI} – 0.072_{(0.0203)}\ \text{ADF}$	280	0.87	0.460	(2m)
	$19.39_{(10.846)}$	$+ 0.450_{(0.0274)}\ \text{NI} – 0.025_{(0.0115)}\ \text{ST} – 0.238_{(0.1153)}\ \text{EE}$	280	0.87	0.381	(2n)
	$42.45_{(6.473)}$	$+ 0.080_{(0.0135)}\ \text{BW}$	566	0.84	0.837	(2o)
	$–62.64_{(7.981)}$	$+ 0.110_{(0.0113)}\ \text{BW} + 0.611_{(0.0357)}\ \text{CP}$	566	0.85	0.714	(2p)
	$–25.93_{(9.910)}$	$+ 0.117_{(0.0111)}\ \text{BW} + 0.668_{(0.0357)}\ \text{CP} – 4.172_{(0.6957)}\ \text{ME}$	564	0.85	0.769	(2q)
	$–75.82_{(8.316)}$	$+ 0.112_{(0.0112)}\ \text{BW} + 0.592_{(0.0351)}\ \text{CP} + 25.02_{(4.421)}\ \text{TF}$	564	0.85	0.772	(2r)
	$–43.52_{(11.263)}$	$+ 0.115_{(0.0111)}\ \text{BW} + 0.643_{(0.0366)}\ \text{CP} – 3.154_{(0.7550)}\ \text{ME} + 16.70_{(4.737)}\ \text{TF}$	564	0.85	0.799	(2s)
FNO =	$–4.072_{(1.6973)}$	$+ 8.507_{(0.2184)}\ \text{DMI}$	570	0.94	0.311	(3a)
	$–16.43_{(2.696)}$	$+ 8.614_{(0.2081)}\ \text{DMI} + 0.076_{(0.0132)}\ \text{CP}$	570	0.94	0.278	(3b)
	$13.71_{(3.511)}$	$+ 8.405_{(0.1969)}\ \text{DMI} + 0.111_{(0.0125)}\ \text{CP} – 2.958_{(0.2451)}\ \text{ME}$	564	0.96	0.323	(3c)
	$–18.01_{(2.762)}$	$+ 8.584_{(0.2076)}\ \text{DMI} + 0.073_{(0.0132)}\ \text{CP} – 3.645_{(1.6253)}\ \text{TF}$	570	0.95	0.273	(3d)
	$17.61_{(3.916)}$	$+ 8.441_{(0.1971)}\ \text{DMI} + 0.116_{(0.0127)}\ \text{CP} – 3.828_{(1.6730)}\ \text{TF} – 3.185_{(0.2641)}\ \text{ME}$	564	0.96	0.321	(3e)
	$30.41_{(6.374)}$	$+ 8.472_{(0.2254)}\ \text{DMI} + 0.760_{(0.1068)}\ \text{CP} – 0.033_{(0.0083)}\ \text{ADF} – 3.935_{(0.3932)}\ \text{ME}$	278	0.96	0.297	(3f)
	$10.44_{(1.979)}$	$+ 0.256_{(0.0102)}\ \text{NI}$	570	0.93	0.280	(3g)
	$65.57_{(3.588)}$	$+ 0.261_{(0.0086)}\ \text{NI} – 4.824_{(0.2886)}\ \text{ME}$	564	0.94	0.421	(3h)

$72.81_{(4.277)}$	$+ 0.267_{(0.0085)}$ NI $- 5.149_{(0.3057)}$ ME $- 6.976_{(2.2088)}$ TF	564	0.94	0.418	(3i)
$71.41_{(7.645)}$	$+ 0.267_{(0.0108)}$ NI $- 4.908_{(0.4533)}$ ME $- 0.024_{(0.0111)}$ ADF	278	0.94	0.413	(3j)
$-10.96_{(12.067)}$	$+ 0.291_{(0.0108)}$ NI $- 4.711_{(0.3841)}$ ME $+ 0.093_{(0.1153)}$ NDF $+ 0.090_{(0.0122)}$ ST $+ 0.202_{(0.0474)}$ EE	278	0.96	0.353	(3k)
$31.80_{(2.511)}$	$+ 0.051_{(0.0053)}$ BW	570	0.87	0.417	(3l)
$66.51_{(6.030)}$	$+ 0.063_{(0.0067)}$ BW $+ 0.117_{(0.0234)}$ CP $- 4.955_{(0.4375)}$ ME	564	0.88	0.418	(3m)
$54.09_{(9.503)}$	$+ 0.056_{(0.0059)}$ BW $+ 1.606_{(0.2247)}$ CP $- 7.058_{(0.6138)}$ ME $+ 0.038_{(0.0095)}$ ST	278	0.87	0.273	(3n)
$60.30_{(8.721)}$	$+ 0.047_{(0.0060)}$ BW $+ 1.380_{(0.2393)}$ CP $- 5.812_{(0.5337)}$ ME $+ 0.178_{(0.0741)}$ EE	278	0.86	0.361	(3o)
$86.83_{(11.587)}$	$+ 0.055_{(0.0060)}$ BW $+ 1.320_{(0.2348)}$ CP $- 6.845_{(0.5973)}$ ME $- 0.039_{(0.0105)}$ NDF	278	0.86	0.406	(3p)

n = number of observations; R^2 = pseudo correlation coefficient; MPE = mean prediction error; Eq. = equation; MNO = manure nitrogen output; DMI = dry matter intake; CP = diet crude protein concentration; ME = diet metabolisable energy concentration; TF = diet total forage; ADF = diet acid-detergent fibre concentration; NDF = diet neutral-detergent fibre concentration; NI = nitrogen intake; ST = diet starch concentration; EE = diet ether extract concentration; BW = body weight; UNO = urine nitrogen output; FNO = faeces nitrogen output

[a] Units: g/d for MNO, UNO, FNO, NI; kg/d for DMI; g/kg DM for CP, ADF, NDF, ST, EE; MJ/kg DM for ME; g/100g DM for TF. The effect of all explanatory variables was significant according to the Wald statistic (Fpr < 0.05). The random effects of the individual experiment, animal, treatment and growth stage were accounted for all predicted variables. The random factors were chosen according to changes in deviance during the development of the random model.

[b] MPE derived from an external validation (details presented in Table A2).

Table 3 Single and multiple linear prediction of nitrogen excretion in manure, urine and faeces using intakes of feed, nutrient and energy, or body weight, diet chemical composition, energy concentrationsand forage proportion and (ii) data representing low feed protein concentrations.

	Equations[a]		n	R^2	MPE_{LL}[b]	MPE_{AL}[b]	Eq.
MNO =	$10.05_{(6.191)}$	$+ 15.03_{(0.850)}$ DMI	190	0.93	0.389	0.540	(4a)
	$–51.06_{(14.100)}$	$+ 14.97_{(0.764)}$ DMI $+ 0.477_{(0.1028)}$ CP	190	0.93	0.282	0.244	(4b)
	$–30.02_{(12.917)}$	$+ 14.38_{(0.661)}$ DMI $+ 0.748_{(0.0919)}$ CP $– 4.543_{(0.9507)}$ ME	188	0.94	0.398	0.396	(4c)
	$–90.46_{(22.516)}$	$+ 12.71_{(0.711)}$ DMI $+ 0.748_{(0.1596)}$ CP $– 0.145_{(0.0586)}$ ADF $+ 0.125_{(0.0419)}$ NDF	89	0.90	0.266	0.472	(4d)
	$13.87_{(4.703)}$	$+ 0.699_{(0.0316)}$ NI	190	0.94	0.232	0.237	(4e)
	$72.34_{(10.128)}$	$+ 0.691_{(0.0278)}$ NI $– 5.004_{(0.8378)}$ ME	188	0.94	0.404	0.429	(4f)
	$57.96_{(7.783)}$	$+ 0.131_{(0.0162)}$ BW	190	0.88	0.416	0.526	(4g)
	$–6.121_{(12.9010)}$	$+ 0.138_{(0.0160)}$ BW $+ 0.475_{(0.1387)}$ CP	190	0.88	0.351	0.341	(4h)
	$19.19_{(18.433)}$	$+ 0.150_{(0.0139)}$ BW $+ 1.014_{(0.1348)}$ CP $– 8.773_{(1.3907)}$ ME	188	0.91	0.470	0.468	(4i)
UNO =	$17.11_{(0.881)}$	$+ 6.412_{(0.7810)}$ DMI	188	0.88	0.782	0.991	(5a)
	$–48.87_{(12.530)}$	$+ 6.428_{(0.7109)}$ DMI $+ 0.512_{(0.0907)}$ CP	188	0.87	0.628	0.594	(5b)
	$14.14_{(4.792)}$	$+ 0.332_{(0.0313)}$ NI	188	0.88	0.637	0.642	(5c)
	$27.69_{(5.087)}$	$+ 0.080_{(0.1044)}$ BW	188	0.90	0.788	0.973	(5d)
	$–48.08_{(12.746)}$	$+ 0.089_{(0.0101)}$ BW $+ 0.560_{(0.0905)}$ CP	188	0.89	0.682	0.673	(5e)
	$–27.85_{(13.365)}$	$+ 0.098_{(0.0097)}$ BW $+ 0.772_{(0.0960)}$ CP $– 4.499_{(0.9617)}$ ME	188	0.90	0.820	0.793	(5f)
	$–66.42_{(13.700)}$	$+ 0.091_{(0.0010)}$ BW $+ 0.599_{(0.0890)}$ CP $+ 19.66_{(6.659)}$ TF	188	0.88	0.772	0.790	(5g)
FNO =	$–4.043_{(2.1234)}$	$+ 8.258_{(0.2981)}$ DMI	190	0.94	0.364	0.386	(6a)
	$11.44_{(5.545)}$	$+ 7.993_{(0.2827)}$ DMI $+ 0.117_{(0.0392)}$ CP $– 2.536_{(0.0109)}$ ME	188	0.96	0.340	0.354	(6b)
	$18.83_{(6.091)}$	$+ 8.047_{(0.2758)}$ DMI $+ 0.1223_{(0.0387)}$ CP $– 2.899_{(0.4210)}$ ME $– 6.828_{(2.5161)}$ TF	188	0.96	0.354	0.354	(6c)
	$3.327_{(2.5177)}$	$+ 0.348_{(0.0166)}$ NI	190	0.96	0.341	0.333	(6d)
	$50.86_{(4.945)}$	$+ 0.340_{(0.0143)}$ NI $– 4.104_{(0.4157)}$ ME	188	0.95	0.375	0.295	(6e)
	$57.99_{(6.004)}$	$+ 0.343_{(0.0139)}$ NI $– 4.384_{(0.4386)}$ ME $– 6.705_{(2.9635)}$ TF	188	0.95	0.353	0.271	(6f)
	$33.20_{(4.182)}$	$+ 0.044_{(0.0088)}$ BW	190	0.82	0.341	0.347	(6g)
	$42.09_{(10.559)}$	$+ 0.053_{(0.0084)}$ BW $+ 0.290_{(0.0791)}$ CP $– 4.397_{(0.8380)}$ ME	188	0.84	0.215	0.263	(6h)

n = number of observations; R^2 = pseudo correlation coefficient; MPE_{LL} = mean prediction error derived from the validation of the above equations by using the low CP sub-set of the literature database; MPE_{AL} = mean prediction error derived from the validation of the identical Table 2 equations by using the low CP sub-set of the literature database; Eq. = equation; MNO = manure nitrogen output; DMI = dry matter intake; CP = diet crude protein concentration; ME = diet metabolisable energy concentration; ADF = diet acid-detergent fibre concentration; NDF = diet neutral-detergent fibre concentration; NI = nitrogen intake; BW = body weight; UNO = urine nitrogen output; TF = diet total forage; FNO = faeces nitrogen output

[a] Units: g/d for MNO, UNO, FNO; kg/d for DMI; g/kg DM for CP, ADF, NDF; MJ/kg DM for ME; g/d for NI; g/100g DM for TF. The effect of all explanatory variables was significant according to the Wald statistic (Fpr < 0.05). The random effects of the individual experiment, animal and treatment were accounted for all predicted variables. The random factors were chosen according to changes in deviance during the development of the random model.

[b] MPE_{LL} and MPE_{AL} derived from an external validation (details presented in Table A3 and Table A4, respectively).

Table 4 Single and multiple linear prediction of nitrogen excretion in manure, urine and faeces using (i) intakes of feed, nutrient and energy, or body weight, diet chemical composition, energy concentrationsand forage proportion, and apparent total tract digestibility and (ii) data representing medium feed protein concentrations.

	Equations[a]		n	R^2	MPE_{MM}[b]	MPE_{AM}[b]	Eq.
MNO =	$9.452_{(5.7980)}$	$+ 17.96_{(0.803)}$ DMI	190	0.94	0.338	0.324	(7a)
	$–205.9_{(39.14)}$	$+ 18.43_{(0.723)}$ DMI $+ 1.376_{(0.2470)}$ CP	190	0.93	0.245	0.264	(7b)
	$–151.7_{(38.85)}$	$+ 18.11_{(0.662)}$ DMI $+ 1.325_{(0.2281)}$ CP $– 3.717_{(1.1480)}$ ME	189	0.94	0.197	0.227	(7c)
	$5.472_{(5.3840)}$	$+ 0.753_{(0.0304)}$ NI	190	0.94	0.229	0.239	(7d)
	$51.28_{(15.045)}$	$+ 0.739_{(0.0280)}$ NI $– 3.662_{(1.1648)}$ ME	189	0.95	0.287	0.322	(7e)
	$98.17_{(21.770)}$	$+ 0.643_{(0.0390)}$ NI $– 9.935_{(1.9633)}$ ME $+ 0.094_{(0.0223)}$ ST	80	0.93	0.272	NA	(7f)
	$42.00_{(9.248)}$	$+ 0.219_{(0.0208)}$ BW	190	0.81	0.445	0.443	(7g)
UNO =	$17.61_{(0.881)}$	$+ 3.126_{(0.7810)}$ DMI	190	0.94	0.639	0.455	(8a)
	$–191.0_{(39.44)}$	$+ 9.682_{(0.7419)}$ DMI $+ 1.328_{(0.2487)}$ CP	189	0.85	0.392	0.391	(8b)
	$13.60_{(5.681)}$	$+ 0.395_{(0.0319)}$ NI	189	0.86	0.384	0.364	(8c)
	$–48.47_{(29.944)}$	$+ 0.359_{(0.0584)}$ NI $+ 0.171_{(0.0795)}$ ADF $+ 0.095_{(0.0405)}$ ST	80	0.76	0.230	NA	(8d)
	$21.07_{(6.468)}$	$+ 0.142_{(0.0149)}$ BW	189	0.77	0.531	0.541	(8e)
	$–72.39_{(42.859)}$	$+ 0.140_{(0.0149)}$ BW $+ 0.612_{(0.2795)}$ CP	189	0.76	0.521	0.530	(8f)
FNO =	$–7.151_{(2.2516)}$	$+ 8.720_{(0.3120)}$ DMI	190	0.96	0.446	0.459	(9a)
	$–7.388_{(2.2725)}$	$+ 0.356_{(0.0129)}$ NI	190	0.96	0.407	0.393	(9b)
	$26.22_{(6.932)}$	$+ 0.350_{(0.0134)}$ NI $– 2.761_{(0.5293)}$ ME	189	0.96	0.328	0.424	(9c)
	$24.55_{(4.787)}$	$+ 0.068_{(0.0104)}$ BW	190	0.88	0.445	0.435	(9d)
	$179.0_{(27.65)}$	$+ 0.066_{(0.0098)}$ BW $– 0.589_{(0.1694)}$ CP $– 5.291_{(0.8655)}$ ME	189	0.85	0.451	0.394	(9e)

n = number of observations; R^2 = pseudo correlation coefficient; MPE_{MM} = mean prediction error derived from the validation of the above equations by using the medium CP sub-set of the literature database; MPE_{AM} = mean prediction error derived from the validation of the identical Table 2 equations by using the medium CP sub-set of the literature database; Eq. = equation; MNO = manure nitrogen output; DMI = dry matter intake; CP = diet crude protein concentration; ME = diet metabolisable energy concentration; NA = Not applicable (no equations were developed with the exact same predictors from the merged database); NI = nitrogen intake; ST = diet starch concentration; BW = body weight; ADF = diet acid-detergent fibre concentration; UNO = urine nitrogen output; FNO = faeces nitrogen output

[a] Units: g/d for MNO, UNO, FNO; kg/d for DMI; g/kg DM for CP, ST, ADF; MJ/kg DM for ME; g/d for NI. The effect of all explanatory variables was significant according to the Wald statistic ($Fpr < 0.05$). The random effects of the individual experiment, animal and treatment were accounted for all predicted variables. The random factors were chosen according to changes in deviance during the development of the random model.

[b] MPE_{MM} and MPE_{AM} derived from an external validation (details presented in Table A3 and Table A4, respectively).

Table 5 Single and multiple linear prediction of nitrogen excretion in manure, urine and faeces using intakes of feed, nutrient and energy, or body weight, diet chemical composition, energy concentrationsand forage proportion, and apparent total tract digestibility, and (ii) data representing high feed protein concentrations.

Equations^{a}			n	R^2	MPE_{HH}^{b}	MPE_{AH}^{b}	Eq.
MNO =	$1.377_{(6.3161)}$	$+ 22.42_{(1.012)}$ DMI	190	0.90	0.356	0.389	(10a)
	$-128.9_{(18.73)}$	$+ 22.84_{(0.936)}$ DMI $+ 0.702_{(0.0992)}$ CP	190	0.91	0.282	0.315	(10b)
	$-126.6_{(18.90)}$	$+ 23.01_{(0.971)}$ DMI $+ 0.621_{(0.1055)}$ CP $+ 18.44_{(7.459)}$ TF	190	0.92	0.282	0.320	(10c)
	$-14.13_{(22.721)}$	$+ 21.97_{(0.802)}$ DMI $+ 0.748_{(0.0956)}$ CP $- 17.92_{(8.438)}$ TF $- 9.347_{(1.4950)}$ ME	187	0.94	0.138	0.120^{c}	(10d)
	$-34.26_{(21.375)}$	$+ 22.07_{(0.845)}$ DMI $+ 0.673_{(0.0857)}$ CP $- 7.424_{(1.1252)}$ ME	187	0.94	0.114	0.130	(10e)
	$3.775_{(36.6646)}$	$+ 22.07_{(1.278)}$ DMI $+ 0.671_{(0.1380)}$ CP $- 0.457_{(0.1627)}$ EE $- 9.172_{(1.6465)}$ ME	111	0.95	0.156	0.128^{c}	(10f)
	$0.970_{(5.5646)}$	$+ 0.772_{(0.0303)}$ NI	190	0.91	0.201	0.226	(10g)
	$103.6_{(13.85)}$	$+ 0.754_{(0.0263)}$ NI $- 8.698_{(1.0859)}$ ME	187	0.94	0.113	0.129	(10h)
	$136.1_{(19.18)}$	$+ 0.759_{(0.0253)}$ NI $- 10.62_{(1.375)}$ ME $- 18.37_{(7.271)}$ TF	187	0.94	0.142	0.132^{c}	(10i)
	$-10.86_{(6.643)}$	$+ 0.772_{(0.0318)}$ NI $+ 18.99_{(7.071)}$ TF	190	0.92	0.199	0.230	(10j)
	$168.8_{(30.38)}$	$+ 0.816_{(0.0463)}$ NI $- 0.127_{(0.0446)}$ ADF $- 13.08_{(2.042)}$ ME	111	0.95	0.132	0.350^{c}	(10k)
	$51.72_{(7.424)}$	$+ 0.249_{(0.0190)}$ BW	190	0.94	0.490	0.554	(10l)
	$-35.94_{(25.843)}$	$+ 0.248_{(0.0187)}$ BW $+ 0.483_{(0.1374)}$ CP	190	0.93	0.461	0.497	(10m)
	$123.9_{(28.36)}$	$+ 0.236_{(0.0172)}$ BW $+ 0.626_{(0.1207)}$ CP $- 16.00_{(1.639)}$ ME	187	0.92	0.241	0.253	(10n)
	$84.6_{(32.48)}$	$+ 0.240_{(0.0172)}$ BW $+ 0.509_{(0.1288)}$ CP $- 12.68_{(2.162)}$ ME $+ 34.26_{(13.591)}$ TF	187	0.92	0.278	0.310	(10o)
	$-175.2_{(40.38)}$	$+ 0.266_{(0.0281)}$ BW $+ 0.937_{(0.2251)}$ CP $+ 0.292_{(0.0537)}$ ADF	114	0.87	0.384	0.416	(10p)
UNO =	$2.814_{(5.758)}$	$+ 13.87_{(0.920)}$ DMI	189	0.82	0.558	0.605	(11a)
	$-94.09_{(17.423)}$	$+ 14.11_{(0.884)}$ DMI $+ 0.524_{(0.0920)}$ CP	189	0.84	0.448	0.497	(11b)
	$-47.44_{(22.503)}$	$+ 13.75_{(0.886)}$ DMI $+ 0.523_{(0.0902)}$ CP $- 3.889_{(1.1880)}$ ME	187	0.86	0.140	0.154	(11c)
	$0.343_{(5.2566)}$	$+ 0.490_{(0.0284)}$ NI	189	0.85	0.328	0.352	(11d)
	$54.87_{(14.693)}$	$+ 0.482_{(0.0278)}$ NI $- 4.651_{(1.1608)}$ ME	187	0.86	0.155	0.162	(11e)
	$79.41_{(30.540)}$	$+ 0.569_{(0.0514)}$ NI $- 5.870_{(1.8754)}$ ME $- 0.075_{(0.0361)}$ NDF	111	0.86	0.250	0.135^{c}	(11f)
	$93.75_{(29.511)}$	$+ 0.572_{(0.0493)}$ NI $- 5.819_{(1.8253)}$ ME $- 0.074_{(0.0343)}$ NDF $- 0.528_{(0.1712)}$ EE	111	0.87	0.248	0.198^{c}	(11g)
	$25.75_{(5.350)}$	$+ 0.180_{(0.0142)}$ BW	189	0.90	0.646	0.707	(11h)
	$-51.17_{(18.785)}$	$+ 0.178_{(0.0137)}$ BW $+ 0.426_{(0.0999)}$ CP	189	0.89	0.554	0.562	(11i)
	$37.89_{(22.266)}$	$+ 0.183_{(0.0131)}$ BW $+ 0.468_{(0.0935)}$ CP $- 8.656_{(1.2762)}$ ME	187	0.88	0.204	0.248	(11j)
	$16.16_{(25.076)}$	$+ 0.186_{(0.0133)}$ BW $+ 0.380_{(0.1025)}$ CP $- 6.603_{(1.6858)}$ ME $+ 21.16_{(10.179)}$ TF	187	0.89	0.224	0.314	(11k)
FNO =	$-0.490_{(2.0148)}$	$+ 8.445_{(0.3215)}$ DMI	190	0.96	0.298	0.281	(12a)
	$-26.35_{(6.378)}$	$+ 8.481_{(0.2991)}$ DMI $+ 0.141_{(0.0331)}$ CP	190	0.96	0.276	0.280	(12b)
	$10.03_{(7.196)}$	$+ 8.499_{(0.2599)}$ DMI $+ 0.138_{(0.0290)}$ CP $- 3.163_{(0.3949)}$ ME	187	0.97	0.135	0.144	(12c)
	$-21.69_{(6.056)}$	$+ 8.499_{(0.2613)}$ DMI $+ 0.082_{(0.0343)}$ CP $+ 9.501_{(2.1859)}$ TF	190	0.95	0.256	0.264	(12d)
	$1.578_{(1.9637)}$	$+ 0.277_{(0.0107)}$ NI	190	0.94	0.256	0.284	(12e)
	$47.95_{(5.424)}$	$+ 0.272_{(0.0102)}$ NI $- 3.987_{(0.4355)}$ ME	187	0.96	0.152	0.233	(12f)
	$64.00_{(7.486)}$	$+ 0.276_{(0.0100)}$ NI $- 4.974_{(0.5358)}$ ME $- 8.793_{(2.8886)}$ TF	187	0.96	0.189	0.271	(12g)
	$28.63_{(3.313)}$	$+ 0.062_{(0.0082)}$ BW	190	0.92	0.382	0.390	(12h)
	$81.15_{(12.341)}$	$+ 0.053_{(0.0077)}$ BW $+ 0.171_{(0.0528)}$ CP $- 7.135_{(0.6852)}$ ME	187	0.88	0.348	0.360	(12i)

n = number of observations; R^2 = pseudo correlation coefficient; MPE_{HH} = mean prediction error derived from the validation of the above equations by using the highCP sub-set of the literature database; MPE_{AH} = mean prediction error derived from the validation of the identical Table 2 equations by using the high CP sub-set of the literature database; Eq. = equation; MNO = manure nitrogen output; DMI = dry matter intake; CP = diet crude protein concentration; TF = diet total forage; ME = diet metabolisable energy concentration; EE = diet ether extract concentration; NI = nitrogen intake; ADF = diet acid-detergent fibre concentration; BW = body weight; UNO = urine nitrogen output; FNO = faeces nitrogen output

[a] Units: g/d for MNO, UNO, FNO; kg/d for DMI; g/kg DM for CP, ADF, NDF; g/100g DM for TF; MJ/kg DM for ME, EE; g/d for NI. The effect of all explanatory variables was significant according to the Wald statistic ($Fpr < 0.05$). The random effects of the individual experiment, animal and treatment were accounted for all predicted variables. The random factors were chosen according to changes in deviance during the development of the random model.

[b] MPE_{HH} and MPE_{AH} derived from an external validation (details presented in Table A3 and Table A4, respectively).

[c] Equations developed from the merged digestibility trials database to mimic 10d, 10f, 10i and 10k for the prediction of MNO and 11f and 11g for the prediction of UNO, have one or more predictors that was/were not significant according to the Wald statistic.

Appendix

Summary of the data used

A list of the mean, standard deviation, minimum and maximum observed values, coefficient of variation, number of observations for bodyweight, diet forage proportion, chemical composition and energy concentrations, nutrient and energy intakes, diet digestibility parameters, N outputs and NUE parameters is shown in Table 1. A high level of variation was observed among the variables used for the development of the prediction models. For example, the minimum and maximum bodyweight values differed by 478 kg, and the forage proportion in the diet ranged between 20% and 100% of the total DM. Maximum observed values regarding diet composition were up to 26 times higher (for ST) than minimum values, with maximum values of NDF, ADF and EE being more than 4, 5 and 9 times higher than their minimum values, respectively. Maximum ME concentration was 2.2 times higher than the minimum value. Highest intake values for DM and N were more than 5 and 7 times higher than their respective lower values, while maximum intakes of both GE and ME were nearly 5 times higher, compared to the lowest ones. The difference observed when comparing the highest and the lowest values for N output was 234.5, 167.3 and 94.3 g/d, for MNO, UNO and FNO respectively.

Table A1 External equations validation using the literature database: Prediction of manure, urine, and faeces nitrogen output as presented by other authors.

	Equations[a]	MPE[b]	Eq.[c]
MNO	$=6.91 + 0.759\ \mathrm{NI}$	0.230	(E1)
	$13.8 + 0.698\ \mathrm{NI}$	0.235	(E2)
	$0.775\ \mathrm{NI}$	0.214	(E3)
	$8.6 + 1.385\ \mathrm{MBW}$	0.559	(E4)
	$-24.7 + 0.609\ \mathrm{NI} + 0.599\ \mathrm{MBW}$	0.260	(E5)
	$15 + (0.55 + 0.032\ \mathrm{NI/DMI})\ \mathrm{MBW}$	0.455	(E6)
	$26.4 + (0.071 + 0.523\ \mathrm{NI/MEI})\ \mathrm{MBW}$	0.473	(E7)
	$-25.8 + 0.595\ \mathrm{MBW} + (0.579 + 0.058\ \mathrm{FP})\ \mathrm{NI}$	0.261	(E8)
	$11.50 + 0.65\ \mathrm{NI} - 4.47\ \mathrm{ME} + 1.77\ \mathrm{CP} + 0.432\ \mathrm{MBW}$	0.271	(E9)
UNO	$=0.23\ \mathrm{NI}^{1.15}$	0.330	(E10)
	$6.8 + 0.405\ \mathrm{NI}$	0.443	(E11)
	$-21.18 + 0.56\ \mathrm{NI}$	0.343	(E12)
	$-14.12 + 0.51\ \mathrm{NI}$	0.380	(E13)
	$-21.52 + 5.91\ \mathrm{CP}$	0.910	(E14)
	$-22 + 6.04\ \mathrm{CP}$	0.907	(E15)
	$-3.93 + 0.62\ \mathrm{NI} - 3.72\ \mathrm{DMI}$	0.384	(E16)
	$-71.2 + 0.265\ \mathrm{NI} + 3.76\ \mathrm{CP} + 0.468\ \mathrm{MBW}$	0.489	(E17)
FNO	$=4.91\ \mathrm{DMI}^{1.21}$	0.715	(E18)
	$0.506 + 0.352\ \mathrm{NI}$	0.562	(E19)
	$24.28 + 0.154\ \mathrm{NI}$	0.306	(E20)
	$15.82 + 0.2\ \mathrm{NI}$	0.286	(E21)
	$30.91 + 1.165\ \mathrm{CP}$	0.508	(E22)
	$19.68 + 1.81\ \mathrm{CP}$	0.525	(E23)

MPE = mean prediction error; Eq. = equation; MNO = manure nitrogen output; NI = nitrogen intake; MBW = metabolic body weight (body weight$^{0.75}$); DMI = dry matter intake; MEI = metabolisable energy intake; FP = diet forage proportion; ME = metabolisable energy; CP = diet crude protein concentration.

[a] Units: g/d for NI; kg for MBW; kg/d for DMI; MJ/d for MEI; kg/kg DM for FP; MJ/kg DM for ME; g/100g DM for CP.

[b] MPE derived from a validation against the literature database that was used to validate new equations developed in the current study.

[c] References: E1, E9, E11, E17, E19, (Reed *et al.*, 2015); E2 - E8, (Yan *et al.*, 2007); E10, E18, (Hirooka, 2010); E12, E14, E16, E20, E22, (Waldrip *et al.*, 2013); E13, E15, E21, E23, (Dong *et al.*, 2014).

Table A2 External validation using the literature database, equations developed from the merged digestibility trials database and previously published equations (n=570)

							Predicted – Actual			
Eq.[a]	Predicted	Actual	r^2	MPE	SE	Rc	Mean	SD	Min	Max
Manure nitrogen output (g/d)										
(1a)	135.1	121.5	0.64	0.460	20.71	0.67	14.18	37.19	-133.8	93.55
(1b)	125.5	121.5	0.84	0.305	18.94	0.88	6.135	24.82	-73.92	96.54
(1c)	120.0	121.5	0.84	0.270	13.80	0.86	11.98	17.86	-35.07	49.89
(1d)	122.9	121.5	0.84	0.303	17.96	0.88	3.147	25.03	-75.93	95.74
(1e)	129.7	121.5	0.79	0.336	19.84	0.84	12.56	25.26	-71.69	109.1
(1f)	139.9	121.5	0.74	0.297	23.10	0.77	22.06	27.34	-63.90	125.9
(1g)	125.1	121.5	0.92	0.242	13.07	0.92	5.810	20.15	-50.79	58.82
(1h)	121.8	121.5	0.92	0.241	12.52	0.92	2.081	20.77	-57.44	55.50
(1i)	122.7	121.5	0.78	0.317	17.04	0.81	14.45	20.65	-21.75	82.54
(1j)	116.9	121.5	0.98	0.129	6.405	0.97	-4.536	10.64	-24.42	12.72
(1k)	135.6	121.5	0.91	0.262	15.24	0.92	5.446	22.52	-53.28	55.20
(1l)	121.8	121.5	0.41	0.569	12.66	0.33	0.194	50.72	-177.9	105.8
(1m)	111.3	121.5	0.63	0.472	18.62	0.63	-8.859	40.05	-133.5	95.72
(1n)	100.6	121.5	0.42	0.456	19.38	0.59	-0.680	29.43	-72.64	48.44
(1o)	101.8	121.5	0.51	0.541	20.34	0.52	-19.23	43.82	-151.0	58.99
(1p)	97.22	121.5	0.35	0.484	22.76	0.56	-3.648	31.42	-75.41	51.99
(E1)	128.5	121.5	0.92	0.230	20.34	0.93	9.512	17.68	-34.01	69.90
(E2)	125.6	121.5	0.92	0.235	13.56	0.92	6.425	19.27	-46.33	61.60
(E3)	124.1	121.5	0.92	0.214	15.06	0.95	5.219	17.39	-35.88	66.98
(E4)	122.6	121.5	0.41	0.559	23.10	0.51	1.335	46.64	-173.2	126.1
(E5)	121.9	121.5	0.88	0.260	17.93	0.92	2.409	21.39	-62.13	72.09
(E6)	118.1	121.5	0.64	0.455	19.67	0.68	-2.169	38.65	-135.5	95.44
(E7)	108.8	121.5	0.39	0.473	20.91	0.56	9.124	30.21	-53.08	100.1
(E8)	118.9	121.5	0.89	0.261	17.33	0.92	-0.990	21.70	-62.92	62.23
(E9)	111.2	121.5	0.81	0.271	15.25	0.86	10.85	16.73	-21.97	67.98
Urine nitrogen output (g/d)										
(2a)	80.95	67.68	0.66	0.695	10.61	0.42	-1.721	37.80	-107.5	72.10
(2b)	76.26	67.68	0.81	0.536	13.59	0.80	-4.312	27.09	-74.57	39.65
(2c)	73.61	67.68	0.80	0.555	13.07	0.77	-7.007	28.19	-80.81	39.97
(2d)	77.30	67.68	0.85	0.489	12.58	0.76	7.496	24.56	-46.75	50.30
(2e)	74.64	67.68	0.56	0.616	17.54	0.74	4.715	28.47	-52.16	44.84
(2f)	80.47	67.68	0.81	0.504	13.71	0.82	-4.394	25.57	-51.20	44.77
(2g)	78.60	67.68	0.88	0.476	12.39	0.82	-3.477	25.51	-49.06	44.81
(2h)	91.00	67.68	0.94	0.443	7.902	0.81	-9.060	23.63	-50.99	25.88
(2i)	83.76	67.68	0.98	0.289	3.799	0.88	6.575	15.92	-10.29	24.71
(2j)	79.72	67.68	0.91	0.424	9.841	0.83	-1.999	22.12	-56.71	44.32
(2k)	75.81	67.68	0.88	0.474	10.87	0.80	-5.890	24.49	-65.94	51.05
(2l)	76.45	67.68	0.72	0.518	14.56	0.77	7.069	24.06	-35.47	51.61

(2m)	76.96	67.68	0.85	0.460	13.19	0.81	6.053	23.03	-45.74	62.89
(2n)	102.3	67.68	0.97	0.381	6.688	0.90	-15.17	16.86	-42.16	3.476
(2o)	72.28	67.68	0.44	0.837	8.991	0.25	-7.757	45.43	-127.3	61.75
(2p)	64.54	67.68	0.63	0.714	15.77	0.69	-13.62	35.46	-106.9	37.68
(2q)	52.06	67.68	0.18	0.769	13.57	0.56	-3.169	34.30	-68.97	29.54
(2r)	60.29	67.68	0.57	0.772	15.84	0.60	-17.84	37.80	-118.4	23.99
(2s)	51.63	67.68	0.11	0.799	12.96	0.54	-3.483	35.71	-53.42	32.59
(E10)	88.86	67.68	0.91	0.330	12.82	0.88	6.066	15.54	-33.21	45.98
(E11)	77.62	67.68	0.91	0.443	9.350	0.82	-3.958	23.32	-60.83	43.15
(E12)	76.75	67.68	0.91	0.343	12.93	0.91	-5.840	16.33	-46.99	35.57
(E13)	75.07	67.68	0.90	0.380	11.77	0.89	-7.199	18.04	-53.42	36.05
(E14)	63.73	67.68	0.24	0.910	17.84	0.45	-12.75	44.59	-119.9	68.20
(E15)	65.12	67.68	0.25	0.907	18.24	0.46	-11.30	44.54	-118.4	69.90
(E16)	76.00	67.68	0.89	0.384	13.13	0.90	-5.066	18.57	-54.10	34.41
(E17)	66.84	67.68	0.87	0.489	13.03	0.90	-13.76	22.61	-75.82	17.33
Faeces nitrogen output (g/d)										
(3a)	61.08	47.84	0.75	0.311	10.27	0.64	7.397	10.30	-26.09	37.37
(3b)	60.50	47.84	0.80	0.278	9.329	0.68	6.679	9.282	-19.59	35.37
(3c)	56.73	47.84	0.74	0.323	7.967	0.72	10.84	7.756	-0.421	28.17
(3d)	59.73	47.84	0.80	0.273	9.342	0.70	6.003	9.305	-20.20	33.39
(3e)	57.31	47.84	0.78	0.321	7.451	0.70	11.41	7.296	1.913	27.88
(3f)	54.83	47.84	0.83	0.297	7.293	0.81	10.58	7.123	2.226	27.06
(3g)	55.12	47.84	0.74	0.280	10.13	0.73	2.069	10.33	-19.23	26.07
(3h)	58.82	47.84	0.51	0.421	11.10	0.66	12.92	10.96	-8.892	45.26
(3i)	59.89	47.84	0.58	0.418	10.66	0.63	13.99	10.39	-5.788	44.62
(3j)	59.29	47.84	0.69	0.413	10.11	0.66	15.04	9.740	-0.960	41.79
(3k)	69.44	47.84	0.15	0.353	5.206	0.94	7.630	4.685	2.023	11.79
(3l)	50.54	47.84	0.48	0.417	5.461	0.37	-0.220	15.67	-50.50	25.29
(3m)	51.10	47.84	0.24	0.418	8.712	0.52	9.177	10.46	-6.338	29.27
(3n)	39.58	47.84	0.76	0.273	3.096	0.46	5.630	9.169	-9.144	12.00
(3o)	45.05	47.84	0.03	0.361	3.831	0.50	-0.951	8.025	-9.767	7.747
(3p)	46.40	47.84	0.16	0.406	7.805	0.41	5.859	10.79	-10.07	25.25
(E18)	81.77	47.84	0.75	0.715	15.20	0.36	26.26	16.64	-0.912	70.15
(E19)	61.99	47.84	0.35	0.562	22.08	0.39	7.535	22.18	-41.20	85.46
(E20)	51.21	47.84	0.74	0.306	6.107	0.67	-0.727	10.87	-25.27	21.60
(E21)	50.80	47.84	0.74	0.286	7.931	0.72	-1.647	9.895	-23.80	18.94
(E22)	47.71	47.84	0.06	0.508	4.488	0.14	-2.680	18.58	-43.61	-40.50
(E23)	45.79	47.84	0.07	0.525	6.973	0.19	-4.688	18.73	-40.49	35.64

Eq. = equation; r^2 = correlation between predicted and actual values; MPE = mean prediction error; SE = standard error; Rc = Lin's concordance correlation coefficient; SD = standard deviation; Min = minimum value observed; Max = maximum value observed.

[a] Equations are presented in Table 2 (Eq. 1a-1p, 2a-2s, 3a-3p) and Table A1 (Eq. E1-E23).

Table A3 External validation using the literature database, partitioned in 3 groups according to their CP concentrationand equations developed from the merged digestibility trials database, representing low (n=190), medium (n=190) and high (n=190) protein concentrations

							Predicted – Actual			
Eq.[a]	Predicted	Actual	r^2	MPE	SE	Rc	Mean	SD	Min	Max
Manure nitrogen output (g/d)										
Low CP group										
(4a)	110.8	86.78	0.73	0.389	13.17	0.61	24.42	15.77	-29.68	61.53
(4b)	99.16	86.78	0.81	0.282	11.84	0.79	14.47	13.41	-35.08	41.32
(4c)	107.9	86.78	0.59	0.398	13.80	0.60	16.65	20.34	-38.36	48.88
(4d)	90.12	86.78	0.73	0.266	13.25	0.82	7.610	14.30	-29.63	31.94
(4e)	93.39	86.78	0.85	0.232	10.37	0.86	9.982	11.92	-23.30	39.04
(4f)	112.1	86.78	0.63	0.404	14.11	0.59	20.38	19.36	-18.48	62.11
(4g)	102.9	86.78	0.53	0.416	8.700	0.41	15.90	23.35	-66.08	46.99
(4h)	90.94	86.78	0.60	0.351	9.894	0.61	5.682	21.15	-71.14	33.11
(4i)	84.10	86.78	0.27	0.470	18.36	0.45	-9.222	27.28	-75.63	37.69
Medium CP group										
(7a)	145.6	120.1	0.77	0.338	18.29	0.73	24.97	21.71	-24.98	96.73
(7b)	120.4	120.1	0.78	0.245	18.64	0.90	-0.369	20.29	-39.83	62.53
(7c)	121.6	120.1	0.86	0.197	14.83	0.92	0.145	15.93	-31.97	39.01
(7d)	129.5	120.1	0.86	0.229	13.64	0.88	8.937	17.80	-27.23	54.36
(7e)	130.4	120.1	0.72	0.287	19.54	0.81	9.444	22.17	-17.17	74.64
(7f)	114.7	120.1	0.76	0.272	15.74	0.82	-4.363	22.16	-31.73	33.40
(7g)	124.2	120.1	0.38	0.445	21.82	0.54	4.280	35.97	-86.16	122.5
High CP group										
(10a)	166.3	155.1	0.74	0.356	30.62	0.83	13.14	36.26	-91.10	102.3
(10b)	163.6	155.1	0.83	0.282	25.74	0.89	10.89	28.97	-52.53	101.4
(10c)	158.3	155.1	0.83	0.282	25.66	0.90	5.238	29.55	-60.66	95.99
(10d)	133.8	155.1	0.98	0.138	9.738	0.95	15.99	9.545	5.966	31.30
(10e)	129.0	155.1	0.98	0.114	9.093	0.97	11.14	8.808	-2.505	26.34
(10f)	156.8	155.1	0.94	0.156	8.834	0.91	-3.220	15.51	-17.97	20.82
(10g)	156.9	155.1	0.92	0.201	17.04	0.95	3.799	21.23	-35.85	67.20
(10h)	129.7	155.1	0.98	0.113	7.786	0.97	12.08	8.116	-3.240	25.45
(10i)	135.2	155.1	0.98	0.142	8.930	0.94	17.75	8.472	7.471	33.06
(10j)	150.7	155.1	0.93	0.199	16.12	0.95	-2.717	21.24	-43.91	57.62
(10k)	134.7	155.1	0.99	0.132	8.321	0.96	13.83	10.54	-0.208	30.68
(10l)	144.3	155.1	0.52	0.490	24.28	0.55	-13.84	52.45	-154.6	66.35
(10m)	140.9	155.1	0.60	0.461	23.76	0.61	-16.96	48.94	-129.2	54.46
(10n)	108.6	155.1	0.85	0.241	14.35	0.78	21.88	14.45	-7.844	30.99
(10o)	103.3	155.1	0.76	0.278	17.64	0.77	17.52	18.71	-18.84	30.47
(10p)	142.7	155.1	0.68	0.384	27.04	0.77	-8.303	39.24	-106.7	48.92
Urine nitrogen output (g/d)										
Low CP group										

(5a)	60.11	42.68	0.50	0.782	7.675	0.36	17.58	20.21	-64.82	57.88
(5b)	47.70	42.68	0.60	0.628	8.686	0.60	7.034	17.97	-69.44	31.74
(5c)	51.90	42.68	0.65	0.637	7.561	0.55	10.82	17.89	-68.40	40.88
(5d)	55.21	42.68	0.38	0.788	6.072	0.27	12.53	22.70	-85.42	46.86
(5e)	41.05	42.68	0.47	0.682	9.082	0.53	0.440	20.23	-89.93	24.29
(5f)	39.34	42.68	0.31	0.820	12.28	0.41	-9.001	24.02	-70.11	30.20
(5g)	38.11	42.68	0.30	0.772	10.92	0.42	-2.673	22.41	-100.7	29.05
Medium CP group										
(8a)	41.31	70.20	0.68	0.639	3.768	0.18	-29.19	28.07	-130.7	12.40
(8b)	62.45	70.20	0.74	0.392	11.91	0.77	-8.843	17.80	-83.19	27.40
(8c)	78.61	70.20	0.79	0.384	8.739	0.73	7.966	18.71	-73.60	39.03
(8d)	80.98	70.20	0.86	0.230	5.557	0.87	1.853	9.191	-13.81	20.71
(8e)	74.58	70.20	0.45	0.531	13.46	0.55	3.730	25.44	-95.22	36.25
(8f)	63.23	70.20	0.49	0.521	13.67	0.58	-7.707	24.54	-104.0	24.64
High CP group										
(11a)	104.9	90.66	0.57	0.558	21.31	0.68	7.708	33.32	-69.31	93.92
(11b)	102.7	90.66	0.72	0.448	20.24	0.81	6.918	26.90	-49.19	83.81
(11c)	80.62	90.66	0.97	0.140	6.571	0.97	6.438	6.916	-4.840	20.42
(11d)	99.35	90.66	0.87	0.328	13.91	0.89	4.586	20.31	-39.36	73.13
(11e)	81.81	90.66	0.97	0.155	6.115	0.96	7.897	7.605	-3.756	23.08
(11f)	85.75	90.66	0.94	0.250	12.09	0.92	11.83	13.43	-5.371	32.32
(11g)	107.4	90.66	0.89	0.248	8.898	0.87	4.718	13.64	-12.65	22.98
(11h)	92.57	90.66	0.40	0.646	20.17	0.50	-3.701	40.46	-105.5	76.31
(11i)	89.59	90.66	0.58	0.554	19.44	0.65	-5.430	34.77	-91.50	66.89
(11j)	64.80	90.66	0.94	0.204	7.210	0.87	12.06	6.584	-1.916	19.39
(11k)	61.73	90.66	0.90	0.224	8.789	0.88	9.660	8.173	-8.290	14.29
Faeces nitrogen output (g/d)										
Low CP group										
(6a)	51.34	43.80	0.42	0.364	10.74	0.54	7.540	10.90	-9.785	55.49
(6b)	56.27	43.80	0.74	0.340	5.712	0.41	11.55	6.185	-0.863	18.34
(6c)	57.68	43.80	0.71	0.354	5.473	0.35	12.96	5.621	1.965	20.44
(6d)	42.90	43.80	0.35	0.341	10.91	0.58	-0.901	11.32	-19.03	45.92
(6e)	52.65	43.80	0.67	0.375	7.985	0.50	7.926	9.041	-5.537	28.56
(6f)	54.11	43.80	0.67	0.353	7.405	0.47	9.385	8.085	-2.459	27.52
(6g)	48.46	43.80	0.25	0.341	3.741	0.29	4.512	9.884	-22.74	25.60
(6h)	43.69	43.80	0.55	0.215	5.949	0.71	-1.033	5.782	-6.941	17.57
Medium CP group										
(9a)	58.95	48.23	0.42	0.446	13.92	0.54	10.21	14.33	-12.75	54.75
(9b)	51.20	48.23	0.37	0.407	13.18	0.60	2.806	14.15	-20.49	46.46
(9c)	52.42	48.23	0.59	0.328	10.79	0.73	5.469	10.96	-5.929	36.16
(9d)	50.16	48.23	0.15	0.445	8.197	0.33	1.667	14.65	-28.82	30.50
(9e)	60.74	48.23	0.39	0.451	8.584	0.38	13.79	12.48	-2.280	41.31

High CP group										
(12a)	61.64	52.09	0.73	0.298	10.34	0.82	5.742	10.46	-23.09	38.63
(12b)	60.99	52.09	0.77	0.276	9.878	0.84	5.566	9.841	-15.57	33.92
(12c)	48.43	52.09	0.96	0.135	3.650	0.94	4.782	3.657	-0.733	13.65
(12d)	58.16	52.09	0.77	0.256	9.480	0.87	2.569	9.523	-19.36	30.89
(12e)	57.55	52.09	0.79	0.256	9.784	0.87	3.408	9.727	-14.87	29.00
(12f)	47.80	52.09	0.93	0.152	4.878	0.93	4.147	4.699	-2.441	13.67
(12g)	50.42	52.09	0.94	0.189	4.874	0.89	6.771	5.164	0.420	18.09
(12h)	51.56	52.09	0.55	0.382	5.918	0.55	-1.833	14.34	-49.32	21.70
(12i)	43.99	52.09	0.47	0.348	6.147	0.47	8.404	9.224	-5.633	16.62

Eq. = equation; r^2 = correlation between predicted and actual values; MPE = mean prediction error; SE = standard error; Rc = Lin's concordance correlation coefficient; SD = standard deviation; Min = minimum value observed; Max = maximum value observed.

[a] Equations are presented in Table 3 (Eq. 4a-4i, 5a-5g, 6a-6h), Table 4 (Eq. 7a-7g, 8a-8f, 9a-9e) and Table 5 (Eq. 10a-10p, 11a-11k, 12a-12i).

Table A4 External validation using the literature database, partitioned in 3 groups according to their CP concentrationand equations developed from the merged digestibility trials database (n=570)

								Predicted – Actual			
Eq.[a]	Equiv. Eq.	Predicted	Actual	r^2	MPE	SE	Rc	Mean	SD	Min	Max
Manure nitrogen output (g/d)											
Low CP group											
(1a)	(4a)	127.2	86.78	0.73	0.540	13.70	0.42	40.75	15.75	-11.90	78.05
(1b)	(4b)	92.60	86.78	0.81	0.244	13.51	0.86	8.775	13.74	-34.65	41.68
(1c)	(4c)	107.7	86.78	0.60	0.396	15.13	0.62	16.99	20.05	-35.07	49.67
(1f)	(4d)	115.4	86.78	0.68	0.472	20.39	0.54	31.26	20.25	-6.334	69.75
(1g)	(4e)	93.84	86.78	0.85	0.237	9.974	0.85	10.30	12.09	-25.09	39.00
(1i)	(4f)	112.6	86.78	0.56	0.429	15.82	0.55	20.74	20.97	-18.33	66.28
(1l)	(4g)	119.2	86.78	0.53	0.526	8.913	0.27	32.17	23.23	-49.61	62.93
(1m)	(4h)	87.84	86.78	0.60	0.341	12.18	0.69	3.067	20.10	-70.72	35.40
(1n)	(4i)	88.15	86.78	0.24	0.468	18.26	0.44	-5.536	27.77	-72.64	42.49
Medium CP group											
(1a)	(7a)	140.8	120.1	0.77	0.324	15.92	0.74	20.28	22.62	-37.44	93.55
(1b)	(7b)	129.0	120.1	0.80	0.264	16.36	0.85	8.357	20.79	-40.84	76.62
(1c)	(7c)	126.6	120.1	0.82	0.227	15.64	0.88	5.158	17.99	-28.93	49.89
(1g)	(7d)	128.2	120.1	0.86	0.239	12.19	0.86	7.654	19.36	-34.57	55.42
(1i)	(7e)	129.4	120.1	0.64	0.322	22.08	0.77	7.907	25.28	-21.75	82.54
(NA[*])	(7f)										
(1l)	(7g)	119.4	120.1	0.65	0.336	11.20	0.59	2.276	29.03	-52.91	37.92
High CP group											
(1a)	(10a)	137.3	155.1	0.74	0.389	21.36	0.72	-16.41	41.01	-133.9	54.60
(1b)	(10b)	154.8	155.1	0.82	0.315	20.26	0.84	1.498	34.24	-73.92	96.54
(1d)	(10c)	150.7	155.1	0.82	0.320	20.17	0.83	-2.807	34.81	-75.93	95.74
(**)	(10d)	130.0	155.1	0.98	0.120	6.884	0.96	12.18	12.18	-7.825	27.73
(1c)	(10e)	130.3	155.1	0.99	0.130	5.972	0.95	12.31	11.87	-10.08	26.58
(**)	(10f)	164.8	155.1	0.96	0.128	7.674	0.94	4.810	12.49	-8.629	25.00
(1g)	(10g)	153.2	155.1	0.92	0.226	14.85	0.92	-0.160	25.04	-50.79	58.82
(1i)	(10h)	129.9	155.1	0.98	0.129	8.145	0.96	12.44	10.42	-6.630	29.60
(**)	(10i)	131.9	155.1	0.98	0.132	9.013	0.95	14.50	9.204	-2.209	31.42
(1h)	(10j)	148.4	155.1	0.93	0.230	14.00	0.91	-5.199	25.53	-57.44	51.35
(**)	(10k)	129.0	155.1	0.95	0.350	13.84	0.75	-48.11	17.57	-81.14	-21.44
(1l)	(10l)	122.9	155.1	0.52	0.554	13.05	0.29	-36.01	59.59	-177.9	58.06
(1m)	(10m)	136.1	155.1	0.56	0.497	19.37	0.48	-22.28	53.73	-133.5	56.73
(1n)	(10n)	112.3	155.1	0.88	0.253	10.20	0.68	25.28	16.06	0.021	35.97
(1p)	(10o)	107.1	155.1	0.72	0.310	13.98	0.64	20.50	21.54	-12.01	36.15
(**)	(10p)	138.5	155.1	0.68	0.416	17.11	0.60	-12.55	46.17	-118.4	55.49
Urine nitrogen output (g/d)											
Low CP group											
(2a)	(5a)	74.05	42.68	0.50	0.991	8.683	0.25	31.53	19.70	-47.61	72.10

(2b)	(5b)	43.32	42.68	0.60	0.594	10.99	0.71	3.136	16.88	-64.78	30.63
(2j)	(5c)	53.66	42.68	0.65	0.642	9.708	0.61	13.03	16.48	-58.23	44.32
(2o)	(5d)	70.12	42.68	0.38	0.973	6.106	0.17	27.44	22.69	-70.45	61.75
(2p)	(5e)	39.00	42.68	0.48	0.673	10.50	0.58	-1.444	19.59	-88.80	24.59
(2q)	(5f)	40.62	42.68	0.35	0.793	11.47	0.43	-7.793	23.53	-68.97	29.54
(2r)	(5g)	37.89	42.68	0.27	0.790	12.65	0.44	-3.032	22.74	-101.1	33.09
Medium CP group											
(2a)	(8a)	80.39	70.20	0.68	0.455	8.744	0.59	9.514	22.36	-78.78	49.54
(2b)	(8b)	70.15	70.20	0.74	0.391	9.435	0.73	-0.911	19.72	-82.97	37.10
(2j)	(8c)	75.43	70.20	0.79	0.364	9.444	0.78	4.743	17.88	-74.40	36.17
(NA*)	(8d)										
(2o)	(8e)	72.66	70.20	0.45	0.541	7.598	0.37	2.033	27.98	-102.4	36.12
(2p)	(8f)	61.55	70.20	0.50	0.530	10.99	0.50	-9.280	25.47	-108.2	19.57
High CP group											
(2a)	(11a)	78.76	90.66	0.57	0.605	11.14	0.42	-15.29	39.06	-107.5	49.53
(2b)	(11b)	94.68	90.66	0.67	0.497	16.79	0.71	1.931	31.48	-74.48	85.94
(2e)	(11c)	81.16	90.66	0.98	0.154	4.932	0.95	6.942	8.660	-5.547	19.79
(2j)	(11d)	91.26	90.66	0.87	0.352	12.10	0.85	-2.972	22.91	-53.68	62.02
(2l)	(11e)	76.01	90.66	0.96	0.162	6.611	0.96	2.252	9.823	-10.80	21.34
(**)	(11f)	77.24	90.66	0.97	0.135	5.947	0.97	3.329	7.700	-7.385	18.29
(**)	(11g)	100.4	90.66	0.93	0.198	7.074	0.91	-2.279	11.65	-13.59	15.63
(2o)	(11h)	72.34	90.66	0.40	0.707	9.022	0.23	-22.46	45.08	-127.3	38.28
(2p)	(11i)	85.42	90.66	0.59	0.562	16.25	0.59	-8.066	36.10	-106.9	47.58
(2q)	(11j)	66.03	90.66	0.92	0.248	5.022	0.74	12.76	10.76	-8.014	20.15
(2s)	(11k)	62.47	90.66	0.80	0.314	7.361	0.71	9.535	13.65	-15.16	19.77
Faeces nitrogen output (g/d)											
Low CP group											
(3a)	(6a)	52.98	43.80	0.42	0.386	11.07	0.50	9.181	11.17	-8.022	58.10
(3c)	(6b)	56.37	43.80	0.75	0.354	5.909	0.42	11.65	6.626	-1.228	19.98
(3e)	(6c)	56.99	43.80	0.74	0.354	5.661	0.39	12.27	6.188	0.179	19.50
(3g)	(6d)	39.50	43.80	0.35	0.333	8.015	0.54	-4.297	9.598	-23.42	34.28
(3h)	(6e)	48.72	43.80	0.60	0.295	8.136	0.59	3.996	8.480	-5.788	26.68
(3i)	(6f)	50.13	43.80	0.61	0.271	7.142	0.58	5.406	7.272	-8.892	25.67
(3l)	(6g)	49.18	43.80	0.25	0.347	4.262	0.31	5.233	9.822	-22.85	27.04
(3m)	(6h)	47.23	43.80	0.40	0.263	7.573	0.57	2.510	7.375	-6.368	20.52
Medium CP group											
(3a)	(9a)	60.42	48.23	0.42	0.459	13.58	0.51	11.69	14.08	-11.58	55.55
(3g)	(9b)	52.55	48.23	0.37	0.393	9.472	0.56	4.199	12.47	-17.54	40.31
(3h)	(9c)	54.94	48.23	0.38	0.424	12.20	0.54	7.994	13.53	-5.132	45.26
(3l)	(9d)	50.77	48.23	0.15	0.435	6.073	0.27	2.368	14.40	-25.69	-16.72
(3m)	(9e)	49.43	48.23	0.33	0.394	8.616	0.52	2.478	13.04	30.25	29.27
High CP group											

(3a)	(12a)	58.51	52.09	0.73	0.281	10.42	0.84	2.588	10.51	-26.09	35.64
(3b)	(12b)	60.42	52.09	0.76	0.280	10.05	0.84	4.716	10.03	-19.59	35.55
(3c)	(12c)	49.05	52.09	0.96	0.144	3.708	0.93	5.400	3.599	-0.421	14.48
(3d)	(12d)	59.14	52.09	0.77	0.264	9.793	0.86	3.449	9.800	-20.20	33.54
(3g)	(12e)	62.03	52.09	0.79	0.284	9.018	0.82	8.049	9.045	-10.44	32.18
(3h)	(12f)	54.05	52.09	0.93	0.233	4.368	0.81	10.40	4.218	3.706	17.96
(3i)	(12g)	56.26	52.09	0.94	0.271	4.525	0.76	12.60	4.478	6.445	22.25
(3l)	(12h)	50.57	52.09	0.55	0.390	4.844	0.47	-2.680	15.05	-50.49	21.51
(3m)	(12i)	46.87	52.09	0.65	0.360	5.285	0.48	11.29	7.640	-1.606	18.24

Eq. = equation; r^2 = correlation between predicted and actual values; MPE = mean prediction error; SE = standard error; Rc = Lin’s concordance correlation coefficient; SD = standard deviation; Min = minimum value observed; Max = maximum value observed.

[a] Equations are presented in Table 2 (Eq. 1a-1p, 2a-2s, 3a-3p), Table 3 (Eq. 4a-4i, 5a-5g, 6a-6h), Table 4 (Eq. 7a-7h, 8a-8f, 9a-9e) and Table 5 (Eq. 10a-10p, 11a-11k, 12a-12i).

[*] Equations using the same predictors and the merged digestibility trials database were not available and could not be produced in that case.

[**] Equations using the same predictors and the merged digestibility trials database were produced in order to assist the comparison