Effects of Dietary Protein and Energy Levels on Cow Manure Excretion and Ammonia Volatilization

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ABSTRACT

Adjusting dietary composition is considered an effective way to reduce nutrient losses to the environment. The effects of various dietary protein and energy levels on manure composition (Ca, Mg, K, Na, N, P, and pH) were studied by determining total and direct available (free) nutrient concentrations in 8 slurries obtained from a feeding trial. Furthermore, the effects of dietary changes on NH₃ volatilization from manure slurries were studied. Increasing the crude protein (CP) content of the feed (108 to 190 g/kg of dry matter) resulted in an average increase in total N and P content of the slurries of 56 and 48%, respectively. Feeding the cows more energy (5,050 to 6,840 kJ/kg of dry matter) increased total N and P content of the slurries by 27 and 39%, respectively. Total ammoniacal nitrogen (TAN) amounted to 52 to 77% of the total N content present in manure slurries. A low protein content or a low energy content of the diets reduced TAN concentrations in the slurries by 43% (CP) or 25% (energy). Changes in the protein content or the energy content of the feed did not significantly affect the free:total ratios of Na, Ca, and Mg content of the slurries. In agreement with the calculated NH_{3, aq} (aqueous) content, the total amount of NH₃ volatilized from manure slurries was much greater (on average 10 times greater) when the cows were fed greater levels of CP. Although the slurries contained more TAN when cows were fed diets richer in energy, NH₃ volatilization from the slurries was lower.

Key words: dietary adjustment, dairy cow, manure composition, ammonia volatilization

INTRODUCTION

Agriculture, especially in the Netherlands, has become more intensive and more productive in the last

decades. To ensure high crop yields, farmers apply large amounts of manure slurry (a mixture of feces, urine, bedding material, and wastewater) to their land. In dairy farming, nitrogen (N) and phosphorus (P) use efficiencies of cows vary between 15 and 30% (Aarts et al., 1992) and, consequently, most of the N and P present in the feed will be excreted by the animal. Land application of slurry that delivers excessive amounts of nutrients to the soil can result in losses of these nutrients to the environment, where they can contribute to eutrophication and acidification problems (Tilman et al., 2001). Applying manure slurry to soils has also led to increased K, Ca, and Mg concentrations in topsoils and increased nitrate N, Ca, and Mg concentrations in subsoils (Edmeades, 2003). Several measures can be undertaken to restrict nutrient losses to the environment while maintaining productivity; manipulating the diets of animals is considered one of the most promising techniques to achieve this (Phillips et al., 1999). The effect of dietary changes on N and P speciation and ammonia (NH₃) volatilization is already studied extensively, although in many cases NH₃ volatilization is estimated by using different model calculations. For other nutrients, information is mostly restricted to estimations of total nutrient concentrations based on DM intake, nutrient concentrations of the feed, and the length of the dry period of the cow (Anonymous, 2005b; Nennich et al., 2005).

Changing the CP content or the digestibility of the feed will affect both the N content and the N composition of manure slurry, because, in both cases, urinary N excretion is affected more than fecal excretion of N (Kebreab et al., 2002). Lowering the CP content of diets, especially when CP is fed above protein requirements (as is usually the case), will not only decrease the amount of N excreted by dairy cattle, but will also reduce the short-term N availability of manure, making it less susceptible to leaching and volatilization (Paul et al., 1998). Sørensen et al. (2003) observed an increase in the concentration of N in feces dry matter when the digestibility of the diets increased. Nitrogen utilization efficiency increased when lactating dairy cows were fed grass silage diets enriched with a low-degradable starch

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source instead of a high-degradable starch source (Castillo et al. 2001).

Excessive N is mainly excreted by the cow as urea via the urinary tract (Vérité and Delaby, 2000; Børsting et al., 2003). After contact with the enzyme urease, which is present in feces, urea is rapidly degraded into NH_3 , which is susceptible to volatilization. Ammonia is considered an important source of acidifying gaseous N emissions. Furthermore, NH_3 can act as a source of N in low-nutrient ecosystems and it can react with atmospheric acids to form particulates, which can be spread over a wide area (Sommer and Hutchings, 2001; Webb et al., 2005). In Europe, about 75% of the NH_3 emitted to the atmosphere can be attributed to livestock production, and measures restricting NH_3 emissions from the livestock sector are considered the most effective approach to reduce the impact of NH_3 on the environment (Webb et al., 2005). Besides the total ammoniacal nitrogen (**TAN**) concentration [$\text{TAN} = \text{NH}_4^+ + \text{NH}_{3,\text{aq}}$ (aqueous)] in manure slurry, the pH and the DM content of the slurry are the most important parameters determining the NH_3 volatilization potential (Jarvis and Pain, 1990; Sommer et al., 2003). Paul et al. (1998), in 2 feeding trials, observed decreases in NH_3 emissions from manure slurry when the dietary CP content decreased. In one experiment, CP levels were lowered from 16.4 to 12.3%, which reduced NH_3 emissions by 40%, whereas in the other experiment, CP levels were reduced from 18.3 to 15.3%, which reduced NH_3 emissions by 20%. Similar decreases in NH_3 emissions with decreasing protein content of the feeds were reported by James et al. (1999) and Külling et al. (2001).

The aim of this research was to investigate how manure composition was affected by dietary changes. The slurries were produced in a feeding trial in which nonlactating cows were fed specific diets that varied in protein and energy content (Reijs et al., 2007). The effect of feeding strategy on manure composition was studied by measuring total as well as direct available (free) nutrient concentrations (N, P, K, Ca, Mg, and Na) in different manure slurries. In addition, the effects of diet composition and manure characteristics on NH_3 volatilization were investigated.

MATERIALS AND METHODS

Feeding Trial

To study the effect of diet composition on manure slurry quality, a feeding trial was carried out at experimental farm "De Meenthoeve" (Rhenen, the Netherlands) from January until March 2003. The feeding trial was described in more detail by Reijs et al. (2007). In the trial, 8 pairs of nonpregnant, nonlactating, ma-

ture Holstein-Friesian cows were fed high or low protein levels (190 or 108 g/kg of DM) in combinations with high or low energy levels (6,840 or 5,050 kJ/kg of DM). The 8 feeding regimens (Table 1) can be categorized into 4 groups: 1) high in protein and high in energy content (**HPHE**); 2) high protein content with a low energy content (**HPLE**); 3) low protein content with high energy content (**LPHE**); and 4) low protein content and low energy content (**LPLE**). The feeding regimens were created by combinations of 4 different forages (i.e., high-digestible grass silage, maize silage, low-digestible grass silage, and straw) and 3 concentrate ingredients (i.e., soybean meal, maize, and beet pulp). For each group, 2 feeding regimens were chosen, which are denoted by the subscript letters a or b following the group codes (Table 1), and were included in the statistical analysis as replicates. Compared with daily practices, extreme differences in the amounts of protein and energy fed to the nonlactating cows were chosen to obtain maximum differences in manure composition.

During the trial, the cows were housed in a tie-stall barn, where they were fed concentrates twice a day. After finishing the concentrates, cows were fed forages *ad libitum*. Every 2 d, before the following morning feeding, refusals were collected and weighed. The bedding-free manure slurries were collected in a slurry pit, which consisted of 8 compartments. Manure of the 2 cows belonging to the same feeding regimen was combined in 1 compartment. To minimize NH_3 volatilization, manure slurries were not mixed during manure collection. After a 3-wk adaptation period, manure was collected for 2 wk. Just before collection, the slurries were thoroughly mixed and transferred to a 1,000-L polyethylene container. During the transfer, subsamples were taken and subsequently transferred to 25-L barrels, closed, and stored for 5 mo at 4°C. In cases in which the viscosity of the slurries prevented pumping, water was added (Table 2). The total and free nutrient (N, P, K, Na, Ca, and Mg) concentrations of the different slurries were determined following the procedure described by Van der Stelt et al. (2005).

Manure Analyses

Immediately before the manure slurries were used in the experiments (d 0), pH, DM content (DM at 105°C), and electrical conductivity (**EC**) of the different manure slurries were determined. Slurry pH was measured by using a combined glass-calomel electrode (Radiometer Analytical SAS, Lyon, France) and EC by a multi-parameter analyzer (Eijkelpamp; type 18.21 SA, Eijkelpamp, the Netherlands). The measured conductivities were converted into the ionic strength of the manure slurries, using the empiric relationship ionic

Table 1. Feed composition, DM intake, C:N ratios of the diets, mean BW (SD in parentheses) of the cows at the start of the experiment, dietary characteristics, and mean nutrient contents of the diets

Treat- ment ¹	Forage ²	Concentrate ³	Forage intake, kg of DM/d	Concentrate intake, kg of DM/d	C:N ⁴	BW, kg	NE _M , kJ	Dietary characteristics, per kg of DM					Mean nutrient content, g/kg of DM				
								CP, g	NDF, g	ADF, g	Dig. ⁵ OM, %	K	Na	Ca	Mg	P	N
HPHE _a	60% MS + 40% HDGS	90% S + 10% M	12.3	3.6	15.0	556 (53)	6,800	184	379	216	73	22.8	1.0	4.0	2.5	4.1	29.4
HPHE _b	100% HDGS	40% S + 60% M	9.3	3.4	13.0	557 (35)	6,800	199	405	247	80	22.7	1.6	3.6	2.1	3.6	31.8
HPLE _a	100% LDGS	100% S	7.4	2.8	14.3	555 (29)	5,300	188	483	324	68	24.7	3.0	5.4	3.3	4.4	30.1
HPLE _b	100% STR	75% S + 25% M	4.7	4.1	15.2	565 (81)	4,845	189	510	335	60	18.0	1.3	2.7	2.6	3.7	30.2
LPHE _a	60% MS + 40% HDGS	55% M + 45% B	10.2	3.1	22.9	559 (61)	6,870	114	397	239	73	19.0	1.2	4.4	2.1	3.0	18.2
LPHE _b	100% MS	43% S + 21% M + 36% B	11.9	2.4	27.9	562 (10)	6,880	101	376	232	73	14.8	0.4	3.7	2.0	2.7	16.2
LPLE _a	100% LDGS	19% S + 81% B	7.2	2.6	22.5	482 (99)	5,170	110	539	350	64	21.5	3.4	6.9	3.0	3.0	17.6
LPLE _b	100% STR	21% S + 21% M + 58% B	3.9	4	26.3	563 (91)	4,900	105	556	350	64	14.1	1.8	4.8	2.4	2.1	16.8

¹HP = high protein; HE = high energy; LP = low protein; LE = low energy; for each group 2 feeding regimens were chosen, which are denoted by subscript letters a or b following the treatment code.

²Forages: MS = maize silage; HDGS = high digestible grass silage; LDGS = low digestible grass silage; STR = straw.

³Concentrates: S = soybean meal; M = maize; B = beet pulp.

⁴C:N ratios of the diets.

⁵Dig. OM = digested OM.

strength = $0.013 \times \text{EC}$, as described by Griffin and Jurinak (1973). Ionic strength is expressed in moles per liter, and EC is expressed in millimhos per centimeter (at 25°C).

Before the slurry samples were analyzed for total nutrient concentrations, the samples were first dried for 3 d in a drying oven (Heraeus 6060, Kendro Laboratory Products, Hanau, Germany) at 70°C. After drying, the samples were ground (<1 mm) using a Culatti MFC-type Micro Hammer Mill (Culatti AG, Zürich, Switzerland).

Next, the slurry samples were digested by microwave digestion with HNO₃, H₂O₂, and HF (Novozamsky et al., 1996) to determine total nutrient concentrations of Mg, Ca, K, and Na. Furthermore, the dried and ground manure slurry samples were digested using H₂SO₄, salicylic acid, H₂O₂, and selenium (Novozamsky et al., 1983) to determine total P concentrations in the manure samples. Potassium, Mg, Na, and Ca concentrations were determined by inductively coupled plasma atomic emission spectrometry (Varian (Vista-pro), Palo Alto, CA). Total P was measured by segmented-flow analysis (Skalar, Breda, the Netherlands). Total C was measured in the dried slurry samples on a CHN-analyzer (EA 1108, Fisons Instruments Milan, Italy), and total N was measured in fresh slurry samples using the Kjeldahl method (method ISO5983; ISO, 1979). Carbon losses during drying were minimized by using a forced-air drying oven. The C/N ratios of the slurries were calculated from the total C and total N data.

Determination of Free Nutrient Concentrations

The Donnan membrane technique manure cell consists of an acceptor solution separated from manure slurry by 2 negatively charged cation exchange membranes (Van der Stelt et al., 2005). The membranes allow transport of positively charged cations, whereas transport of neutral and negative ions is restricted. Within 5 d, (Donnan) equilibrium is reached between free cation concentrations in manure slurry and free cation concentrations in the acceptor solution.

Before starting the experiment, each manure slurry was homogenized, after which 10 kg of slurry was transferred into a plastic container (206 mm height, 11.3 L; Fisher Scientific, Waltham, MA), and 3 Donnan membrane technique cells were immersed in each slurry. The containers were closed with lids that contained a small opening into which a stirrer was placed. During the experiment, the slurries were continuously mixed to prevent settling of the solid phase. At different times (0, 7, 10, and 14 d), samples were taken of both the acceptor solution (3 mL) and the manure slurry (~250 mL).

Table 2. Chemical properties, dilution characteristics, and the distribution of total ammoniacal nitrogen (TAN)¹ content over NH₄⁺ and NH_{3,eq} of the manure slurries used in the ammonia volatilization experiment

Treatment ²	DM, ³ %	Dilution ⁴	pH	I, ⁵ M	N components ⁶ (g of N/kg of DM)		NH _{3,eq}	% (NH _{3,eq} :TAN)
					TAN (%)	NH ₄ ⁺ (%)		
HPHE _a	9.33 ^a	0.00	7.64 ^c	0.36 ^e	51.0 (66)	50.2 (65)	0.8	1.6
HPHE _b	10.18 ^{ab}	0.00	8.03 ^d	0.36 ^e	53.6 (71)	51.5 (68)	2.0	3.8
HPLE _a	13.49 ^c	0.00	8.24 ^{de}	0.28 ^d	32.3 (56)	30.3 (53)	2.0	6.1
HPLE _b	9.73 ^a	0.11	8.39 ^e	0.27 ^{cd}	49.5 (77)	45.3 (70)	4.2	8.4
LPHE _a	11.03 ^b	0.09	7.23 ^a	0.26 ^c	31.1 (59)	30.9 (59)	0.2	0.6
LPHE _b	11.19 ^b	0.07	7.17 ^a	0.20 ^b	31.0 (66)	30.8 (65)	0.2	0.6
LPLE _a	12.89 ^c	0.04	7.37 ^{ab}	0.18 ^{ab}	17.7 (52)	17.5 (52)	0.2	0.9
LPLE _b	10.39 ^{ab}	0.19	7.59 ^{bc}	0.17 ^a	26.5 (62)	26.1 (61)	0.4	1.5

^{a-c}Means within a column followed by different superscripts differ ($P < 0.05$).

¹TAN = N-NH_{3,eq} + N-NH₄⁺.

²HP = high protein; HE = high energy; LP = low protein; LE = low energy; for each group 2 feeding regimens were chosen, which are denoted by subscript letters a or b following the treatment code; the diets are described in more detail in Table 1.

³DM = DM content (105°C).

⁴The relative amount of water added to the slurries (during manure collection) to be able to mix the slurries.

⁵I = ionic strength.

⁶The percentages of TAN and NH₄⁺ compared with the total N content of the manure slurries are shown in parentheses.

No pretreatments were required to measure free nutrient concentrations in the sampled acceptor solutions, because only free positively charged ions can pass the membrane. Free K, Ca, Mg, and Na concentrations were determined by inductively coupled plasma atomic emission spectrometry. Subsamples of the acceptor solution were taken, diluted 200 times with ultrapure water, and measured by segmented-flow analysis to determine the free ammonium (NH₄⁺) concentration present in manure slurry. The measured potassium data were used to correct for differences in ionic strength between acceptor solution and manure slurries in accordance with Van der Stelt et al. (2005). The ammonia (NH_{3,eq}) concentrations and the TAN concentrations of the slurries were calculated by the speciation program Ecosat (Keijzer and van Riemsdijk, 2002), using the equilibrium reactions of the different species in combination with the measured pH and NH₄⁺ concentrations. Because nutrient concentrations were constant during the experiment, mean nutrients concentrations have been presented (Table 3).

NH₃ Volatilization

Volatilization of NH₃ from the different manure slurries was measured using a passive ammonia acid trap, which was developed by Velthof et al. (2005). A subsample (0.5 ± 0.01 kg) of (fresh) homogenized manure slurry was transferred to a plastic jar (1-L wide-neck square bottle; Kautex Textron GmbH, Bonn, Germany). On top of the slurry was placed a small plastic container (20 mL, Greiner Bio-One B.V., Alphen aan

den Rijn, the Netherlands) containing 12.5 mL of 3.2 M H₂SO₄, using a small ring of etha-foam (Recticel, Brussels, Belgium) to aid flotation. Volatilized NH₃ from the slurry is trapped as NH₄⁺ inside the acid solution in the small container (Van der Stelt et al., 2007). After closing the jars with screw tops, the jars were randomly placed in an incubator (Heraeus 6420, Kendro Laboratory Products). The jars were incubated at 12°C, which is within temperature boundaries (10 to 15°C) found in manure-slurry storage facilities during autumn (Sommer et al., 2000). After 0, 4, 8, 16, 24, and 32 d, the acid-containing flasks were replaced. The acid solution was diluted to a total volume of 50 mL with ultrapure water. Total N concentrations in the samples were determined by segmented-flow analysis. For each treatment, 4 jars were filled with manure slurry to study NH₃ volatilization. The data were described by an equation given by Groot et al. (1996):

$$G = \frac{A}{1 + \left(\frac{B}{t}\right)^C},$$

where G represents the (relative) amount of NH₃ volatilized at time t (d) after start of the incubation; A represents the (relative) asymptotic gas production (mmol of NH₃/mol of TAN); B denotes the time (d) required for half of the amount of gas produced to be formed; and constant C determines the curvature and, thereby, the position of the point of inflection. For $C \leq 1$, the profile has no point of inflection ($t \geq 0$).

Table 3. Properties and mean chemical composition (SE in parentheses) of the manure slurries

Treat- ment ¹	DM, ² %	Total C, %	C:N ratio ²	Nutrients								N components, g/kg of DM		
				K, total, g/kg of DM	Na, total, g/kg of DM	Na, free, % of total	Ca, total, g/kg of DM	Ca, free, % of total	Mg, total, g/kg of DM	Mg, free, % of total	P, total, g/kg of DM	Total	TAN, ³	Norg ⁴
HPHE _a	9.3 (0.2) ^a	35.8 (0.3) ^{bc}	4.6 (0.6) ^a	68.5 (1.8) ^f	4.2 (0.06) ^e	82 (0.2) ^{bc}	8.6 (0.2) ^a	3.8 (0.2) ^a	7.7 (0.3) ^d	13.1 (0.7) ^b	10.3 (0.2) ^e	77.2 (0.4) ^h	51.0 (1.8) ^c	26.2 (2.2) ^a
HPHE _b	10.2 (0.2) ^{ab}	34.6 (0.1) ^b	4.6 (0.1) ^c	80.4 (0.1) ^g	6.3 (0.07) ^g	82 (0.1) ^c	12.9 (0.1) ^c	0.5 (0.1) ^c	9.4 (0.1) ^e	0.43 (0.13) ^b	14.0 (0.2) ^f	75.6 (0.6) ^g	53.6 (3.3) ^c	22.0 (3.8) ^a
HPLE _a	13.5 (0.3) ^c	31.0 (0.4) ^a	5.4 (0.8) ^a	53.7 (0.6) ^d	3.2 (0.01) ^d	83 (0.5) ^{ab}	8.9 (0.2) ^a	7.9 (0.5) ^a	7.0 (0.2) ^{bcd}	16.7 (0.6) ^a	9.0 (0.3) ^d	57.7 (0.1) ^e	32.3 (3.2) ^b	25.4 (2.7) ^a
HPLE _b	11.0 (0.2) ^a	39.6 (0.2) ^e	6.1 (0.7) ^a	33.0 (0.6) ^b	2.8 (0.04) ^c	80 (0.1) ^{ab}	9.0 (0.3) ^a	1.3 (0.3) ^b	5.9 (0.3) ^a	4.5 (0.3) ^{ab}	7.2 (0.4) ^{abc}	64.6 (0.0) ^f	49.5 (1.3) ^c	15.1 (1.3) ^a
LPHE _a	12.2 (0.1) ^b	36.7 (0.1) ^{bcd}	7.0 (0.3) ^b	62.0 (1.7) ^e	4.9 (0.05) ^f	73 (0.6) ^{bc}	11.3 (0.1) ^b	10.0 (0.1) ^a	7.3 (0.0) ^{bcd}	16.7 (0.5) ^b	7.7 (0.5) ^c	52.3 (0.1) ^d	31.1 (1.8) ^b	21.3 (1.7) ^a
LPHE _b	12.1 (0.2) ^b	38.9 (0.2) ^{de}	8.3 (0.8) ^a	43.7 (1.2) ^c	1.8 (0.03) ^a	81 (0.0) ^{ab}	8.8 (0.1) ^a	3.2 (0.1) ^a	6.6 (0.1) ^{abc}	9.9 (0.1) ^b	7.5 (0.1) ^{bc}	47.1 (0.2) ^c	31.0 (1.5) ^b	16.1 (1.7) ^a
LPLE _a	13.4 (0.0) ^c	31.8 (0.1) ^a	9.3 (0.2) ^b	43.6 (1.1) ^c	2.5 (0.06) ^b	102 (0.7) ^{ab}	11.2 (0.2) ^b	3.7 (0.2) ^a	6.4 (0.1) ^{abc}	19.0 (0.2) ^b	6.3 (0.1) ^{ab}	34.0 (0.1) ^a	17.7 (0.3) ^a	16.2 (0.4) ^a
LPLE _b	12.8 (0.2) ^{ab}	37.6 (0.3) ^{cde}	8.7 (1.4) ^c	26.0 (0.4) ^a	3.1 (0.03) ^d	81 (0.0) ^{ab}	14.1 (0.5) ^c	1.4 (0.5) ^{ab}	7.4 (0.2) ^{cd}	15.7 (0.2) ^b	5.9 (0.2) ^a	43.1 (0.1) ^b	26.5 (0.9) ^{ab}	16.6 (1.0) ^a
Ref. ⁵	8.7	—	—	59.0	6.9	—	—	—	8.9	—	8.2	49.6	27.2	22.2
<i>P</i> -values														
Protein	0.003	NS	0.002	0.000	0.000	NS	0.000	0.009	0.000	NS	0.000	0.000	0.000	0.006
Energy	0.000	NS	NS	0.000	0.000	NS	0.049	NS	0.000	NS	0.000	0.000	0.000	NS
Protein × energy	0.004	NS	NS	0.000	0.000	NS	0.000	0.003	0.000	NS	0.001	0.000	NS	NS

^{a-h}Means within a column followed by different superscripts differ ($P < 0.05$).

¹HP = high protein; HE = high energy; LP = low protein; LE = low energy; for each group 2 feeding regimens were chosen, which are denoted by subscript letters a or b following the treatment code; the diets are described in more detail in Table 1.

²DM = DM content (105°C); C/N = total carbon to total nitrogen ratio.

³TAN = total ammoniacal nitrogen content ($\text{N-NH}_{3,\text{aq}} + \text{N-NH}_4^+$).

⁴Norg = organic N content; calculated as the difference between total N and TAN content.

⁵Average composition of wastewater free dairy cattle slurry in the Netherlands (Blgg, 2005).

Statistical Analysis

The SPSS program was used for statistical analysis of the data (SPSS Inc., 2003). Differences in manure composition caused by different feeding strategies were analyzed by ANOVA. Correlations were made between feed characteristics and the chemical composition of manures. The effects of dietary changes in protein and energy content on manure composition were tested for the 4 groups (1 to 4) described earlier, using the model: $y = \text{protein} + \text{energy} + \text{protein} \times \text{energy} + \text{rep} (\text{protein} \times \text{energy})$. Analysis of the effects of feed characteristics on ammonia volatilization was performed using repeated measurement analyses. Data were transformed when necessary to achieve equality of variances.

RESULTS AND DISCUSSION

Manure Characteristics

The composition of the different manure slurries expressed on a DM basis is given in Table 3. The DM content of the manure slurries ranged from 9.3% (HPHE_a) to 13.5% (HPLE_a). Similar DM content can be calculated from data reported by Holter and Urban (1992) for slurries produced by (pregnant) dry cows (13.4 and 14.9% DM, respectively), assuming a DM content of urine of 3.5% (Oenema et al., 2000). The DM content of the manure slurries was, on average, 15% greater ($P < 0.05$) when the CP content of the feeds of the animals was less (e.g., 108 or 190 g/kg of DM). At a greater protein concentration, more N will be excreted via the urinary tract, likely increasing the volume of urinary water required for diluting the N metabolites (Valadares et al., 1999; Broderick, 2003), and hence will result in lower DM content of the slurries. Both the lower C content and the greater N content of the slurries, when cows were fed diets with greater protein content, resulted in lower C:N ratios (38% on average) of the manures (Table 3).

Increasing the energy content from 5,050 to 6,840 kJ/kg of DM (and simultaneously improving the digestibility of the feed; Table 1) reduced the DM content of the manure slurries. This result agrees with results reported by Broderick (2003), who observed a decrease in fecal DM quantity, when the digestibility of the feed increased. Moreover, at a greater energy content of the diet, more feed (and N) was consumed by the animals in this experiment, adding to the excess of N (discussed in the next section). Excess N will be mostly excreted via the urinary tract, which will decrease the DM content of the slurry. On average, the DM content of the slurries was 14% less when the energy content of the feeding regimens was 35% greater. The C:N ratios of

the manure slurries were, on average, 17% less when the digestibility of the organic matter was approximately 17% greater.

Total Nutrient Content

The total DMI of the animals (forage + concentrates) ranged from 1.4% (LPLE_b) to 2.9% (HPHE_a and HPHE_b) of the mean BW, which is similar to the range reported for nonlactating cows in the standard of the American Society of Agricultural Engineers (0.7–2.2%; ASAE, 2005).

The total K content of the slurries ranged from 26 to 80 g/kg of DM (Table 3) and was, except for the straw-based feeding regimens (LPLE_b and HPLE_b), similar to the normal K content found in dairy slurries produced in the Netherlands (± 59 g/kg of DM; Blgg, 2005).

The amount of K consumed by cows that were fed straw-based diets was approximately half that consumed by the other cows. Subsequently, K content in the LPLE_b and HPLE_b slurries was approximately 50% lower than in the other slurries. The total Na content of the slurries varied between 1.8 and 6.3 g/kg of DM (Table 3). The Na content of all tested slurries was lower than the mean Na content found in dairy slurries (± 7 g/kg of DM). This suggests that the feeding regimens contained low amounts of Na. Nevertheless, minimum daily Na intakes required by cows (7 g/d; CVB, 2003) were met for all feeding regimens (Table 1) except for the LPHE_b treatment, from which slightly less Na was consumed (6 g/d) than required.

The Ca content of the slurries varied considerably between the different diets (SEM = 0.7 g/kg of DM). The least total Ca content was found for the HPHE_a slurry (8.6 g/kg of DM) and the greatest Ca content was found for slurry LPLE_b (14.1 g/kg of DM). However, the mean daily amounts of Ca excreted were almost equal for the these 2 extremes [e.g., 43 g/cow per day for HPHE_a and 44 g/cow per day for LPLE_b], which shows that, in addition to the content, the absolute amount of manure excreted is also important. For all feeding regimens, the mean daily Ca excretion was 44 ± 7 g/cow per day.

Total Mg content of the slurries varied from 5.9 g/kg of DM for the HPLE_b treatment to 9.4 g/kg of DM for the HPHE_b treatment. For all feeding regimens, the mean daily amount of Mg excreted was 31 ± 7 g/cow per day. All slurries except HPHE_b had Mg content comparable to the mean Mg content found in dairy slurries (Table 3), whereas total Mg content of the HPHE_b slurry was approximately 34% less. The Mg content of the slurries was positively correlated with the total K content of the slurries (Pearson = 0.744; $P < 0.001$). A greater K content in manure slurries is the result of an

increase in the dietary K content. A high K content in the feed has a negative effect on the digestibility of Mg (Schonewille et al., 1999; Weiss, 2004), leading to an increase in the amount of Mg excreted by the animal.

The total P content of the slurry based on the highly digestible grass silage treatment (HPHE_b; 14 g/kg of DM) was greater than the mean total P content found in dairy slurry (8.2 g/kg of DM; *t*-test; $P < 0.05$; Anonymous 2005a). The P content of the other treatments varied from 5.9 (LPLE_b) to 10.3 g/kg of DM (HPHE_a).

The total N content of slurries produced by dry cows fed diets containing high protein and high energy contents (regimens HPHE_a and HPHE_b) were approximately 54% greater than the mean N content found in dairy slurries (Table 3). All other treatments had total N content comparable to the mean N content found in dairy slurries, except for the LPLE_a slurry, which was approximately 32% lower than the mean N content. The total N content of slurries produced by nonlactating cows fed diets containing a high protein content or a high energy content were, on average, 56 and 27% greater (CP: $P < 0.001$; NE_L: $P < 0.01$) than the N content of slurries produced by cows fed diets with low protein or low energy contents. In contrast, Broderick (2003) observed a decrease in total N excreted in manure slurry of lactating dairy cows, when the energy content of the feed increased. These contradictory observations are likely to be related to the lesser efficiency of N utilization of nonlactating cows used in this experiment compared with the lactating cows used by Broderick (2003). In the case of nonlactating cows (in the present experiment), no N was converted into milk N protein, and N requirements for maintenance were lower. Consequently, feeding extra CP or energy to the cows will result in greater amounts of excreted N than for lactating cows.

Similar to the total N content, the total P content of the slurries increased with greater protein (48%) or energy content (39%), or both, of the feeding regimens ($P < 0.01$). The N:P ratios of the slurries varied from 5.4 to 9.0 and were on average 10% greater than the mean N:P ratio found in manure slurries (6.1; Table 3). The N:P ratio required by crops is about 8:1 (Lefcourt and Meisinger, 2001). Because manure application is primarily based on N requirements of plants, a greater N:P ratio of slurry manure will decrease the amount P applied (in excess) to the soil, which will reduce the risk of P loading of soils. Total P present in manure slurry was positively related to the Mg and TAN content of manure slurry, which might relate to the potential presence of minerals (e.g., struvite) in manure slurry (Van der Stelt et al., 2005).

Free Nutrient Content

Almost all Na present in manure slurry existed as free ions (73 to 100%), whereas only small amounts of the divalent cations Ca and Mg (1 to 10% and 0 to 19%, respectively) were present in manure slurry as free ions, as can be derived from Table 3. The relative free Na content in the slurries correlates (Pearson = 0.714; $P < 0.05$) with the Na content of the feed (Table 1), which indicates that Na supply was sufficient during the feeding trial. The low free Ca and Mg contents are most likely caused by precipitation of minerals [e.g., CaCO₃ (calcite) and MgNH₄PO₄·H₂O (struvite)] or adsorption to organic matter (Sommer and Husted, 1995).

Changes in the protein content or in the energy content/digestibility of the feed did not significantly affect the relative free nutrient content of Na, Ca, and Mg. Total ammoniacal N accounted for 52 to 77% of the total N content present in manure slurry. Both the TAN content and the organic N content of the slurries were greater ($P < 0.01$) with greater CP content of the feed. However, the increase in TAN was 3 times greater than the increase in organic N, indicating that more N is excreted via the urinary tract with greater CP content of the feed. Similar observations were reported by Broderick (2003). In contrast to the observations of Broderick (2003), however, the TAN content in our experiment was greater for the high-energy diets (~32%; $P < 0.001$). This discrepancy is related to the greater N intake of the cows receiving the high-energy diets, in combination with the physiological status of the cows. Unlike lactating cows, nonlactating cows are not able to use this extra N uptake efficiently through the production of milk. Therefore, the extra N uptake is excreted in urine, causing a greater TAN content in the slurry.

Both the free Ca²⁺ and the free Mg²⁺ contents were negatively correlated to the TAN content present in manure slurry (Ca²⁺: Pearson = -0.462, $P < 0.05$; Mg²⁺: Pearson = -0.514, $P < 0.05$). This is probably related to the exchange of Ca²⁺ and Mg²⁺ from the liquid phase with NH₄⁺ adsorbed to organic matter, which was described previously by Sommer et al. (2003).

Ammonia Volatilization

The chemical composition of the (diluted) manure slurries used in the ammonia volatilization experiment is given in Table 2. The ionic strengths of the slurries were greater when the feeding regimens contained either more energy or proteins, ranging from 0.17 *M* in case of the straw based regimen with a low protein content (LPLE_b) to 0.36 *M* for the regimens high in energy and high in protein content (treatments HPHE_a and HPHE_b). The ionic strengths of the slurries are

within the range (e.g., 0.1 to 0.4 *M*) previously reported by Sommer et al. (2003). The pH values of the manure slurries at the start of the experiment ranged from 7.2 to 7.6 for the feeding regimens low in protein and from 7.6 to 8.4 for the regimens high in protein. Similarly, both Külling et al. (2001) and Paul et al. (1998) measured higher slurry pH values when dairy cattle were fed more CP. Slurry pH values were lower when slurries were obtained from feeding regimens containing a high energy content. At greater dietary energy content, more feed is taken in by the animal per unit of time (Table 1) and hence, the passage rate of the feeds through the animal is greater. Feeding energy-rich diets will stimulate volatile fatty acid formation in the hindgut, which will decrease slurry pH, as was shown to occur for energy-rich diets in feeding trials with lactating cows (Reynolds et al., 2001).

The $\text{NH}_{3,\text{aq}}$ content in manure slurries produced from feeding regimens with a high CP content were, during the complete experiment, considerably greater than the $\text{NH}_{3,\text{aq}}$ content in slurries produced from regimens with a low CP content (on average 10 times greater). Moreover, the range in $\text{NH}_{3,\text{aq}}$ content was variable for the slurries based on feeds containing a high CP content; for example, varying from 0.8 to 4.2 g of N/ kg of DM. Comparable differences in slurry $\text{NH}_{3,\text{aq}}$ content were calculated for slurries studied in feeding trials by Paul et al. (1998), where the $\text{NH}_{3,\text{aq}}$ content was more than 4 times greater when the feed contained 15.3% instead of 12.3% CP. The $\text{NH}_{3,\text{aq}}$ content of the slurries were barely affected by changes in the energy content of the feed. The $\text{NH}_{3,\text{aq}}$ content of both straw-based treatments (HPLE_b and LPLE_b) were 2 times greater than the other treatments containing a similar amount of protein in the feed. The greater $\text{NH}_{3,\text{aq}}$ content for the straw treatments are most likely caused by the high carbon content of the slurries (Table 2), which stimulated the ammonification process (Külling et al., 2001) and because of the higher pH, which shifted the $\text{NH}_4^+/\text{NH}_{3,\text{aq}}$ equilibrium in favor of $\text{NH}_{3,\text{aq}}$.

Figure 1a shows the mean cumulative NH_3 amounts volatilized per day from the different manure slurries incubated at 12°C for 32 d. The absolute NH_3 amounts volatilized are expressed per cow per day to correct for differences in amounts of manure slurry produced per treatment. The amounts of NH_3 volatilized per cow per day varied, for the low CP treatments, between 0.13 and 0.21 g of NH_3 and for the high CP treatments between 0.93 and 1.41 g of NH_3 . Compared with previous studies the amounts of NH_3 volatilized in 32 d were low. Misselbrook et al. (2005) reported that similar amounts of NH_3 were volatilized from cattle slurry surfaces in 50 h of incubation. Under normal conditions, NH_3 emissions from manure slurries are the combined results of

diffusion and convectional processes occurring at the surfaces of slurries (Sommer and Hutchings, 2001). In most laboratory studies, NH_3 volatilization is simulated by transporting air over the slurry surface (as in the study by Misselbrook et al., 2005). In our experiment, active transport of air was minimized, and thus, NH_3 emissions due to convectional processes should be minimized. Hence, lesser amounts of NH_3 will volatilize per unit of time. Extrapolating the measured data to conditions in which both diffusional and convectional processes occur is problematic because diffusion is determined mainly by the concentration gradient (e.g., solubility of NH_3), whereas convection is determined mainly by air velocity and temperature. However, our method is suited to compare NH_3 volatilization from different treatments relatively and to assess the effects of dietary changes on NH_3 volatilization.

Between the low CP treatments, a difference in volatilized NH_3 amounts was observed only between the LPLE_a and LPHE_a slurries ($P < 0.05$). At high protein content, more NH_3 volatilized (28% on average) from slurries based on feeding regimens with a low energy content than from those with a high energy content ($P < 0.05$), which could be correlated to the pH of the slurries (Pearson = 0.953, $P < 0.01$). As was previously explained, with increasing energy content of the feed, more volatile fatty acids will be produced in slurry, which will lower pH, thereby decreasing the $\text{NH}_3/\text{NH}_4^+$ ratio and thus decreasing the tendency for NH_3 volatilization. Model calculations by Kebreab et al. (2002) showed that total N excreted by lactating cows, the urinary N fraction, and NH_3 emissions are reduced when lactating cows are fed regimens with greater energy contents. Although in this trial, more N was excreted by the nonlactating cows fed diets high in energy, relatively more N was excreted via the feces (data not shown), which reduced ammonia emissions.

The effects of changing dietary CP or energy content on NH_3 emissions from the manure slurries became clearer when the (cumulative) NH_3 amounts volatilized were expressed in proportion to the amount of slurry produced (Figure 1b), or in proportion to the TAN content of the slurries (Figure 1c). Expressed per kilogram of wet manure slurry, the NH_3 amounts volatilized from slurries based on low-CP regimens (108 g/kg of DM) were, on average, 78% lower than the NH_3 amounts volatilized from slurries based on high-CP regimens (190 g/kg of DM). Külling et al. (2001) reported a 69% decrease in the rate of NH_3 emissions when cows were fed 125 g of CP/kg of DM instead of 175 g/kg. At high CP content, on average, 66% more NH_3 was volatilized from manure slurries based on low energy feeds. The differences in amounts of slurry excreted led to similar NH_3 emissions at low energy content when NH_3 is ex-

Figure 1. Cumulative NH_3 emissions of the different manure slurries incubated at 12°C for 32 d: a) expressed as grams of $\text{NH}_3\text{-N}$ per cow per day; b) as milligrams of $\text{NH}_3\text{-N}$ per kilogram of manure slurry; c) as milligrams of $\text{NH}_3\text{-N}$ per gram of total ammoniacal N (TAN). Points denote measured data; lines represent modeled NH_3 emissions. Feeding regimens: HP = high protein; HE = high energy; LP = low protein; LE = low energy; for each group 2 feeding regimens were chosen, which are denoted by subscript letters a or b following the treatment code. The composition of the diets on which the slurries are based are described in Table 1. ^{A-F} Different indices in the graph denote differences ($P < 0.05$) between the treatments.

pressed as milligrams of $\text{NH}_3\text{-N}$ per kilogram of manure (e.g., HPLE_a , HPLE_b ; 32 and 41 L/d), whereas the difference became more evident for the slurries at high energy content (e.g., HPHE_a and HPHE_b ; 54 and 43 L/d). At low CP content, no effects of energy content of the feed on the amount of NH_3 emitted per kilogram of manure slurry were observed and amounts of NH_3 volatilized increased in the order: $\text{LPLE}_a \leq \text{LPHE}_b < \text{LPHE}_a \leq \text{LPLE}_b$.

When NH_3 emissions are expressed as a proportion of the TAN content of the slurries (Figure 1c), the order of the NH_3 emissions reflects the 4 dietary groups. However, at low CP content, no statistical differences ($P < 0.05$) in amounts of NH_3 volatilized were observed between slurries LPHE_a and LPLE_a . Again, NH_3 emissions are much lower when the CP content of the feeding regimens was lower (71%), and increasing

the energy content of the regimens resulted in lower NH_3 emissions, both at high (86%) and low (33%) CP contents.

Dietary changes to improve manure quality and reduce environmental losses are primarily based on reducing CP content and increasing the fiber content (i.e., lowering the net energy content of diets). Our data confirm that lowering dietary CP content can be an effective way to reduce N emissions. In contrast, the effects of increasing the fiber content of the feeds on NH_3 volatilization from manure slurry are not as well defined. Increasing the fiber content of the diet will, in general, decrease the OM content, which is fermented in the rumen. Dry matter intake and the passage rate of OM will be less, which will reduce the efficiency of microbial N synthesis in the rumen. Hence, more N in the rumen will be transformed into NH_3 , which will

subsequently be transformed into urea and (partly) excreted via the urinary tract.

CONCLUSIONS

Adjusting dietary composition is considered an important way to improve the sustainability of farming. Changes in the protein content or the energy content of the feed did not significantly affect the free:total ratios of Na, Ca, and Mg content of the slurries. Lowering the dietary CP content markedly decreased the total N and total P contents of slurries and reduced the potential risk of NH_3 volatilization. Compared with the CP content, the effects of reducing the energy content on manure composition and ammonia volatilization were not as straightforward. Total N, total P, and TAN content in manure slurry decreased, but the amount of NH_3 volatilized increased.

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REFERENCES

- Aarts, H. F. M., E. E. Biewinga, and H. van Keulen. 1992. Dairy farming systems based on efficient nutrient management. *Neth. J. Agric. Sci.* 40:285–299.
- ASAE (Am.Soc. Agric. Eng.). 2005. Manure Production and Characteristics. ASAE, St. Joseph, MI.
- Blgg. 2005. Dutch manure dataset, 2002–2005. Blgg, Oosterbeek, the Netherlands.
- Børsting, C. F., T. Kristensen, L. Misciattelli, T. Hvelplund, and M. R. Weisbjerg. 2003. Reducing nitrogen surplus from dairy farms. Effects of feeding and management. *Livest. Prod. Sci.* 83:165–178.
- Broderick, G. A. 2003. Effects of varying dietary protein and energy levels on the production of lactating dairy cows. *J. Dairy Sci.* 86:1370–1381.
- Castillo, A. R., E. Kebreab, D. E. Beever, J. H. Barbi, J. D. Sutton, H. C. Kirby, and J. France. 2001. The effect of energy supplementation on nitrogen utilization in lactating dairy cows fed grass silage diets. *J. Anim. Sci.* 79:240–246.
- CVB (Centraal Veevoederbureau). 2003. Animal Feed Tables, 2003. Centraal Veevoederbureau, Lelystad, the Netherlands. (in Dutch)
- Edmeades, D. C. 2003. The long-term effects of manures and fertilisers on soil productivity and quality: A review. *Nutr. Cycl. Agroecosyst.* 66:165–180.
- Griffin, R. A., and J. J. Jurinak. 1973. Estimation of activity coefficients from the electrical conductivity of natural aquatic systems and soil extracts. *Soil Sci.* 116:26–30.
- Groot, J. C. J., J. W. Cone, B. A. Williams, F. M. A. Debersaques, and E. A. Lantinga. 1996. Multiphasic analysis of gas production kinetics for in vitro fermentation of ruminant feeds. *Anim. Feed Sci. Technol.* 64:77–89.
- Holter, J. B., and W. E. Urban Jr. 1992. Water partitioning and intake prediction in dry and lactating Holstein cows. *J. Dairy Sci.* 75:1472–1479.
- ISO (International Standardization Organization). 1979. ISO 5983: Animal feeding stuffs, determination of nitrogen content and calculation of crude protein content. ISO, Geneva, Switzerland.
- James, T., D. Meyer, E. Esparza, E. J. Depeters, and H. Perez-Honti. 1999. Effects of dietary nitrogen manipulation on ammonia volatilization from manure from Holstein heifers. *J. Dairy Sci.* 82:2430–2439.
- Jarvis, S. C., and B. F. Pain. 1990. Ammonia volatilisation from agricultural land. *Proc. Fert. Soc.* 298:3–33.
- Kebreab, E., J. France, J. A. N. Mills, R. Allison, and J. Dijkstra. 2002. A dynamic model of N metabolism in the lactating dairy cow and an assessment of impact of N excretion on the environment. *J. Anim. Sci.* 80:248–259.
- Keijzer, M. G., and W. H. van Riemsdijk. 2002. A computer program for the equilibrium calculation of speciation and transport in soil-water systems (ECOSAT 4.7). Wageningen University, Wageningen, the Netherlands.
- Külling, D. R., H. Menzi, T. F. Kröber, A. Neftel, F. Sutter, P. Lischer, and M. Kreuzer. 2001. Emissions of ammonia, nitrous oxide and methane from different types of dairy manure during storage as affected by dietary protein content. *J. Agric. Sci.* 137:235–250.
- Lefcourt, A. M., and J. J. Meisinger. 2001. Effect of adding alum or zeolite to dairy slurry on ammonia volatilization and chemical composition. *J. Dairy Sci.* 84:1814–1821.
- Misselbrook, T. H., J. M. Powell, G. A. Broderick, and J. H. Grabber. 2005. Dietary manipulation in dairy cattle: Laboratory experiments to assess the influence on ammonia emissions. *J. Dairy Sci.* 88:1765–1777.
- Nennich, T. D., J. H. Harrison, L. M. VanWieringen, D. Meyer, A. J. Heinrichs, W. P. Weiss, N. R. St Pierre, R. L. Kincaid, D. L. Davidson, and E. Block. 2005. Prediction of manure and nutrient excretion from dairy cattle. *J. Dairy Sci.* 88:3721–3733.
- Novozamsky, I., and J. J. v. d. Lee. 1996. Solubilization of plant tissue with nitric acid-hydrofluoric acid-hydrogen peroxide in a closed system microwave digester. *Commun. Soil Sci. Plant Anal.* 27:867–875.
- Novozamsky, I., V. J. G. Houba, R. v. Eck, and W. v. Vark. 1983. A novel digestion technique for multi-element plant analysis. *Commun. Soil Sci. Plant Anal.* 14:239–249.
- Oenema, O., G. L. Velthof, P. W. G. Groot Koerkamp, G. J. Monteny, A. Bannink, H. G. Van der Meer, and K. W. Van der Hoek. 2000. Forfaitaire waarden voor gasvormige stikstofverliezen uit stallen en mestopslagen (in Dutch), Alterra, Wageningen, pp. 185.
- Paul, J. W., N. E. Dinn, T. Kannangara, and L. J. Fisher. 1998. Protein content in dairy cattle diets affects ammonia losses and fertilizer nitrogen value. *J. Environ. Qual.* 27: 528–534.
- Phillips, V. R., D. A. Cowell, R. W. Sneath, T. R. Cumby, G. Williams, T. G. M. Demmers, and D. L. Sandars. 1999. An assessment of ways to abate ammonia emissions from UK livestock buildings and waste stores. Part 1: Ranking exercise. *Bioresour. Technol.* 70:143–155.
- Reijs, J., M. P. W. Sonneveld, P. Sørensen, R. L. M. Schils, J. C. J. Groot, and E. A. Lantinga. 2007. Effects of different diets on utilization of nitrogen from cattle slurry applied to grassland on a sandy soil in the Netherlands. *Agric. Ecosyst. Environ.* 118:65–79.
- Reynolds, C. K., S. B. Cammell, D. J. Humphries, D. E. Beever, J. D. Sutton, and J. R. Newbold. 2001. Effects of postrumen starch infusion on milk production and energy metabolism in dairy cows. *J. Dairy Sci.* 84:2250–2259.
- Schonewille, J. T., A. T. Van'T Klooster, H. Wouterse, and A. C. Beynen. 1999. Effects of intrinsic potassium in artificially dried grass and supplemental potassium bicarbonate on apparent magnesium absorption in dry cows. *J. Dairy Sci.* 82:1824–1830.
- Sommer, S. G., S. Générmont, P. Cellier, N. J. Hutchings, J. E. Olesen, and T. Morvan. 2003. Processes controlling ammonia emission from livestock slurry in the field. *Eur. J. Agron.* 19:465–486.

- Sommer, S. G., and S. Husted. 1995. The chemical, buffer system in raw and digested animal slurry. *J. Agric. Sci.* 124:45–53.
- Sommer, S. G., and N. J. Hutchings. 2001. Ammonia emission from field applied manure and its reduction. *Eur. J. Agron.* 15:1–15.
- Sommer, S. G., S. O. Petersen, and H. T. Sogaard. 2000. Greenhouse gas emission from stored livestock slurry. *J. Environ. Qual.* 29:744–751.
- Sørensen, P., M. R. Weisbjerg, and P. Lund. 2003. Dietary effects on the composition and plant utilization of nitrogen in dairy cattle manure. *J. Agric. Sci.* 141:79–91.
- SPSS Inc. 2003. SPSS 12.0 Brief Guide. SPSS Inc., Chicago, IL.
- Tilman, D., J. Fargione, B. Wolff, C. D'Antonio, A. Dobson, R. Howarth, D. Schindler, W. H. Schlesinger, D. Simberloff, and D. Swackhamer. 2001. Forecasting agriculturally driven global environmental change. *Science* 292:281–284.
- Valadares, R. F. D., G. A. Broderick, S. C. Valadares Filho, 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 Stelt, B., E. J. M. Temminghoff, and W. H. Riemsdijk. 2005. Measurement of ion speciation in animal slurries using the Donnan membrane technique. *Anal. Chim. Acta* 552:135–140.
- Van der Stelt, B., E. J. M. Temminghoff, P. C. J. Van Vliet, and W. H. Riemsdijk. 2007. Volatilization of ammonia from manure as affected by manure additives, temperature and mixing. *Bioresour. Technol.* 98:3449–3455.
- Velthof, G. L., J. A. Nelemans, O. Oenema, and P. J. Kuikman. 2005. Gaseous nitrogen and carbon losses from pig manure derived from different diets. *J. Environ. Qual.* 34:698–706.
- Vérité, R., and L. Delaby. 2000. Relation between nutrition, performances and nitrogen excretion in dairy cows. *Ann. Zootech.* 49:217–230.
- Webb, J., H. Menzi, B. F. Pain, T. H. Misselbrook, U. Dämmgen, H. Hendriks, and H. Döhler. 2005. Managing ammonia emissions from livestock production in Europe. *Environ. Pollut.* 135:399–406.
- Weiss, W. P. 2004. Macromineral digestion by lactating dairy cows: Factors affecting digestibility of magnesium. *J. Dairy Sci.* 87:2167–2171.