Nutrient Cycling in Agroecosystems (2006) 74:59–74
DOI 10.1007/s10705-005-6241-9

Reducing nitrate leaching to groundwater in an intensive dairy farming system

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Received 30 August 2005; accepted in revised form 27 December 2005

Key words: Crop rotation, Dairy farming, De Marke, Grass, Grazing, Groundwater, Maize, Nitrate Directive, Nitrogen, Sandy soils

Abstract

Dairy farming is one of the main contributors to nitrate leaching to groundwater, particularly on soils that are susceptible to leaching, such as light well-drained sandy soils. In the Netherlands, as in many other European countries, these soils are predominantly used for dairy farming. A prototype dairy farming system that has been implemented in practice in 1989 has continuously been adapted since then to meet environmental standards (i.e. the EU-standard of 50 mg NO_3^- l^{-1}) without reducing milk production intensity (11900 kg ha^{-1}). After an initial decline in nitrate concentration from 193 mg l^{-1} to 63 upon implementation, it subsequently 'stabilized' at a level higher than the environmental standard: 55 mg l^{-1}. The goal of this paper is to examine causes of excessive nitrate leaching. This was done by relating measured nitrate concentrations with management characteristics such as N balances, cropping patterns and grazing intensities. Special attention was paid to aspects that were supposed to be conducive for leaching: crop rotation of grass and maize and grazing. No evidence was found for enhanced nitrate leaching due to the rotation of grass with maize compared to permanent cultivation. This could be ascribed to the reduction in fertilization levels in first and second year maize with 90 and 45 kg N ha^{-1}, respectively to account for the expected N release from the ploughed-in grass sod. Triticale was found to lead to higher leaching than grass or maize which is attributed to its poor growth in the period that it should function as catch crop in maize. Grazing contributed to a nitrate increase of about 30 mg NO_3^- l^{-1} on grassland. As grazing management and intensity is already strictly optimized in order to restrict nitrate leaching, this result underpins the need to develop sustainable grazing methods on soil that is susceptible to nitrate leaching.

Introduction

Nitrate leaching and dairy farming

Nitrogen (N) and phosphorus (P) are indispensable external inputs in sustainable agricultural production systems, to replenish the nutrients exported in products and removed in unavoidable losses (Von Liebig 1841). However, especially in high-intensity production systems, inputs of N and P from external sources have increased disproportionally in recent decades in comparison to their outputs. As a consequence, surpluses, defined as nutrient inputs minus nutrient outputs in products, have increased dramatically (Smaling et al. 1999; van der Meer 2000). Especially N-surpluses are associated with losses from the system through nitrate leaching, ammonia volatilization and dissipation as N_2 or NO_x (Hilhorst et al. 2001; Delgado 2002). The losses can negatively affect the quality of groundwater (Boumans et al. 2005), surface water (Collingwood 1977; Jensen et al. 1991) and air (Monteny 2000). Nitrate leaching to groundwater presents risks for drinking water supplies and is associated with eutrophication in streams and lakes (Hosper 1997; Scheffer 1998). According to the EU Nitrate Directive (Council Directive 91/676/EEC), European Union member States are obliged to establish action programs that guarantee nitrate concentrations in groundwater in leaching-sensitive areas not exceeding the standard of 50 mg l^{-1}

In West European countries, agriculture is the major contributor to nitrate contamination of groundwater (De Walle and Sevenster 1998; De Clercq et al. 2001), with dairy farming as the sector with the largest share. N losses are particularly high on soils that are susceptible to leaching in regions with high animal densities (Anonymous 1993), as found in various countries in northern and western Europe and in some federal States of the USA (De Walle and Sevenster 1998; Stout et al. 2000; Burkart and Stoner 2002). The combination of intensive dairy farming, high N-inputs, low N-utilization and high levels of nitrate leaching is particularly evident on the light sandy soils in the eastern and southern parts of the Netherlands (Fraters et al. 1998), where in the period 1992–1995, average nitrate concentrations exceeding 150 mg l^{-1} were monitored in the upper meter of the groundwater, associated with application of organic N doses of 320 k ha^{-1} (Aarts et al. 1999a). In commercial farming, such high rates of manure application apparently result in excessive nitrate leaching. Reducing leaching by reducing the nitrogen application rate, i.e. transforming to low input and therefore extensive dairy farming, with the consequence of reduced milk production per ha (Aarts et al. 1999a), is economically unattractive. Therefore, a need exists to develop highly productive systems with enhanced utilization of manure-N, reduced surpluses and thus reduced levels of nitrate leaching.

Integrated system research at De Marke

In response to this need, the research project De Marke was established, in which possibilities are being investigated to operate a dairy farming system that is both environmentally and economically sustainable (Aarts et al. 1992, 2000a). The project uses an integrated, whole-farm approach, based on the many feedbacks within the system, i.e. the cluster of interactions between the sub-systems herd, manure, soil, crop and feeds. This research has a single replicate character, but this potential disadvantage is overcome by following a systematic procedure of modeling, system design, implementation in practice, evaluation and adjustment (Aarts et al. 1992).

Long-term EU and national environmental standards (Table 1) were set as boundary conditions for system design. In accordance with the EU Nitrate Directive, maximum permitted nitrate concentration in the upper meter of groundwater was set to 50 mg l^{-1}, corresponding to 34 kg N ha^{-1} leaching for the average annual precipitation surplus of 300 mm under Dutch conditions. Ammonia emissions from faeces and urine should not exceed 30 kg N ha^{-1}. Assuming no N accumulation in the soil 14 kg N ha^{-1} yr^{-1} volatilization from crops and silage, and estimated 50 kg N ha^{-1} yr^{-1} losses by denitrification, the N surplus should not exceed 128 kg ha^{-1} yr^{-1} at farm level (Aarts et al. 2000b). Maximum P concentration in groundwater was set to the Dutch surface water threshold value (0.15 mg l^{-1}), corresponding to an annual P surplus of 0.45 kg ha^{-1}. These goals have to be realized at a milk production intensity of at least the national average of 11,900 kg ha^{-1} in order to be representative for Dutch circumstances, and without exporting slurry to prevent

Table 1. Environmental objectives with regard to nutrients (Aarts et al. 1992).

Objective	Maximum value
Nitrate leaching	50 mg l^{-1} in upper meter of groundwater
Ammonia volatilization	30 kg N ha^{-1} yr^{-1} from manure
N surplus	128 kg N ha^{-1} yr^{-1} as farm inputs[a] minus outputs assuming no accumulation on the soil
P leaching	0.15 mg P l^{-1} in upper meter of groundwater
P surplus	0.45 kg P ha^{-1} yr^{-1}

[a]Including deposition and fixation by clover.

shifting of problems involved in efficient use of slurry in intensive farming (Schröder et al. 2003).

In this paper, the effects of the specific De Marke management on nitrate leaching are evaluated to identify possible 'weak spots' in the system. The evaluation is based on nitrate concentration measurements. In the analysis, encompassing data of 1996–2003, the effects of the main crops, grass, maize and triticale, and of the crop rotations are examined, in relation to underlying management aspects, such as (i) the magnitude of the surpluses on the soil balance for specific crops; (ii) the management of nitrogen release from the ploughed-in grass sod; (iii) re-sowing of permanent pasture; (iv) grazing. The effect of maize receives special attention, because under current practice, maize presumably contributes to high nitrate concentrations, while at De Marke maize occupies a large proportion (31%) of the land. Moreover, exploring whether the rotation enhances nitrate leaching is warranted, as some studies indicate that ploughing grassland for arable crops can lead to substantial increases in nitrate leaching (Whitmore et al. 1992; Hoffman 1999). Possibilities for improvement of the system are discussed.

Materials and methods

Dairy farming system De Marke

Site characteristics

De Marke is situated in the eastern part of the Netherlands on very light sandy soil. Its 55 ha of land was reclaimed from heather [*Calluna vulgaris* (L.) Hull] at the beginning of the 20th century. The soils at De Marke are characterized by a 25–30 cm antropogenic upper layer, with an average organic matter content of 4.8%, overlying a layer of yellow sand, very low in organic matter and hardly penetrable by roots (Aarts et al. 2000b). The hydrological basis, extending to 70–120 m below the surface, consists of various formations of which the oldest and deepest are of marine origin and those at 6–30 m depth consist of fluviatile coarse sandy sediments. The upper layers, of eolian origin are finer-textured and low in organic matter and calcium contents (Van der Grift et al. 2002). Groundwater depth is 1–3 m below soil surface, i.e. upward water transport from the saturated zone to the root zone is negligible in periods that potential evapotranspiration exceeds precipitation. Plant-available water holding capacity is below 50 mm on 50% and below 100 mm on 78% of the land (Dekkers 1992), restricting unlimited crop transpiration to about 10 days during a dry period in summer. From 1996 to 2003 average annual precipitation was 757 mm. Water transport is predominantly vertical (Van der Grift et al. 2002), hence management of individual fields should be reflected in nitrate concentrations in the groundwater below the fields.

Before 1989 the land was in use by a number of commercial dairy farmers. In the period 1989–1991, when the De Marke management was under development, no cattle were present and only chemical fertilizer was used. From 1993 onwards, the integrated management system has been fully implemented.

System layout and land management

The farm area is divided into permanent grassland and two crop rotations (Table 2; Figure 1). Rotation I is implemented on fields close to the homestead that can be irrigated. Rotation II is implemented on fields situated further from the homestead that can not be irrigated. From 1996 till 1999, maize was the only arable crop, after which triticale was introduced as the last crop in the arable phase. On maize land, Italian ryegrass was sown as a catch crop between the rows in early summer. In early spring it was ploughed-in, some months before sowing the subsequent crop.

N fertilization of crops aimed at complying with crop requirements (Table 3). In calculating N requirements of maize and grassland, incomplete availability of N from organic manure was taken into account. In calculating manure N requirements

Table 2. Farm plan of De Marke (ha) and crop sequence of the two types of rotation.

Parameter (unit)	Average 1996–2003
Total area	55
Permanent grassland	11
Ley	20
Maize	17
Triticale	7
Rotation I	3 years grassland – > 3 years arable crops – > etc.
Rotation II	3 years grassland – > 5 years arable crops – > etc.

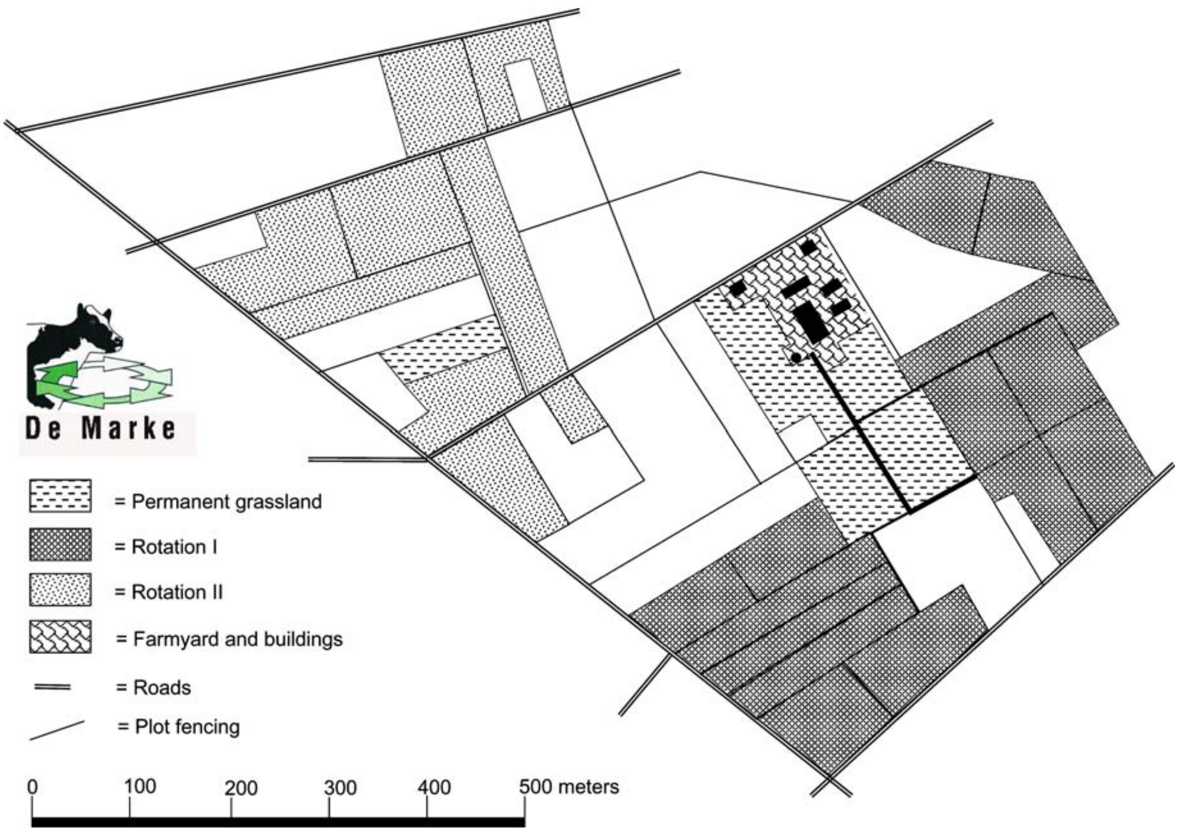

Figure 1. Plan of the experimental farming system 'De Marke'.

Table 3. Nitrogen balances (kg/ha) for maize, triticale and grassland at De Marke; means for 1996–2003.

N-flow	Maize				Triticale	Grassland				
	1st yr	2nd yr	>2nd yr	All		1st yr	2nd yr	3rd yr	All	Permanent grassland
Inputs										
Excretion during grazing	–	–	–	–	–	46	40	65	48	88
Organic manure[a]	41	91	128	88	220	243	252	255	245	179
Chemical fertilizer	–	–	–	–	–	98	83	82	91	106
Deposition	49	49	49	49	49	49	49	49	49	49
Clover	–	–	–	–	24	31	36	22	26	12
Total	90	140	177	137	293	467	459	475	458	432
Output (Harvest)	152	124	127	135	179	290	296	303	289	278
Input–Output	−62	−21	50	1	76	177	163	172	169	146
Sd	48	28	37	–	19	43	22	43	–	35

[a]Slurry (faces + urine) following ammonia volatilization.

for maize, a net release of N of 90 kg ha^{-1} in the first year and 45 kg in the second year from the ploughed-in grass sod was taken into account, resulting in rates in 1st and 2nd year maize that are lower then those in 3rd and 4th year maize. Differences in N surpluses for the various crops in different phases of the rotation reflect this fertilization strategy. The variability in surpluses, expressed as the standard deviation, Sd, for specific phases in the rotation is comparable for maize and grass (Table 3). On grassland, fertilizer application started on the 1st of March and ended in August.

Fertilizer on maize was applied shortly after sowing (early May).

A total of 31 ha of grassland were available for grazing by 80 cows and young stock (Table 2). A rotational grazing system was applied, in which the cattle grazed for 5–7 days on individual plots of 1–3 ha, after which they were transferred to a next plot. In practice, grazing intensities were higher on the permanent grassland than on most of the leys, because permanent grassland is situated near the homestead and is thus easily accessible, while especially the leys of rotation system II are too far away for grazing. Grazing intensities, expressed as N excretion during grazing, are presented in Table 3. The dates on which grazing started and ended is specified per year in Table 4. Average seasonal grazing duration for the whole period, expressed as cow grazing days, was 103.

Data collection

The total area of De Marke is sub-divided in 30 plots of 1–3 ha, each, for which crop management, nutrient flows and yields were monitored separately (Figure 1). Relevant management data, i.e. rate, timing and method of manure application, harvesting/cutting, grazing, re-sowing and ploughing were monitored (Aarts et al. 1992). Organic mass flows (harvested crop material and applied slurry) were measured by weighing and the related nutrient flows were quantified on the basis of chemical analyses of representative samples. N-fixation by clover was estimated from its dry matter yield, assuming 50 kg N-fixation Mg^{-1} (Van der Meer and Baan Hofman 1989; Elgersma and Hassink 1997). Fresh grass consumption by cattle was calculated by estimating standing biomass just before and after grazing and correcting for growth during grazing. N in excreta during grazing was estimated from feed intake, by subtracting N output in milk and meat and in excretion indoors. N output in milk was quantified by monitoring protein levels (mg l^{-1}) and milk production (l). Milk production per cow was measured daily. Atmospheric deposition was derived from the national monitoring network. In late autumn, the upper meter of groundwater was sampled at 170 points. The sampling procedure is described in detail by Boumans et al. (2001).

Table 4. Onset and end of the grazing period in 1996–2003.

Year	Onset of grazing season	End of grazing season
1996	May 3	October 1
1997	April 30	October 19
1998	April 6	October 1
1999	April 15	October 1
2000	April 19	September 16
2001	May 28	September 17
2002	May 30	September 21

Nitrate-related principles of system development

To restrict nitrate leaching, in the design of dairy farming system 'De Marke', two general strategies were followed:

1. limiting the intensity of N-fluxes within the system;
2. abatement of specific processes that induce nitrate leaching.

Limiting the intensity of internal N-fluxes

Within the farming system, the sub-systems feeds, cattle, manure, soil and crops are distinguished. In order to minimize losses, N transfers from manure to soil, from soil to crops, from crops to feeds, from feeds to cattle and finally, to exported products should be as complete as possible. Restricting the intensity of internal N-fluxes is required when N-contents of sub-systems exceed critical levels, above which the sub-systems become 'N-saturated'. High N-contents in (any of) the sub-systems make the whole system susceptible to N losses. In each of the sub-systems distinguished, the proportion of N transferred from that sub-system tends to decrease with increasing N-content in the sub-system. For example, intake of N in excess of the N (protein) requirements of cattle, results in 'N-saturation' of the animals and subsequently in increased N-excretion (Bannink et al. 1999; Kebreab et al. 2003). Excretion of urine-N on the soil is directly associated with nitrate leaching (Ryden 1984), but above critical levels, also additions of total manure-N negatively affect the efficiency of nutrient cycling in the soil, leading to higher leaching losses (Kolenbrander 1981; Ten Berge, 2002; Nevens and Reheul 2003a). Similar 'saturation-type' effects take place in other sub-systems.

To restrict the internal N-flows, the *inputs* of N (in concentrates and chemical fertilizer) must be restricted. At a fixed milk production level, the input of concentrates can be restricted by covering the feed requirements of the herd as much as possible by homegrown crops, producing an optimum mix of energy and protein. On dry sandy soil this can be realized by growing maize for supply of energy (with low protein levels), in addition to grass for protein supply (with low energy levels) (Aarts et al. 1999b). N-fertilizer inputs can be restricted through efficient fertilization strategies. Moreover, N-use efficiency, expressed as the ratio of dry matter production to N input, can be maximized through optimum crop management. Introduction of these strategies in an integral system model suggested that at farm level at the average milk production intensity, an N-surplus of 128 kg N ha^{-1} yr^{-1} could be realized, associated with an anticipated N surplus on the soil balance of 78 kg N ha^{-1} yr^{-1} (Hilhorst et al. 2001).

Abatement of specific processes

N-excretion during grazing presents a risk for nitrate leaching to groundwater (Ryden 1984; Van der Meer and Meeuwissen 1989; Sauer and Harrach 1996). Urine N is deposited in mineral form in urine spots at rates estimated at 340–410 kg N ha^{-1} (Vertes et al. 1997; Vellinga et al. 2001) and is susceptible to leaching. Direct uptake is often hampered by damage caused by scorching and/or trampling. N-utilization from urine further declines with overlapping urine deposits (Haynes and Williams 1993), of which the frequency increases with higher grazing intensities (Richards and Wolton 1976; Vellinga et al. 2001). Therefore, rotational grazing is an effective strategy to restrict nitrate leaching, as it results in a large area with relatively low grazing-N rates, thus avoiding occurrence of spots with extremely high rates.

Slurry N-application and urine N-excretion during grazing in late summer and early autumn enhance nitrate leaching (Titchen et al. 1993). At that time of the year, crop growth is slow, and so are water and N uptake rates, resulting in reduced utilization of applied N (Sluismans and Kolenbrander 1976; Cuttle and Bourne 1993). Thus, excessive nitrate leaching can be prevented by avoiding N-applications and restricting grazing at the end of the growing season (Aarts et al. 2000b).

On sandy soils, nitrate leaching was found to be approximately twice as high on maize land than on grassland (Fraters et al. 1997). Hence, additional measures are required to prevent excessive nitrate leaching in maize. One of those is crop rotation. A crop rotation that includes a grassland phase in addition to an arable phase is preferred to continuous maize, as it may prevent the development of increasing susceptibility of the soil to nitrate leaching. Under continuous maize, the organic matter content in the top soil layer declines, due to the low return of organic matter compared to grassland, and to intensive soil tillage (Dam Kofoed 1982; Nevens and Reheul 2003b). On dry sandy soils that are already low in organic matter, a further decline should be avoided to not jeopardize the water storage capacity of the rooting zone (Bell and van Keulen 1995). However, upon transfer from the grassland phase to the arable phase, large quantities of mineral N are released, following ploughing in of the grass sod (Nevens and Reheul 2002). This phase should be managed carefully, as it may lead to high rates of nitrate leaching (Whitmore et al. 1992; Francis 1995; Hoffman 1999; Goulding 2000; Eriksen 2001). To prevent mineral N levels exceeding the potential uptake capacity of maize, the N fertilizer dose for first year maize should be corrected for the expected release from the ploughed-in grass. Various studies have pointed out the positive role of catch crops in preventing leaching of residual mineral N from the profile after the harvest of maize (Schröder et al. 1992; Alvenas and Marstorp 1993; Parente et al. 2003).

Identifying weak spots in the system with respect to nitrate leaching

System evaluation is required to examine whether system performance meets environmental and agronomic targets. Earlier studies have indicated the success of the management strategy implemented at De Marke in reducing the levels of nitrate leaching (Boumans et al. 2001). However, the initial decline is not sufficient, as nitrate concentrations in the upper groundwater 'stabilized' around average levels of 55 mg l^{-1} (Aarts et al. 2001). As observed crop production was in good agreement with the levels predicted in system design (Hilhorst et al. 2001), and no indications of nutrient mining effects on crop productivity were found (Corré et al. 2004), a more specific focus on N-losses is warranted. Increased insight in the processes involved in nitrate leaching might result in identification of ways for further reduction.

Evaluation is carried out by relating plot management at De Marke to measured nitrate concentrations in the groundwater, to examine whether correlations can be established with environmental conditions and related soil processes. Nitrate concentrations reflect the interacting effects of management practices, random variability of the system and weather conditions. These effects have to be disentangled for sound evaluation, which could be done by modeling the effects of random system variability. Boumans et al. (2001) concluded specifically for De Marke that measured nitrate concentrations have to be corrected for variable dilution effects caused by the annual variability in precipitation surplus. Moreover, the effect of variability in groundwater level and water soluble organic matter content in groundwater (expressed as Dissolved Organic Carbon, DOC) should be taken into account, as denitrification is stimulated by the simultaneous occurrence of shallow groundwater levels and high contents of organic matter (Burford and Bremner 1975; Spalding and Exner 1993; Fraters et al. 2002).

Analysis

The analysis is focused upon the effects of crop rotation, grazing, N surplus and resowing on nitrate leaching. To account for known effects of system variability on nitrate leaching, possibly masking or confounding management effects, the effects of the precipitation surplus, groundwater level and dissolved carbon are also taken into account. Each year groundwater was sampled at the same location. During sampling the groundwater level was recorded and in each sample DOC was measured. In addition, for each sample a value for the precipitation surplus was calculated (Boumans et al. 2005).

The REML algorithm (method of residual maximum likelihood; Genstat 7.3 (2004)) was applied that estimates treatment effects and variance components in a linear mixed model and was developed especially for unbalanced datasets. Unbalanced datasets typically result from observational studies such as performed in the whole-farm approach followed at De Marke, in contrast to balanced datasets that follow from experimental designs where each treatment is randomly applied to a number of plots.

Linear mixed models (Table 5) are constructed by relating measured nitrate concentrations (dependent variable) to cropping history, grazing, N surplus, groundwater level, DOC concentration and precipitation surplus (fixed effects, Genstat 7.3). The unknown influence of sampling location is modeled as a random effect.

To investigate whether rotation leads to higher nitrate concentrations, two models were developed (Table 5):

(1) CROPS-model, consisting of four factors ($Crop_{-1}$, $Crop_{-2}$, $Crop_{-3}$, $Crop_{-4}$), referring to the 4 years before the year of nitrate sampling. Each factor can take either of two 'values', i.e. "grass" or "maize". Their effect in this model only depends on their temporal position (in years) with respect to the moment of nitrate sampling, irrespective of the rotation.[1] The CROPS-model allows predictions for every possible four-year sequence of grass and maize.
(2) ROTATION-model, consisting of one factor (rotation phase), comprising 8 main sequences and 4 minor sequences of grass and maize which have been realized in 4 four-year periods. The ROTATION-model allows predictions for realized sequences only. Some realized crop sequences deviated from the normal rotation I or rotation II scheme. These were analyzed as well, in addition to the 'normal' crop sequences. The natural factors were included in both the CROPS-model and the ROTATION-model as co-variables.

The differences between the results (95% confidence intervals) of the CROPS-model and the ROTATION-model were used to assess rotation effects. If rotation effects are significant, the CROPS-model will have larger and different confidence intervals than the ROTATION-model and modeled nitrate concentrations in first and second year maize will

[1] $Crop_{-2}$ = Crop type two years before the year of sampling, either maize or grass (triticale). If it is grass, it refers to all plots that where used as grassland two years before sampling, irrespective of their position in the rotation. So, it includes permanent grassland as well as first, second and third year ley.

Table 5. Models used to evaluate the influence of management variables.

Model	Structure	
1: CROPS-model	Response:	Measured nitrate concentration
	Fixed variables:	Dissolved Organic Carbon + groundwater level + precipitation surplus + grazing* + N surplus* + Crop_{-1} + Crop_{-2} + Crop_{-3} + Crop_{-4}
	Random variable:	Sampling location
	Crop_{-1}:	Crop type 1 year before the year of sampling, maize or grass (triticale)
	Crop_{-2}:	Crop type 2 years before the year of sampling, maize or grass (triticale)
	Etc.	* = *added to the model separately to study effect*
2: ROTATION-model	Response:	Measured nitrate concentration
	Fixed variables:	Dissolved Organic Carbon + groundwater level + precipitation excess + rotation phase;
	Random variable:	Sampling location
	Rotation phase:	Realized crop sequence:
	Normal rotations	
	First year maize	Grass–Grass–Grass–Maize
	Second year maize-1	Grass–Grass–Maize–Maize
	Third year maize	Grass–Maize–Maize–Maize
	Fourth year maize	Maize–Maize–Maize–Maize
	First year grass-1	Maize–Maize–Maize–Grass
	Second year grass-1	Maize–Maize–Grass–Grass
	Third year grass	Maize–Grass–Grass–Grass
	Fourth year grass	Grass–Grass–Grass–Grass
	A-typical rotations	
	Second year maize-2	Grass–Maize–Grass–Grass
	Second year grass-2	Grass–Maize–Maize–Grass
	First year grass-2	Grass–Grass–Maize–Grass
	First year maize-2	Maize–Grass–Grass–Maize

be higher than in subsequent maize years and in first and second year grassland higher than in subsequent grass years. No distinction was made between permanent grass and fourth year ley, as a preliminary analysis showed no effect (data not reported). To explore the effect of triticale, it was introduced as an additional crop type in the CROPS-model, and confidence limits for its contribution to the nitrate concentration in the four years following its cultivation were calculated.

Three of the permanent grassland plots have been resown between 1996 and 2003. All observations of these three plots have also been used in the CROPS-model. For all model residuals, a percentile value was calculated. The influence of resowing on nitrate concentrations was assessed by comparing the percentile values of plot residuals before and after resowing.

The effects of grazing and N surpluses were investigated by introducing these variables jointly in the CROPS-model and by judging their effects on results (95% confidence limits) for grassland (grazing) and for maize and grass (N surplus).

Residuals appeared to be strongly non-Gaussian and bimodal, which makes the use of confidence limits and standard errors questionable. After transformation (power 1/3) and selection of responses (nitrate concentrations exceeding 1 mg/l), the residuals showed a more Gaussian distribution. Comparison of the results of the non-transformed and non-selected responses to those of the transformed and selected gave no reason to change the conclusions (data not reported).

Results

Measured and modeled nitrate concentrations in grass and maize

Table 6 presents measured nitrate concentrations in different phases of the rotation and confidence intervals for means estimated by the CROPS-model and the ROTATION-model. Mean nitrate concentrations in groundwater were in general higher the year after maize than the year after grassland

(Table 6, column 3). Disregarding the values that are represented by only 6 and 15 observations, the following pattern can be recognized (Table 6): The values for first, second and third year maize ($G_{-4}G_{-3}G_{-2}M_{-1}$, $G_{-4}G_{-3}M_{-2}M_{-1}$ and $G_{-4}M_{-3}M_{-2}M_{-1}$) are higher than for fourth year maize. The values for first and second year grass ($M_{-4}M_{-3}M_{-2}G_{-1}$ and $M_{-4}M_{-3}G_{-2}G_{-1}$) are lower than for fourth year grass. The mean nitrate concentration in groundwater was lower in the year after four years maize (45 mg NO_3^- l^{-1}) than after four years grass (63 mg NO_3^- l^{-1}).

The results of the CROPS-model (column 5) and the ROTATION-model (column 7) include corrections for effects of the natural factors, DOC, groundwater level and precipitation surplus, that may have influenced measured values according to the method summarized in Table 5. In the CROPS-model, the code G_{-n}, referring to grassland grown n years before the nitrate measurement, includes grassland in all positions in the rotation, i.e. first, second or third year ley, as well as permanent grass. The results of the ROTATION-model describe the combined effect of the crops in the 4 years prior to the nitrate measurement *and* rotation.

The results of the CROPS-model are rather similar to the measured nitrate concentrations except for $G_{-4}+M_{-3}+M_{-2}+M_{-1}$ where model results are well below the mean of the measured values and for the a-typical rotations. The results of the ROTATION-model and the CROPS-model are similar, except for the a-typical rotations, and third ($G_{-4}M_{-3}M_{-2}M_{-1}$) and fourth ($M_{-4}M_{-3}M_{-2}M_{-1}$) year maize. For these rotations, the results of the ROTATION-model are in closer agreement with measured values than the results of the CROPS-model.

Effects of triticale, N-surpluses, grazing and resowing

Mean modeled nitrate concentrations and confidence intervals of the CROPS- and ROTATION-model for triticale are presented in Table 6 (section Rotations with triticale). The results of the CROPS- and ROTATION-model include correction for natural factors following the same method applied to maize and grass. Effects of triticale on mean measured nitrate concentrations in groundwater follow from comparison of rotations with triticale and rotations in which the position of triticale is occupied by maize (Table 6, column 3). Differences between rotations with triticale and rotations with maize are not consistent: (i) values for three years maize followed by triticale ($M_{-4}M_{-3}M_{-2}T_{-1}$) were higher than for 4 years maize ($M_{-4}M_{-3}M_{-2}M_{-1}$), (ii) values for two years grass, preceded by triticale ($M_{-4}T_{-3}G_{-2}G_{-1}$) were higher than those with maize on that position ($M_{-4}M_{-3}G_{-2}G_{-1}$), (iii) the difference between first year grass preceded by triticale ($M_{-4}M_{-3}T_{-2}G_{-1}$) and its maize equivalent ($M_{-4}M_{-3}M_{-2}G_{-1}$) was insignificant, (iv) values for two years maize followed by triticale ($G_{-4}M_{-3}M_{-2}T_{-1}$) were lower than for three years maize ($G_{-4}M_{-3}M_{-2}M_{-1}$). On average, the contribution of triticale to measured nitrate was somewhat higher than that of maize. However, the modeled concentrations from the CROPS-model are high compared to measured nitrate concentrations (measured values lie in the low range of the 95% confidence interval of the CROPS-model). Consequently, modeled concentrations from the CROPS-model for most rotations with triticale were much higher than those for their maize equivalents and the differences were larger than in measured values. Similarly to measured nitrate concentrations, the values of the CROPS-model for $G_{-4}M_{-3}M_{-2}T_{-1}$ were lower than for its maize equivalent. However, according to the CROPS-model the differences were marginal.

In the CROPS-model, the average effect of grazing in the period 1996–2003 at farm level was estimated for an average annual grazing intensity of 103 cow grazing days. Model results indicate that the nitrate concentration after four years grassland without grazing ($G_{-4}+G_{-3}+G_{-2}+G_{-1}$) would have been 23–49 mg l^{-1}(95% confidence limits) instead of 59–74 mg l^{-1} (Table 6, column 5).

Table 7 presents measured nitrate concentrations and modeled concentrations of the CROPS-model separately for categories of surpluses classified as 'low' and 'high', without distinguishing between grass and maize. However, grass is the dominant crop in the category with high surpluses and maize in the category with low surpluses (Table 3). Measured nitrate concentrations are higher for the category low surpluses than for high surpluses. The results of the CROPS-model also refer to grass and maize, but effects of the N surplus are corrected for crop effects (and for natural effects). Values of the CROPS-model are lower for low than for high surpluses.

Table 6. Mean measured nitrate concentrations in different phases of the crop rotation.[a]

Rotation phase[a]	Measured values		CROPS-MODEL		ROTATION-MODEL	
	Observations (number)	Means	Crop cultivated *n* years before nitrate measurement[b]	Estimated intervals for the mean	Rotation phase[a]	Estimated intervals for the mean
Column (1)	(2)	(3)	(4)	(5)	(6)	(7)
Normal rotations						
$G_{-4}G_{-3}G_{-2}M_{-1}$	124	84	$G_{-4}+G_{-3}+G_{-2}+M_{-1}$	75–91	$G_{-4}G_{-3}G_{-2}M_{-1}$	68–87
$G_{-4}G_{-3}M_{-2}M_{-1}$	71	97	$G_{-4}+G_{-3}+M_{-2}+M_{-1}$	86–103	$G_{-4}G_{-3}M_{-2}M_{-1}$	81–104
$G_{-4}M_{-3}M_{-2}M_{-1}$	43	92	$G_{-4}+M_{-3}+M_{-2}+M_{-1}$	63–82	$G_{-4}M_{-3}M_{-2}M_{-1}$	77–107
$M_{-4}M_{-3}M_{-2}M_{-1}$	43	45	$M_{-4}+M_{-3}+M_{-2}+M_{-1}$	45–66	$M_{-4}M_{-3}M_{-2}M_{-1}$	36–54
$M_{-4}M_{-3}M_{-2}G_{-1}$	63	42	$M_{-4}+M_{-3}+M_{-2}+G_{-1}$	30–48	$M_{-4}M_{-3}M_{-2}G_{-1}$	28-53
$M_{-4}M_{-3}G_{-2}G_{-1}$	95	28	$M_{-4}+M_{-3}+G_{-2}+G_{-1}$	19–36	$M_{-4}M_{-3}G_{-2}G_{-1}$	10–31
$M_{-4}G_{-3}G_{-2}G_{-1}$	118	52	$M_{-4}+G_{-3}+G_{-2}+G_{-1}$	41–57	$M_{-4}G_{-3}G_{-2}G_{-1}$	43–62
$G_{-4}G_{-3}G_{-2}G_{-1}$	229	63	$G_{-4}+G_{-3}+G_{-2}+G_{-1}$	59–74	$G_{-4}G_{-3}G_{-2}G_{-1}$	61–79
			$G_{-4}+G_{-3}+G_{-2}+G_{-1}$(ung)[c]	23–49		
A-typical rotations						
$G_{-4}G_{-3}M_{-2}G_{-1}$	15	21	$G_{-4}+G_{-3}+M_{-2}+G_{-1}$	66–90	$G_{-4}G_{-3}M_{-2}G_{-1}$	10-62
$G_{-4}M_{-3}G_{-2}G_{-1}$	6	27	$G_{-4}+M_{-3}+G_{-2}+G_{-1}$	32–57	$G_{-4}M_{-3}G_{-2}G_{-1}$	0–56
$G_{-4}M_{-3}M_{-2}G_{-1}$	6	85	$G_{-4}+M_{-3}+M_{-2}+G_{-1}$	44–68	$G_{-4}M_{-3}M_{-2}G_{-1}$	45–125
$M_{-4}G_{-3}G_{-2}M_{-1}$	6	141	$M_{-4}+G_{-3}+G_{-2}+M_{-1}$	53–78	$M_{-4}G_{-3}G_{-2}M_{-1}$	89–170
Rotations with triticale						
$M_{-4}T_{-3}G_{-2}G_{-1}$	25	56	$M_{-4}+T_{-3}+G_{-2}+G_{-1}$	48–86	$M_{-4}T_{-3}G_{-2}G_{-1}$	47–85
$M_{-4}M_{-3}T_{-2}G_{-1}$	49	44	$M_{-4}+M_{-3}+T_{-2}+G_{-1}$	34–62	$M_{-4}M_{-3}T_{-2}G_{-1}$	34–61
$M_{-4}M_{-3}M_{-2}T_{-1}$	25	54	$M_{-4}+M_{-3}+M_{-2}+T_{-1}$	37–63	$M_{-4}M_{-3}M_{-2}T_{-1}$	35–72
$G_{-4}M_{-3}G_{-2}T_{-1}$	34	59	$G_{-4}+M_{-3}+G_{-2}+T_{-1}$	52–77	$G_{-4}M_{-3}G_{-2}T_{-1}$	44–76
A-typical rotations						
$T_{-4}G_{-3}G_{-2}M_{-1}$	6	82	41–118	41–118	$T_{-4}G_{-3}G_{-2}M_{-1}$	42–118

Results of the CROPS-model: estimates of mean nitrate concentrations of maize and grass cropping on De Marke related to the time interval (years) between crop cultivation and year of nitrate measurement (95% confidence limits); results of the ROTATION-model: estimates of the mean nitrate concentrations of maize and grass cropping on De Marke related to the time interval (years) between crop cultivation and year of nitrate measurement and rotation (95% confidence limits) period 1996–2003.

[a]The subscripts in the crop code represent the time interval (in years) between the moment of nitrate measurement and the time of cultivation. The sequence in the code represents the rotation. Thus, code $G_{-4}G_{-3}M_{-2}M_{-1}$ refers to nitrate measurements that were carried out 1 year after 'second year maize' was grown.

[b]The codes C_{-n} refer to the length of the time period *n*, in years, of cultivation of crop C before the nitrate measurement.

[c]Ungrazed grass.

The mean values of the percentiles of the residuals of modeled nitrate concentrations in the years before and after resowing permanent grassland plots (Table 8) show that for plot 8 resowing results in a clearly higher percentile value in the first year. The value of 82 in plot 14 does not indicate resowing effects as on this plot the percentiles are rather high in *all* years before and after resowing.

Table 8. Mean of percentiles of the model residuals of measured nitrate concentrations in the years before resowing (−3, −2, −1), the year of resowing (0) and in the years following resowing (1 to 5).

Time lapse from year of resowing	Plot number		
	K3 (autumn)	8 (spring)	14 (autumn)
−3	76	32	
−2	8	3	
−1	56	17	76
0	63	46	48
1	60	83	82
2	34	57	39
3	33		32
4			43
5			60

Discussion

Crop-effects or rotation effects

The mean measured nitrate concentrations, the results of the CROPS-model and the results of the ROTATION-model (Table 6) show similar patterns: (i) nitrate concentrations are higher after 4 years grassland than after 4 years maize, (ii) nitrate concentrations are higher the first 3 years after grassland has been replaced by maize, (iii) concentrations are lower the first 2 years after maize has been replaced by grassland. These patterns thus refer to management effects, which are supposed to be disentangled from effects of natural factors.

The differences between the results of the CROPS-model and measured nitrate concentrations for a-typical rotations might be associated with the low number of observations and the resulting low accuracies. However, the differences also indicate that rotation effects indeed play a role when management deviates from the planned practices. In 'normal' rotations, the CROPS-model results deviate from measured nitrate concentrations in third-year ($G_{-4}M_{-3}M_{-2}M_{-1}$) and fourth-year ($M_{-4}M_{-3}M_{-2}M_{-1}$) maize, which would imply occurrence of rotation effects. However, the measured values and estimated means of the ROTATION-model for third-year maize are doubtful, as they are very high compared to $M_{-4}M_{-3}M_{-2}M_{-1}$. This difference can not be explained by rotation effects.

Table 7. Mean measured nitrate concentrations for plots with low and high N surpluses (maize and grass), results of the CROPS-model: estimates of mean nitrate concentrations related to N surpluses (95% confidence limits).

Category	Observations (number)	Measured (means)	CROPS-model (estimated interval for the mean)
Low	382	70	33–50
High	388	54	51–68

Hence, this difference warrants further investigation to clarify the cause of the high nitrate values in third-year maize. This could reveal a 'weak spot' for nitrate leaching.

In general, the mean nitrate concentration for De Marke is *not* significantly influenced by the rotation of maize and grassland, as the CROPS-model (Table 6) accurately estimates nitrate concentration for almost every possible sequence of maize and grassland. Hence, this mean nitrate concentration mainly depends on the areas of maize and grass, irrespective of their rotation. This conclusion is corroborated by the results of the ROTATION-model that estimates the lowest nitrate concentrations for $M_{-4}M_{-3}G_{-2}G_{-1}$ instead of for $G_{-4}G_{-3}G_{-2}G_{-1}$ or $M_{-4}M_{-3}M_{-2}M_{-1}$.

The observed nitrate concentrations are thus related to the specific management, as 'crops' in the models represent specific crop/management combinations. N fertilizer application to maize was reduced with 90 kg ha^{-1} in the first year and 45 kg in the second year to correct for N release from the ploughed-in grass sod. Apparently, this strategy effectively prevents nitrogen leaching in the grassland-maize transition. This is in agreement with results reported by Van Dijk (1999), who found that the N dose in the first and second year maize following grass could be reduced by 80–100 and 30–40 kg, respectively. Eriksen (2001) reported residual effects in first year cereals following three year grassland, varying from 25 kg N ha^{-1} yr^{-1} for cut ryegrass, via 90–100 kg for grazed ryegrass to 115 kg for grass/clover mixtures. In the second year, residual effects were negative for cut grass, 40 kg N ha^{-1} yr^{-1} for grazed grass and 60 kg for grass/clover. The results of Nevens and Reheul (2002) point at somewhat higher residual effects, i.e. 124, 81 and 52 kg N in first, second and third year maize, respectively. Although the residual effects are variable, a zero N rate strategy in first year maize can prevent rotation-induced enhanced nitrate leaching.

Indirectly, crop rotation may be responsible for the relatively low levels of nitrate leaching in maize. Corré et al. (2004) concluded that inclusion of grass in the rotation prevents the rapid decline in soil organic matter content, associated with continuous maize, which leads to increased susceptibility of the soil for nitrate leaching (reduced buffering capacity for both water and nutrients).

Effects of maize and grass

The results of the CROPS-model suggest that maize results in lower nitrate concentrations than grassland, as can be deduced from Table 6 for sequences with maize in all years (−4, −3, −2, −1) before the year of nitrate measurement (45–66 mg NO_3^- l^{-1}) and sequences with grass in all years (59–74 mg l^{-1}). For permanent grassland without grazing, the CROPS -model with grazing added, estimated confidence limits (23–49 mg l^{-1}), below those for maize (45–66 mg l^{-1}).

The contribution of maize to nitrate leaching is smaller at De Marke than in commercial farming in comparable conditions. The results of the CROPS-model, showing that the contribution of maize cropping to nitrate leaching is lower than that of grazed grassland, are not in agreement with observations in current practice (Fraters et al. 1997). In addition to the strategy of reduced fertilization in first and second year maize, this might be attributed to the strategy of growing catch crops. N-uptake in roots, stubble and leaves of Italian ryegrass at De Marke is estimated at 108 kg ha^{-1} yr^{-1} (Aarts et al. 1994). This quantity would contribute to N-leaching, if catch crops were not grown. This is supported by results of the CROPS-model for triticale, showing a much larger contribution to nitrate leaching than of grass or maize. This is probably associated with its poor performance as a catch crop. Italian ryegrass as a catch crop is sown between the maize shortly after germination. As a result, its biomass in winter is better developed than that of triticale that is sown shortly after harvest.

The general perception of increased nitrate concentrations caused by replacing grass with maize neglects long-term effects. Modeled and measured nitrate concentrations are low when maize was present 4 and 3 years before nitrate measurement and higher when grassland was present in that period. Measurements indicate that nitrate concentrations are low in the year following grass and high in the year following maize. But according to the CROPS-model, high nitrate concentrations are associated with grass in the earlier years (3 and 4 years before the measurement) and low nitrate concentrations with maize in the earlier years (Table 8). Thus, when grass is followed by maize (as may happen on commercial farms, but also in field trials), leaching effects of maize cannot adequately be quantified by monitoring the groundwater 1 year after maize cropping. The 'memory effect' of the soil may cause delayed grass effects that may erroneously be attributed to maize.

Other effects

Grazing

According to the CROPS-model, grazing at the intensity practiced at De Marke in the period 1996–2003 contributed about 30 mg l^{-1} of nitrate to the measured concentration in the upper groundwater of grassland. Assuming a linear relation between grazing intensity and nitrate concentration, this result suggests an urgent need to reduce grazing intensity. However, adaptation of the grazing system, leading to a reduction in nitrate leaching, while maintaining the grazing intensity, would be even more interesting. A further reduction in daily grazing time below the current 6 h is practically not feasible, as the beneficial effects of grazing (assuming these to be proportional to length of the grazing period) would no longer warrant the required (unchanged) labor investments. A feasible way to reduce grazing-related leaching might be to stop grazing earlier in autumn. Currently, grazing continues until mid-September, the exact moment depending on grass production in late summer and autumn. This may be sub-optimal in terms of nitrate leaching, as utilization of nitrogen from urine deposits declines with later excretion (Deenen and Middelkoop 1992; Cuttle and Bourne 1993; Titchen et al. 1993; Lord 1993; Van der Putten and Vellinga 1996). Moreover, according to Vellinga and Hilhorst (2001), grazing management could be further optimized. They point out that the recommended yield for grazing can often not be realized in September and October, which leads to N-contents exceeding 30 g kg^{-1} in the grazed material. This observation supports the suggestion to end the grazing season earlier.

Another aspect that deserves attention is the composition of the ration during grazing, which might be a major cause of excessive N deposition in grazed grassland (Van Vuuren and Meijs 1987; Van Vuuren et al. 1993; Valk 1994). Although the strategy at De Marke is to prevent intake of protein in excess of the requirements, during grazing high protein intake levels may have occurred.

The ultimate abatement of grazing-related nitrate leaching is to stop grazing completely. Although in a production environment that aims at high production levels within the boundaries of environmental standards, this may appear an attractive option, for De Marke it is the last resort. Grazing is appreciated for its contribution to an attractive rural landscape, while it enhances animal health and welfare, although the exact consequences of full time stabling are far from clear. Further research in this field is urgently needed, because if, in spite of further optimization of grazing management, full time stabling will appear inevitable, the consequences for a variety of aspects will have to be explored at farming system level.

N-surpluses

Measured nitrate concentrations were lower in grass and maize with high surpluses than in grass and maize with low surpluses. This can be attributed to the fact that grass (with lower measured nitrate concentrations than maize) is the dominant crop in the category with high surpluses, while maize (with higher measured nitrate concentrations) is dominant in the category with low surpluses. Hence, crop effects and surplus effects both affected measured nitrate concentrations. The difference in surpluses between grass and maize is caused by the crop-specific management with different input levels for grass and maize (Table 3). The results of the CROPS-model indicate the opposite, with higher modeled values for high surpluses than for low surpluses. In the CROPS-model, crop effects and effects of surplus are disentangled. It should be stressed that the variability in surpluses evaluated in the CROPS-model is not dependent on crop type and position in the rotation (Table 3). Instead, the variability is associated with variability in weather conditions, plot characteristics, such as phosphate availability or organic matter content (Corré et al. 2004) and sometimes pests and diseases. This variability in N-surpluses appeared a significant factor in nitrate leaching, that would not have been detected if effects of crop and of surplus would not have been disentangled. This is clearly illustrated by the contradiction between measured nitrate concentrations and results of the CROPS-model (Table 7). Lack of data prevented separate modeling of the specific effect of the surpluses in maize and grass. However, extensive evaluation of field experiments (Ten Berge 2002; Bobe et al. 2004) indicated that the risk of nitrate leaching at a given level of exceedence of the critical N-rate (defined here as the fertilizer application rate necessary to bring available N at the level of potential crop uptake) is much higher in maize than in grassland, which is attributed to the much higher denitrification rates in grassland (Colbourn and Dowdell 1984; Paustian et al. 1990). Therefore, restricting incidences of exceeding critical N-rates in maize, which may have occurred in $G_{-4}M_{-3}M_{-2}M_{-1}$, might lead to further reduced nitrate leaching. An option might be to improve plot-specific estimates of potential N-uptake rates, as a basis for plot-specific fertilizer recommendations. This option will have to be explored in further research.

Resowing

The number of resowings (3) is too low to allow firm conclusions from the results. However, in two of the three situations, where resowing took place in autumn, nitrate concentrations in groundwater in the years after resowing were not markedly affected. The third resowing, in spring, resulted in high nitrate levels 1 year after resowing. These results are in disagreement with the general perception, supported by experimental evidence, that resowing in spring has no effect, whereas resowing in autumn increases nitrate leaching (Francis 1995; Velthof and Hoving 2004; Seidel et al. 2004).

Implications for N-management at farm level

To reduce nitrate leaching, it is advisable to replace triticale by another crop and to abate grazing-related contributions, for instance by earlier ending the grazing season. A next step could be to reduce the share of maize in roughage production, as nitrate leaching in maize is higher than in non-grazed grassland. Such an adaptation will have a strong impact on the flows of energy and nutrients within the production system. Therefore, for sound judgment of this option, a thorough (re-)analysis is required of changes in productivity of roughage, N requirements of the crops, N inputs through purchase of concentrates and changes in crop transpiration. Results of that analysis will be reported in a follow-up paper.

Conclusions

No indications were found for enhanced nitrate concentrations due to rotation of grass and maize.

Nitrate concentrations caused by triticale were higher than those caused by maize. This high value was attributed to the poor growth of the crop in the period that it should function as a catch crop after harvest of maize.

Grazing contributes up to 30 mg NO_3^{-} l^{-1} on grassland. As grazing management and intensity have been optimized already to restrict nitrate leaching, this result underpins the need to develop sustainable grazing methods on soils susceptible to nitrate leaching.

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