Nutrient Cycling in Agroecosystems **50:** 271–276, 1998.

Evaluation of nitrate leaching risk at site and farm level

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Key words: nitrogen, monitoring, dairy farming, simulation models, risk assessment, soil variability

Abstract

At the ‘De Marke’ experimental farm a dairy farm was set up with the aim of meeting environmental and economic goals. The farm management with respect to nitrogen emphasized reduction of fertilization and a cattle grazing system that should result in nitrate concentrations in the groundwater below the EC-directive level of 11.3 mg l^{-1} nitrate-N. At six sites in six different fields of ‘De Marke’, these concentrations were monitored for 4 years. A direct comparison with the chosen limit was possible for these sites, but an evaluation of the environmental achievements of the farming system at farm level was also required. This was achieved by using simulation models and additional information about soils and field management. Based on multiple soil profile descriptions, frequency distributions of model output were generated, allowing a risk assessment for the total farm. The probability of exceeding the chosen threshold value of 11.3 mg l^{-1} nitrate-N during the period of summer 1991- spring 1995 was 63% for the whole farm, with marked differences between years, crops and hydrological conditions.

Introduction

In the Netherlands, dairy farming is facing serious environmental problems. At ’De Marke’, an experimental dairy farm was set up with the aim of meeting both environmental and economic goals [1]. For nitrogen losses to the groundwater, the farm aims for nitrate-N concentrations in the shallow groundwater below the EC-directive of 11.3 mg l^{-1}. Management of the farm therefore includes, for instance, the reduction of manure and fertilizer applications and growing of a catch crop during winter after silage maize.

A monitoring programme, which would allow an evaluation of the success of the farm in achieving the various goals, was started in 1991. The monitoring included measurements to quantify nitrogen dynamics [2, 6]. Intensive monitoring of nitrogen flows was carried out at six sites, each located in different fields of the farm. This provided local information, whereas the environmental goal was set for the farm as a whole. The data of the six sites were used for validation of simulation models for water and nitrogen behaviour in the unsaturated zone and then these models could be used for extrapolation to farm level.

The purpose of this study is to show how a monitoring programme at site level in combination with simulation modelling and additional information on soil variability allows a risk assessment at farm level.

Materials and methods

Experimental farm

The ‘De Marke’ experimental farm is located in the eastern sand region of the Netherlands on drought-susceptible soils. A soil map of the farm was based on a soil survey carried out for a regular grid with approximately 250 locations [3]. The predominant soil type is a Cambic Podzol with an organic matter content of 3 to 5% in the top soil. Silt + clay contents in the upper layers vary from 8 to 11% in the southern and western parts of the farm and from 10 to 17% in the eastern and northern areas of the farm. Groundwater levels are shallower in the northern region than in the southern part.

The farm area amounts to about 55 ha of which about 9 ha was used as permanent grassland. The rest of the land was used for a rotation of grass, silage maize and fodder beet. The grassland is used for rotational grazing and during these grazing periods the cattle are in the field during 8 hours per day. Supplementary irrigation to ensure grazing was allowed only on grassland near the farm. Fodder beets were grown after three years of grass. The ploughed-in grass sward was expected to increase mineralization and fodder beets were expected to take up this increased amount of N. After one year of fodder beet, silage maize was grown for two to five years with Italian ryegrass as a winter catch crop to prevent nitrate leaching.

The annual N-inputs during the monitored years for grassland were 150 to 275 kg N per ha with slurry and 85 to 200 kg N per ha as inorganic fertilizer [6, 10]. Return of N during grazing ranged from 65 to 155 kg N per ha in dung and urine. N-fixation by white clover in the pastures was estimated to range from 0 to 50 kg N per ha. Deposition is expected to be 50 kg N per ha per year. For silage maize, N-additions with slurry ranged from 40 to 160 kg N and N-additions with inorganic fertilizer from 0 to 30 kg N per ha per year. For fodder beet, only animal manure was applied containing 55 to 240 kg N per ha per year.

Monitoring sites

Based on the soil map, six sites were chosen for monitoring in six fields with different soils, groundwater depths and rotations. Two sites were located in permanent pastures, of which one was in a relatively wet field (groundwater levels varied from 0.0 to 2.0 m depth) and the second site was in a dry field (groundwater levels varied from 0.5 to 2.8 m depth). Similarly two sites were chosen in the rotation area with two or three years of silage maize and the last two sites were located in fields with a rotation with four or five years of maize. Each monitoring site was 20x20 m, within which all measurements on crops, soil, soil moisture and groundwater were performed. For each monitoring site, soil physical characteristics were determined [8] and hydrological measurements, performed on a fortnightly basis, included soil moisture contents, pressure heads and groundwater depths. Nitrate concentrations were measured in soil water samples from suction cups or groundwater samples, which were taken once a month on average [6, 9]. Monitoring was carried out from autumn 1991 to spring 1995.

Modelling

For simulating unsaturated soil water behaviour and nitrogen dynamics, the models SWACROP [4] and ANIMO [11] were used, respectively. Input data for the models (soils, groundwater, crops) were available from the monitoring programme. Furthermore, meteorological data were measured on the farm. The models were calibrated with data from 1991 to April 1993 and the remaining data until spring 1995 were used for validation [9].

Extrapolation to farm level

The data obtained by monitoring of the six sites resulted in local information, but the evaluation of environmental achievements was required for the whole farm. The validated simulation models were used, for extrapolation from site information to field and farm results. Simulations were performed for 211 points of the soil survey grid. The resulting output of these 211 simulation runs is presented as a frequency distribution, which is considered to represent the whole farm including all occurrences of soil variability.

According to the approach for defining functional layers [5], in total 14 sets of significantly different soil physical characteristics were available from the measurements for the six monitoring sites. These sets of characteristics were assigned to all distinguished soil horizons of the soil profile descriptions. Furthermore for each grid point, groundwater levels were derived from the measured levels at the six sites and the soil surface altitude determined at each point [3]. Additional required input data per field were supplementary irrigation, crop data and fertilizer and manure applications, including dung and urine from grazing cattle.

Results and discussion

Monitoring

As an example, the measured nitrate concentrations at the two permanent grassland sites are presented in Figure 1. Measurements for all sites were presented before [6]. In the diagram, the EC-directive which is used as the limit for the farm is presented as well. The measured concentrations at the ‘wet’ site 17 were mostly below the limit, whereas at the dry site 9 this was rarely the case. For the other sites, similar data were registered with smaller standard deviations for

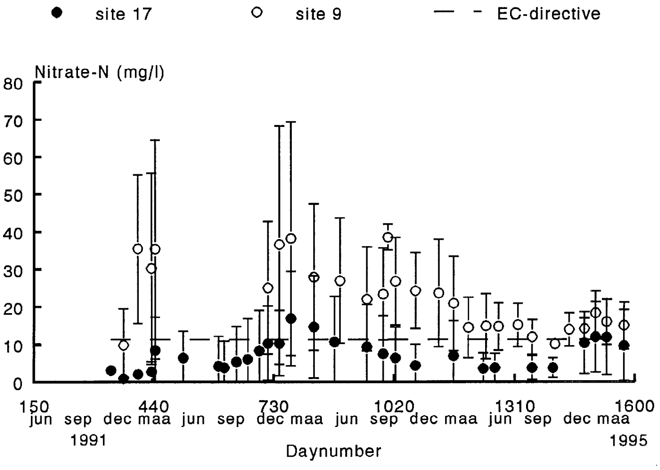

Figure 1. Measured nitrate-N concentrations and standard deviations for two sites in permanent grassland

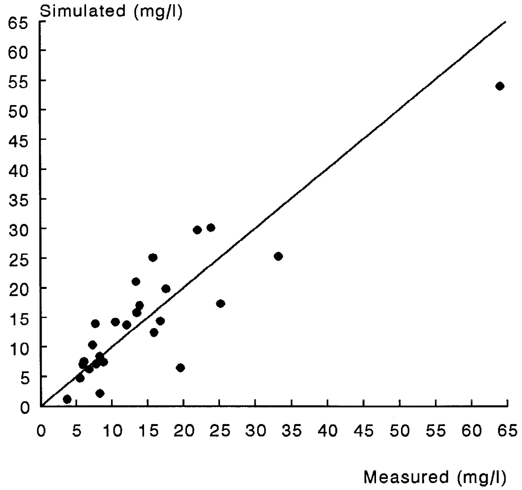

Figure 2. Comparison of measured and simulated annual average nitrate-N concentrations for the six monitoring sites

other crops, but at the wetter sites, the concentrations measured were generally lower than at the dry sites.

Model validation

First the soil water dynamics were simulated with SWACROP and subsequently nitrogen transformations and transport in the soil was simulated with ANIMO. The resulting nitrate concentrations are presented as annual average values per hydrological year (1 April-31 March). Figure 2 shows the comparison between the annual average values of the measurements and the simulations. We considered these results as satisfactory for our purpose of extrapolation.

Results for the total farm

The model output for 211 profiles and 4 years resulted in a frequency distribution of nitrate concentrations at 1 m depth as presented in Figure 3. The limit of 11.3 mg l^{-1} nitrate-N is also indicated, showing that 37% of the simulated values at that depth are below the limit. It should be noted that nitrate concentrations in groundwater will generally be lower than the concentrations at 1 m depth. In Figure 4 the results for the whole farm are split up in three different ways. Considering temporal variability as a result of mainly weather differences and some differences in farm management (e.g. grazing intensity), Figure 4a shows that the differences between years can be rather important. For instance, dilution resulted in relatively low nitrate concentrations in the wet year 1994/95. Next, Figure 4b shows how different crops also resulted in different nitrate concentrations. For grassland, with high N-inputs and N-returns during grazing, simulated leaching was highest. Although it was expected that especially low nitrate concentrations would be achieved with fodder beets the differences between maize (+Italian ryegrass) and fodder beet were small. With regard to the measurements, we expected that the 'wet' sites would result in lower nitrate concentrations than the 'dry' sites (Fig. 4c). In Table 1 the results are presented in terms of risk of exceeding the limit of 11.3 mg l^{-1} nitrate-N. As can be concluded from the steep slopes of the diagrams (Figs.

Table 1. Probability of annual average nitrate-N concentrations at 1 m depth exceeding a threshold value at 'De Marke'

	threshold value	
	11.3 mg per l nitrate-N	22.6 mg per l nitrate-N
total farm:	63%	23%
per simulated year:		
1991	67%	17%
1992	84%	45%
1993	65%	29%
1994	36%	2%
per crop:		
grassland	71%	29%
silage maize	49%	15%
fodder beet	64%	19%
per groundwater depth group:		
'dry'	71%	25%
'wet'	41%	17%

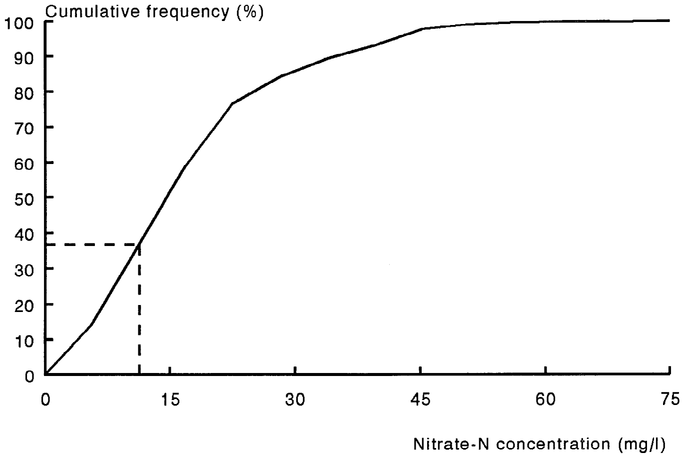

Figure 3. Cumulative frequency distribution of annual average nitrate concentrations at 1 m depth for the whole farm

3 and 4), the exceeding of the limit does not necessarily imply extremely high concentrations. The probability of exceeding the limit twice in Table 1 (22.6 mg l^{-1} nitrate-N) emphasizes this as well.

Conclusions

Use of simulation models enables the extrapolation of local information to farm level. Based on data on soil variability, a frequency distribution of model output can be generated which allows a risk assessment in terms of the probability that a threshold value is exceeded.

Taking the nitrate-N concentration at 1 m depth as an indicator for environmental achievements, it can be concluded that for the 'De Marke' experimental farm as a whole, the probability of exceeding the threshold value of 11.3 mg l^{-1} nitrate-N during the period of summer 1991- spring 1995 was 63%. Differences

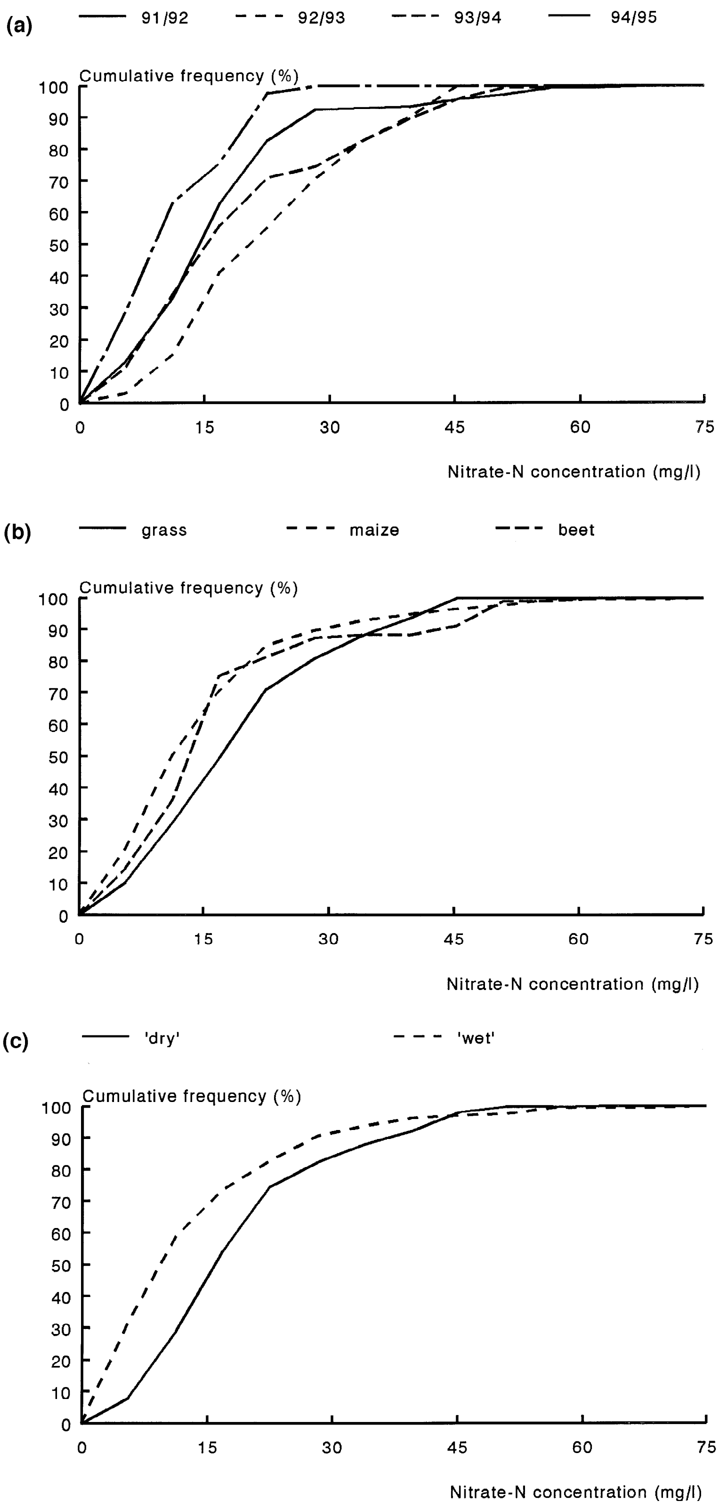

Figure 4. Cumulative frequency distribution of annual average nitrate concentrations at 1 m depth for the whole farm per year (a), per crop (b) and for the 'dry' and 'wet' sites (c)

between years however can be large due mainly to weather conditions (temporal variability). Risk assessments should therefore not be based on too few years.

Especially grazing in pastures resulted in higher nitrate leaching for grassland than for other crops. Reduced fertilization and careful grazing management might reduce nitrate concentrations as was also concluded in former studies [7, 9]. Because the leaching risk is lower in the ‘wet’ areas than in the ‘dry’ areas, allocation of crops and field management accordingly might reduce the overall nitrate leaching risk of the farm.

Acknowledgements

The authors gratefully acknowledge the provision of data by especially ing. G.J. Hilhorst (De Marke) and the cooperation with ir. H.F.M. Aarts (DLO-Institute for Agrobiology and Soil Fertility).

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