Effects of combinations of land use history and nitrogen application on nitrate concentration in the groundwater

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Received 10 February 2003; accepted 24 May 2003

Abstract

Effects of differences in both land use history and levels of nitrogen (N) application on nitrate concentration in the groundwater were studied for permanent pastures located on a single soil series in the Frisian Woodlands in the north of the Netherlands. The study was carried out for three fields: A, B and C. Field A was an old pasture, field B was a reseeded pasture and field C had been previously used for growing silage maize. The models SWAP and ANIMO were used for long-term simulations of the soil organic matter and soil N dynamics. The soil data from fields A, B and C were combined with different N application levels derived from commercial dairy farms on the same soil series for 2000. Soil organic matter and soil organic N were lower in field C than in fields A and B. In field C also the probability of exceeding the environmental threshold for nitrate in groundwater of 50 mg l^{-1} was lowest, which was ascribed to net immobilization irrespective of the high levels of N applied. However, this probability increased rapidly when the soil properties were similar to those of the old pasture (field A). Simulated levels of N uptake were higher for field A than for fields B and C at all levels of N applied. On old pasture, reducing N application levels can lower the probability of exceeding the environmental threshold for nitrate by up to 20% whilst hardly affecting N uptake.

Additional keywords: nitrate leaching, EU nitrate standard, simulation models, grassland

Introduction

Many farmers consider it advantageous to renew ageing swards because of a perceived decline in productivity and quality (Hopkins *et al.*, 1995). Renovation has resulted in a substantial portion of the grasslands in the Netherlands being ploughed and reseeded. In the 1990s, this portion ranged from about 4 to 8% of the total grassland area (Verstraten, 1996; Anon., 2000). Grasslands are on average reseeded every 8 or 9 years and in most cases are not older than 15 years at the time of reseeding (Anon., 2000). Although grassland renovation appears common practice, for decades it has been widely debated among scientists (Minderhoud, 1959). It generally is a costly operation with considerable risk of failure, which sometimes even results in a lower dry matter production than was obtained with the original, ageing sward (Hoogerkamp, 1974; Woldring, 1975; Hopkins *et al.*, 1995). Recently, environmental concerns have resulted in other arguments against grassland renovation (Verstraten, 1996; Vellinga *et al.*, 2000) and even in a complete ban by the Dutch government on ploughing grassland in the period 16 September – 31 January (Anon., 2001). Most of the concerns focus on the fact that ploughing grassland will potentially lead to an increase in the leaching of nitrate to the groundwater, which eventually may affect the quality of drinking water. This is caused by mineralization of organic nitrogen (N) after tillage (Whitehead, 1995). Some evidence for this comes from studies that focused on the conversion of pasture into arable land (Garwood & Ryden, 1986; Whitehead *et al.*, 1990; Lloyd, 1992). On chalk soils in the UK, Cameron & Wild (1984) identified ploughed grasslands followed by winter wheat as a major potential source of nitrate in drinking water. The study of Whitmore *et al.* (1992) even showed that in some parts of the UK, ploughed grasslands were the main source of nitrate leaching to the groundwater. Substantial amounts of nitrate can also be leached from the soil in ley-arable land systems where short grassland periods are alternated with periods of arable farming (Ryden *et al.*, 1984; Francis, 1995; Djurhuus & Olsen, 1997). Although such systems are often favourable for an arable crop like silage maize (*Zea mays*) (Van Dijk *et al.*, 1996), the overall effectiveness may be debatable when large amounts of N are lost following ploughing (Catt *et al.*, 1992). In general, the amount of N mineralized will increase with (1) increasing time the sward has been remained intact, and (2) increasing fertilization rate, whereas it will also be higher after grazing than with cutting (Whitehead *et al.*, 1990). Also the time of ploughing significantly affects nitrate leaching (Whitehead *et al.*, 1990; Jarvis, 2000). When ploughing is followed by a long period of arable cropping, e.g. continuous cropping of silage maize, N losses are in general expected to be substantial. In contrast to arable cropping, grassland renovation involves no annual soil tillage and results in a full canopy cover during subsequent winters (Shepherd *et al.*, 2001). If grassland is reseeded, the increase in nitrate leaching is expected to be mainly short-lived (Vellinga *et al.*, 2000; Jarvis, 2000). This is also confirmed by Shepherd *et al.* (2001) who found that the largest losses through leaching were in the first winter after reseeding; no significant increases in nitrate losses occurred in subsequent years.

Old pastures are expected to have equilibrium levels of organic carbon and organic N in the soil. Estimates of time required for reaching this equilibrium after arable cropping range from 50 to 200 years (Whitehead, 1995). Pastures with organic N levels below equilibrium level will show net immobilization of N. This takes place at rates from 50 to 150 kg N ha^{-1} $year^{-1}$, but initial high rates will decrease as accumulation of organic N is asymptotic (Ryden, 1984; Scholefield *et al.*, 1988; Hassink, 1995).

In old pastures nitrogen immobilization is at equilibrium with nitrogen mineralization. In reseeded pastures and pastures converted from arable cropping, both reduced aeration and lower organic matter contents will lead to lower mineralization rates (Scholefield *et al.*, 1993).

In the area of the northern Frisian Woodlands, farmers have traditionally opposed ploughing grassland for the conversion to arable cropping or ley-arable land systems (Veenenbos, 1949). Especially old pastures were known to have an 'old force' (Edelman, 1949), which withheld some farmers from ploughing their old grassland. Also the fact that in some parts of the fields the less fertile subsoil could be brought to the surface prevented farmers from ploughing and reseeding (Van Der Ploeg, 1999). Nonetheless, during the last decades, grassland renovation and growing silage maize have increased in this area. An earlier study showed a significant relationship between land use history and organic carbon and organic N contents of the topsoil of a major sandy soil series (cHn23) in this area (Sonneveld *et al.*, 2002). Because of increased environmental concerns, some of the reseeded pastures and the pastures established after arable cropping may be used in the future as permanent pasture, i.e., without any cultivation. In terms of nitrate leaching and in comparison with old pastures these ageing swards are likely to respond differently to constant levels of N application over time.

The objective of this study was to describe the effects of both differences in land use history and different levels of N application on long-term nitrate concentrations in the groundwater for cHn23 soils under permanent pasture. This was done using dynamic water and N simulation models. Simulation results will be discussed in the context of the current EU standard of 50 mg l^{-1} for nitrate concentrations in the upper groundwater (Anon., 1991) and MINAS, the Dutch Mineral Accounting System (Van Den Brandt & Smit, 1998).

Materials and methods

Area description and field selection

The region of the Frisian Woodlands is situated on the northern edge of a till plateau and mostly consists of sandy soils with some peaty and clayey soils in the northern part. Using soil survey data from Stiboka (Anon., 1981), it was found that more than 40% of the area belongs to one soil series, cHn23 (Figure 1), which is classified as a Plagganthreptic Alorthod (Anon., 1998). This sandy soil series with its characteristic anthropogenic topsoil is generally regarded as an excellent soil for agricultural purposes. As soils belonging to this soil series are mainly situated on top of the plateau, most of the corresponding hydrological regimes fall into classes Vb and VI, indicating a mean highest groundwater table below 25 cm or 40 cm, respectively, and a mean lowest groundwater table below 120 cm.

From a larger data set (Sonneveld *et al.*, 2002), three fields under pasture (A, B and C) were selected at commercial dairy farms that fulfilled the requirements for the cHn23 series but with different land use histories. Field A was an old pasture where

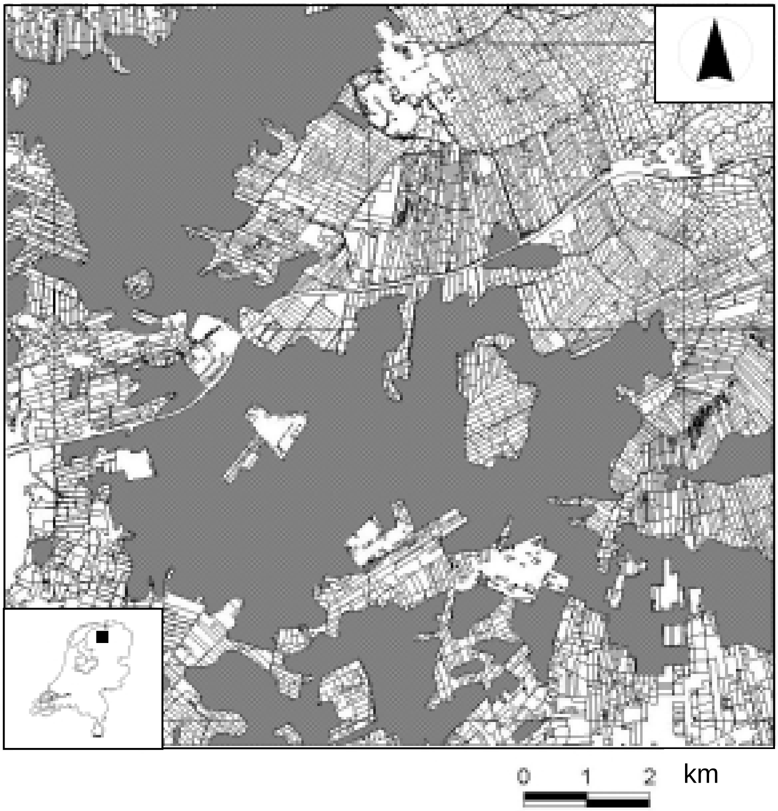

Figure 1. Location of the Frisian Woodlands in the Netherlands and distribution of the cHn23 soil series.

no tillage had been applied for the last 50 years. Field B was a reseeded pasture that had been ploughed and reseeded some 10 years ago, with no other crop for the last 50 years. Field C was a recently established pasture following 12 years of continuous cropping with silage maize. In 2000, samples were taken from all fields from both topsoil (10–20 cm) and subsoil (25 cm – lower boundary of A horizon) and analysed for soil organic carbon and soil organic N contents.

Field management

Data available for the year 2000 of several commercial dairy farms located on the cHn23 soil series were used to calculate mineral surpluses using MINAS. This Mineral Accounting System introduced by the Dutch government to restrict emission of nutrients to the environment involves registration at farm level of N inputs in fertilizers and feed, and of N outputs in products and manure. Three farms were selected (I, II, and III) that differed in calculated N-surpluses: 278, 250 and 203 kg ha^{-1}, respectively. At each of these farms, two fields were selected where in 2000 only cutting and

Table 1. Amounts of N (kg ha^{-1}) applied to the selected fields of each farm for the year 2000, and the assigned N management levels.

Farm	N from fertilizer	N from slurry	Total N	N level
I	141	20	241	1
	284	275	559	6
II	159	168	327	2
	159	336	495	5
III	189	188	377	3
	188	259	447	4

no grazing had taken place. Field management data from these fields were used as input for the simulation models. Amounts of N applied with organic manure (slurry) were calculated using chemical characterization of the slurry from each of the three farms. Amounts of N applied to every field for the year 2000 are given in Table 1. In this table each field has been given a unique N management number (N level) that corresponds with a ranking in total N applied.

Simulation models

To be able to compare the dynamic behaviour of the selected soils the agro-hydrological model SWAP (Kroes *et al.*, 1999; Van Dam *et al.*, 1997) and the N model ANIMO (Groenendijk & Kroes, 1999; Kroes & Roelsma, 1998) were used to simulate water and N fluxes in the soil. Model input for calibration purposes was derived by monitoring – during one year – of soil water contents, weather conditions, grassland management and groundwater level fluctuations in fields A, B and C. Soil hydraulic characteristics were derived by means of pedo-transfer functions. Since the ANIMO model has been calibrated and validated with annual averages (Hack-Ten Broeke & De Groot, 1998) using the model implies that only annual nitrate concentrations in the groundwater will be compared. Homogeneous flow was assumed for the three sites.

A 30-year (1971–2000) climatic data set was obtained from a nearby weather station, and a long-term record of groundwater-level fluctuations was available from a local piezometer at farm I over the same period (groundwater class VI). Farm-specific data regarding the chemical composition of the slurry were used in the ANIMO model. Distribution of organic matter over different pools in the soil was calculated using data from Römkens *et al.* (1999) assuming a carbon content of 0.58 for organic matter. The ANIMO model was further calibrated assuming that following ploughing and reseeding, a 50-year period of permanent pasture would result in the properties of the old pasture of field A for all levels of N application. In a given year, N from fertilizer or from slurry was applied to the soil on days that corresponded with the days of the actual applications in 2000. The nitrate concentrations were calculated for a depth of 1.7 m below soil surface as this depth was mostly within the groundwater zone.

Results and discussion

Field and soil properties

Soil and other characteristics of fields A, B and C are given in Table 2. Total soil organic matter and soil organic N contents for a 1-m soil profile were calculated on the basis of the analyses and the distribution over the various organic matter pools in the ANIMO model. Soil organic matter content was lower for fields B and C than for field A (11 and 21%, respectively). Also soil organic N content was lower for fields B and C (10 and 19%, respectively). When field A was ploughed for arable cultivation, as much as 3.2 t N ha^{-1} could have been lost from the soil profile. Because the effects of increased compaction (and hence higher bulk densities) for site C were not taken into account, N losses will probably be somewhat lower in practice.

Model simulations

Mean annual nitrate concentrations at 1.7 m depth were averaged over the different N application levels and plotted as cumulative frequency curves (Figure 2). Nitrate concentrations in the groundwater varied between years and levels of N application from 0 to 107 mg NO_3 l^{-1}. Frequency distributions for fields B and C were almost similar. On average, field A showed the highest probability of exceeding the nitrate standard of 50 mg l^{-1}. This was also true for each N application level separately. Table 3 lists the probabilities of exceeding an average annual nitrate concentration of 50 mg l^{-1} at 1.7 m depth for the soil map unit (cHn23-Vb/VI) under grassland with different types of land use history and N application levels. These probabilities were derived by linear interpolation between the closest points. Probabilities were generally lower for

Table 2. Field and soil characteristics of fields A, B and C. Soil texture is given for the topsoil, and total soil organic matter and soil organic nitrogen are given for a 1-metre profile.

Field	Land use history	Grassland age	Dominant groundwater class	Texture (particles <)		Total organic matter	Total organic nitrogen
				2 µm	50 µm		
		(years)		- - - - - (%) - - - - -		- - - - - - (t ha^{-1}) - - - - - -	
A	Old pasture	50	Vb	5.2	26.8	392.2	16.5
B	Reseeded pasture	10	VI	5.3	30.5	349.3	14.9
C	Previously cropped to maize	3	VI	3.8	18.8	309.7	13.3

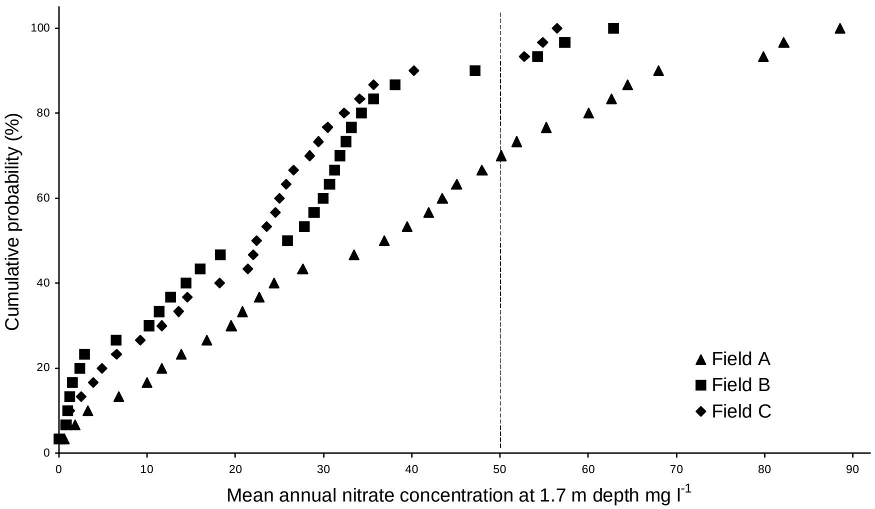

Figure 2. Cumulative probability of the mean annual nitrate concentration at 1.7 m depth for one soil map unit (cHn23-Vb/VI) for the three selected fields. Data are averages over the different levels of N applied. Vertical interrupted line indicates the EU standard of 50 mg l^{-1}.

field C than for the other fields. For field C, higher N levels were not always reflected in higher probability values, as could be expected, but showed fluctuating values. For example, probabilities for N-level 3 were always higher than for levels 1, 2, 4 and 5. This can be explained by the different chemical characteristics of the slurry from each farm while at the same time also total amounts of slurry applied varied among N

Table 3. Probabilities (%) for exceeding an average annual nitrate concentration of 50 mg l^{-1} at 1.7 m depth for soil map unit cHn23-Vb/VI under grassland with different land use histories and amounts of N (kg ha^{-1}) applied. Corresponding N levels are given in brackets.

Field (land use history)	Total N applied					
	241 (1)	327 (2)	377 (3)	446 (4)	495 (5)	559 (6)
Field A (Old pasture)	21.6	18.9	30.2	13.0	19.1	47.1
Field B (Reseeded pasture)	7.1	7.1	8.7	6.7	7.0	13.2
Field C (Previously cropped to maize)	4.8	0.0	7.8	0.0	7.1	9.9

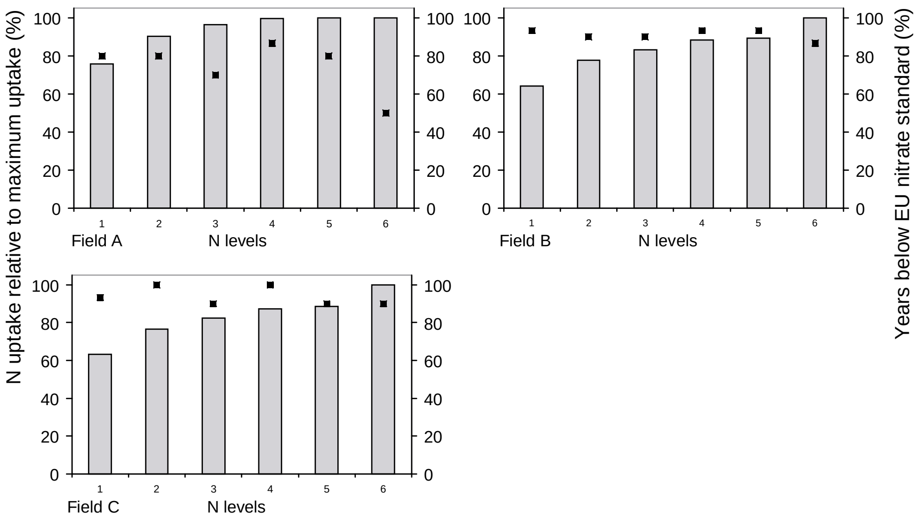

Figure 3. Average relative N uptake (bars – left y-axis) and percentage of years in which the EU standard of 50 mg l^{-1} was not exceeded (square points – right y-axis). Data presented for 6 N application levels and three fields with a different land use history. Field A: old pasture; field B: reseeded pasture; field C: previously cropped to maize. Values for N uptake are relative to the N uptake at the highest N level for field A (100%).

levels. For example, for N-application level 3, only 17% of the total N applied was in organic form whereas all other levels showed values between 20 and 28%. For the highest N application level (level 6), the probabilities for exceeding the 50 mg threshold for a particular field were always higher than for lower application levels. The combination old pasture (field A) with 559 kg N ha^{-1} yielded the highest probability of exceeding the EU nitrate standard (47.1%). Other probabilities for field A were less than half this value, except for N-level 3.

In general the findings are in agreement with Scholefield *et al.* (1988; 1993) who studied the effects of reseeding on nitrate leaching on a clay loam in successive years. In a trial with 400 kg fertilizer N per hectare, Scholefield *et al.* (1988) found that nitrate leaching from an undrained, reseeded sward was a factor 2 lower than from a 40-year old sward. When drainage was included the authors found an even higher reduction in nitrate leaching. Cuttle & Scholefield (1995) reported that nitrate leaching from a grass ley sown after a period of arable cropping was minimal in the second and third year after establishment but increased appreciably in subsequent years in spite of fertilizer inputs remaining unchanged at 200 kg N ha^{-1}. The greater leaching losses from year 4 onwards were assumed to have resulted from an increased supply of N from mineralization of soil organic matter and/or reduced immobilization of fertilizer N. Both processes will also affect the uptake of N by the sward.

For the three fields in our study, also simulated N uptake was given extra consideration. N uptake was always highest for the old pasture (field A) with high levels of N applied (N-levels 4–6). Other N uptakes were calculated per year relative to the ones calculated for field A for these levels. Results were then averaged per field for each level of N application. In Figure 3 the average relative N uptake and the percentage of years in which the EU nitrate standard of 50 mg l^{-1} was not exceeded are plotted for the 6 N levels in each of the 3 fields. N uptake was lowest for the lowest N level in fields B and C (63 and 64%, respectively). N level 6, however, always showed maximum N uptake in all fields. Although leaching to the groundwater at this N level in field C is not much higher than at the other N levels, considerably more leaching is expected when the conditions of the old pasture are met (field A). Moreover, with 182 kg N ha^{-1} less (level 3), a total N uptake close to the maximum can be obtained in field A (96%). For this combination, the probability of exceeding the EU standard is almost 20% lower. If a reduction in N uptake of 10% and a probability of exceeding the EU nitrate standard for groundwater of less than 20% is considered to be acceptable, even 327 kg N ha^{-1} (level 2) can be applied, which is substantially lower than the highest N application level (6). Also the model simulations by Cuttle & Scholefield (1995) showed that any effects of increases in N losses associated with sward age can be avoided provided that fertilizer inputs are lowered to take the increasing supply of N from mineralization of soil organic matter into account.

MINAS

Field management data were from farms with different N surpluses as based on the MINAS system. Both the highest and the lowest level of N application at field level came from farm I, which had the highest MINAS-N surplus. For this farm, probabilities of exceeding the EU nitrate standard varied between about 5 and 47%, depending on the combination of land use history and level of N applied. Farms II and III showed less variation for the same combinations: between 0 and 19% and 0 and 30%, respectively. However, the MINAS surplus standard, which for 2003 is set by the Dutch government at 180 kg N ha^{-1}, probably does not guarantee that the annual average nitrate concentration in the groundwater is always met. Farm III – with a N surplus of 203 kg ha^{-1}, which is close to the final MINAS standard – still will exceed the EU nitrate standard of 50 mg l^{-1} in 30% of the years for the simulated combination of old pasture with N level 3. Such probabilities, however, may be regarded as acceptable.

Final remarks

The results from this study indicate that the cHn23 soils cannot be unambiguously evaluated with respect to the 50 mg l^{-1} nitrate threshold without taking field management and land use history into account. The question as to which probability of exceeding the EU standard is still acceptable from an environmental point of view is not addressed here; we only have presented the data to enable others to make such a judgement. Soil properties are not only related to landscape characteristics as defined by soil genetic processes in traditional soil science, but also to land use to the extent that transformations of N can be significantly different within one soil series. Land use studies using soil maps, including so-called 'representative profiles', also need to pay attention to land use history.

Our study shows that low N application levels are most suitable for old pastures. Such a combination gives relatively high levels of N uptake with a modest probability of nitrate leaching. If the new sward does not take up all mineralized N and if acceptable levels of N uptake are to be maintained over a long period, reseeded pastures may require higher levels of N input. At farm level, the balance between the benefits of feeding a reduced-N diet of maize silage and the risk of increased leaching after ploughing should also be taken into consideration.

Soils can be considered as results of co-production between nature and man and can reflect social and economic processes in society. This opens up a new perspective for soil science. The search for innovative farmers and contrasting types of land use becomes relevant to discover soils that 'fit' in their context of economic and environmental demands. Modern simulation models as used in this study can further characterize their dynamic behaviour. Projects in which both farmers and soil scientists participate to describe and further explore the behaviour of soils, are a useful contribution to the development of sustainable agricultural systems.

Acknowledgements

Frank Verhoeven is acknowledged for providing the farm management data and Frederik De Vries for his contribution to the model simulation work. The authors wish to thank Tom Veldkamp, Mirjam Hack-Ten Broeke and Piet Groenendijk for their useful comments on an earlier version of this paper. The Social Sciences Research Council of the Netherlands Organization for Scientific Research (NWO) supported this study.

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