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Nitrogen fluxes in the plant component of the 'De Marke' farming system, related to groundwater nitrate content

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Abstract

Sandy areas in the Netherlands are mainly used for intensive dairy farming. In conventional farming systems, losses of nitrate to the groundwater are high, threatening other valuable functions of the rural area, like conservation of nature and 'production' of drinking water. Possibilities were examined to improve farm management in such a way that the desired upper groundwater quality could be realized without reducing milk production intensity (11,900 kg milk ha^{-1}) and without exporting manure. A prototype system was established on an experimental farm. Nitrogen fluxes, including mineralization, were studied in detail. Actual nitrogen surplus of the plant component of that system decreased from 337 kg ha^{-1} (conventional system) to 128 kg ha^{-1}, which still is 49 kg ha^{-1} higher than estimated in the design phase. Of this 128-kg surplus probably about 40 kg accumulated as organic N in the root zone, 29 kg denitrified and 59 kg was leached as nitrate. Nitrate content of the upper groundwater decreased from 220 to 55 mg l^{-1}, which is close to the target value of 50 mg l^{-1}. Because accumulation is a finite process and groundwater nitrate content is still too high, the N surplus has to be further reduced by at least 40 kg ha^{-1}. Calculations suggest scope for such a reduction.

Keywords: nitrogen, nitrate, leaching, groundwater, dairy farming, systems research, environment, sandy soils.

Introduction

Although sandy soils in the Netherlands are mainly used for intensive dairy farming, they are increasingly 'called upon' to supply society with drinking water, conserve and develop nature and facilitate recreation. These functions are seriously threatened. The leached nitrate and the increased water consumption by the heavily fertilized and irrigated grass and forage crops, lead to a reduction in the availability of high quality water on which these functions depend. Expanding farm area could reduce these environmental damages by reducing milk production intensity per unit area. However, land is very expensive and is also needed for other societal purposes.

Export of slurry, to increase farm output of nutrients, can lead to environmental problems elsewhere. In project 'De Marke', improved utilization efficiency of fertilizers, feed and water is aimed at as a strategy to realize environmental targets in an economically attractive way. In the project, the experimental farming system with the same name plays an important role. The system has to demonstrate that strict environmental goals can be attained on a practical farm scale. One of the goals is a maximum nitrate content in the upper groundwater of 50 mg l^{-1}. Milk production intensity is 11,900 kg ha^{-1}, which is equal to the country's average. Most of the farmland was bought in 1989 and has been managed in an environmentally acceptable way since. In 1993 cattle was introduced.

Goals, layout and management of the experimental farming system are discussed by Hilhorst *et al.* (2001). This paper focuses on the nitrogen (N) fluxes in the plant component in relation to groundwater nitrate content. For information on research methodology, including measurements and analyses, reference is made to Aarts (2000).

Materials and methods

The farming system was designed in such a way that external farm inputs of feed and fertilizers are minimized by maximizing utilization efficiency of the 'home made' proportions of these resources. A relatively high milk production per cow (fewer cows, and thus lower maintenance requirements) and lowering the numbers of calves and heifers to the minimum needed for replacement (Table 1), reduce feed requirements for milk production. The share of grassland in the total crop area of 'De Marke' is smaller, and that of forage maize consequently larger than on conventional farms. Low-N feed is needed to compensate for the rather high N contents of the grass products in the ration, so that N excretion by the cattle is reduced. Moreover, water and fertilizer requirements of grass are much higher and dry matter and energy yields lower than those of maize. Nevertheless, also at 'De Marke', the area of grassland exceeds that of forage crops, because grass can be grazed, and as its nutrient uptake is higher, it can utilize more animal manure. Grazing of lactating cows is re-

Table 1. Main characteristics of the plant component of experimental dairy farming system 'De Marke' (Hilhorst *et al.*, 2001) and of an average conventional farm with a comparable intensity of milk production (period 1993–1998; Aarts, 2000).

Characteristics	'De Marke'	Commercial farm
Cows ha^{-1}	1.4	1.6
Young stock ha^{-1}	1.0	1.5
Grazing season	1 May – 1 Oct.	1 May – 1 Nov.
Daily grazing (hours, average season)	8	14
Area grass : area maize	55 : 45	75 : 25
(Re)sowing grassland	spring/early summer	autumn
Fertilization period grassland	1 March – 15 Aug.	1 Febr.– 1 Sept.
Crop rotation	yes	no
Catch crop after maize	yes	no

stricted to 8 hours per day and in autumn cows are stabled one month earlier than in common practice. These management practices reduce (i) the number of urine and dung patches at pasture, (ii) the associated nitrate leaching from these 'hot spots', and (iii) the yield losses caused by trampling. Moreover, production of utilizable 'home made' fertilizer is higher, reducing needs for external fertilizers.

The farm area is divided into 11 ha of permanent grassland and two ley-arable crop rotations. In rotation I (30 ha), a three-year grassland period is alternated with three years maize, in rotation II (14 ha) the arable-cropping period is five years. The main purpose of alternating grass and maize is to stimulate maize growth. In the first year after grass, the maize is not fertilized; decomposition of the ploughed-in grass sod provides sufficient mineral N. Every year, when the maize has a height of 60 cm, Italian ryegrass is sown between the maize rows. From the end of summer onwards this catch crop takes up excess fertilizer and mineralized N, which results in an 'automatic transfer' of N-uptake between maize and grass. Early spring, the Italian ryegrass sward is ploughed in to stop transpiration and start decomposition timely to make nutrients available for the subsequent maize crop. On most commercial farms, fields are used continuously, either for growing maize or for grass, and growing a catch crop after maize is rare.

N fertilization levels at 'De Marke', including N from slurry, clover and residual effects of ploughed-in Italian ryegrass and grass sod, are about 40% lower than on conventional farms. About 75% of the slurry, containing 3.45 kg N m^{-3}, is applied on grassland. On permanent grassland 50 m^3 ha^{-1} is applied, on grass ley 73 m^3 ha^{-1}. Maize is fertilized with 25 m^3 ha^{-1} on average. Chemical N fertilizers are applied on grassland only (126 kg ha^{-1}). Slurry and chemical fertilizers are applied between 1 March and 15 August to reduce the risk of nitrate leaching in the period with low temperatures and low radiation levels, which limit crop growth and therefore cause a precipitation surplus.

Results

N fluxes in the plant component

The overall balance sheet

Model calculations underlying the experimental system suggest that the N surplus of the plant component can be reduced to 79 kg ha^{-1}. This is 77% below common practice. It was assumed that the system does not affect the organic N store in the soil so that the N surplus must be lost by denitrification (assumed to be 47 kg ha^{-1}) and by leaching to the groundwater (32 kg ha^{-1}). At an annual precipitation surplus of 300 mm – the 'standard' long-term Dutch average – nitrate content of the groundwater would be just below 50 mg l^{-1} (Aarts *et al.*, 2000a).

Table 2 shows that the actual N supply to the soil in the experimental system was underestimated by only 12 kg ha^{-1} (3%). Much more organic fertilizer (slurry) was applied than estimated, but this higher input was largely offset by a lower amount of N fixation by the clover. Actual N yield was underestimated by 14% (38 kg ha^{-1}), probably because of an above-average frequency of dry periods during the growing seasons. N yields are considerably lower than on commercial farms because of 10% lower dry matter yields, a higher proportion of maize and 10% lower N contents. The latter is caused by N deficiency resulting from reduced fertilization. As a result of the lower output and the higher input, actual N surplus (128 kg ha^{-1}) of the plant component of the experimental system exceeds the predicted value by 49 kg ha^{-1}. However, because of excessive inputs of chemical fertilizers, more excretion during grazing and high harvest and grazing losses, the N surplus (337 kg ha^{-1}) in common practice is still much higher.

N surpluses of sub-systems of the plant component

Individual fields are managed differentially, and can therefore differ in N surplus. Data in Table 3 illustrate that the surplus for permanent grassland is below that for grass ley. The main reason is that the latter receives additional fertilizer (70 kg N ha^{-1}) in its first year to compensate for N investments in roots and stubble. Moreover, on rotational grassland much more slurry is applied. Part of the N in the slurry is organic, so about 25% of the N will accumulate in the soil. Only in the long run this N will become available for uptake by the crop through mineralization. In total, fertilizer input on rotational grassland is 53 kg N ha^{-1} higher, whereas N yield is only 6 kg ha^{-1} higher. The N surplus for the maize crop increases with the length of the arable period after the grass ley. The gradual decrease in mineralization of the grass sod leads to an increased need for fertilizers, and a reduction in crop vitality, result-

Table 2. Estimated and realized N balance (kg ha^{-1}) of the plant component of experimental dairy farming system 'De Marke' and of a conventional dairy farm with a comparable intensity of milk production (period 1993–1998; Aarts, 2000).

	'De Marke'			Conventional
	Estimated	Realized	Min.-Max.	
INPUT				
Urine and dung patches	51[1]	48[1]	35-59[1]	114
Organic fertilizer	137	177	154-182	206[2]
Mineral fertilizer	67	70	52-96	242
Atmospheric deposition	49	49		49
Harvest and grazing losses (crop residues)	21	17	14-20	112
Fixation by clover	30	6	3-12	0
Total	355	367	316-454	723
OUTPUT				
Gross crop yield	276	238	216-275	386
INPUT-OUTPUT (surplus)	79	128	86-184	337

[1] After volatilization of ammonia; indoor and outdoor volatilization from excreta causes losses of about 20 kg N ha^{-1}.
[2] Of which 45 kg ha^{-1} from neighbouring pig farms (with almost no agricultural area).

Table 3. N surplus (including ammonia volatilization; kg ha^{-1} per year) of parts of the plant component (rotation I = 3 years of grass, followed by 3 years of maize; rotation II = 3 years of grass, followed by 5 years of maize).

Land use	1993	1994	1995	1996	1997	1998	93/98
Farm area							
Permanent grassland	120	219	213	193	190	213	193
Crop rotation I	127	197	151	94	153	145	146
Crop rotation II	24	167	94	104	88	132	102
Crop							
Grass ley, 1st year	248	284	256	318	294	236	271
Grass ley, 2nd year	210	275	213	216	283	232	239
Grass ley, 3rd year	163	296	184	206	249	261	221
Maize, 1st year	–87[1]	–109[1]	34[1]	–65	–15	–30	–43
Maize, 2nd year	8	35	17	14	45	54	32
Maize, >2nd year	–13	145	70	29	88	72	66

[1] One field only.

ing in lower yields. For the first maize crop grown after grass the N surplus is even negative, because no fertilizers are needed and yields are high. The average N surplus for the complete rotation is 47 kg ha^{-1} less than that of permanent grassland for rotation I, and 91 kg ha^{-1} for rotation II.

Soil processes

The quantity of organic N stored in the upper soil layers of the 'De Marke' farming system (about 6000 kg ha^{-1}) fluctuates. It decreases because of mineralization, transforming organic N into mineral N, and increases through inputs by harvest and grazing losses, application of organic manure (on average 189 kg N ha^{-1}, Figure 1), and the formation of stubble and roots (on average 197 kg N ha^{-1}). If inputs exceed mineralization, organic N in the soil increases. Results from analyses for the period 1989–1997 suggest that the quantity of organic N stored in the soil increased on average by 40 kg ha^{-1} per year (Aarts, 2000). For permanent grassland the increase was about 10 kg ha^{-1} above average. Because of this accumulation, real losses from the plant component of the dairy farming system were probably only 128 (N surplus, presented in Table 2) minus 40 = 88 kg ha^{-1}.

Intensive measurements on 6 locations in the period 1992–1998 showed that mineralization resulted in 345 kg mineral N ha^{-1} per year on average, with 120 kg ha^{-1} and 750 kg as extreme values for individual locations or years (Corré, 2000). In short, mineralization results in high quantities of mineral N that even exceed the sum of fertilization, N-fixation by clover and atmospheric deposition (178 kg N ha^{-1}). N mineralized in a specific field in a specific year strongly depends on the moment in the rotation (Table 4). For grass ley, mineralization appears to increase with age whereas for arable land the opposite holds.

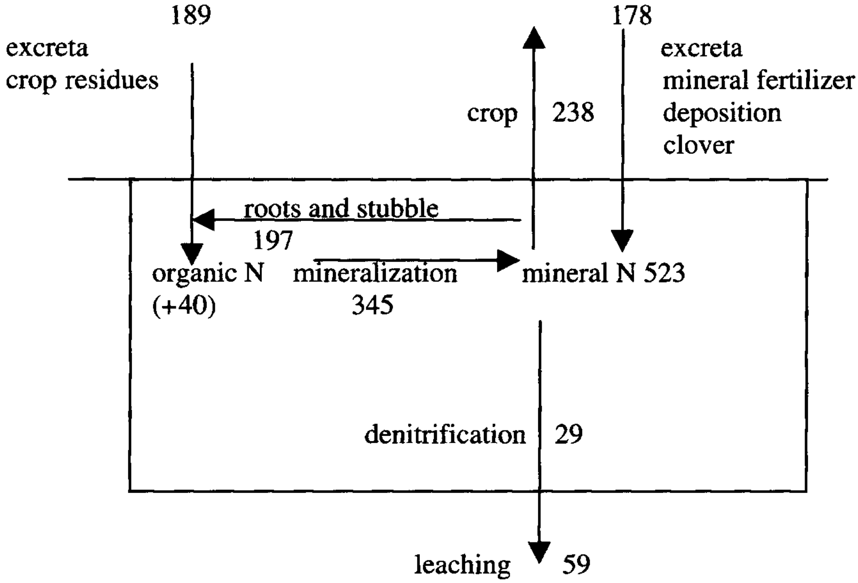

Figure 1. The main N fluxes in the plant component of the 'De Marke' experimental farming system (kg ha^{-1}; average 1993–1998).

The process of mineralization is complex and results in a rather unpredictable supply of mineral N. Mineral N can be taken up by the crop, but can also be lost by leaching and denitrifiation. During the growing season the risk of substantial losses of mineral N is low. Conditions favourable for mineralization generally are also favourable for crop uptake, assuming the presence of a well-established crop. Under a 'De Marke'-type management, grassland can also take up most of the N mineralized 'outside' the growing season. Moreover, N mineralized in autumn and winter on maize land was almost completely recovered in the roots, stubble and leaves of the Italian ryegrass shortly before this was ploughed in (Aarts, 1994).

In spite of the above-average frequency of drought periods during the growing seasons, average annual rainfall was 78 mm above the Dutch long-term average of

Table 4. Mineral N originating from mineralization (1992–1998; kg N ha^{-1} per year). n = number of observations.

Land use	n	Average	Standard deviation
Permanent grassland	11	414	143
Grass ley, 1st year	4	356	160
Grass ley, 2nd year	4	497	66
Grass ley, 3rd year	2	626	177
Maize, 1st year	2	385	57
Maize, 2nd year	4	242	98
Maize >2nd year	9	158	36

Table 5. The most probable fate of the N surplus of the plant component of experimental dairy farming system 'De Marke' (kg ha^{-1} per year, 1993–1998).

	Estimated	Actual
Surplus	79	128
Accumulation as soil organic N	0	40
Denitrification (N_2 en N_2O)	47	29
Leaching (NO_3)	32	59

758 mm. Calculated actual evapotranspiration by the crops was 361 mm per year, which is 55 mm less than in conventional systems. Consequently, the actual annual precipitation surplus was 475 mm (Aarts, 2000; Aarts *et al.*, 2000b), which is considerably higher than was assumed (300 mm). At an average nitrate content of 55 mg l^{-1} (as discussed later), leaching would amount to 59 kg N ha^{-1} per year.

Under anaerobic conditions soil nitrate will be denitrified provided easily decomposable organic matter is available and temperatures are not too low. In the calculations underlying the design of the system, annual denitrification was assumed to be 47 kg N ha^{-1}. Given an actual surplus of 128 kg N ha^{-1} (Table 2), an assumed accumulation of 40 kg organic N ha^{-1} and leaching losses of 59 kg N ha^{-1}, denitrification will be approximately 29 kg N ha^{-1} (Table 5). It is plausible that the denitrification process is more intensive on grassland than on maize land. On grassland more mineral N is available as a result of the higher fertilization level and the more intensive mineralization. Moreover, because of high doses of organic manure, grazing losses and the turnover of stubble and roots, more easily decomposable organic matter is available. (Partial) anaerobiosis in the upper soil layers of grassland can easily occur because of intensive root activity and trampling during grazing. The contribution of denitrification to mineral N losses in grassland is assumed to be twice as high as that of arable land (Lippold *et al.*, 1981). For 'De Marke' this implies an average annual loss of 38 kg N ha^{-1} for grassland, and 19 kg ha^{-1} for maize land. Results of occasional measurements of denitrification on 'De Marke' do not contradict these assumptions (Corré, 2000).

Nitrate content of the upper groundwater

Since 1989, the nitrate content of the upper groundwater in the fields in use at 'De Marke' (Table 6) has fallen rapidly to levels around the defined upper limit (50 mg l^{-1}). A much slower decline was expected. The large quantities of organic manure applied before research was started, were expected to have resulted in large quantities of 'difficult-to-manage' mineral N. Between 1993 and 1996, the nitrate concentration was rather stable at acceptable levels. In the following two years, the nitrate concentration increased, but in the last year it decreased again. Farm average over the period 1993–1999 was 55 mg l^{-1}, which is slightly above the defined maximum of 50 mg l^{-1}. There appears no strong correlation between land use in a particular year and groundwater nitrate content in the autumn of that year (Table 7). Generally, the upper metre of groundwater reflects a precipitation surplus of one year, but the resi-

Table 6. Nitrate content (mg l^{-1}) of the upper groundwater of the 'De Marke' fields in use since 1989.

Land use	1990	1992	1993	1994	1995	1996	1997	1998	1999
Perm. grassland	159	80	50	43	60	52	96	43	66
Crop rotation I	220	117	43	46	54	36	49	93	70
Crop rotation II	181	104	53	35	35	20	47	97	50
Farm average	199	107	47	43	51	35	57	83	64

dence time can vary strongly from year to year (Boumans *et al.*, 2001). Moreover, as sampling takes place in October and November, in most years the excess mineral N from the current season has not yet reached the groundwater at the time of sampling. This explains the correlation with farm management in the preceding year, as found by Conijn (2000).

Generally, the nitrate content of groundwater below grass ley decreases with age, but below maize the opposite seems to occur. Consequently, rotation results in an oscillating pattern of the nitrate content. The relatively stable nitrate level under permanent grassland can be considered an equilibrium.

In 1998, nitrate contents were alarmingly high under first year grass ley and under maize. These crops have in common that they are sown in spring. In spring 1998, rainfall was exceptionally high, so that recently applied fertilizers and mineralized N were leached beyond the root zone. Uptake of mineral N by permanent grassland starts earlier, and demand for N is higher because of the presence of a well-developed 'hungry' grass sod (fertilization stopped early in the preceding growing season).

Attempts to explain differences in nitrate content among fields on the basis of differences in soil conditions or crop management, using multiple linear regression, showed a weak correlation only (Conijn, 2000). This could be the result of the field-specific farm management at 'De Marke', which aims at avoiding exceptionally high nitrate levels for individual fields. In other words, adapted management smoothes part of the effects of differences created by soil or crops. With arable crops, 62% of the annual variation in nitrate content could be explained by differences in weather

Table 7. Nitrate content of the upper groundwater (mg l^{-1}) under various crops. Fields acquired after 1989 are included.

Land use	1993	1994	1995	1996	1997	1998	Ave.
Permanent grassland	50	43	55	42	84	41	53
Grass ley, 1st year	84	65	61	43	62	127	76
Grass ley, 2nd year	20	66	54	16	61	28	43
Grass ley, 3rd year	28	28	45	28	27	36	33
Maize, 1st year	177[1]	30[1]	9[1]	24	16	132	47
Maize, 2nd year	75	43	40	13	67	139	67
Maize, >2nd year	51	39	56	30	72	115	63

[1] One field only.

conditions, especially rainfall distribution. For grassland, no clear correlation with weather conditions was found.

Discussion

Most characteristics of the prototype system change very slowly. So in spite of ten years of operation, no definite conclusions can be drawn (yet). The research results obtained so far nevertheless present indications that are helpful in discussing development strategies for dairy farming systems in areas susceptible to nitrate leaching.

The first question is to what extent can improved management lead to a reduction of N surpluses of the plant component of a dairy farming system, without having to reduce milk production intensity or increase export of slurry. Compared with a conventional system, input of N in purchased fertilizers could be reduced by 77%, and input of 'home made' nutrients by 32%. This is the result of improved utilization of cattle manure, reduced fertilization levels, a larger maize area (lower fertilizer needs compared with grassland), crop rotation, and growing a catch crop after maize. Reduced crop yields resulting from lower fertilization levels could be compensated by reducing conservation and grazing losses and by increasing the maize area. Dry matter and energy yields are considerably higher for maize than for grass. So purchases of feed were even lower than those of comparable commercial farms (Aarts *et al.*, 1999b). Consequently, N surpluses of the crop component were also substantially lower. They decreased from 337 to 128 kg ha^{-1}. Part of the N surplus (about 40 kg ha^{-1}) was 'harmless', because of assumed accumulation as organic N in the root zone. More of the surplus will be lost by leaching when soil organic N reaches a new equilibrium in combination with a higher level of mineralization.

Another question is whether improved resource management can lead to the desired quality of the upper groundwater. Average nitrate content of the upper groundwater rapidly decreased from 200 to 55 mg l^{-1}. This still is 10% above the permitted upper limit. For that reason, and because accumulation as organic N is a finite process, a further reduction in N surplus of at least 40 kg ha^{-1} is necessary. Calculations suggest scope for such a reduction. The need for chemical fertilizers can be reduced by further improving the utilization of manure, e.g. by a better timing of slurry application, and by shortening grazing time so as to reduce excretion at pasture. Also fine tuning of grassland fertilization, and reducing young stock appear important ways to achieve this goal (Aarts & Van Keulen, 2000; Vellinga & Hilhorst, 2001).

The MINeral Accounting System (MINAS; Henkens & Van Keulen, 2001) of the Dutch government forces Dutch dairy farmers on light sandy soils to reduce the N-surplus of the plant component by roughly 50% before 2003. In the mid-nineties this surplus was 337 kg ha^{-1}. Reducing fertilization levels and growing a catch crop following maize are effective and simple measures to achieve this (Aarts *et al.*, 1999b). Restricting grazing – fewer hours per day and ending earlier in autumn – is very effective too. Because grass needs more nutrients than maize, replacing grass by maize can be attractive if all animal manure can be used effectively as fertilizer. In the long run, growing maize in rotation with grass ley could result in improved utilization of N inputs in the plant component, probably because of better functioning root systems. This leads to lower fertilizer requirements, higher yields and lower N losses. To guarantee a well-developed sod in autumn and winter, capable of taking up mineralized N, grassland is (re)sown only in spring or early summer.

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