Prediction of Ammonia Emission from Dairy Barns Using Feed Characteristics Part I: Relation Between Feed Characteristics and Urinary Urea Concentration

I. J. M. de Boer,* M. C. J. Smits,† H. Mollenhorst,*
G. van Duinkerken,‡ and G. J. Monteny†

*Animal Production Systems Group,

Wageningen Institute of Animal Sciences

†Institute of Agricultural and Environmental Engineering

‡Research Institute for Animal Husbandry

Wageningen University and Research Center, Wageningen,
The Netherlands

ABSTRACT

Urinary urea concentration is an important predictor of NH_3 emission from dairy barns. To reduce urinary urea concentration, accurate and precise prediction of urea concentration for different feeding regimes is a prerequisite. The objective of this research, therefore, was to predict urinary urea concentration of a cow using feed characteristics. To compute urinary urea concentration of a cow, we predicted: urine volume; urinary N excretion, using a regression or a mechanistic model; and the relationship between urinary urea concentration and urinary N concentration, which was derived from experimental data. Model results were validated using experimental data. Cows were fed one of nine diets, which was a combination of one of three rumen-degradable protein balances, and one of three roughage compositions. Each diet was repeated once. Measured parameters included herd, diet, and urine characteristics. Observed urinary urea concentration can be predicted with reasonable accuracy from existing models to predict urine volume and urinary N excretion using feed characteristics. The regression model predicted N excretion slightly better than the mechanistic model. In addition, input parameters required for the regression model are recorded at each dairy farm in the Netherlands. This regression model, therefore, can be used by animal nutritionists and producers to determine diets that result in a reduced NH_3 emission.

(Key words: ammonia emission, dairy barns, urinary urea concentration, feed characteristics)

Abbreviation key: DVE = intestine digestible protein, OEB = rumen-degradable protein balance, UUC = urinary urea concentration.

INTRODUCTION

Emission of NH_3 is a main cause of environmental eutrophication and acidification. In the Netherlands, for example, NH_3 emission causes about 46% of the acid deposition (Erismann and Bleeker, 1997). To minimize environmental damage related to NH_3 emission, the Dutch government aims to reduce the level of NH_3 emission in 2005 by 70% of the level in 1980 (the reference year), i.e., 216 ktons (van der Hoek, 2000).

In the Netherlands, dairy cattle production has been predicted to be responsible for almost half of the total NH_3 emission, based on model simulation (Steenvoorden et al., 1999). In dairy cattle production, NH_3 volatilizes mainly from manure application on the field and from barns. The amount of NH_3 that volatilizes from outdoor manure storage facilities, from crop residues, and during grazing is relatively small. New techniques to apply manure and to cover storage facilities, currently enforced by law, have reduced total NH_3 emission from dairy cattle production (van der Hoek, 2000). To achieve a further reduction, however, NH_3 emission from dairy barns must be reduced.

Emission of NH_3 from the dairy barn depends on the cow's diet (Smits et al., 1995), the design of the barn (Braam et al., 1997), the outdoor and indoor climate, and the management of the farm, e.g., grazing regime (Monteny, 1998). For a producer, altering the cow's diet is a relatively easy measure to reduce NH_3 emission in the short term. Lower N intake results in reduced excretion of urinary N (mainly urea) and fecal N. Urea concentration, however, appears to be an important predictor of NH_3 emission from dairy barns (Elzing and Monteny, 1997; Monteny et al., 1998). Nutritional measurements related to NH_3 emission should focus on reduction of urinary urea concentration (UUC), rather by lowering diet N than by increasing urine volume (Smits et al., 1997). To reduce UUC, accurate and pre-

Received March 15, 2002.

Accepted July 9, 2002.

Corresponding author: I. J. M. de Boer; e-mail: Imke.deBoer@wur.nl.

Figure 1. Schematic illustration of general modeling strategy used to predict UUC, i.e., urinary urea concentration.

cise prediction of its values for different feeding regimes is a prerequisite.

Prediction of UUC of a cow using feed characteristics, however, is not yet described. It is measured currently by sampling and analyzing urine. Collection of urine samples, however, is too labor-intensive for practical, on-farm application. The objective of this research, therefore, was to predict UUC of a cow using feed characteristics. The model was validated using data from an experiment at the Research Institute for Animal Husbandry in Lelystad.

MATERIALS AND METHODS

Dairy cattle excrete about 80% of their N intake through feces and urine (Tamminga, 1992). Fecal N contains mainly undigested feed protein and metabolic fecal N, whereas urinary N contains mainly urea. NH_3 is produced from enzymatic conversion of urinary urea and of mineralized fecal N (Muck and Steenhuis, 1982). NH_3 production from fecal N, however, is relatively unimportant due to low mineralization rates (Muck and Steenhuis, 1982), and, therefore, was neglected in this study.

NH_3 production from urinary urea is catalyzed by the enzyme urease (Muck and Steenhuis, 1981). Urease is produced by microorganisms present in feces (Ketelaars and Rap, 1994). Rate of conversion of urea into NH_3 , therefore, depends on UUC and urease activity (Monteny et al., 1998). Urease activity mainly is related to fouling of the surface by feces and is independent of diet, whereas UUC depends largely on diet (Smits et al., 1997). Percentage of urea in urinary N, which ranges from 59 to 89%, increases with surplus of RDP in the diet (Bristow et al., 1992).

To compute UUC for a dairy cow, it is necessary to predict three variables: 1) urine volume, 2) urinary N excretion, and 3) the relationship between UUC and urinary N concentration (see Figure 1). Before ex-

plaining computation of these variables, we will describe the experiment used to collect data required to predict these variables, such as feed and herd characteristics, and to validate these variables, such as urinary N concentration and UUC.

Experimental Data

Animal groups. During the entire experiment, 56 cows on average, were housed in a naturally ventilated free-stall barn at the experimental farm, "The Waiboerhoeve" in Lelystad, the Netherlands. The barn had two rows of stalls, one row on each side of a feeding alley. Young stock were housed separately. Ten d before calving, dry cows (on average eight) were housed with milking cows. Therefore, three groups of cows were distinguished: milking cows, dry cows fed different feed than milking cows, and dry cows fed the same feed as milking cows. Animal numbers for each group were averaged weekly.

Feed characteristics. For each of nine 3-wk periods, all cows were fed one of nine diets at random. Each 3-wk period comprised 2 wk for adjustment and 1 wk for data collection. Each diet was a combination of one of three RDP balances (*Onbestendig Eiwit Balans* or **OEB**) of 0, 500, and 1000 g/d per cow, and one of three roughage compositions (grass silage, corn silage, or both). For each roughage composition, cows were fed according to their requirements with respect to intestine digestible protein (**DVE**) and energy. Three OEB levels were examined to study their effect on urinary N excretion, whereas various roughage compositions were examined to study their effect on urine volume (Valaderes et al., 1999). The OEB level and roughage composition, therefore, are expected to affect UUC. Each diet was repeated once. The entire experiment lasted from wk 12 in 1998, through wk 13 in 1999. For each replicate, diet characteristics, and corresponding DMI and FCM are given in Table 1.

Urine samples. On days 1, 3, and 5 of a data collection wk, urine was sampled from each of 15 randomly selected cows, on average, 13 milking cows and two dry cows, and pooled. The pooled sample was analyzed for total N, UUC, pH, and creatinine (NEN 6472, 1983; NEN 6642, 1983). Results were averaged weekly over the 3 d.

Urine Volume

Urine volume for each cow was predicted using a regression model based on data regarding the intake of K, Na, and N and milk production (Bannink et al., 1999). Average urine volume of the herd was computed by statistically weighting the volume for an average

Table 1. Diet characteristics, and corresponding DMI and FCM.

Diet	Wk/yr	OEB g/cow/d ¹		DVE ¹ g/cow/d	NE _L ² NE _L /cow/d	DMI kg/cow/d	FCM kg/cow/d	Code
		Planned	Realized					
Replicate-1								
Grass	18-20/98	0	-114	1484	15988	11.3	26.2	G0-P1
	33-35/98	500	436	1396	15987	12.1	24.1	G500-P1
	30-32/98	1000	1043	1275	15258	20.0	22.1	G1000-P1
Grass-Corn	36-39/98	0	42	1578	18146	14.8	25.4	GC0-P1
	12-14/98	500	420	1586	18248	14.2	27.0	GC500-P1
	15-17/98	1000	704	1744	19396	15.8	29.6	GC1000-P1
Corn	27-29/98	0	-81	1708	19354	17.0	26.0	C0-P1
	21-23/98	500	427	1997	21527	18.8	30.5	C500-P1
	24-26/98	1000	960	1861	20516	18.7	29.2	C1000-P1
Replicate-2								
Grass	43-45/98	0	7	1410	15765	12.0	22.9	G0-P2
	5-7/99	500	400	1599	17151	12.7	25.5	G500-P2
	2-4/99	1000	655	1466	16309	12.3	23.3	G1000-P2
Grass-Corn	49-51/98	0	-27	1606	17782	14.2	26.5	GC0-P2
	52-1/98	500	391	1574	17686	14.5	25.6	GC500-P2
	40-42/98	1000	1028	1626	18210	15.9	26.9	GC1000-P2
Corn	8-10/99	0	10	2032	21039	17.5	31.4	C0-P2
	46-48/98	500	523	1903	19331	17.2	25.9	C500-P2
	11-13/99	1000	934	1950	20885	18.4	32.4	C1000-P2

¹OEB = rumen-degradable protein balance; DVE = intestine digestible protein; values were quantified according to Tamminga et al. (1994).

²NE_L was quantified according to van Es (1987).

milking cow and an average dry cow by their relative proportion in the herd.

Predicted urine volume was validated using the creatinine content measured in a pooled urine sample. Average daily urinary creatinine excretion of a high-producing Dutch cow is about 16.8 g (van Vuuren and Smits, 1997). Urinary creatinine concentration is used frequently as a predictor of urine volume of a cow (Ciszuk and Gebregziabher, 1994; Gonda and Lindberg, 1994; Meijer et al., 1996). In this study, observed and predicted urinary creatinine concentrations were compared. The latter was computed by dividing an average daily creatinine excretion of 16.8 g by predicted daily urine volume.

Urinary N Excretion

Urinary N excretion of a cow was computed based on observed feed characteristics and herd composition and on two models that predict N excretion by a cow, a regression model and a mechanistic model.

Regression model. The regression model (van Dongen, 1999) uses variables of the Dutch protein evaluation system, i.e., diet OEB and DVE (Tamminga et al., 1994), to predict N excretion by a cow. A schematic representation of the N flux through a cow is in Figure 2.

The N fraction in the rumen consists of RDP and RUP. Given sufficient available energy, microorganisms in the rumen use RDP to synthesize microbial

protein. The (im)balance between potential microbial protein synthesis from available RDP and that from available rumen energy is denoted as OEB (Tamminga et al., 1994). In case of energy shortage, i.e., positive OEB, surplus N in the rumen is excreted in urine (N_{OEB}, Figure 2). In case of N shortage, i.e., negative OEB, microbial protein synthesis is impaired. The optimum OEB value in a diet, therefore, is zero or slightly higher.

Figure 2. Schematic representation of the N-flow through a cow according to the Dutch protein evaluation system (van Dongen, 1999 based on Tamminga et al., 1994), where OEB is the rumen degradable protein balance and DVE is intestine digestible protein.

Figure 3. Schematic representation of the N-flow through a cow according to the mechanistic model developed by van Straalen (van Straalen, 1995), where NPN is Non Protein Nitrogen and AA-N is Amino Acid N.

The RUP and microbial protein, that are truly digested and absorbed in the intestine (i.e., digestible protein intestine), are denoted as DVE (Tamminga et al., 1994). The RUP and microbial protein not digested in the intestine are excreted through feces. A cow requires DVE for maintenance, retention and mobilization of body reserves, gestation, and milk production. This regression model, however, ignores DVE requirements for retention, and mobilization of body reserves, and for gestation. Diet DVE (DVE_{diet}), therefore, can be used for maintenance (DVE_{main}) and milk production (DVE_{milk}). The DVE not used for maintenance or production is denoted as $DVE_{\text{unused}} = (DVE_{\text{diet}} - DVE_{\text{main}} - DVE_{\text{milk}})$.

Urinary N excretion results from three sources: OEB, DVE_{unused} , and DVE_{main} , and is predicted as (van Dongen, 1999):

$$\begin{aligned} N_{\text{urine}} &= (\text{OEB} + DVE_{\text{unused}} + DVE_{\text{maintenance}})/6.25 \quad [1] \\ &= (\text{OEB} + DVE_{\text{diet}})/6.25 - N_{\text{milk}} \\ &= (\text{OEB} + DVE_{\text{diet}})/6.25 - \text{milk protein production}/6.38 \end{aligned}$$

where 6.25 is used to transform feed protein into N, and 6.38 is used to transform milk protein into N. This model, therefore, requires only the OEB and DVE intake of a cow and her milk production.

Mechanistic model. The mechanistic model also predicts N excretion of a cow (van Straalen, 1995; Mollenhorst, 2000). The model consists of four compartments (Figure 3): (1) rumen, (2) small intestine, (3) large intestine, and (4) metabolism. Each feed component entering the rumen, i.e., CP, lipids, NDF, sugar and starch, fermentation products, and miscellaneous

compounds, is divided into three fractions: a direct soluble fraction (S), a total tract indigestible fraction (I), and a potentially degradable fraction ($D = 1 - S - I$). Subsequent fermentation and microbial growth of the S and D fractions are assumed to depend on fractional passage rates and degradation characteristics.

Output from the rumen and subsequent input into the small intestine compartment consists of three OM fractions (Figure 3): escaped OM, rumen microbes, and endogenous excretions. Each fraction is partially digested in the small intestine, and only digested OM enters the metabolism compartment. Undigested OM enters the large intestine, and either ferments or escapes. Fermentation depends on fractional degradation and passage rates of different OM fractions. Fermented OM not used for microbial synthesis is absorbed into the metabolism by the wall of the large intestine. Fecal excretion consists of OM that escaped fermentation in the large intestine and microbial components. The N-input into the metabolism consists of N absorbed in the rumen (NPN), in the small intestine (AA-N, and NPN), and in the large intestine (NPN). The AA-N is used for maintenance (endogenous urine N, endogenous gastrointestinal-N, and N stored in the skin or body reserves) or for milk production. Unused AA-N and NPN are excreted in the urine.

Relationship Between UUC and Urinary N Concentration

Urinary N concentration was computed as urinary N excretion divided by urine volume. Urinary N excretion itself, however, consists of two parts: a fixed part, mainly allantoin and creatinine, and a variable part, mainly urea. This variable part increases as OEB of the diet increases (van Vuuren and Smits, 1997). The UUC (in g N/liter), therefore, was predicted as (see Figure 1):

$$\text{UUC} = a + b \times \text{urinary N concentration} \quad [2]$$

where parameters *a* and *b* were estimated from observed values for urinary N concentration and UUC (see next section).

RESULTS AND DISCUSSION

Urine Volume

Predicted urine volume varied for various diets ($P < 0.05$). On average, urine volume was highest for diets containing grass silage (35.1 kg/d) and lowest for diets containing corn silage (21.9 kg/d). In general, grass contains a higher amount of minerals than corn, especially K and Na. A surplus of digested minerals is excreted

Figure 4. Predicted creatinine concentration ($\mu\text{mol/kg}$) versus observed creatinine concentration ($\mu\text{mol/liter}$) (corn: $\circ$; grass/corn: $\diamond$; grass: $\bullet$).

in the urine by the kidney. The kidney, however, can concentrate the amount of minerals in urine only to a certain extent. As a result, grass-fed cows consume and excrete more water to remove this mineral surplus (van Vuuren and Smits, 1997; Bannink et al., 1999; Valadares et al., 1999).

Figure 4 shows the relation between observed creatinine concentration (x-axis) and predicted creatinine concentration (y-axis). For low x-values, creatinine concentration was overpredicted, whereas for moderate and high x-values, creatinine concentration was underpredicted, i.e., $y = 0.65x + 1570$ ($R^2 = 0.69$). The intercept and the regression coefficient differed significantly from 0 and 1, respectively ($P < 0.05$).

Creatinine, which is produced in muscle tissue, generally is considered to be excreted in proportion to lean body mass, and, therefore, might differ among breeds or due to changes in body composition (Valadares et al., 1999). Experimental diets used, however, did not affect body composition. Valadares et al. (1999) found a daily excretion of 18.3 instead of 16.8 g creatinine per cow, due to a breed difference. Assuming a higher daily excretion of 18.3 g per cow (Valadares et al., 1999), however, only affected the intercept of the estimated regression line but not the regression coefficient. The fact that also the regression coefficient differed from 1 is due to underprediction of large urine volumes and overprediction of small urine volumes (Bannink et al., 1999). Urine volume of cows fed corn was overpredicted resulting in underprediction of the corresponding creatinine concentration, whereas urine volume of cows fed

Figure 5. Urinary N excretion (g N/cow/day) for various diets (code see Table 1) studied using the regression (white) or the mechanistic model (grey), for replicate 1 (no fill) and 2 (dotted).

grass was underpredicted resulting in overprediction of corresponding creatinine concentration (Figure 4).

Urinary N Excretion

Urinary N excretion was predicted using a regression and a mechanistic model (Figure 5). For each roughage composition, urinary N excretion increased as OEB level of the diet increased ($P < 0.01$). In addition, urinary N excretion was slightly higher for cows fed corn than for cows fed grass ($P < 0.01$). The effect of OEB on urinary N-excretion is larger than the effect of roughage composition. According to equation [1], urinary N results from degradable protein balance (OEB) and intestine digestible protein (DVE). Cows were fed according to their DVE requirements, so that, differences in urinary N excretion resulted mainly from differences in diet OEB. The higher urinary N excretion of corn fed cows was due to an unplanned higher DVE supply (Table 1).

The regression and the mechanistic model underestimate urinary N concentration (Figure 6). The underestimation of the mechanistic model, however, is larger ($P < 0.01$). The regression coefficient (Figure 6) for the regression model (i.e., 0.84) and the mechanistic model (i.e., 0.79) differed significantly from 1. This results from underestimation of urinary N excretion, incorrect prediction of urine volume, or both. As described previously, large urine volumes from cows fed grass might be underpredicted, whereas small urine volumes from cows fed corn might be overpredicted (Bannink et al., 1999). Predicted urine volume, however, could not be fully validated because urine volume was not measured directly but rather indirectly through urinary creatinine concentration.

Underestimation of total urinary N is unlikely because, for example, the regression model ignores N retention and mobilization in body reserves and in the

Figure 6. Predicted urinary N concentration (g N/kg) versus observed urinary N concentration (g N/kg). The first is computed as urinary N excretion, predicted via regression (□) or mechanistic model (▲), divided by urine volume.

unborn calf (van Dongen, 1999). As a result, feed N excreted through milk is not overestimated, unless cows are in strong negative energy balance. The latter was not the case in this study.

Urinary Urea Concentration

A strong relationship was found between measured UUC (Figure 7; y-axis in g N/L) and measured urinary N concentration (x-axis in g N/kg): for $y > 0$, $UUC =$

Figure 7. Observed urinary urea concentration (g N/L) versus observed urinary nitrogen (N) concentration (g N/kg).

$-1.16 + 0.86 \times (\text{N-concentration})$ ($R^2 = 0.97$; $SE = 0.5$). The intercept differed from zero, and the regression coefficient differed from unity ($P < 0.01$), implying that using a fixed ratio of UUC versus urinary N concentration is not correct (van Vuuren and Smits, 1997). Urinary N excreted by a cow consists of a fixed part of, mainly allantoin and creatinine, and a variable part of mainly urea (van Vuuren and Smits, 1997). The fixed amount of urinary N excretion can be predicted from the above-mentioned equation by setting $UUC = 0$, i.e., $0 = -1.16 + 0.86 \times \text{N-concentration}$, and solving for N-concentration, i.e., 1.35 g N/kg urine. Estimated values for the intercept (-1.16) and the regression coefficient (0.86) were used in equation [2] to predict UUC. Consequently, incorrect prediction of urinary N concentration will result in incorrect prediction of UUC.

CONCLUSIONS

Observed UUC can be predicted with reasonable accuracy from existing models to predict urine volume (Bannink et al., 1999) and urinary N excretion (van Straalen, 1995; van Dongen, 1999) using feed characteristics. The regression model, based on the Dutch protein evaluation system, predicted urinary N excretion slightly better than the mechanistic model. In addition, input parameters required for the regression model (i.e., diet OEB and DVE and milk production data) are recorded at each dairy farm in the Netherlands. This regression model, therefore, can be used by animal nutritionists and producers to determine diets that result in a reduced NH_3 emission.

ACKNOWLEDGMENTS

The authors thank Marjolein van Huik for her contribution to this research during her M. Sc. thesis work. We wish to thank Mike Grossman for technical correction of the manuscript.

REFERENCES

- Bannink, A., H. Valk, and A. M. van Vuuren. 1999. Intake and excretion of sodium, potassium, and nitrogen and the effects on urine production by lactating dairy cows. *J. Dairy Sci.* 82:1008–1018.
- Braam, C. R., J. J. M. H. Ketelaars, and M. C. J. Smits. 1997. Effects of floor design and floor cleaning on ammonia emission from cubicle houses for dairy cows. *Neth. J. Agric. Sci.* 45:49–64.
- Bristow, A. W., D. C. Whitehead, and J. E. Cockburn. 1992. Nitrogenous constituents in the urine of cattle, sheep, and goats. *J. Sci. Food Agric.* 59:387–394.
- Cizuk, P., and T. Gebregziabher. 1994. Milk urea as an estimate of urine nitrogen of dairy cows and goats. *Acta Agric. Scand.* 44:87–95.
- Elzing, A., and G. J. Monteny. 1997. Modeling and experimental determination of ammonia emissions rates from a scale model dairy-cow house. *Transactions ASAE* 40 (3):721–726.

- Erisman, J. W., and A. Bleeker. 1997. Emission concentration and deposition of acidifying substances. Pages 21–82 in *Studies in Environmental Research* 69. Elsevier Science, Amsterdam.
- Gonda, H. L., and J. E. Lindberg. 1994. Evaluation of dietary nitrogen utilization in dairy cows based on urea concentrations in blood, urine, and milk, and on urinary concentration of purine derivatives. *Acta Agric. Scand.* 44:236–245.
- Ketelaars, J. J. M. H., and H. Rap. 1994. Ammonia volatilization from urine applied to the floor of a dairy cow barn. Pages 413–417 in *Grassland and Society*, Wageningen Press, Wageningen.
- Meijer, R. G. M., G. J. Remmelink, and T. Boxem. 1996. OEB-level in dairy cow diets. Publ. No. 116, Res. Institute for Anim. Husbandry, Lelystad.
- Mollenhorst, H. 2000. Modeling the influence of feed characteristics on urine production of dairy cows and ammonia emission from their houses. M.Sc. Thesis, Wageningen Univ., Wageningen.
- Monteny, G. J., D. D. Schulte, A. Elzing, and E. J. J. Lamaker. 1998. A conceptual mechanistic model for the ammonia emissions from free-stall cubicle dairy-cow houses. *Transactions of the ASAE* 41 (1):193–201.
- Muck, R. E., and T. S. Steenhuis. 1981. Nitrogen losses in free stall dairy barns. Pages 406–409 in *Livestock Wastes: A Renewable Source*. Am. Soc. of Agric. Engineers, St. Joseph, MI.
- Muck, R. E., and T. S. Steenhuis. 1982. Nitrogen losses from manure storages. *Agric. Wastes* 4:41–54.
- NEN 6472, 1983. Ammonium-N (in Dutch). Dutch Normalization Institute, Delft, the Netherlands.
- NEN 6641, 1983. Kjeldahl-N (in Dutch). Dutch Normalization Institute, Delft, the Netherlands.
- Smits, M. C. J., H. Valk, A. Elzing, and A. Keen, 1995. Effect of protein nutrition on ammonia emission from a cubicle house for dairy cattle. *Livest. Prod. Sci.* 44:147–156.
- Smits, M. C. J., H. Valk, G. J. Monteny, and A. M. van Vuuren. 1997. Effect of protein nutrition on ammonia emission from cow houses. Pages 101–107 in *Gaseous Nitrogen Emissions from Grasslands*. CAB Int. 1997. Oxon.
- Steenvoorden, J. H. A. M., W. J. Bruins, M. M. van Eerd, M. W. Hoogeveen, N. Hoogervorst, J. F. M. Huijsmans, H. Leneman, H. G. van der Meer, G. J. Monteny, and F. J. de Ruijter. 1999. Monitoring of the national ammonia emission from agriculture: to an improved calculation method (in Dutch) Page 141 in *Environmental Plan Bureau* 6, Wageningen.
- Tamminga, S. 1992. Nutrition management of dairy cows as a contribution to pollution control. *J. Dairy Sci.* 75:345–357.
- Tamminga, S., W. M. van Straalen, A. P. J. Subnel, R. G. M. Meijer, A. Steg, C. J. G. Wever, and M. C. Blok. 1994. The Dutch protein evaluation system: the DVE/OEB system. *Livest. Prod. Sci.* 40:139–155.
- Valadares, R. F. D., G. A. Broderick, S. C. Valadares, and M. K. Clayton. 1999. Effect of replacing alfalfa silage with high-moisture corn on ruminal protein synthesis estimated from excretion of total purine derivatives. *J. Dairy Sci.* 82:2686–2696.
- van der Hoek, K. W. 2000. Basics of the manure and ammonia calculations 1997/1998 used for the Environmental Balance study 99 (in Dutch). Natl. Institute of Public Health and the Environment (RIVM), Bilthoven.
- van Dongen, C. F. J. 1999. Dairy cattle feeding and ammonia emission on practical farms. Pages 21–27 in *Annual on Fertilizers and Fertilization, Nutrient Management Institute*, Wageningen.
- van Es, A. J. H. 1987. Feed evaluation of ruminants. I. The system in use from May 1977 onwards in The Netherlands. *Livest. Prod. Sci.* 5:331–345.
- van Straalen, W. M. 1995. Modeling of nitrogen flow and excretion in dairy cows. Ph.D. Diss, Wageningen Univ., Wageningen.
- van Vuuren, A. M., and M. C. J. Smits. 1997. Effect of nitrogen and sodium chloride intake on production and composition of urine in dairy cows. Pages 95–99 in *Gaseous Nitrogen Emissions from Grasslands*. CAB Int. 1997. Oxon.