Short communication: Evaluation of nitrogen excretion equations from cattle

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ABSTRACT

Nitrogen excretion in dairy manure is a precursor for N_2O and NH_3 formation in livestock housing, manure storage facilities, and after manure is applied to land. Nitrous oxide is a major contributor to greenhouse gas emissions, and reducing N output from dairy production facilities can reduce the amount of anthropogenic N_2O entering the atmosphere. The objective of the study was to conduct a comprehensive evaluation of extant prediction models for N excretion in feces and urine using extensive literature data. A total of 45 N excretion equations were evaluated for lactating cows, heifers, and nonlactating cows and steers. These equations were evaluated with 215 treatment means from 69 published studies collected over 20 yr from 1995 to 2015. Two evaluation methods were used: the root mean square prediction error and the concordance correlation coefficient. Equations constructed using a more rigorous development process fared better than older extant equations. Equations for heifers and nonlactating cows had greater error of prediction compared with equations used for lactating cows. This could be due to limited amount of data available for construction and evaluation of the equations. Urinary N equations had greater prediction errors than other forms of excretion, possibly due to high variability in urinary N excretion and challenges in urine collection. Fecal N equations had low error bias and reached an acceptable level of precision and accuracy.

Key words: empirical equation, nitrogen utilization, cattle

Short Communication

Livestock N emissions are one of the leading contributors to NH_3 and N_2O emissions in the United States (Davidson, 2009). Cattle operations, in particular beef and dairy, account for the majority of emissions, respectively contributing 41 and 20% of total livestock emis-

sions (Gerber et al., 2013). In addition to N_2O escape, manure N can contribute to eutrophication of surface waters through runoff and acid rain (McCubbin et al., 2002; Diaz and Rosenberg, 2008); over-fertilization of soils can impair crop growth; and NH_3 and nitrate emissions can lead to formation of particulate matter, which forms when NH_3 combines with nitrates and sulfates to form fine particulates (Fowler et al., 2013). The surplus of anthropogenic N compounds in the atmosphere has a detrimental effect on the environment and is linked to significant human health problems including odor problems, lung diseases, chronic bronchitis, and premature mortality (McCubbin et al., 2002; Fowler et al., 2013). As the human population continues to rise, the demand for meat and dairy products will continue to increase, and the challenge is to meet this demand while minimizing damage to the environment.

Mitigation strategies to reduce the amount of N lost to the environment from cattle production systems fall into 2 broad categories: (1) feeding strategies to reduce the amount of N excreted by the dairy cow per unit of milk or meat produced, and (2) manure management strategies to reduce the amount of N lost during storage and land application. To assess effectiveness of strategies to reduce negative environmental effect requires quantification of nutrient losses under different management alternatives. Widely used N excretion prediction equations include international, national, and regional approaches for estimating greenhouse gas emissions. Most countries use the Intergovernmental Panel on Climate Change (IPCC) Tier 1 or 2 default values to report total N (TN) excretion, which are scalar multipliers of the total animal mass (IPCC, 2006). In the US National Greenhouse Gas Inventory, the US Environmental Protection Agency (EPA) estimates TN as the difference between total N intake (NI) and the sum of estimated secreted milk N (MN) and N retained in animal tissue (EPA, 2014). Fecal (FN) and urinary N (UN) excretions have different effects on the environment, so equations predicting UN and FN separately improve estimation of N partitioning to air and soil. Several equations have been developed to estimate FN and UN excretion separately and have been reported to improve the accuracy of estimation

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Table 1. Summary of nitrogen data collected from 1995 to 2015 by animal class

Item	Number of observations	Minimum (g/d)	Median (g/d)	Mean (SD; g/d)	Maximum (g/d)
Lactating cows					
Urine N	215	39.50	187.50	192.90 (70.54)	331.00
Fecal N	213	69.20	176.00	177.30 (51.26)	308.00
Milk N	188	65.60	147.00	147.70 (35.21)	223.00
Intake N	207	187.50	559.00	545.80 (130.86)	803.00
Retained N	104	−94.70	32.2.00	31.460 (41.51)	219.00
Total manure N	211	151.20	368.00	370.10 (98.94)	606.40
Heifers and nonlactating cows					
Urine N	25	36.00	50.96	59.13 (48.20)	147.00
Fecal N	25	21.70	68.70	75.36 (38.04)	174.00
Intake N	25	87.60	137.20	158.90 (121.86)	376.00
Retained N	16	−29.00	24.96	22.27 (22.89)	49.14
Total manure N	25	68.00	117.90	134.50 (83.59)	318.00
Steers					
Urine N	45	5.50	52.08	53.99 (27.30)	132.00
Fecal N	57	24.20	50.80	58.15 (25.42)	119.00
Intake N	57	43.80	147.10	166.80 (78.58)	413.00
Retained N	45	8.90	43.83	40.66 (16.93)	72.60
Total manure N	57	35.00	99.60	101.10 (38.10)	208.60

(Reed et al., 2015b). Most extant equations predicting N excretion from cattle were developed from a small pool of potential covariates and selected based on either biological knowledge or a stepwise selection method, both of which are subject to criticism. A more rigorous equation development strategy and thorough search of available covariates and equation parameter space is likely to improve prediction ability. However, when the number of possible covariates is large, equation selection can be a time- and computation-intensive process. The genetic algorithm used by Reed et al. (2015b) facilitated the selection process and reduced the time required to identify the best possible equation based on a given criteria. Although the equations developed by Reed et al. (2015b) performed well in internal evaluation, the most recent observation in the data used for equation development and evaluation was collected in 1994, so the prediction accuracy of the equations for modern cows is uncertain. Thus, the objective of this study was to evaluate the accuracy and precision of existing N excretion prediction equations for 3 animal classes and 3 forms of N excretion using N balance data collected from recently published studies.

Published data from the National Center for Biotechnology Information (PubMed) and BIOSIS were collected using the key phrase “nitrogen utilization and excretion from dairy cattle” and from additional searches including the words “steers,” “lactating cows,” “heifers,” and “non-lactating cows.” Manuscripts were selected if the title or abstract of the article included any or all of the key words “nitrogen,” “dairy,” and “fecal/urine.” Data collection was limited to studies published between 1994 and 2015 to ensure current data were used for evaluation. Data were collected for 3

animal classes, lactating cows, heifers and nonlactating cows, and steers, to be able to evaluate equations for the 3 animal classes reported by Reed et al. (2015b). The majority of articles collected did not report the ME content of the feed, which is a predictor in several of the equations being evaluated. If diet ME was not provided by the study and if 95% or greater of the ME values of the ingredients were either reported or available in nutrient composition tables, diet ME was calculated using the summative approach described in the NRC (2001). A total of 69 studies were collected, which covered lactating cows ($n = 57$), heifer and nonlactating cows ($n = 6$), and steers ($n = 13$), resulting in 215, 23, and 57 treatment means, respectively (Table 1). A list of the references used for data collection is provided in Table 2.

The equations evaluated were listed by Reed et al. (2015a,b). An additional literature search was conducted to add to the total number of equations, resulting in 46 equations (Table 3). For each animal class, equations predicting fecal, urine, milk, and total manure N were included. Two methods were used to evaluate the equations: the root mean square prediction error (**RMSPE**) and the concordance correlation coefficient (**CCC**; Lin, 1989, 2000). The RMSPE was calculated using the following equation:

$$\text{RMSPE} = \left[\left(\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}} \right)^T \left(\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}} \right) n^{-1} \right]^{1/2},$$

where $\mathbf{y}$ is the vector of observations, $\mathbf{X}$ is the matrix of explanatory variables, $\hat{\boldsymbol{\beta}}$ is the vector of fixed-effect parameter estimates, n is the number of observations in

each fold, and the superscript T denotes the transpose function. The RMSPE was decomposed into the error of central tendency, the error due to regression, and the error of dispersion as described by Bibby and Toutenburg (1977). Smaller prediction errors are more desirable, and although there are no explicit rules for the amount of acceptable error, a guideline proposed by Reed et al. (2015a) states that an RMSPE as a percentage of the mean observed value below 25% is deemed acceptable and an RMSPE below 10% of the mean is considered good. In reference to the error decomposition, mean or systemic bias larger than 5% of the total error is considered a deviation from the desired random

error. The CCC was calculated using the *epi.ccc* function in the *epiR* package (Stevenson et al., 2014) in R statistical software (R Core Group, Vienna, Austria) and is defined by the equation

$$\rho_c = \frac{2\sigma_{xy}}{\sigma_x^2 + \sigma_y^2 + (\mu_y - \mu_x)^2},$$

where ρ_c represents the CCC; σ_{xy} is the covariance between the vectors of observed ($\mathbf{X}$) and predicted ($\mathbf{Y}$) values; σ_x^2 and σ_y^2 are the variances of vectors $\mathbf{X}$ and $\mathbf{Y}$; and μ_x and μ_y are the means of vectors $\mathbf{X}$ and $\mathbf{Y}$. The CCC combines measures of both precision and accuracy to determine how far the observed data deviate from the line of perfect concordance (a line at 45° on a square scatter plot) with values close to 1 indicating agreement between observed and predicted (Lin, 1989, 2000). Like the RMSPE, the CCC can be decomposed to estimate a scale or slope shift (v), location bias (u) relative to scale shift, and a bias correction factor (C_b) where values closer to 0 indicate less bias for v and u and values close to 1 indicate little to no deviation of the best fit line from the 45° line.

Urinary N excretion in lactating cows was best predicted by Equations [1] and [6] (Table 3) based on values of RMPSE as a percentage of observed mean of 25.0% (Table 4). The CCC of Equation [6] was slightly larger than Equation [1]; however, the ED was larger in Equation [1] than in Equation [6]. The scale shift (u) and location shift (v) of the CCC were considerably greater in Equation [6] than Equation [1], which indicated Equation [6] had more bias, perhaps because Equation [6] requires 6 independent variables, and greater potential error from measurement and estimation of the input variables. Equations [12] and [15] had similar RMSPE and CCC values and both appear to predict FN well. Although Equation [15] requires fewer inputs, it performed as well as Equation [12]. Equations [18] and [19] had lowest RMSPE and CCC decomposition values in predicting TN. Both equations performed equally well despite Equation [19] requiring 5 more input variables compared with Equation [18]. Equations [26] and [27] were the best equations for predicting MN. Both Equations [26] and [27] performed well with RMSPE as a percentage of observed mean and CCC values of 14% and 0.73 vs. 15% and 0.81, respectively. However, almost all error in Equation [26] came from random sources indicating little bias.

Equations for heifers and nonlactating cows consistently resulted in a large amount of bias in part due to the small number of observations available for

Table 2. List of every study used to evaluate N excretion equations

Study and group	
Lactating cows	
Agle et al. (2010a)	Kolver et al. (1998)
Agle et al. (2010b)	Kamiya et al. (2005)
Arriaga et al. (2010)	Kauffman and St-Pierre (2001)
Aschemann et al. (2012)	Korhonen et al. (2002)
Beckman and Weiss (2005)	Kröber et al. (2000)
Benchaa et al. (2014)	Lapierre et al. (2002)
Benchaa et al. (2013)	Lee et al. (2009)
Borucki Castro et al. (2008)	Lee et al. (2011)
Castillo et al. (2001)	Leiva et al. (2000)
Chen et al. (2011)	Mitani et al. (2005)
Cherney et al. (2003)	Mitsuru et al. (2005)
Chibisa et al. (2008)	Miyaji et al. (2012)
Colombini et al. (2012)	Miyaji et al. (2013)
Davidson et al. (2003)	Miyaji et al. (2014)
De Campeneere et al. (2006)	Monteils et al. (2002)
De Campeneere et al. (2009)	Moorby and Theobald (1999)
Dewhurst et al. (2010)	Noftsker and St-Pierre (2003)
Eriksson et al. (2004)	Ramirez et al. (2012)
Ferris et al. (1999)	Ruiz et al. (2001)
Foley et al. (2006)	Ruiz et al. (2002)
Galo et al. (2003)	Sannes et al. (2002)
Gelman and Kononoff (2010)	Tas et al. (2006)
Gozho and Mutsvangwa (2008)	Tasja et al. (2011)
Gozho et al. (2008)	Vanhatalo et al. (2009)
Haig et al. (2002)	Wattiaux and Karg (2004)
Hassanat et al. (2013)	Whelan et al. (2011)
Higgs et al. (2013)	Wilkerson et al. (1997)
Hristov and Ropp (2003)	Wright et al. (1998)
Hristov et al. (2004)	Wright et al. (2003)
Kälber et al. (2012)	
Heifers and nonlactating cows	
Fisher et al. (2000)	Lascano and Heinrichs (2011)
Grimaud and Doreau (1995)	Marini and Van Amburgh (2003)
Hoffman et al. (2001)	Moorby et al. (2008)
Steers	
Archibeque et al. (2007)	Kang et al. (2014)
Cole et al. (2011)	Lehloanya et al. (2008)
Eisemann et al. (1989)	Piao et al. (2012)
Elliott et al. (1997)	Spiehs and Varel (2009)
Fiems et al. (1997)	Valkeners et al. (2008)
Gunun et al. (2013)	Waggoner et al. (2009)
Hussein et al. (1996)	

Table 3. List of extant equations evaluated in this study¹

Equation number	Predicting	Equation	Reference
Lactating cows			
1	UN	$UN = 12.0 + 0.333 \times NI$	Reed et al. (2015b)
2	UN	$UN = 0.83 \times NI - MN-97$	Jonker et al. (1998)
3	UN	$UN = 30.4 \times e^{0.0036 \times NI}$	Castillo et al. (2000)
4	UN	$UN = -126 + 0.676 \times NI$	Huhtanen et al. (2008)
5	UN	$UN = 27 + 0.844 \times NI - 13 \times DMI$	Huhtanen et al. (2008)
6	UN	$UN = 104 + 0.855 \times NI - 13.2 \times DMI - 6.8 \times ME$	Huhtanen et al. (2008)
7	UN	$UN = 40 + 0.879 \times NI - 9 \times DMI - 3.9 \times MILK$	Huhtanen et al. (2008)
8	UN	$UN = 20 + 0.38 \times NI$	Kebreab et al. (2010)
9	UN	$UN = 47.8 + 0.56 \times NI - 71.4 \times ME$	Kebreab et al. (2010)
10	UN	$UN = -223.9 + 10.2 \times 1_{EU} + 24.81 \times 1_{EU} \times CP + 25.47 \times 1_{NA} \times CP$	Spek et al. (2013)
11	FN	$FN = -18.5 + 10.1 \times DMI$	Reed et al. (2015b)
12	FN	$FN = 81.4 - 11.8 \times ME - 0.437 \times NDF + 3.52 \times CP + 0.161 \times ForR + 9.32 \times DMI - 0.0184 \times DIM$	Reed et al. (2015b)
13	FN	$FN = 52.3 + 0.21 \times NI$	Castillo et al. (2000)
14	FN	$FN = -28 + 9.9 \times DMI$	Huhtanen et al. (2008)
15	FN	$FN = -21 + 6.73 \times DMI + 0.101 \times NI$	Huhtanen et al. (2008)
16	FN	$FN = 10 + 0.28 \times NI$	Kebreab et al. (2010)
17	FN	$FN = -21 + DMI \times 6.25 + NI \times 0.17$	Higgs et al. (2012)
18	TN	$TN = 20.3 + 0.654 \times NI$	Reed et al. (2015b)
19	TN	$TN = 2.16 + 0.631 \times NI - 12.8 \times ME + 0.392 \times NDF + 4.81 \times CP + 0.137 \times DIM + 0.426 \times MBS$	Reed et al. (2015b)
20	TN	$TN = 122.61 + 0.778 \times NI - 6.93 \times DMI$	Tomlinson et al. (1992)
21	TN	$TN = 346 + 2.82 \times MILK$	Nennich et al. (2005)
22	TN	$TN = 0.196 \times BW + 84.1 \times CP \times DMI$	Nennich et al. (2005)
23	TN	$TN = 7 + 0.710 \times NI$	Yan et al. (2006)
24	TN	$TN = -18 + 0.741 \times NI + 0.072 \times BW - 1.486 \times MILK$	Yan et al. (2006)
25	TN	$TN = -41 + CP \times [0.00287 \times BW + 0.02328 - MILK]$	Yan et al. (2006)
26	MN	$MN = -19.0 + 8.13 \times DMI$	Reed et al. (2015b)
27	MN	$MN = 5.62 + 4.62 \times ME - 0.389 \times NDF + 1.70 \times CP + 6.66 \times DMI - 0.194 \times DIM - 0.275 \times MBS$	Reed et al. (2015b)
Heifers and nonlactating cows			
28	UN	$UN = 14.3 + 0.510 \times NI$	Reed et al. (2015b)
29	UN	$UN = -43.8 + 0.429 \times NI - 2.10 \times ME + 0.292 \times ADF + 3.35 \times CP + 0.284 \times MBS$	Reed et al. (2015b)
30	FN	$FN = 0.345 + 0.317 \times NI$	Reed et al. (2015b)
31	FN	$FN = 107 + 0.359 \times NI - 4.18 \times ME - 0.141 \times DM - 0.246 \times ADF - 1.00 \times ASH - 2.32 \times CP + 0.0792 \times MBW$	Reed et al. (2015b)
32	TN	$TN = 15.1 + 0.828 \times NI$	Reed et al. (2015b)
33	TN	$TN = -49.5 + 0.793 \times NI - 6.04 \times ME + 0.825 \times CP + 0.190 \times MBS$	Reed et al. (2015b)
Steers			
34	UN	$UN = 6.80 + 0.405 \times NI$	Reed et al. (2015b)
35	UN	$UN = -71.2 + 0.265 \times NI + 3.76 \times CP + 0.468 \times MBS$	Reed et al. (2015b)
36	UN	$UN = 0.62 \times NI - 3.72 \times DMI - 3.93$	Waldrip et al. (2013) ²
37	UN	$UN = 0.56 \times NI - 21.18$	Waldrip et al. (2013) ²
38	UN	$UN = 5.91 \times CP - 21.52$	Waldrip et al. (2013) ²
39	UN	$UN = 6.04 \times CP - 22.00$	Dong et al. (2014) ²
40	UN	$UN = 0.51 \times NI - 14.12$	Dong et al. (2014) ²
41	FN	$FN = 0.506 + 0.352 \times NI$	Reed et al. (2015b)
42	FN	$FN = 0.154 \times NI + 24.28$	Waldrip et al. (2013) ²
43	FN	$FN = 1.165 \times CP + 30.91$	Waldrip et al. (2013) ²
44	FN	$FN = 1.81 \times CP + 19.68$	Dong et al. (2014) ²
45	FN	$FN = 0.20 \times NI + 15.82$	Dong et al. (2014) ²
46	TN	$TN = 6.91 + 0.759 \times NI$	Reed et al. (2015b)

¹Parameter estimates with standard errors in parentheses. UN = urine nitrogen, FN = fecal nitrogen, MN = milk nitrogen, TN = total manure nitrogen, NI = nitrogen intake (g/d), CP (% of DM), DE = digestible energy content (kJ/kg of DM), NDF (% of DM), MBS = metabolic body size ($BW^{3/4}$, kg), DMI (kg/d), ME (kJ/kg), ADF (% of DM), ForR = proportion of forage in the diet, ASH = ash content (% of DM); 1_{EU} and 1_{NA} indicate whether the observation is from Europe or North America, respectively.

²Equations were developed and conducted on beef cattle.

Table 4. Evaluation results using the root mean square prediction error (RMSPE), concordance correlation coefficient (CCC), and their decompositions¹

Equation	Variable estimated	n	RMSPE (g)	RMSPE % of observations mean	ECT	ER	ED	CCC	<i>u</i>	<i>v</i>	Cb
Lactating cows											
1	UN	205	50.1	0.25	0.00	0.01	0.98	0.62	0.61	0.00	0.89
2	UN	182	52.6	0.27	0.12	0.25	0.62	0.70	0.63	0.28	0.95
3	UN	205	86.3	0.45	0.27	0.40	0.33	0.53	1.49	0.56	0.81
4	UN	205	81.1	0.42	0.40	0.22	0.38	0.56	1.24	0.66	0.81
5	UN	171	61.7	0.32	0.35	0.16	0.50	0.71	1.14	0.47	0.89
6	UN	87	47.6	0.29	0.35	0.17	0.48	0.82	1.16	0.36	0.93
7	UN	154	57.7	0.31	0.43	0.12	0.45	0.74	1.13	0.51	0.88
8	UN	205	62.0	0.33	0.32	0.00	0.68	0.57	0.69	0.59	0.81
9	UN	98	63.0	0.33	0.99	0.00	0.00	0.02	1.23	−8.09	0.03
10	UN	124	99.76	0.50	0.09	0.58	0.33	0.48	1.65	−0.34	0.84
11	FN	173	28.3	0.16	0.00	0.00	0.99	0.77	0.77	0.07	0.97
12	FN	29	31.6	0.14	0.04	0.07	0.89	0.60	0.54	−0.20	0.82
13	FN	207	32.7	0.18	0.10	0.08	0.82	0.60	0.54	−0.32	0.80
14	FN	173	28.0	0.16	0.09	0.00	0.91	0.72	0.76	−0.23	0.94
15	FN	173	26.2	0.14	0.13	0.01	0.86	0.76	0.74	−0.26	0.93
16	FN	207	32.7	0.18	0.18	0.00	0.82	0.67	0.72	−0.37	0.89
17	FN	173	31.9	0.18	0.23	0.00	0.76	0.77	0.87	0.34	0.94
18	TN	205	41.6	0.11	0.01	0.00	0.99	0.87	0.86	0.06	0.99
19	TN	52	44.3	0.11	0.02	0.00	0.98	0.88	0.89	−0.07	0.99
20	TN	171	58.2	0.16	0.37	0.01	0.61	0.82	0.84	0.38	0.92
21	TN	192	117	0.30	0.29	0.05	0.66	0.13	0.21	1.30	0.30
22	TN	111	82.8	0.21	0.00	0.14	0.85	0.69	0.99	0.06	1.00
23	TN	205	48.2	0.13	0.19	0.01	0.80	0.85	0.94	0.24	0.97
24	TN	160	48.4	0.13	0.16	0.00	0.84	0.86	0.88	0.22	0.97
25	TN	117	112	0.28	0.11	0.38	0.51	0.56	1.30	−0.32	0.92
26	MN	148	21.3	0.14	0.00	0.00	0.99	0.73	0.77	−0.03	0.97
27	MN	41	24.4	0.15	0.26	0.06	0.68	0.81	0.75	0.33	0.91
Heifers and nonlactating cows											
28	UN	25	30.4	0.36	0.55	0.22	0.23	0.80	1.28	0.54	0.87
29	UN	8	20.0	0.30	0.97	0.00	0.03	0.00	0.22	−2.9	0.14
30	FN	25	11.7	0.17	0.49	0.00	0.51	0.87	0.93	−0.36	0.94
31	FN	8	7.2	0.14	0.73	0.17	0.10	0.20	1.60	1.75	0.37
32	TN	25	17.3	0.13	0.42	0.01	0.58	0.95	0.99	0.20	0.96
33	TN	8	89.2	0.82	0.99	0.00	0.01	0.00	0.60	−14.3	0.01
Steers											
34	UN	45	21.2	0.39	0.37	0.02	0.60	0.72	0.73	0.50	0.85
35	UN	38	30.1	0.53	0.01	0.54	0.44	0.74	1.46	−0.08	0.98
36	UN	41	31.2	0.57	0.01	0.33	0.66	0.76	1.22	0.06	0.98
37	UN	45	17.3	0.32	0.13	0.07	0.79	0.82	1.01	0.22	0.98
38	UN	38	21.0	0.37	0.03	0.22	0.75	0.74	1.11	−0.12	0.99
39	UN	38	21.4	0.38	0.01	0.25	0.73	0.74	1.13	−0.08	0.99
40	UN	57	16.8	0.31	0.13	0.02	0.85	0.82	0.92	0.22	0.97
41	FN	57	10.3	0.18	0.00	0.21	0.79	0.74	1.09	0.04	0.99
42	FN	57	6.30	0.13	0.17	0.11	0.72	0.53	0.47	−0.47	0.71
43	FN	50	61.2	1.30	0.90	0.00	0.10	0.02	0.21	−6.19	0.05
44	FN	50	10.2	0.22	0.31	0.00	0.69	0.15	0.33	−1.10	0.43
45	FN	57	6.53	0.14	0.22	0.03	0.76	0.61	0.62	−0.45	0.82
46	TN	45	23.8	0.24	0.50	0.01	0.49	0.84	0.98	0.42	0.92

¹RMSPE decomposes into the error of central tendency (ECT), the error due to regression (ER), and the dispersion error (ED). The CCC decomposes into the scale shift (*v*), the location shift (*u*), and the bias correction factor (Cb), fecal nitrogen (FN), urine nitrogen (UN), total nitrogen (TN), milk nitrogen (MN).

evaluation. More data are needed to better assess the predictive power of the equations. The simpler equations (Equations [28], [30], and [32]) consistently outperformed more complex equations (Equations [29], [31], and [33]) in predicting UN, FN, and TN in heifers and nonlactating cows. However, a limited amount of data was available to evaluate complex equations be-

cause of their greater input requirements. Equations [37] and [40] performed well in predicting steer UN. However, Equation [40] had a slightly greater ED of 85% of RMSPE. Equations [42] and [45] both showed good predictive ability to predict steer FN with only slight differences in sources of error. Only Equation [46] estimated steer TN with RMSPE as a proportion of

observed mean value of 24%; however, 50% of error came from mean bias.

Irrespective of animal class, equations with fewer independent variables were evaluated with more observations (Table 4), which might have contributed to better performance compared with more complex equations. In several instances, increasing the number of independent variables did not improve predictive ability. In addition to the discrepancies in size of the evaluation data set, the varied performance of models with more input variables could be due to larger variation in the N excretion response to dietary factors beyond intake and CP content. For example, if the effect of increasing dietary fiber does not uniformly increase UN excretion in heifers and nonlactating cows across all the diets and feeding scenarios evaluated, then the addition of fiber to the prediction model would not increase model accuracy. In general, equations predicting TN had the lowest RMSPE and most of the error tended to be random in nature with minimal mean and slope biases. Urinary N typically had the most bias compared with other excretion forms. This could be due to several factors including (1) UN volatilize quickly as NH_3 , which may result in underestimation of UN measurements; (2) UN is composed of several N-containing compounds including urea N and purine derivatives that originate predominantly from microbial N compounds, all of which are affected by different components of the diet contributing to variability (Dijkstra et al., 2013). Predictor variables that appeared consistently in the best performing models are NI and DMI. Biologically, FN is a direct function of NI and digestibility. More variation is present in UN for a given NI; however, as more N is ingested, N excretion in urine is expected to increase through many avenues including increased purine derivatives from an increase in microbial protein production, increased urea synthesis from increased absorption of NH_3 across the rumen wall, and increased urea synthesis from amino acid oxidation especially as protein supply exceeds requirement. Crude protein content and ME also appear in several of the proposed equations but do not appear to contribute to prediction accuracy.

The equations developed by Reed et al. (2015b) for lactating cows resulted in less prediction error and bias compared with other extant equations evaluated here. The equation development procedure implemented by Reed et al. (2015b) differs from other studies in size and quality of the data used for equation development and the rigorous equation-selection process implemented. This process included a multistep, multilevel selection process to narrow down the number of potential equations followed by a genetic algorithm to select the best

equation(s) from large pool of equations (Reed et al., 2015b). Other extant equations were developed from smaller data sets and used equation selection techniques, such as stepwise regression, that are subject to criticism (Reed et al., 2015a). Future equation selection and development should take advantage of advances in computing power and modern statistical approaches like the genetic algorithm illustrated by Reed et al. (2015b) in addition to knowledge of the biological significance of model inputs to advance the accuracy of N excretion prediction equations.

The equations evaluated here that demonstrated best predictive power for each animal class and form of excretion are recommended for use. For lactating dairy cattle, UN excretion was best predicted by Equation [1]. Equations [12] and [15] showed similar accuracy in predicting FN; therefore, both equations are recommended for use, the choice of which depends on the availability of input variables. Similarly, Equations [18] and [19] had very close accuracy in predicting TN, so both are recommended. Equation [26] provided the best prediction power for MN and is recommended for use. For the heifers and nonlactating cow class, Equations [28], [30], and [32] are recommended for FN, UN, and TN, respectively. In the steer animal class, the equations with the smallest amount of prediction error and bias were Equations [37] for UN, [42] and [45] for FN and [46] for TN; however, UN equations for steers did not perform well in general. Steer diets can have highly variable compositions ranging from 100% forage to 80% concentrate and 20% forage. This wide range of ingredients could contribute to the poor predictive ability of the UN models, especially if the development data did not span the same ingredient range as the evaluation data. Although sufficient data are available on lactating dairy cows, there is a paucity of N balance studies on heifers and nonlactating cows. The generally lower prediction accuracy from equations for heifers and nonlactating cows could be in part due to the small amount of data available for equation development and evaluation. It is recommended that more data be collected on heifers and nonlactating so that better equations can be developed and more thoroughly evaluated. Our results show that N equations have a better predictive power if the equations were developed from larger data sets and if sufficient data are available with which to evaluate the equations. Although, ideally prediction equations are expected to perform well on all data, an evaluation data set should be large enough to capture the equation's performance over a variety of input scenarios. In small evaluation data sets, observations that may be outliers can have an unduly large effect on the assessment of the equation's predictive ability. To assess

whether an evaluation data set is sufficiently large, one can employ a power analysis to see if enough data are available to detect if the difference between observed and predicted (D) values is within a certain range of the mean. Such a test applied to Equation [30] using $\alpha = 0.05$, and testing for the ability to detect prediction accuracy within 10% of the mean would only have a power of 0.8 or above if the true mean of D is within 4.8% of the mean observed values for FN. To detect a difference of 10% or less of the mean with a power of 0.8 or greater, at least 40 observations would be needed to evaluate Equation [30].

The predictive equations of UN and FN for the lactating cow and heifers and nonlactating animal classes performed well: less than 30% and 20% prediction error, respectively. Because excreted N sources affect downstream estimates of potential pollutants such as NH_3 and N_2O , using specific equations for UN and FN could improve assessment of N emissions from cattle production facilities. Volatilization of NH_3 from urinary urea-N is the main source of N that affects air quality, whereas FN and other UN compounds are more likely to contribute to N overload in the soil. Thus, the origin of the excretion should be taken into consideration in the effort to determine how N lost from dairy production facilities affects the ecosystem.

In conclusion, mathematical equations evaluated in this study could be used to assess mitigation strategies that are aimed in reducing N pollution from cattle facilities and improve national and international inventories for accounting greenhouse gas emissions, especially N_2O . Equations that partition N excretion into urine and fecal origin are useful in estimating N emissions to air or N potentially available for plant uptake and leaching to ground water. Equations developed with large amount of data and employ state-of-the-art statistical techniques were among the best predictors of N excretion in this study.

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