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Nitrate leaching to groundwater at experimental farm 'De Marke' and other Dutch sandy soils

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Abstract

This study focuses on nitrate leaching to the groundwater as a result of the land use system of experimental farm 'De Marke', translated to other sandy soils in the Netherlands. The land use was extrapolated to five major sandy soil map units, selected from the 1: 50 000 Soil Map of the Netherlands, using simulation models. To allow extrapolation to other conditions, the land use system was described in terms of decision rules for fertilization, grassland management, sowing and harvesting of silage maize, and supplementary irrigation. The decision rules were used as input to simulation models that were calibrated and validated using data from 'De Marke'. Then, simulations were performed for 30 consecutive years. For 'De Marke' the calculated annual average nitrate concentration at 1 m depth was 67 mg l^{-1}. The nitrate concentration for the soil map unit covering the largest area of sandy soils in the Netherlands (Cambic Podzol, Hn21-VI) would be higher than for 'De Marke', but for the four other soil map units the calculated nitrate concentrations would be lower. It was concluded that the land use system of 'De Marke' would result in annual average nitrate concentrations lower than 50 mg l^{-1} at several locations in the Dutch sandy areas.

Keywords: dairy farming, nitrogen, land use, simulation models.

Introduction

A major objective of experimental farm 'De Marke' is to realize nitrate concentrations in the upper groundwater below the predefined limit of 50 mg l^{-1} (Aarts *et al.*, 1992; Biewinga *et al.*, 1992). Once a year the National Institute for Public Health and the Environment (RIVM) takes groundwater samples from all fields on the farm. In these samples the nitrate concentration is measured (Boumans *et al.*, 2001). In addition, in the period autumn 1991 – spring 1995, an intensive monitoring programme was carried out at six sites, that focused on the interaction between soil moisture supply, nitrogen (N) dynamics, crop growth and field management (Hack-Ten Broeke & Aarts, 1996; Hack-Ten Broeke *et al.*, 1996a). The results from this programme allowed a study of nitrate losses in relation to soil type, groundwater depth and crop or parcel type.

The farm area of 'De Marke' is about 55 ha, 56% of which is used as grassland and 44% for growing silage maize (Biewinga *et al.*, 1996). Italian ryegrass is sown between the rows of each maize crop to take up the N left in the soil after the maize harvest. The farm comprises three parcel types: permanent grassland (11 ha; parcel type A), fields with a rotation of three years grassland and three years maize (30 ha; parcel type B) and fields with a rotation of three years grassland and five years maize (14 ha; parcel type C). It is assumed, especially in the first year of silage maize after grassland, that additional N becomes available through mineralization from the ploughed grassland. Fertilization of the maize crop is adapted accordingly. Fertilization strategies for the parcel types of 'De Marke' are described by Hilhorst *et al.* (2001).

Experimental farm 'De Marke' is located on drought-susceptible sandy soils (Dekkers, 1992). Under dry conditions N losses to the groundwater are often higher than in the case of ample moisture supply. The question has been raised whether it is possible on these dry soils to reach the defined goals for nitrate losses to the groundwater. It is expected that at other locations within the sandy areas of the Netherlands, it would be easier to comply with the economic goals and the environmental constraints. So this study focuses on the results of the land use system of 'De Marke', translated to the five major sandy-soil map units of the Netherlands.

Simulation models describing water and N dynamics in the soil were used for this extrapolation. The models were calibrated and validated using the data from the monitoring programme at the six experimental sites during the period 1991–1995. To enable extrapolation of the land use system of 'De Marke' to other locations or climatic conditions, decision rules had to be defined describing the field management in relation to weather, taking into account fertilization, rotational grazing and cutting (for grassland), supplementary irrigation, and finally sowing and harvesting of silage maize. The effects of temporal variability resulting from annual weather variation can be calculated using these decision rules. Long-term weather data for a period of 30 years were used for simulations for all fields of 'De Marke' and for the five major sandy soil map units (Schut & Hack-Ten Broeke, 1997; Hack-Ten Broeke *et al.*, 1999). Spatial soil variability within fields was not taken into account.

In this paper, first the results of the monitoring programme and the calculated N loads to the groundwater are presented. Next, the extrapolation study of the land use system of 'De Marke' to the five major sandy soil map units of the Netherlands is described. The main purpose of this study was to answer the question whether the land use system of 'De Marke' might lead to nitrate concentrations in the groundwater of the sandy areas in the Netherlands to levels below 50 mg l^{-1}, i.e., the EU standard for drinking water.

Materials and methods

Monitoring soil moisture and nitrate concentrations

On the basis of the soil survey of 'De Marke', six monitoring sites were selected that represented the main soil types and groundwater regimes occurring on the farm. Two sites were located on permanent grassland, one site on a dry field (field 9) and one on a relatively wet location (in field 17). Similarly, two sites were located on fields of parcel type B and two sites on fields of parcel type C. On these sites, moisture conditions were monitored every two weeks during the period autumn 1991 – spring 1995. Measurements consisted of groundwater levels on the one hand and pressure head and moisture content values at 8 depths (10, 20, 30, 40, 60, 90, 120 and 150 cm) on the other. Roughly once a month nitrate concentrations were measured in samples from 20 porous cups at 1 m depth or from the upper groundwater sampled in 8 piezometers (Hack-Ten Broeke *et al.*, 1996b; Hack-Ten Broeke & De Groot, 1996). Water fluxes were calculated from the data on soil moisture conditions in relation to crops and meteorological data for each of the six sites. Combined with the nitrate concentrations, this allows calculation of leached N in kg ha^{-1} for each site.

Simulation models

The deterministic models SWACROP and ANIMO were used for the simulation of water and N dynamics, respectively. SWACROP describes soil water dynamics in the unsaturated zone for a heterogeneous soil profile (Feddes *et al.*, 1988). ANIMO is used for simulating the carbon and N cycles and their interrelations in the soil (Rijtema & Kroes, 1991). Model input comprises values for the so-called upper and lower boundaries, the initial situation, and parameters describing the soil processes. After successful model calibration and validation, these simulation tools can be used for extrapolation, for example, to other years with different weather or to other soil types and groundwater levels within the range of model validation. In other words, satisfactory model validation for the sandy soils of 'De Marke' does not mean that the models can also be used for clay soils.

For calibration and validation of SWACROP and ANIMO, data were used from the monitoring period 1991–1995. Meteorological data and crop data were available from the experimental farm and were used for calculating evapotranspiration (upper boundary). For the lower boundary, the measured groundwater levels were used. Initial moisture conditions were derived from the measurements in 1991. Soil physical parameters, data on supplementary irrigation, fertilization and field management were also available (Hack-Ten Broeke, 2000). For calibration, model parameters are adapted within a predefined range until model results are in satisfactory agreement with experimental data. In the case of simulations for 'De Marke', only the parameters describing root water uptake in SWACROP were used as calibration parameters, and in ANIMO only the parameters describing the diffusion of oxygen in the soil. During validation, all parameters are left unchanged and a comparison is made between model results and measurements for an independent set of data. In this study the data for the period 1991 – spring 1993 were used for calibration, and the remaining data until spring 1995 for the validation phase.

Decision rules

For extrapolation of the land use system of 'De Marke' to other years and other sandy soils, it was necessary to define quantitative decision rules to describe land use, especially field management per parcel type. These decision rules for the fertilization of grassland and silage maize, grassland management and supplementary irrigation were established in close co-operation with experts on the farm. These rules are described by Hack-Ten Broeke *et al.* (1999).

With respect to fertilizing, first the available animal manure is distributed over crops and parcel types. The amount of animal manure required for the maize fields is calculated on the basis of soil moisture supply capacity and expected mineralization. The amount applied on the permanent grassland fields (parcel type A) is determined by the phosphate requirements. The remaining animal manure is then distributed over the other grassland fields of parcel types B and C. Chemical fertilizer is used to cover any further N requirement, calculated according to the fertilization recommendation defined by Agterberg *et al.* (1993). For grassland at 'De Marke' the total annual N application amounts to 250 kg ha^{-1}.

Fertilization of grassland and grassland management for the three different parcel types are presented schematically in Figure 1. The first animal manure is applied when the temperature sum has reached 180 degree days, but never before 15 February or later than 1 March. The first chemical fertilizer is applied when the temperature sum has reached 280 degree days, but never before 15 or later than 31 March. For the applications of animal manure and chemical fertilizer the trafficability of the land is also taken into account. Application takes place when the soil moisture pressure head at 5 cm depth has reached the threshold value for trafficability of $h = -70$ cm, but always before 1 or 31 March for animal manure and chemical fertilizer, respectively. Figure 1 shows all N applications, but N is also added in the form of excreta during grazing.

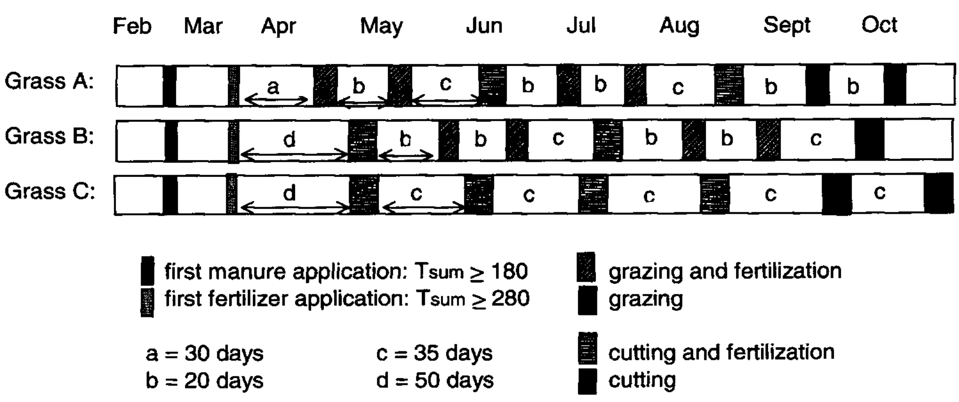

Figure 1. Schematic representation of decision rules for fertilization, cutting and grazing of grassland (A = permanent pasture; B = rotation of 3 years grass and 3 years maize; C = rotation of 3 years grass and 5 years maize).

Table 1. The five major soil map units in sandy areas of the Netherlands and the prevailing classification of the average highest (AHG) and average lowest (ALG) groundwater level (cm).

Map unit code	Description	AHG	ALG
Hn21 – VI	Cambic Podzol	40–80	> 120
zEZ21 – VII	Cumulic Anthrosol	80–140	> 120
pZg23 – III	Umbric Gleysol	< 40	80–120
Hn23x – V	Cambic Podzol with boulder clay	< 40	> 120
pZn21 – III	Dystric Gleysol	< 40	80–120

Supplementary irrigation is applied to the grassland of parcel types A and B when the soil moisture pressure head in the root zone drops below $h = -500$ cm ($pF = 2.7$). No irrigation takes place during grazing, or during the two days before and after a grazing period or cut. Silage maize is sown on 25 April and harvested on 25 September. The maize is undersown with Italian ryegrass.

Simulations for extrapolation

The decision rules were used as input to the models SWACROP and ANIMO for extrapolation to the whole farm of 'De Marke', using weather data for 30 years from meteorological station De Bilt. The dominant soil map unit was selected from the available soil map of the farm (Dekkers, 1992) for each of the 56 fields of 'De Marke'. Groundwater levels for all these fields and years were generated using a sine function with a correction for annual rainfall and soil surface altitude (Schut & Hack-Ten Broeke, 1997).

Next, simulations were carried out for other sandy soils. The five soil series covering the largest area of sandy soils were selected from the 1: 50 000 Soil Map of the Netherlands. Within each series the groundwater class covering the largest area was selected, which resulted in five soil map units (see Table 1). Groundwater classes represent the Dutch standard description of the groundwater regime in terms of the average highest (AHG) and average lowest (ALG) groundwater level. GC III is the wettest groundwater class (GC) of the five selected soil map units. For the simulations an AHG of 17 cm and an ALG of 103 cm were used for this class. GC VII is the driest class, for which an AHG of 100 cm and an ALG of 190 cm were used (Schut & Hack-Ten Broeke, 1997). Soil data for deriving model input were obtained for each soil map unit using all available soil profile descriptions for this mapping unit, according to De Vries (1994). For each soil horizon, texture data were used to derive the Van Genuchten parameters, describing soil hydraulic characteristics (Wösten *et al.*, 1995). For the simulations, farms were assumed to be homogeneous, so all fields of the three parcel types had the same soil type. The decision rules for describing the land use system of 'De Marke' were then applied to all 56 fields for the same period of 30 years.

Table 2. Average annual nitrate concentrations (Conc., mg l^{-1}) and N leaching (Lea., kg ha^{-1}).

Monitoring site (parcel type)	1992		1993		1994	
	Conc.	Lea.	Conc.	Lea.	Conc.	Lea.
2 (C)	194	*	100	45	51	39
9 (A)	111	42	130	110	69	96
11 (B)	48	22	45	32	66	57
17 (A)	23	1	45	44	19	21
19 (B)	46	3	35	52	26	39
21 (C)	181	74	41	42	4	6

* Not calculated.

Results and discussion

Nitrate concentrations and calculated N leaching

The annual average nitrate concentrations for the six sites during the monitoring period, and the calculated N leaching values for the same years are presented in Table 2. For the relatively wet sites (17, 19 and 21), average nitrate concentrations were mostly below the predefined limit of 50 mg l^{-1}. The values in the table clearly show that similar concentrations can be the result of different amounts of leached N, because of differences in rainfall surplus.

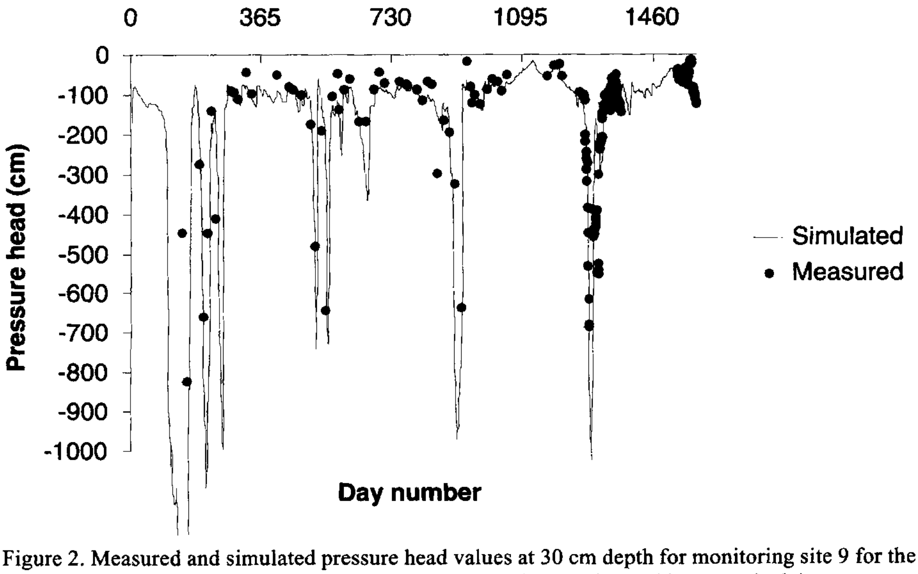

Figure 2. Measured and simulated pressure head values at 30 cm depth for monitoring site 9 for the period 1 January 1991 – 31 March 1995 (day number 1 and day number 1582, respectively).

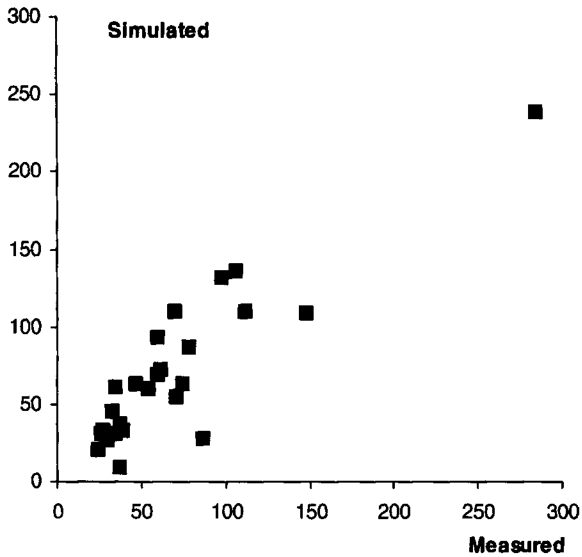

Figure 3. Comparison of simulated and measured seasonal average nitrate concentrations for the six monitoring sites.

Simulation modelling

An example of the calibration and validation results for SWACROP over the entire monitoring and simulation period is shown in Figure 2. Results for all sites are presented by Hack-Ten Broeke *et al.* (1996b). All measurements on soil moisture content and pressure head were used for testing the SWACROP model. The output of ANIMO was compared with measured concentrations and the available data of the N cycle, like N uptake by the crops, mineral N contents in the soil and measured mineralization (Aarts, 1996). For the average nitrate concentrations the result is presented in Figure 3.

Simulation results

Figure 4 shows the results of model simulations for 30 years and 56 fields of 'De Marke' as a frequency distribution of annual farm average nitrate concentrations. The average nitrate concentration was 67 mg l^{-1}, which is similar to the calculated average of 70 mg l^{-1} based on measurements in the upper groundwater by RIVM (Boumans *et al.*, 2001). Furthermore, the frequency distribution of Figure 4 shows that the probability of exceeding the EU standard for drinking water (50 mg l^{-1} nitrate) is 67%. The highest values for the farm average concentrations in Figure 4 are associated with dry weather conditions. The lowest values are mostly found in wet years.

A similar frequency distribution of farm average concentrations was produced for the five homogeneous farms with the selected major sandy soils (Figure 5). The differences between the frequency distributions in Figure 5 are all statistically signifi-

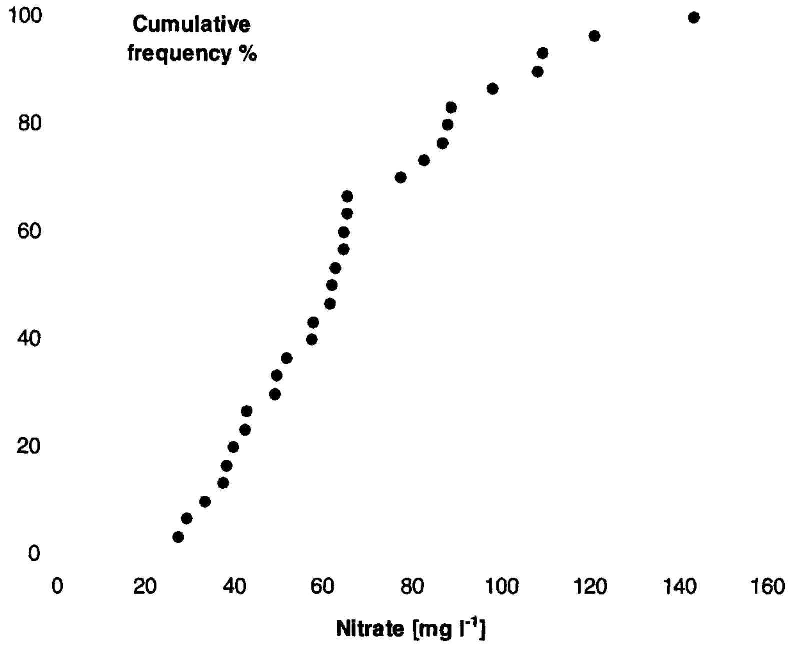

Figure 4. Cumulative frequency distribution of the annual farm average nitrate concentration at 1 m depth for 'De Marke'.

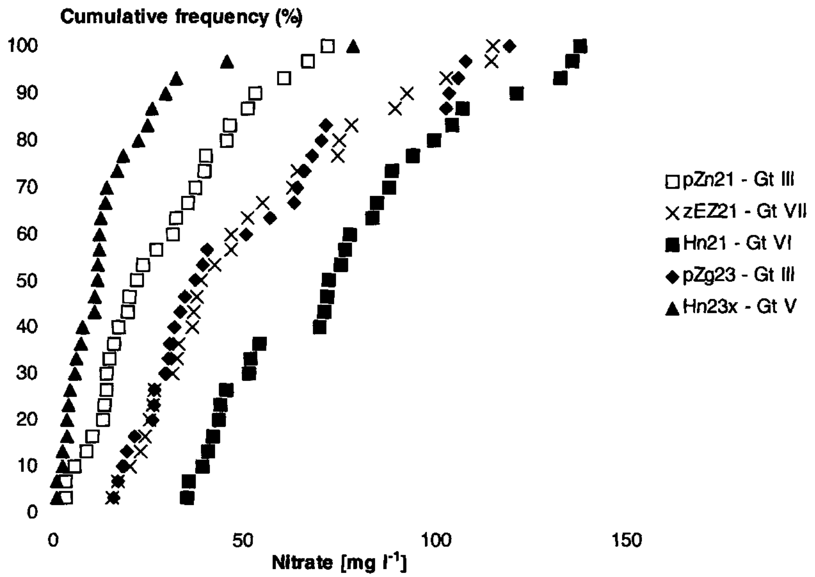

Figure 5. Cumulative frequency distribution of the annual farm average nitrate concentrations at 1 m depth for five soil map units.

Table 3. Annual average nitrate concentrations at 1 m depth for five major soil map units for each farm, parcel type (A, B or C) and crop, and the probability of exceeding the EU norm for drinking water (50 mg nitrate l^{-1}).

Soil map unit	Average nitrate concentration (mg l^{-1})						Probability of exceeding norm of 50 mg l^{-1} (%)
	Farm	A	B	C	Maize	Grass	
Hn21 – VI	76	117	75	58	67	86	73
zEZ21 – VII	50	74	54	33	45	57	40
pZg23 – III	50	83	47	38	41	59	43
Hn23x – V	15	12	18	14	16	16	3
pZn21 – III	28	35	28	26	26	31	17

cant, except for the difference between soil map units zEZ21-VII and pZg23-III. Average concentrations per farm and per parcel type are given in Table 3.

Only for the soil map unit covering the largest area in the Netherlands (Cambic Podzol Hn21-VI), the calculated average concentrations are higher than for 'De Marke'. For all other soil map units, annual average concentrations are lower and the probabilities of exceeding the predefined threshold value are smaller than 50%. It is not clear how the EU standard for drinking water should be used and whether this comparison with the 50 mg l^{-1} nitrate as a threshold value makes any sense. However, this is not relevant for comparing the results of the different soil map units. Table 3 shows distinct differences between crops and between parcel types. The highest average concentrations were always found under the permanent pastures of parcel type A, the lowest always on parcel type C, except for the podzol with boulder clay (Hn23x), where all concentrations were low. The differences are caused by differences in crop rotation, grazing intensity, fertilization and supplementary irrigation. In almost all situations, concentrations were higher under grass than under maize.

Conclusions

1. The calculated annual farm average nitrate concentration at 1 m depth at 'De Marke' was 67 mg l^{-1} and the probability of exceeding the EU standard for drinking water (50 mg l^{-1}) at that depth was 67%. So additional efforts are needed at 'De Marke' to reach the predefined objective for nitrate leaching to the groundwater.
2. For four major sandy soil types of the Netherlands it was calculated that the land use of 'De Marke' would result in lower nitrate concentrations than were realized at 'De Marke'. On a farm with soils of the soil map unit covering the largest area in the Netherlands (Hn21-VI), the concentrations would be higher than at 'De Marke'.
3. Nitrate concentrations were almost always highest under permanent pastures and lowest under parcel type C (with a rotation of three years grass and five years silage maize), as a result of differences in crop rotation, fertilization, grazing and supplementary irrigation. So to reduce the environmental impact of land use it would be worthwhile to locate land use with a high leaching risk, like permanent grassland, on the least vulnerable soils, and vice versa.

4. If it would be considered valid to compare the annual farm average nitrate concentration at 1 m depth with the EU standard for drinking water as an environmental goal, this study would show that on the majority of sandy soils in the Netherlands, the land use system of 'De Marke' would meet this objective.

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