Interpretation of results from on-farm experiments: manure-nitrogen recovery on grassland as affected by manure quality and application technique. 1. An agronomic analysis

J.C.J. Groot[1,*] , J.D. Van Der Ploeg[2], F.P.M. Verhoeven[2] and E.A. Lantinga[1]

[1] Biological Farming Systems Group, Wageningen University, Marijkeweg 22, NL-6709 PG Wageningen, The Netherlands
[2] Rural Sociology Group, Wageningen University, Wageningen, The Netherlands
[*] Corresponding author (e-mail: jeroen.groot@wur.nl)

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Abstract

In a 5-year field experiment, a comparison was made between the manure application practices of two adjacent dairy farms in the north of the Netherlands. Grassland management systems at Drogeham and Harkema contrasted in manure application technique (surface application versus shallow injection, respectively), quality of applied manure (slurry + MX: slurry with Euromestmix® clay mineral additive versus regular slurry), and some relevant site characteristics (high versus low soil organic matter content and soil moisture supply). Effects of manure types and application techniques, and treatment of the soil with a micro-organism supplement, were tested in a factorial experiment at the two sites, two blocks per site, one with and one without additional application of 157 kg N ha^{-1} $year^{-1}$ inorganic fertilizer. Apparent N recovery was higher after shallow injection than after surface application. For plots receiving no additional inorganic fertilizer, this difference was largest for slurry + MX applied at site Harkema, since this slurry–site combination resulted in the highest observed average apparent N recovery following shallow injection (47%) and the lowest N recovery following surface application (20%). For plots receiving additional inorganic fertilizer N the contrasts between treatments were less pronounced. Year effects on N uptake and dry matter production could be related to cumulative temperature and precipitation surplus over the growing season. A simple comparison between the grassland management systems was carried out based on the response curves derived from the experiment. This demonstrated that the grassland system where slurry was applied by shallow injection is not necessarily the lowest in actual amount of N not accounted for (i.e., potentially lost). The efficiency of the Harkema system strongly depended on high N recovery, but showed high potential losses in some years and a high herbage crude protein content in other years, due to the low DM production capacity. On the other hand, the Drogeham system was tuned to high DM production and was characterized by higher system stability, as reflected by more stable relationships between DM production and N not accounted for and herbage crude protein content. These differences between the systems were probably to a large extent caused by differences in water balance and soil organic matter content.

Additional keywords: dairy farming system, nutrient use efficiency, soil organic matter, stability, Monte Carlo simulation

Introduction

Following the wide acknowledgement of the adverse effects of intensive agricultural practices on agro-ecosystem functioning in temperate regions, regulations and restrictions on nutrient inputs have been implemented in recent years (Henkens & Van Keulen, 2001). In response, farmers had to significantly adapt their farm management to improve nutrient use efficiency (Ondersteijn *et al.*, 2002; Groot *et al.*, 2006). This required a change from increasing external inputs to increasing utilization of internal resources in farming systems, denoted as a shift from technological to eco-technological management (Groot *et al.*, 2003; 2004). Central to this transition is the improvement of nutrient cycling between the components of farming systems. For commercial farms in the Netherlands, nationwide and regional nutrient management projects have emerged to perform on-farm analysis of nutrient cycling and to assist farmers in the transition to farming with reduced nutrient inputs (e.g. Oenema *et al.*, 2001; Spears *et al.*, 2003).

An example of a regional project is the Nutrient Management Project (NMP), which was initiated by the environmental co-operatives VEL and VANLA that were founded by dairy farmers in the northern part of the Netherlands (Renting & Van Der Ploeg, 2001). In the NMP a package of adjustments in farm management was formulated, based on hypotheses and experiences of researchers and advanced farmers (Van Bruchem *et al.*, 1999; Verhoeven *et al.*, 2003). This package describes an integrated approach focusing on optimization of efficiency of all system components, and was labelled the re-balancing strategy (Verhoeven *et al.*, 2003). The first adjustment proposed was to reduce inorganic fertilizer N input. Simultaneously, recommendations were made for grassland and soil management to enhance the production of grass with lower crude protein (CP) and higher crude fibre contents by postponing the silage cut. Secondly, the package promoted feeding the cows a ration containing less CP to enhance N conversion efficiency, and more fibre to stimulate rumen function while providing sufficient amounts of energy to maintain animal production levels (Van Bruchem *et al.*, 1999). The higher animal N conversion efficiency was expected to lead to changes in manure quality, with lower total N content and a larger proportion of organically bound N less prone to losses through volatilization and leaching. Thirdly, manure with a higher carbon to nitrogen (C/N) ratio was hypothesized to improve soil quality, thereby contributing to grassland productivity in the long run (Van Bruchem *et al.*, 1999). Methods used are application of slurry with a higher C/N ratio, minimization of use of heavy machinery and surface application of slurry rather than injection, which were hypothesized to minimize sward damage and deterioration of soil structure, and to spare soil biota.

From this approach it can be concluded that quality and utilization of slurry can be considered as key aspects of the strategies to improve nutrient cycling. So experimentation with soil and slurry additives such as Euromestmix® (MX) and Effective Microbes® (EM) was initiated to explore further possibilities to increase slurry quality and utilization. Adding clay minerals in the form of Euromestmix® to the slurry is expected to cause N ions in the slurry to be less reactive and to bind toxic substances. This would result in reduction of N emission after slurry application and less negative effects on soil biota and soil biological processes. EM is a mixture of micro-organisms that was assumed to contribute to enhancement of the soil microbial diversity and activity (Higa, 1994). Part of the farmers experimented with EM, applying it to one or more components of the system (e.g. soil, feed, slurry).

Several of the measures described above deviate from the generally recommended farming practices in the Netherlands, which has resulted in debates among and between farmers, researchers, extension workers and policy makers (see also Van Der Ploeg *et al.*, 2007). For instance, the nitrogen recovery from slurry after surface application is generally lower than after shallow injection (Huijsmans *et al.*, 2001; Sommer & Hutchings, 2001; Mattila & Joki-Tokola, 2003). This results in lower nitrogen use efficiency and higher potential losses within the time frame of the experiments conducted, whereas long-term effects are often not considered. As to the additives no consistent positive effects on slurry-N recovery have been reported from experimental work (De Goede *et al.*, 2003). Conclusions concerning nitrogen use efficiency of slurry applications are often drawn from experiments where the measures were studied in isolation, whereas interactions between factors and implications for the performance of the whole farming system are often omitted.

In this paper a comparison is made of two grassland management systems contrasting in location, slurry application technique and slurry type/additives use in an on-farm field experiment. Preliminary results on aspects of grassland productivity and soil biology have been published by De Goede *et al.* (2003), Schils & Kok (2003) and Verhoeven *et al.* (2003). This paper is the first analysis of the complete 5-year experiment. Additionally, the experiment is considered from a systems analysis viewpoint by evaluating the performance of the combination of practices that constitute a grassland management system. We shall first present a thorough analysis of the experimental results and then demonstrate the effects on the grassland management system performance in terms of efficiency and quality of grass dry matter production. In a companion paper the societal setting of this type of on-farm experiments will be discussed (Van Der Ploeg *et al.*, 2007).

Materials and methods

Data collection and processing

The on-farm field experiment was carried out at two farm sites to determine the effects of slurry application (slurry quality and application technique). The farms were located adjacent to each other, with a distance between the experimental fields of ca. 1000 m. The fields were located on the same soil type (soil series CHn23, Plagganthreptic Alorthod; Anon., 1998; Sonneveld & Bouma, 2003) and had been utilized as permanent grassland for grazing and cutting as silage or hay for more than 50 years. Grassland management systems applied at farm sites Drogeham and Harkema before the start of the experiment had contrasted in manure application technique (surface application versus shallow injection, respectively) and the quality of applied manure (slurry with Euromestmix® clay mineral additive versus regular slurry). These systems had been applied for 17 and 10 years prior to the experiment, respectively.

The layout of the experiment and the initial site conditions in terms of soil characteristics and botanical composition of the swards have been described in detail by Schils & Kok (2003). These authors have also given a description of the experimental treatments (harvesting, fertilizer and slurry applications) and measurements, which are summarized below. The time scheme of slurry applications and harvests for the entire experimental period is given in Table 1. Climatic data were obtained from the nearby Eelde weather station. For an overview of cumulative temperature, precipitation and evapotranspiration throughout the growing seasons see Table 2, which also gives the average soil organic matter and soil nitrogen contents for the two sites at the end of each growing season.

The experiment was conducted for 5 subsequent years. Within fields at each of the two farms, two blocks were located, one with and one without inorganic fertilizer N (IF) application (rates of on average 157 and 0 kg N ha^{-1} $year^{-1}$ for +IF and –IF, respectively). Within these blocks, two randomized replicate sub-blocks were distinguished, comprising all treatment combinations for slurry application. Slurry application techniques were shallow injection and surface application. The two applied slurries were collected on the two farms. The slurry from farm Harkema was denoted as regular

Table 1. Time schedule of inorganic fertilizer and cattle slurry application (A) and cutting (C) dates for the 5 cuts during the 5 years of the experiment. Month numbers in Roman numerals.

Year	Cut									
	1		2		3		4		5	
	A	C	A	C	A	C	A	C	A	C
1999	18 III	6 V		4 VI	9 VI	15 VII		24 VIII		18 X
2000	29 III	11 V		20 VI	23 VI	25 VII	27 VII	29 VIII		16 X
2001		25 V	6 VI	27 VI	28 VI	3 VIII	8 VIII	5 IX		26 X
2002	27 III	14 V		18 VI	20 VI	25 VII	29 VII	31 X		24 X
2003	11 III	22 V		26 VI	30 VI	31 VII	4 VIII	17 X		

Table 2. Climatic and soil conditions during the experiment. Cumulative and average temperature, precipitation and evapotranspiration (Hooghart & Lablans, 1988) were recorded for the growing season, defined as the period between 1 March and the date of the final harvest of each year. Soil organic matter and soil nitrogen content at Drogeham (D) and Harkema (H) refer to the soil layer 0–30 cm.

Year	Temperature		Total precipitation	Total evapo-transpiration	Soil organic matter		Soil nitrogen	
	Cumulative	Average			D	H	D	H
	(°C.d)	(°C)	----- (mm) -----		(g /kg dry soil)		(mg/kg dry soil)	
1999	2913	12.6	470	512	64	51	276	216
2000	2763	12.1	475	453	63	52	263	220
2001	2641	11.0	678	483	66	47	290	216
2002	2917	12.3	416	480	65	45	280	218
2003	2941	12.8	383	546	63	47	274	224

Table 3. Annual amount of slurry-N, applied by surface broadcast or shallow injection, and dry matter (DM), inorganic and organic N content and C/N ratio of the fresh slurry applied.

Type of slurry	Year	N applied		Composition slurry			
		Surface	Injection	DM	$N_{inorganic}$	$N_{organic}$	C/N
		--- (kg ha^{-1}) ---		-------- (g kg^{-1}) -------			
Slurry	1999	212	212	100.5	2.15	3.15	6.95
	2000	122	142	56.3	1.60	1.78	6.30
	2001	109	111	47.2	1.60	1.34	5.51
	2002	156	160	79.6	1.87	1.93	7.58
	2003	131	131	44.1	1.43	1.30	5.90
Slurry + MX [1]	1999	168	168	87.5	1.90	2.30	7.25
	2000	146	165	84.5	1.69	2.14	8.18
	2001	144	140	86.8	1.88	2.01	8.23
	2002	143	143	78.5	1.68	1.73	8.41
	2003	159	141	78.7	1.70	1.93	7.96

[1] Slurry + MX = slurry with Euromestmix®, clay mineral additive.

slurry, whereas the slurry from farm Drogeham was amended with MX and is referred to as slurry + MX. The fields were either sprayed with Effective Microbes® suspension (+EM) or remained untreated (–EM) (Schils & Kok, 2003).

The application rates and composition of the slurries are given in Table 3. The total N application rate of slurry + MX was higher than of regular slurry in years in which dry matter content of regular slurry was relatively low (years 2000, 2001 and 2003), whereas the opposite was true for the years 1999 and 2002. This was also associated with differences in the proportion between inorganic and organic N in fresh slurry. The C/N ratio of slurry + MX was higher than that of regular slurry (Table 3).

For a detailed analysis of the effects of N application on dry matter yield a distinction was made between apparent N recovery and N conversion efficiency, i.e., a quadrant analysis (see De Wit, 1992). Apparent N recovery (R_T) represents the effects of total N application on crop N uptake corrected for nitrogen delivery by the soil (Equation 1). N conversion efficiency (E_C) denotes the dry matter yield that is reached by the crop at a given N uptake level (Equation 2).

$$R_T = \frac{U-C}{N_T} \tag{1}$$

$$E_C = \frac{Y}{U} \tag{2}$$

where

N_T = total N application (kg N ha^{-1} year^{-1}),

U = N uptake (kg N ha^{-1} year^{-1}),

C = N uptake in unfertilized control plot (kg ha^{-1} year^{-1}),

Y = dry matter yield (kg DM ha^{-1} year^{-1}).

The annual amount of N available for plant uptake from slurry and inorganic fertilizer (N_A; Equation 3) was estimated as the sum of inorganic N in slurry (N_I), inorganic fertilizer (IF) and the calculated mineralization of organic N from slurry (N_M; Equation 4). The parameter values proposed by Groot *et al.* (2003: p. 172) were used in these calculations: k_F = 0.4 year^{-1}, ε = 0.30 kg kg^{-1} and q_M = 8.0. The N recovery on the basis of the estimated available inorganic N (R_A) was calculated from Equation 5.

$$N_A = IF + N_I + N_M \tag{3}$$

$$N_M = \frac{K_F C_F}{1-\varepsilon}\left(\frac{1}{q_F} - \frac{\varepsilon}{q_M}\right) \tag{4}$$

$$R_A = \frac{U-C}{N_A} \tag{5}$$

where

k_F = fractional degradation rate (year^{-1}),

C_F = amount of carbon applied in slurry (kg ha^{-1} year^{-1}),

q_F = ratio of carbon and organic N in slurry (–),
ε = efficiency of biomass conversion by soil biota (kg kg^{-1}),
q_M = C/N ratio of soil biota (–).

Statistical analysis

The results were statistically analysed in two steps. Firstly, imposed treatment effects on annual dry matter yield, apparent N recovery and N conversion efficiency were analysed using ANOVA. In the full model a split was made for the replicate sub-blocks, and terms for application technique, slurry quality and EM treatment and their interactions were included. The blocks with and without additional inorganic fertilizer were analysed separately. Secondly, annual dry matter and nitrogen yields were related to weather conditions (cumulative temperature, precipitation and evapotranspiration), soil organic matter and nitrogen contents, slurry dry matter content and slurry C/N ratio. The full models used were different for response variates and are presented in the results section. Terms in the full model and their interactions (with a factorial expansion limit of four) were added to the regression model by a stepwise regression procedure. The criterion for selecting or removing terms was reduction in the residual sum of squares, with a significance level for acceptance of a change in the model of $P < 0.001$. Additionally, the response curves of grass dry matter production to N uptake that were significantly different according to the stepwise regression procedure were fitted with separate Michaelis-Menten models (Equation 6) by nonlinear optimization. The statistical programme Genstat Release 1 was used for all analyses (Anon., 2002).

$$Y = \frac{bcU}{bU+c} \qquad (6)$$

where
b = initial response of Y to U (kg DM per kg N),
c = asymptote (kg DM).

A simplified grassland management comparison was made on the basis of the quadrant analysis, relating N application to N uptake and dry matter yield (Equations 1 and 6). The resulting model was parameterized from the experimental observations. The aim was a comparison of the systems for the amount of N not accounted for (i.e., potentially lost) and the crude protein content of the herbage. The variance in the model outcomes was explored with a Monte Carlo simulation, which can be used as a method for iteratively evaluating a deterministic model using sets of random numbers as inputs (Wittwer, 2004). The simulations involved 1000 evaluations of the grassland management model per dry matter yield level per management system per year. Random parameter values were assigned following a normal distribution of the parameters, with mean and standard deviation derived from the experiment. The standard deviation of the mean of the model outputs was calculated as a measure of the variance originating from the variation in the input parameters.

Results

Apparent N recovery, N conversion efficiency and dry matter yield of the experimental treatments differed considerably between years and were different for sites Drogeham and Harkema (Figure 1). Year effects, application technique and interactions between year and experimental sites explained most of the variation observed (Table 4). These effects are analysed in more detail below.

Apparent N recovery in relation to experimental factors

Apparent N recovery of total applied slurry nitrogen (R_T) was considerably higher after shallow injection than after surface application when no additional inorganic fertilizer was applied (41.8% versus 26.4% on average). Moreover, R_T of regular slurry was on average higher than for slurry + MX (36.1% versus 32.1%). The main effect of using EM was not statistically significant.

No statistically significant differences in apparent N recovery for plots receiving no additional fertilizer were found between the sites, but the effects on R_T of the experimental treatments were different between sites (Table 5). The highest R_T (46.5%) was found at site Harkema, for the treatment combination typical for the grassland management system usually applied at that site (shallow injection of regular slurry, no EM application; Table 5). At site Harkema, the difference in R_T between surface application and shallow injection tended to be larger than at site Drogeham, particularly when regular slurry was used, whereas for slurry + MX no statistically significant difference in R_T between the sites was observed (S × M × A interaction; P = 0.073; Tables 4 and 5). The low R_T of regular surface applied slurry at site Harkema (19.9%) was partly offset by the treatment with EM up to a recovery of 29.2% (statistically significant S × A × E interaction, P = 0.033).

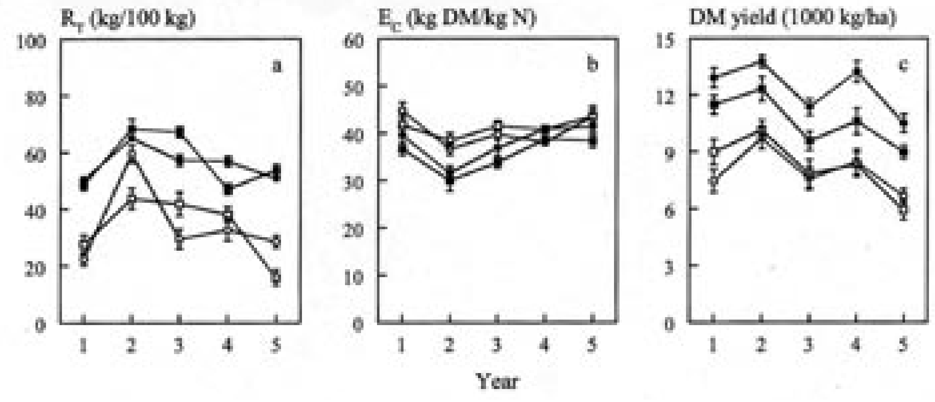

Figure 1. Apparent recovery of total applied nitrogen (R_T, a), N conversion efficiency (E_C, b) and dry matter yield (c) from plots at sites Drogeham (□) and Harkema (○). Observations were made in the years 1999–2003, denoted as 1–5 on the X-axis. Plots were treated without (–IF, open symbols) or with additional inorganic fertilizer at a rate of 157 kg N ha^{-1} year^{-1} (+IF, closed symbols). Bars indicate standard errors.

Table 4. Contribution of terms in the analysis of variance (ANOVA) to the explanation of the variation in apparent recovery of applied total and available N (R_T and R_A), nitrogen conversion efficiency (E_C) and total dry matter (DM) yield. Treatments without or with additional inorganic fertilizer application of on average 157 kg N $ha^{-1} year^{-1}$. Interaction terms that were never statistically significant are not presented[1].

Term	Without inorganic fertilizer				With inorganic fertilizer			
	R_T	R_A	E_U	DM yield	R_T	R_A	E_U	DM yield
Year (Y)	37.9****	39.9****	60.9****	73.8****	38.1****	31.4****	75.3****	57.3****
Site (S)	ns	ns	ns	1.0****	ns	ns	10.4****	31.0****
Slurry type (M)	1.4**	ns	ns	ns	ns	ns	0.3*	ns
Technique (A)	20.8****	20.3****	3.8****	7.1****	4.3***	5.4***	2.2****	0.3*
EM (E)	ns	ns	ns	ns	ns	ns	ns	ns
Y × S	11.2****	10.8****	12.4****	7.6****	9.0****	10.5****	ns	ns
Y × M	ns	ns	ns	1.0***	ns	ns	ns	ns
S × E	ns	ns	ns	ns	1.6*	1.9**	0.5**	ns
S × M × A	0.8*	0.9*	ns	0.7***	ns	ns	ns	ns
S × A × E	1.1**	1.2**	ns	0.7***	ns	ns	ns	ns

[1] Statistical significance levels: **** = $P < 0.001$; *** = $P < 0.01$; ** = $P < 0.05$; * = $P < 0.1$; ns = not statistically significant.

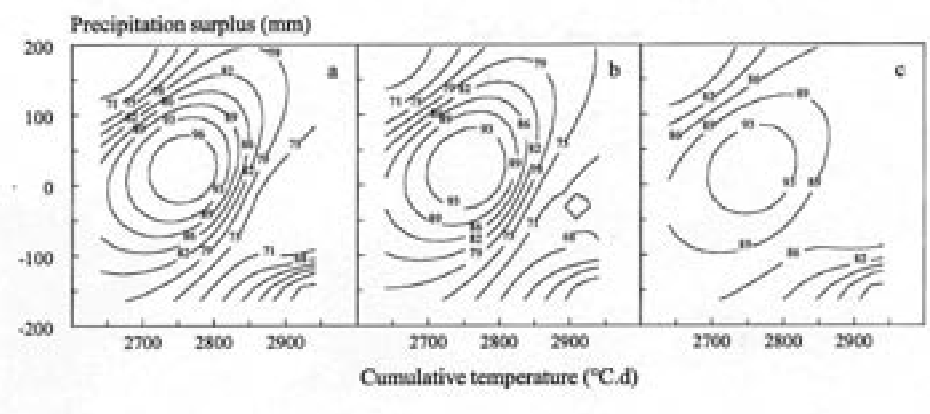

Figure 2. Contour plots of nitrogen delivery by the soil (a), nitrogen uptake (b) and dry matter production (c) relative to the observed maximum (set at 100%) in dependence of annual cumulative temperature and precipitation surplus throughout the growing season of the 5 years in the experiment. Nitrogen uptake and dry matter production are presented for treatments with additional inorganic fertilizer at a rate of 157 kg ha^{-1} $year^{-1}$.

Table 5. Apparent recovery of applied nitrogen in response to applied total and available N (R_T and R_A), nitrogen conversion efficiency (E_C) and total dry matter (DM) yield from plots treated with slurry (regular or treated with an additive), without or with additional inorganic fertilizer at a rate of on average 157 kg N $ha^{-1}year^{-1}$. Slurry was applied by surface broadcast or shallow injection application techniques to plots on two fields. Plots were either sprayed with Effective Microbes® (+EM) or remained untreated (–EM). Treatment combinations, irrespective of inorganic fertilizer supply, that are typical for the systems at Drogeham and Harkema are indicated in bold.

Slurry type	Application technique	Without inorganic fertilizer				With inorganic fertilizer			
		Drogeham		Harkema		Drogeham		Harkema	
		–EM	+EM	–EM	+EM	–EM	+EM	–EM	+EM
		(R_T; kg per 100 kg)							
Slurry	Surface	31.2	30.9	19.9	29.2	58.7	52.6	53.7	58.7
	Injection	42.0	44.1	**46.5**	44.8	58.3	59.2	**58.9**	61.4
Slurry+MX	Surface	**26.4**	22.0	23.2	28.6	**53.7**	52.9	51.5	52.8
	Injection	38.7	41.0	40.2	36.9	57.5	56.3	56.6	62.6
		(R_A; kg per 100 kg)							
Slurry	Surface	48.9	48.1	31.0	45.6	70.7	63.4	64.5	70.3
	Injection	65.2	68.4	**72.1**	69.6	70.6	71.5	**70.9**	74.2
Slurry+MX	Surface	**44.3**	36.9	38.8	47.8	**66.9**	65.8	64.1	65.7
	Injection	64.6	68.5	66.1	60.6	71.5	69.9	70.4	77.7
		(E_C ; kg DM per kg N)							
Slurry	Surface	41.1	41.0	41.6	41.5	37.9	38.9	37.0	35.2
	Injection	40.5	39.4	**40.7**	40.4	36.9	37.4	**34.9**	34.3
Slurry+MX	Surface	**41.5**	40.3	42.2	42.2	**38.9**	38.2	36.5	36.4
	Injection	40.1	40.5	40.3	40.6	37.8	38.4	35.2	34.8
		(DM; kg ha^{-1})							
Slurry	Surface	7811	7772	7476	8044	12499	12102	10593	10505
	Injection	8375	8299	**8885**	8777	12286	12455	**10614**	10653
Slurry+MX	Surface	**7730**	7360	7851	8158	**12489**	12091	10426	19500
	Injection	8218	8445	8538	8398	12468	12477	10512	11005

Table 6. Contribution of terms in the stepwise regression analysis to explanation of the variation observed in grass N uptake and dry matter (DM) yield, and DM response to N uptake. Separate analysis for N uptake and DM yield for plots without or with additional inorganic fertilizer application at a rate of on average 157 kg N ha^{-1} $year^{-1}$ (–IF and +IF). Interaction terms that were never statistically significant [a] are not presented.

Term	N uptake [b]		DM yield [b]		DM response [c]
	–IF	+IF	–IF	+IF	
N uptake (U)	–	–	–	–	89.4
U^2	–	–	–	–	3.8
Temperature (T)	ns	ns	ns	ns	ns
T^2	23.8	ns	20.7	ns	ns
Precipitation surplus (P)	ns	ns	ns	ns	ns
P^2	ns	26.4	2.1	1.5	ns
Application technique (A)	7.1	1.4	7.0	ns	ns
Site (S)	ns	4.2	ns	31.0	ns
$T \times P^2$	12.6	ns	5.2	ns	ns
$T^2 \times P$	ns	18.4	ns	4.5	ns
$T^2 \times P^2$	39.8	39.7	45.9	51.2	ns
$U^2 \times T^2$	–	–	–	–	2.1
$U^2 \times T^2 \times S$	–	–	–	–	1.4
$U \times P$	–	–	–	–	0.2
Total	83.3	90.1	80.9	88.2	96.9

[a] Statistical significance level at $P < 0.001$; ns = not statistically significant.
[b] Full model: $(T + T^2) \times (P + P^2) \times S \times A \times M \times E$, where M is slurry type and E is with or without Effective Microbes® treatment.
[c] Full model: $(U + U^2) \times (T + T^2) \times (P + P^2) \times S \times A \times M \times E$.

The level of R_T was higher for the plots receiving inorganic fertilizer and the differences were less pronounced than for the unfertilized plots (Tables 4 and 5). The effect of inorganic fertilizer was particularly high for years and treatments with a low recovery of slurry N (Figure 1a).

Further analysis of contrast in N recovery

The variables determining apparent N recovery are N application (or availability) and N uptake in grass of fertilized plots and unfertilized plots (terms N_T, N_A, U and C in Equations 1 and 5). These terms were analysed separately to understand the origin of the contrasts in N recovery between years, slurries, sites and application techniques.

Large differences in total N uptake by the grass were observed between years, which could be related to differences in cumulative temperature and precipitation

Table 7. Amounts of total N applied with regular slurry or slurry+MX [1](N_T) and available N (N_A) for treatments without and with inorganic fertilizer, and the overall calculated mineralization of slurry N (N_M) and residual organic N (N_R).

Slurry type	Year	Overall		Without inorganic fertilizer		With inorganic fertilizer	
		N_M	N_R	N_T	N_A	N_T	N_A
		(kg ha^{-1})					
Slurry	1999	42.6	83.4	212.0	128.6	372.0	288.6
	2000	22.5	45.8	130.0	84.1	313.5	267.1
	2001	16.2	33.9	110.8	76.9	262.8	228.9
	2002	19.1	60.8	157.7	96.9	307.7	246.9
	2003	19.4	41.9	128.8	86.9	268.8	226.9
Slurry+MX [1]	1999	26.8	65.2	168.0	102.8	328.0	262.8
	2000	21.0	64.3	153.5	89.2	336.5	272.2
	2001	15.3	57.9	142.1	84.1	293.8	235.9
	2002	13.9	59.0	143.7	84.6	293.7	234.6
	2003	19.0	61.2	151.1	89.9	291.1	229.9

[1] MX = Euromestmix®.

surplus (Figure 2). These terms and their interaction explained 76–85% of the variation observed (Table 6). Maximum N uptake occurred in 2000, characterized by a cumulative temperature of 2763 °C.d and a small precipitation surplus (21.2 mm). N uptake was lower in the years with higher average temperatures combined with negative precipitation surpluses (1999, 2002 and 2003), and in 2001, a year characterized by a lower cumulative temperature and a large precipitation surplus. The contour plots in Figure 2 show that the relative change in N uptake from unfertilized plots and fertilized plots in response to differences in temperature and precipitation was similar. Thus, the absolute difference in N uptake between fertilized and unfertilized plots increased with higher N uptake, contributing to higher calculated recovery values (Equation 1). N uptake was lower after surface application of slurry than after shallow injection. When additional inorganic fertilizer was applied, N uptake was significantly higher at site Drogeham, but differences in N recovery were not statistically different (Tables 4 and 5).

N uptake was not significantly different between slurries (Table 6), indicating that the difference found for R_T between regular slurry and slurry + MX for plots receiving no additional inorganic fertilizer could be attributed only to the amount of N applied. The total amount of N applied (N_T) was larger for slurry + MX than for regular slurry in 3 out of the 5 years (Table 4). The differences in N_T between slurries were considerably larger than the differences in the estimated amount of available inorganic N from fertilizers (N_A) (Table 7). Consequently, the N recovery that was calculated on the basis of available nitrogen (R_A) was not significantly different between slurries (Tables

4 and 5). The differences in N_T were primarily caused by different amounts of organic N from the slurry applied, as inorganic slurry-N and mineralized N were similar. Consequently, also large differences were caused in residual organic N from slurry (N_R).

N conversion efficiency in relation to experimental factors

The efficiency of conversion of N taken up into DM production (E_C) was higher after surface application of the slurry than after shallow injection (Tables 4 and 5). For the plots without additional inorganic fertilizer, this did not fully compensate for the lower N recovery, thus resulting in lower total annual DM yields after surface application (Table 5). At the higher N application rates (with additional inorganic fertilizer), E_C was higher at site Drogeham than at site Harkema, resulting in higher DM yields (12,358 versus 10,601 kg DM ha^{-1} $year^{-1}$ on average). DM yields were higher after shallow injection than after surface application. The highest average of 38.9 kg DM per kg N for E_C was observed for the treatment combination corresponding with the grassland management system used in practice at site Drogeham (Table 5).

Further analysis of dry matter production

Dry matter production strongly differed between sites and years (Figure 1c). DM production differences between years could be related to cumulative temperature and precipitation surplus, explaining 58–74% of the variation (Table 6). However, the relative change in DM production per unit of change in cumulative temperature

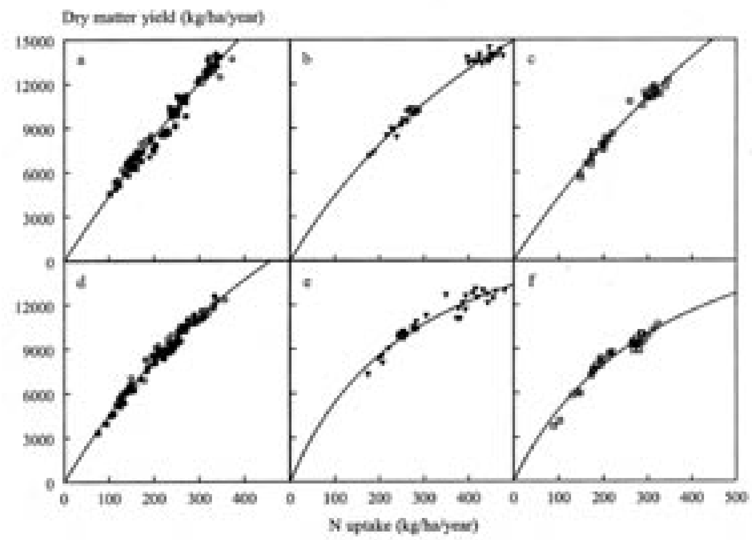

Figure 3. The response of dry matter production to grass N uptake at sites Drogeham (a–c) and Harkema (d–f) for the 5 years of the experiment. Three separate curves at each site were fitted with Equation 6 for (a, d) 1999 (○), 2002 (●) and 2003 (■); (b, e) 2000; and (c, f) 2001; based on significant differences found by stepwise regression analysis (see Table 6).

Table 8. Nitrogen delivery capacity of the soil (NDC – observed N uptake on unfertilized control plots) and apparent recovery of total applied nitrogen (R_T) for systems at Drogeham (slurry + Euromestmix® applied by surface broadcast, without Effective Microbes®) and Harkema (regular slurry applied by shallow injection, without Effective Microbes®) over the period 1999–2003.

System	Year	NDC (kg ha^{-1} year^{-1})	R_T (kg per 100 kg)
Drogeham	1999	151	51.6
	2000	225	60.1
	2001	150	51.2
	2002	153	58.1
	2003	112	47.7
Harkema	1999	144	46.3
	2000	191	73.4
	2001	97	67.9
	2002	134	48.0
	2003	85	58.7

and precipitation surplus was lower than per unit N uptake (Figure 2c). In particular the high N uptake rates in 2000 had no extra positive effect on DM production at the higher fertilization level (+IF). This resulted in high crop-N contents and consequently lower E_C values (Figure 1b).

The increase in DM production with N uptake levelled off faster in years with cumulative temperatures below 2800 °C.d ($U^2 \times T^2$ interaction for DM response in Table 6) and faster at site Harkema than at site Drogeham, in particular in years with lower cumulative temperatures ($U^2 \times T^2 \times F$ interaction; Figure 3). In contrast, the response curves of DM production were not significantly different for the 3 years with cumulative temperatures higher than 2800 °C.d (Figure 3).

Grassland management systems comparison

A simplified comparison between the grassland management systems at sites Drogeham (with surface application of slurry + MX, –EM) and Harkema (with shallow injection of regular slurry, –EM) was made. Calculations were made for individual years based on the observed N delivery by the soil and apparent N recovery (Table 8) and the DM response curves in Figure 3. The aim was to compare the systems for the amount of N not accounted for (i.e., potentially lost) and the crude protein content of the herbage. This analysis focused on the more practical farmer's perspective of herbage dry matter production of good quality in terms of crude protein content (150 to 180 g kg^{-1}). It was assumed that the N in slurry and inorganic fertilizer was applied in the same and constant ratio as in the +IF treatment. Moreover, the apparent recovery was assumed to be constant over the total N application range of 200–400 kg ha^{-1} year^{-1},

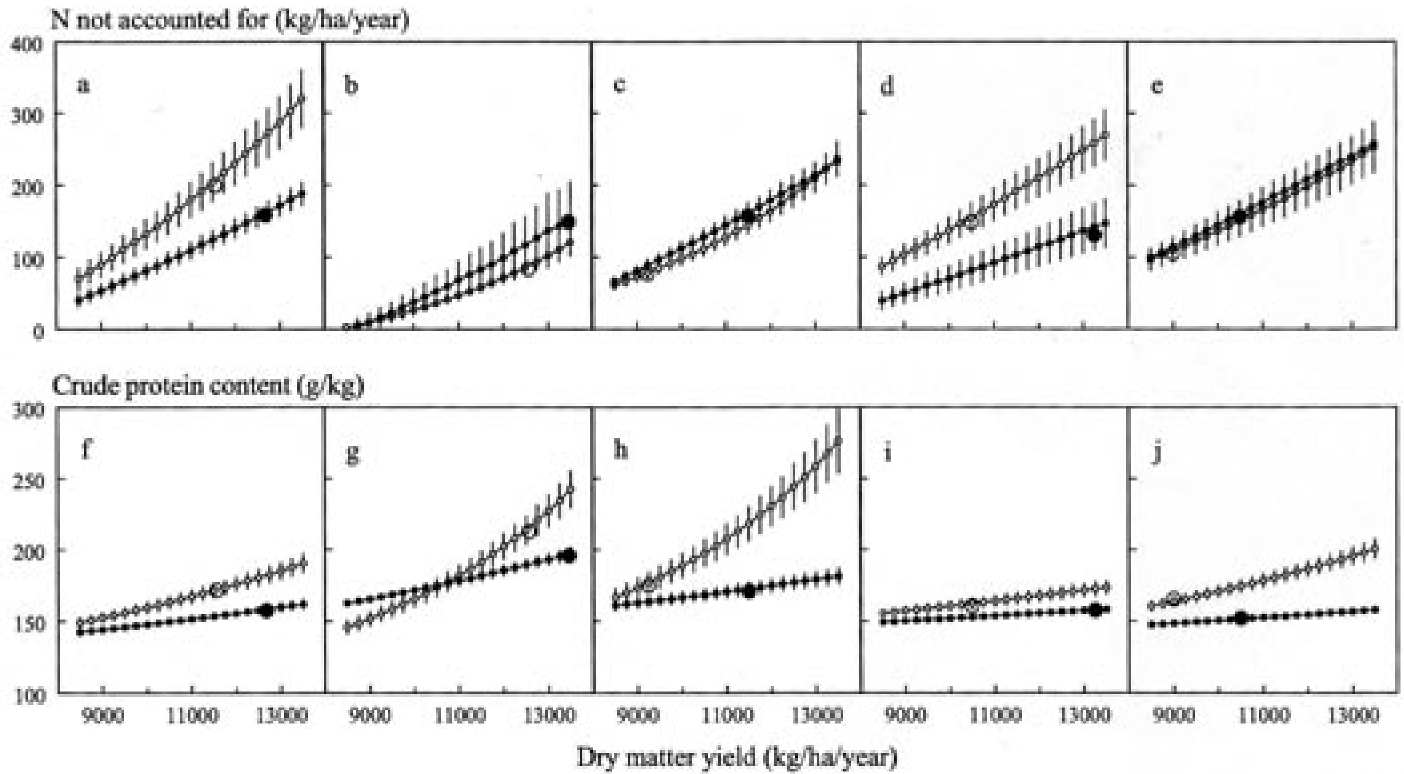

Figure 4. Amount of N not accounted for (a–e) and herbage crude protein content (f–j) at different dry matter production levels in the years 1999 (a, f), 2000 (b, g), 2001 (c, h), 2002 (d, i) and 2003 (e, j). Comparison of grassland management at farms Drogeham (closed symbols) and Harkema (open symbols). Small symbols and bars indicate mean and standard deviation of the Monte Carlo simulation; large symbols indicate the actual observations.

which seems justified given observations made on similar fields (Reijs *et al.*, 2007) and other sandy soils (Lantinga *et al.*, 1999).

In the years 2000, 2001 and 2003, the calculated amount of N not accounted for was slightly higher in the Drogeham system than in the system of Harkema, but the difference increased with production level at similar rates for both grassland management systems (Figures 4b, 4c and 4e). Consequently, at the observed higher DM production level in the Drogeham system, the amount of N not accounted for was considerably higher than in the Harkema system. However, in the years 1999 and 2002, when apparent N recovery in the Harkema system was low (Figure 1a; Table 8), the amount of potentially lost N in the Harkema system increased faster with increasing production level. On the other hand, in the Drogeham system the relationship was similar to other years (Figures 4a and 4d). Even at the lower production level actually observed in the Harkema system, the amount of potentially lost N was higher.

The herbage crude protein content increased faster with production level in the Harkema system than in the Drogeham system (Figures 4f–4j). In particular in the years 2000, 2001 and 2003, with high N-recovery in the Harkema system, the crude protein content tended to increase rapidly to values higher than 180 g kg^{-1} for DM productions higher than 10,000 kg ha^{-1} $year^{-1}$.

Discussion

N recovery was lower after surface application of the slurry than after shallow injection, as observed in other studies comparing slurry application techniques (Sommer & Hutchings, 2001; Mattila & Joki-Tokola, 2003). This can be attributed mainly to the larger exposure to the air and the resulting ammonia-N volatilization after surface application (Huijsmans *et al.*, 2001; Sommer & Hutchings, 2001). Other disadvantages of surface application of the slurry can be smothering and scorching of the sward, unpalatability of the herbage for the ruminants and spreading of diseases and parasites (Van Der Meer *et al.*, 1987). However, the grassland management systems comparison showed that a system with shallow injection is not necessarily the lowest in potential N emission (Figure 4). Moreover, other potential disadvantages of injection techniques in comparison with surface application, such as detrimental effects for sward quality (Misselbrook *et al.*, 1996), soil compaction (Douglas & Crawford, 1998) and extra energy requirements (Hansen *et al.*, 2003) are often not considered when comparing slurry application methods.

Slurry + MX was produced on farm Drogeham, where cows were fed low-protein diets. This resulted in slurry with a higher C/N ratio than on farm Harkema (Table 3). The regular slurry from farm Harkema was highly variable in composition, due to addition of surplus effluent water. The dry matter content of slurry was closely related to other quality characteristics determining fertilizing efficiency of slurry, such as the C/N ratio and the ratio between inorganic and organic N compounds. These differences in slurry composition and consequently N supply for plant growth were taken into account when available N was estimated. Higher availability of inorganic N from slurry with lower C/N ratio has been established previously in slurry storage and application experiments by Külling *et al.* (2001), Sørensen *et al.* (2003) and Reijs *et al.* (2007). After correction for available N no statistically significant differences in N recovery between the slurries were observed. Consequently, no effects solely attributable to slurry dilution (Frost, 1994) or the addition of MX could be detected in this experiment. The surface application of EM suspension only had a positive effect at site Harkema, offsetting the low N recovery after surface application of regular slurry.

The difference in apparent N recovery between surface application and shallow injection was larger at site Harkema than at site Drogeham. On plots at site Harkema receiving no additional fertilizer, the difference in N recovery between application techniques was most pronounced for regular slurry (20% versus 47%). This indicates that the grassland management system originally employed at site Harkema (shallow injection of regular slurry) was particularly tuned to obtaining a high N recovery. This system can be effective in emission reduction by increasing internal nutrient cycling (Groot *et al.*, 2003). However, a drawback could be the system's reduced stability, since it was vulnerable to a change in application technique from shallow injection to surface application. Moreover, the systems comparison demonstrated the high risk of the large dependence of the Harkema system on high N recovery, since the amounts of N not accounted for in years with lower apparent recovery were considerably larger at Harkema than at Drogeham (Figure 4). On the other hand, the system employed at the site Drogeham appeared to be more tuned to a high dry matter production, due to the higher E_C at this site and the higher E_C for surface application. This system was characterized by a high stability as illustrated by the relationships between dry matter production and potentially lost N and crude protein content (Figure 4) and reduced responsiveness to adjustments in slurry quality and application technique (Table 5). In practice, grassland farmers aim for high yields of herbage dry matter of good quality, with a crude protein content of 150 to 180 g kg^{-1}, which is considered desirable for the formulation of low-protein rations to increase animal N conversion efficiency (Tamminga, 1996; Sørensen *et al.*, 2003). The systems comparison showed that this is more effectively achieved with the Drogeham system.

The 'backbone' of the grassland management system practised at site Drogeham is its high DM yield potential (Figures 3a–c). A number of factors can contribute to the observed difference between the sites. However, a direct statistical analysis of the site contrasts and the underlying bio-physical factors, e.g. water balance, soil organic matter, was not possible in the current on-farm experimental set-up. Records of the water balance for the years 2002 and 2003 (data not presented) indicated that soil moisture deficits experienced by the grass sward were probably lower at this site due to the higher groundwater table. This is accompanied by a considerably higher soil organic matter content of all soil layers sampled between 0 and 30 cm than at site Harkema (Table 2). This might indicate better grass root development and higher soil porosity, both contributing to enhanced water uptake capacity for the grass crop (Droogers *et al.*, 1997). The differences in soil structure can be a reflection of the farm management history (Sonneveld & Bouma, 2003), which stresses the importance of adopting a systems approach in the evaluation of nutrient use efficiency of grassland management.

The differences in apparent N recovery, N uptake and DM production observed between years could be related to an interaction between effects of temperature and precipitation surplus. Grassland productivity increases with temperature and moisture availability, but these variables rarely coincide (high precipitation in years with low temperatures and *vice versa*). Therefore, intermediate levels of cumulative temperature of 2800 °C and a balance between precipitation and evapotranspiration (surplus ≈ 0 mm) appeared most favourable for N uptake from unfertilized (i.e., N-delivery by the soil) and fertilized plots (Figures 2a and 2b). DM production was less responsive over a broader range of conditions (Figure 2c). The grassland management systems comparison in Figure 4 demonstrates that this can have large consequences for the actual amounts of N not accounted for and the quality, i.e., crude protein content of the herbage produced.

The differences in nutrient use efficiency between the simulated grassland management systems indicate that on-farm experimentation in combination with systems analysis as elaborated in this paper represents a suitable approach to derive scientific analyses and recommendations for farm management practices. With this approach additional insight is obtained compared with factorial analyses that form the basis of recommended practices. Experimentally obtained results are placed in a relevant context, which facilitates interpretation and translation to contrasting circumstances encountered in other farming systems. Particularly farming systems that operate with reduced levels of inorganic and technological inputs are liable to depend more on biological processes (Ketelaars & Oenema, 1997). The resulting variability in biophysical farm characteristics makes eco-technological management necessarily adaptive in nature. The approach presented can support these more sustainable management practices.

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