Netherlands Journal of Agricultural Science 49 (2001) 229-253

Grassland management and nitrate leaching, a model approach

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Received: 5 June 2001; accepted: 11 October 2001

Abstract

To calculate the effect of strategic, tactical and operational grassland management on nitrate leaching, the model Nitrogen, URine and Pastures (NURP) was developed. Data were collected and relationships developed between (i) herbage production, herbage N content and fertilizer input, (ii) N utilization by cattle and N intake, (iii) soil mineral N accumulation and non-harvested N from fertilizers and urine, and (iv) soil mineral N and nitrate concentration in the upper groundwater. Validation of the model shows good agreement with measured data from farms and monitoring programmes. Calculations show that even on dry sandy soils nitrate concentrations of 50 mg l^{-1} in the upper groundwater can be realized by a combination of restricted grazing during the growing season, housing earlier in the season and reduced fertilizer input. The effects of stocking rate, ratio dairy cows:young stock, milk production level, supplementary feeding, drought and urine scorch are discussed.

Keywords: grassland management, nitrate leaching, modelling, urine scorch.

Introduction

Nitrate concentrations in the upper groundwater in the Netherlands are high (Fraters *et al.*, 1998) and should be reduced to values below 50 mg l^{-1} (Anon., 1991). Intensification of agriculture through increased numbers of cows, increased use of chemical fertilizers and ploughing of old grassland for arable land and leys, lead to an increase in nitrate leaching (Ryden *et al.*, 1984; Aarts *et al.*, 1992; Whitmore *et al.*, 1992). On dairy farms there generally is a certain long-term relationship between fertilizer inputs and stocking rates (Van Burg *et al.*, 1981), but in the short term there is a large independent variation among individual farms in stocking rate, milk production level, grazing system, supplementary feeding, the ratio dairy cows:young stock and susceptibility to drought (Reijneveld, 2001). This variation has received little attention in experiments and modelling on nitrate leaching.

The combined effects of grazing and fertilization on nitrate leaching have been studied extensively (e.g. Van Der Meer *et al.*, 1987; Benke *et al.*, 1992; Barraclough *et al.*, 1992; Cuttle & Bourn, 1993; Scholefield *et al.*, 1993; Clough *et al.*, 1996; Hack-Ten Broeke *et al.*, 1996,1999; Vertes *et al.*, 1997). In some experiments the fate of urine N in relation to time of deposition has been studied (Whitehead & Bristow, 1990; Cuttle & Bourn, 1993; Fraser *et al.*, 1994; Clough *et al.*, 1996; Vertes *et al.*, 1997; Simon *et al.*, 1997; Hack-Ten Broeke & Van Der Putten, 1997). Adaptations in operational grazing management based on these findings show clear decreases in nitrate leaching (Titchen *et al.*, 1993; Lord, 1993; Holshof & Willems, 2001). The mentioned experiments suggest that changes in grassland management could be helpful to reduce nitrate leaching on dairy farms. Especially the combination of several management factors is very effective in reducing N surpluses (Aarts *et al.*, 1992). A model with focus on the large variation in grassland management on dairy farms can be very helpful to find the best changes in management to reduce nitrate leaching that are suitable for the individual farm. To calculate the effect of fertilizer level and grazing on nitrate leaching, models have been developed at catchment level (Rodda *et al.*, 1997), at farm level (Van Der Meer & Meeuwissen, 1989; Scholefield *et al.*, 1991; Goossensen & Van Den Ham, 1992), and at plot level (Decau *et al.*, 1997; Delaby *et al.*, 1997). But a model that focuses on a wide range of grassland management aspects, especially for Dutch farming conditions, is not yet available.

So a model was developed that would meet the following requirements:

1. Describes quantitatively the effects of strategic, tactical and operational management on nitrate leaching. The *strategic* factors are stocking rate (dairy cows and young stock) and milk production level. The *tactical* factors include fertilizer level, grazing system and supplementary feeding. The *operational* factors comprise anticipated drought susceptibility, monthly variation in grazing system, N rate per cut, dry matter yield for grazing and cutting, and grazing time per paddock.
2. Pays attention to time effects of urine depositions, to describe effects of detailed operational grazing management.
3. Emphasizes the independent variation in and the interactions between farm management factors.

Such a model, with emphasis on farm management at all levels, is useful to identify the most effective way to reduce nitrate leaching per individual farm. To be used on dairy farms, the model has to be reliable and simple to handle. Because management is the central issue of the model, detailed information will be used in modelling grass production, grazing systems and animal nutrition. Soil processes like denitrification, which cannot be affected by management, are described in a simple way. The working title of the model is Nitrogen, URine and Pastures (NURP).

Firstly, the model structure will be explained. The model is split up in a number of processes, each of which will be described separately and validated by a literature review. Next, an uncertainty analysis and a validation of the complete model are described. Finally, some results of model calculations will be presented and discussed.

Table 1. Aspects of strategic, tactical and operational grassland management on dairy farms.

Management level	Term	Aspects	Acting on
Strategic	Long (> 1 year)	Stocking rate, cows/young stock ratio, milk production level	Farm
Tactical	Intermediate (1 year)	Grazing system, supplemental feeding, annual N rate	Farm
Operational	Short (<< 1 year to 1 day)	N rates per cut, target yields, grazing time per paddock	Paddock

Model structure

Grassland management can be divided into strategic, tactical and operational management, covering long-, intermediate- and short-term decisions, respectively (Huirne, 1990; Kay & Edwards, 1994). Strategic and tactical management concern the whole farm; they are not paddock-specific (Table 1). Operational aspects of grassland management are related to decisions that can vary from paddock to paddock.

In the Netherlands, rotational grazing of dairy cows is quite common. In practice, paddocks are grazed from 3 to 6 days by dairy cows, heifers or calves. So animals are regularly changed over to new paddocks. Grassland is used for both grazing and cutting. Farmers try to have their paddocks grazed twice. Then follows a silage cut, after which the aftermath is grazed again. Grazing residues are often removed by topping. The grass that is not needed for grazing can be cut for silage. This means that changes in grass production, e.g. by drought or reduced N rates, and changes in herbage intake will lead to changes in the amounts of silage.

The model is split up into two parts: (i) the simulation of strategic and tactical management on a farm basis with the month as the unit of time, and (ii) the simulation of operational grassland management with the paddock as basis and the cut as the unit of time.

A simple scheme of part 1 of the model is shown in Table 2. The nitrate concentration in the farm's groundwater is calculated from Soil Mineral Nitrogen (SMN; in kg ha^{-1}), precipitation surplus and a denitrification factor (Table 2, the lowest line).

Table 2. Parameters used for the calculation of the Soil Mineral Nitrogen (SMN) components in the NURP model, and of the nitrate concentration at the end of the growing season.

Calculation	Period	Parameters
$SMN_{grazing}$	Monthly, April – November	Monthly N urine returns, urine covered area, overlap, urine scorch, drought
$SMN_{cutting}$	Annual, end of growing season	Annual N rate, drought, urine scorch
SMN_{total}	Annual, end of growing season	$SMN_{cutting}$ + $SMN_{grazing}$(April-Nov)
NO_3^- concentration	Winter period	SMN_{total}, precipitation surplus, denitrification

SMN is the sum of non-harvested N from fertilization and N from urine (Table 2, the second line from below). The average amount of urine N per ha on the farm is calculated per month and depends on the N intake and utilization per animal, the number of animals, their daily grazing hours and the total farm area. Urine N is not evenly distributed. The urine spots, with high N loads, are scattered over the grazed area. As most of the grassland is grazed several times during the grazing season, urine spots from consecutive grazings may overlap, which locally can lead to extremely high N loads. The combination of urine N returns and urine-covered area, with growth depression by drought and urine scorch, defines the monthly contribution to $SMN_{grazing}$. $SMN_{cutting}$ is calculated for the complete growing season.

In this abstract simulation, strategic and tactical management factors can be varied independently. Average N rates define the $SMN_{cutting}$. Stocking rate, the ratio dairy cows:young stock, milk production per cow and grazing system with supplementation affect urine N returns and urine-covered area, and define $SMN_{grazing}$.

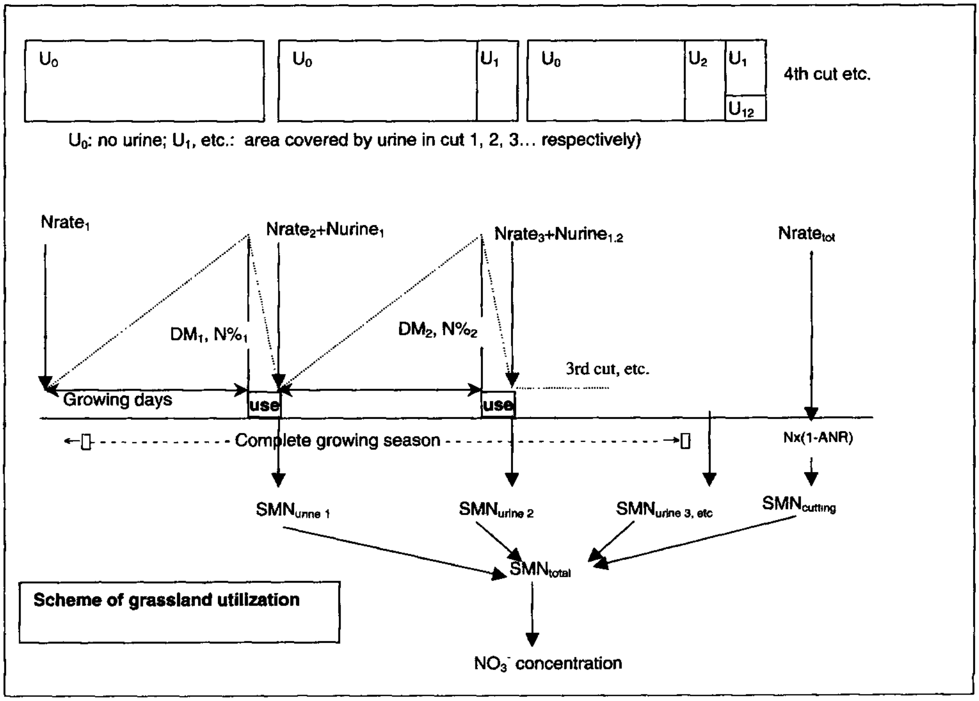


Figure 1. Scheme of grassland utilization with a rotational grazing system, and the way the accumulation of Soil Mineral Nitrogen (SMN) is calculated. N rates per cut consist of effective N from slurry and from chemical fertilizer. After the first grazing, grass production is also affected by N from urine. Dry matter yields per cut and related herbage N content are realized after a number of growing days and are used for grazing or cutting. Total N rates per year are the sum of the N rates per cut. After grazing, part of the area is covered with urine (schematized); after repetitive grazing, overlap of urine spots occurs. SMN originating from urine N is calculated per cut; SMN from fertilizer and slurry N is calculated over all cuts at the end of the growing season. Total SMN is the sum of $SMN_{grazing}$ and $SMN_{cutting}$, and is subject to leaching.

The parameters of the relationship between $SMN_{cutting}$ and $SMN_{grazing}$ on the one hand and tactical and strategic management factors on the other, are derived from simulation of operational management (part 2 of the model), i.e., grass production and utilization per paddock and per cut, as shown in Figure 1. This figure is based on the flow diagram of operational grassland management by Vellinga & Hilhorst (2001).

Slurry and chemical fertilizers are applied per cut. Non-harvested N is an accumulation from several cuts. Grass is used per cut and the herbage N content is the result of N rates and grazing yields per cut. The area covered by urine N and the overlap of urine spots are the result of the grazing time per cut and the number of grazings per paddock. The rules for good operational grassland management as described by Vellinga & Hilhorst (2001) are used as standard in the calculations.

The steps of N uptake per cut, N intake and utilization by animals, the area covered by urine, and the accumulation of SMN are discussed in more detail.

Dry matter yield and N uptake at cutting

N is applied per cut. The N rate per cut is a combination of effective N from slurry and N from chemical fertilizer. The relationships between N rates and N uptake on the one hand and dry matter yield and herbage digestibility for every cut in the grazing season on the other hand, have been derived from growth experiments of Prins *et al.* (1980), Wieling & De Wit (1987), De Wit (1987a; 1987b) and Vellinga (1989). Reduced N uptake by drought is incorporated according to Anon., (1997). Simulation of the grass production per cut, resulting in N rates and dry matter yields per ha per year and N recoveries per year are in good agreement with experimental data of the experiments described by Van Der Meer *et al.* (1987) and Schils *et al.* (1999) (Figure 2).

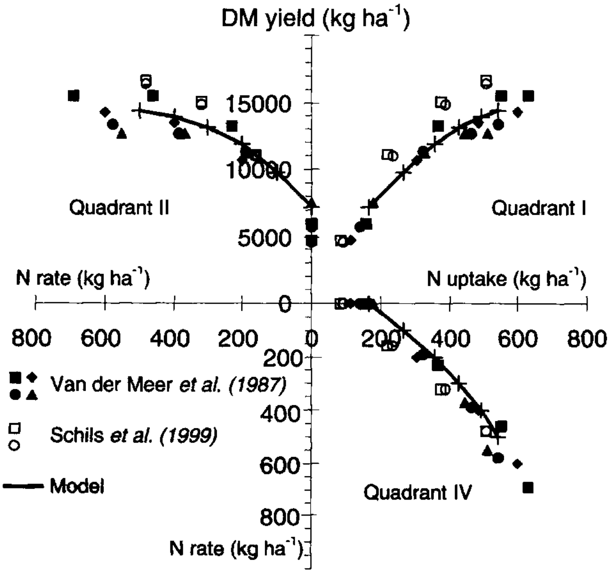


Figure 2. Effects of N fertilizer on N uptake (Quadrant IV), dry matter (DM) yield (Quadrant II), and nutrient use efficiency (NUE) (Quadrant I) for the grass production model (lines) and for the experiments of Van Der Meer *et al.* (1987) (closed symbols) and Schils *et al.* (1999) (open symbols).

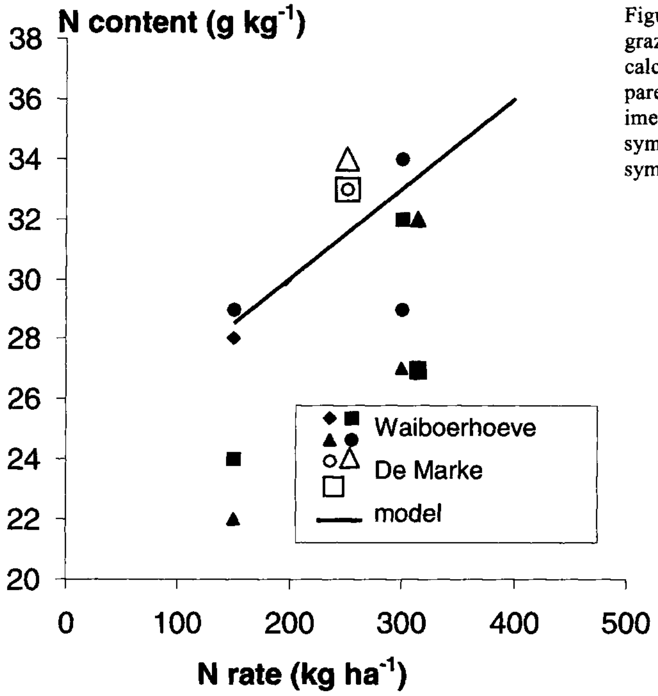


Figure 3. Herbage N content for grazing as affected by N rate. Data calculated by the model (line) compared with data from grazing experiments at the Waiboerhoeve (closed symbols) and at 'De Marke' (open symbols).

Comparison of the calculated herbage N content for grazing with data from grazing experiments on clay (Waiboerhoeve, unpublished data) and at 'De Marke' from 1997–1999 (Vellinga & Hilhorst, 2001) shows a strong year-to-year effect, especially on clay soils. Despite this variation, N content of the herbage is estimated satisfactorily.

N uptake and dry matter yield from urine spots

N uptake and grass production are strongly stimulated in urine spots. The N taken up from these spots is calculated in addition to the N uptake from fertilizers. Urine depositions early in the growing season lead to a higher additional N uptake than depositions late in the season (Figure 4, Van Der Putten, unpublished data; Hack-Ten Broeke & Van Der Putten, 1997). This higher uptake is caused by the good growing conditions in the first half of the growing season and by the long period of N uptake. In the case of early urine depositions apparent N recovery (calculated fraction of deposited N taken up by the grass) is 70% at the most. It decreases to 0 for urine depositions at the end of the growing season. This indicates average apparent N recoveries of 30–35%. Additional N uptake and dry matter (DM) yield are suppressed by increasing N fertilization on the paddock (cf. Cuttle & Scholefield, 1995; Deenen & Middelkoop, 1992). If herbage production is reduced by drought, N uptake from urine spots is reduced proportionally. In the case of overlapping urine spots, additional N uptake is based on the last urine deposition.

Decau *et al.* (1997), reviewing published evidence, calculated an average N recov-

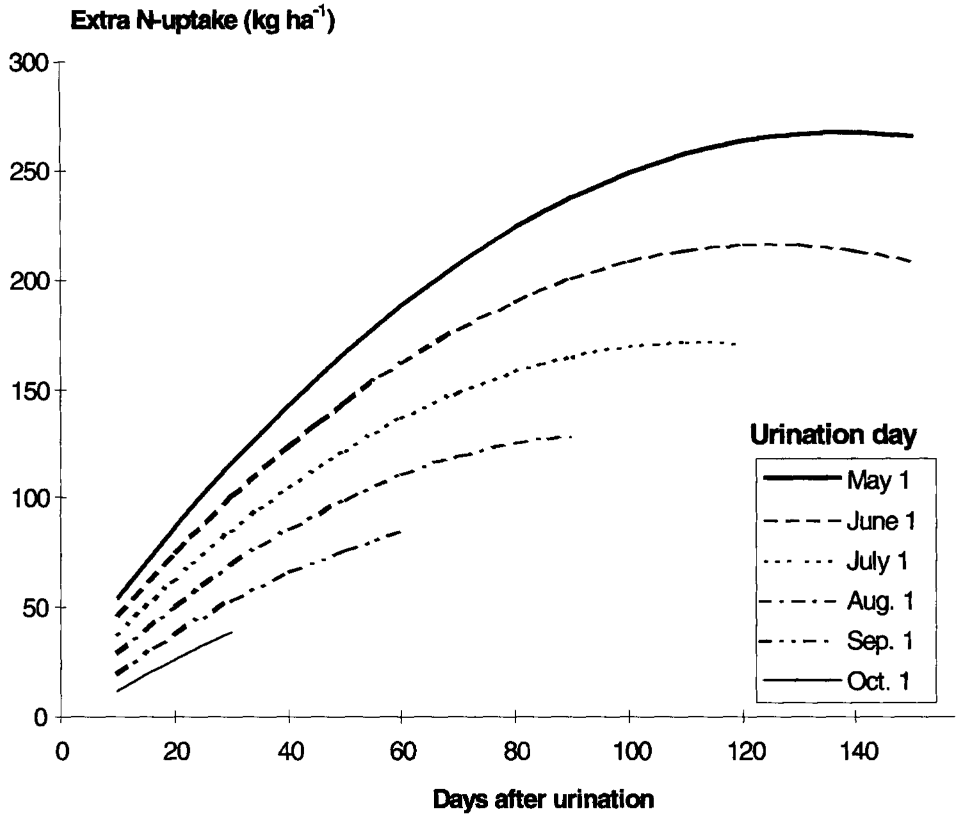


Figure 4. Cumulative additional N uptake from urine spots from different deposition dates. Fertilization level 200 kg N ha^{-1} per year. N load in the urine spots equivalent to 400 kg N ha^{-1}.

ery of 29%. Fraser *et al.* (1994) reported a 43% real N recovery in one year, Whitehead & Bristow (1990) 21% of urine N over the period August-October, and Clough *et al.* (1996) 11–35% from urine spots. These data were derived from experiments using ^{15}N. Experiments with labelled N suggest that Apparent N Recovery (ANR) is often higher than real N recovery, partly as a result of pool substitution of N (Rao *et al.*, 1982). The data obtained by Van Der Putten (unpublished) are in good agreement with the data from the literature.

N from dung hardly contributes to nitrate leaching (Lantinga *et al.*, 1987, Deenen & Middelkoop, 1992).

Grass is more susceptible to urine scorch at high fertilization levels (Lantinga *et al.*, 1987; Deenen & Middelkoop, 1992). Therefore, urine scorch is incorporated optionally in the model. In urine-scorched grass, N uptake from urine and from fertilizer is reduced to 0, which in turn strongly reduces average N recovery from urine. There is no clear relationship between N rate and urine scorch. Moreover, weather conditions play an important role (Lantinga *et al.*, 1987). So a very simple formula was developed in which urine scorch increases from 0% at N rates of 150 to 200 kg

N ha^{-1} per year (half the recommended rates) to 50% in June, July and August at recommended N rates of 350 to 400 kg N ha^{-1} per year. This is similar to 25% urine scorch per 100 kg of N.

N utilization by cows and young stock

N excreted via urine is calculated according to the following equation:

$$N_{urine} = N_{intake} - N_{milk,meat} - N_{dung} \quad \text{(Valk } et\ al.\text{, 1990)} \qquad (1)$$

(all quantities in g kg^{-1} per day)

Intake of N via herbage, supplementary roughage and concentrates for dairy herds and growing young stock is calculated on a daily basis, according to Hijink & Meijer (1987), Mandersloot (1989) and Mandersloot & Van Der Meulen (1991). Energy and protein requirements are calculated according to Van Es (1978) and Tamminga *et al.* (1995). Corrections are made for energy intake by very productive cows (> 7000 kg of milk) (G. Van Duinkerken, pers. comm.). Selective herbage intake results in a 12% higher N intake than calculated herbage intake with an average N content (Meijs, 1980). N output via milk and meat is calculated on the basis of the amounts of protein, dividing these by 6.38 and 6.25, respectively.

N in dung (undigested N and metabolic faecal N) is based on intake and digestibility of N in herbage, supplementary roughage and concentrates. Herbage N digestibility is derived from herbage net energy content. Data from Van Vuuren & Meijs (1987) were used to calibrate N excretion in dung.

Comparison of calculated values of N intake, N in milk and meat, dung and urine, with experimental data from Valk *et al.* (1990) and Delaby *et al.* (1997), shows satisfactory agreement (Figure 5).

Urine production is calculated from urinary N excretion (A.M. Van Vuuren, pers. comm.) using the following equation:

$$U_{day} = 10 + 0.1 \times N_{urine} \qquad (2)$$

where

U_{day} = daily urine production (litres per cow), and

N_{urine} = urine N excretion (g per cow).

Average urine N content varies between 7 and 8 g kg^{-1}. It increases only slightly with increased N excretion, which in turn increases with the amount of urine (Table 3). The average urine N content is in good agreement with average data of Vertès *et al.* (1997), although they found considerable variation.

Area covered by urine spots

For dairy cows the area affected by one urination is assumed to be 0.68 m^2 (Lantinga *et al.*, 1987). For heifers and calves an area of 0.50 m^2 per urination was assumed.

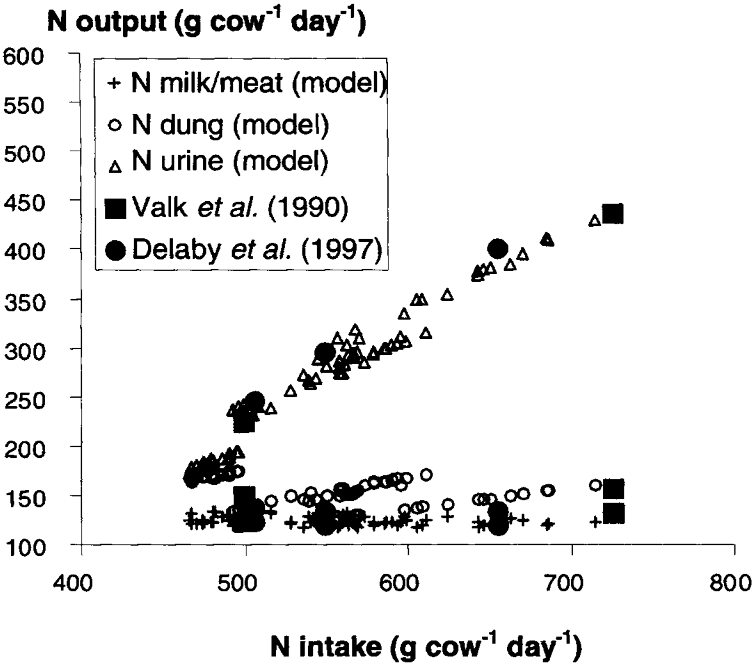


Figure 5. Calculated N production in milk/meat, dung and urine from dairy cows producing 7500 kg milk per cow per year, as affected by N intake via herbage, maize and concentrates. Results compared with data from Valk *et al.* (1990) and Delaby *et al.* (1997).

Amounts of 3.5 and 2.5 kg urine per urination were assumed for dairy cows and young stock, respectively. The calculated N 'load' in urine spots is 340–410 kg N ha^{-1}, which is in good agreement with data of Vertès *et al.* (1997). In paddocks with intensive rotational grazing we assumed no preferential behaviour for grazing and urinating nor overlap within one grazing. But urine spots in one grazing could overlap with urine spots from a previous grazing. The chance of being 'hit' by a urine spot in a second grazing is proportional to the affected and non-affected area in the first grazing. In the case of three grazings, single, double and triple spots are taken into account, and so on. Results of a calculation for seven consecutive grazing events

Table 3. Characteristics of urine depositions in grassland as affected by the N fertilizer level.

	Indication fertilization level (kg ha^{-1} year^{-1})			
	100	225	350	450
N excretion in urine (g cow^{-1} day^{-1})	250	300	350	400
Urine production (l cow^{-1} day^{-1})	35	40	45	50
N concentration in urine (g l^{-1})	7.14	7.50	7.78	8.00
Number of urinations	10	11.4	12.9	14.3
N 'load' under urine spots (kg ha^{-1})	368	387	399	411

Table 4. Areas ($m^2 ha^{-1}$) affected by 0–7 overlapping urine depositions after 7 consecutive grazing periods. Areas calculated by repetitive use (7x) of the non-overlap function, and by the Poisson-distribution according to Richards & Wolton (1976).

	Number of overlapping urine depositions							
Distribution	0	1	2	3	4	5	6	7
Non-overlap (7x)	5863	3253	772	102	8	0	0	0
Poisson	5981	3074	790	135	17	2	0	0

are very similar to those derived from the Poisson distribution developed by Richards & Wolton (1976) (Table 4).

Dairy cows do not graze for the full 24 hours. The fraction of urine deposited in the paddock depends on the grazing system. Day-and-night grazing, day grazing and half-a-day grazing, with 20, 8 and 4 grazing hours, respectively, will lead to fractions of urine deposited in the paddock of 90, 50 and 25%, respectively. Heifers and calves graze for 24 hours and all of the urine is deposited in the paddock. The total area covered by urine is calculated with the following equation:

$$U_t = 0.68 \text{ x } U_{day}/U_{amount} \text{ x } n_{animals} \text{ x days x } \%U \qquad (3)$$

where

U_t = total area covered by urine in one grazing event or in one period (m^2),
U_{day} = urine production per animal per day (litres per animal),
U_{amount} = the amount of urine (kg per urination),
$n_{animals}$ = number of animals during grazing or during one period,
days = actual number of grazing days in the paddock or the number of days in one period, and
%U = percentage of urine depositions in the paddock.

At the end of the management simulations, soil mineral N (SMN) was calculated from non-harvested fertilizer N and from urine N. The next step is to calculate nitrate concentrations from SMN.

Calculation of soil mineral N

N rates and urine N are not completely recovered in the herbage (e.g. Decau *et al.*, 1997; Vellinga & André, 1999) but remain in the soil-plant system. This non-harvested N is partly found back as soil mineral N (SMN) at the end of the growing season (Prins, 1983; Wouters *et al.*, 1995; Tyson *et al.*, 1997; Hack-Ten Broeke *et al.*, 1999). A relationship between non-harvested N and SMN accumulated in the 0–100 cm soil layer at the end of the growing season has been developed for sandy soils using the following equation:

$$SMN_a = -54.5 + 88.3 \text{ x } \exp[-0.0116678\text{x}(SMN_s + N_n)] + 0.774 \text{ x } (SMN_s + N_n)$$
$$(R^2 = 0.85; \text{ residual mean square} = 47.2) \qquad (4)$$

where

$SMN_{a/s}$ = soil mineral N in the 0–100 cm soil layer in autumn (a) and spring (s), respectively, and

N_n = N not harvested in the crop: $[N_{applied} \times (1 - ANR)]$.

Comparison of model results with data from the experiment System of Adjusted Nitrogen Supply (SANS, Hofstede, 1995a, 1995b; Hofstede *et al.*, 1995) showed good agreement. Only for extremely high amounts of precipitation during the growing season – like in1994 – the model overestimates SMN in autumn. The minimum value in the equation is 32 kg N. This value has been adapted for low fertilizer levels to 23 kg N ha^{-1} with data from Wouters & Everts (1996, 1997, 1998, 1999), who observed values below 30 kg N in the 0–100 cm soil layer.

Non-harvested N from the simulation of grass production is used as input in equation (4). The dry sandy soil shows a faster increase in SMN, caused by reduced N uptake under drought (Figure 6). Comparison of the calculated SMN for moist, moderately dry and very dry sandy soils with data on nitrate leaching from Kolenbrander (1981) and Van Der Meer & Meeuwissen (1989) shows that the calculated SMN is higher at low N application rates, but that it increases more gradually with increasing N rate than is suggested by their data (Figure 6). The strong increases in SMN reported by Kolenbrander (1981) and Van Der Meer & Meeuwissen (1989) suggest a

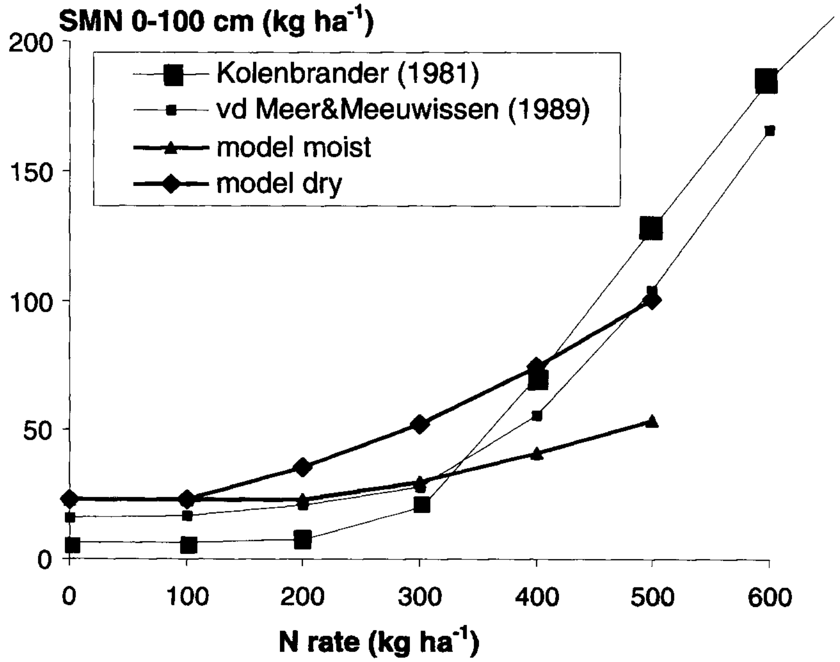


Figure 6. Calculated Soil Mineral Nitrogen (SMN) in autumn in the 0–100 cm soil layer of a dry sandy soil as affected by N rate. Results compared with data from Kolenbrander (1981) and Van Der Meer & Meeuwissen (1989).

strong increase in non-harvested N, indicating a sharp decrease in ANR. This sharp decrease is probably caused by the use of older experiments where ANR was low (Vellinga & André, 1999), or by drought sensitivity. It was concluded that in the range of N rates of 0–450 kg N ha^{-1}, calculated SMN values agree satisfactorily with data from literature.

SMN from urine N is higher in late depositions (Van Der Putten, unpublished data), as shown by the following equation:

$$SMN_a = SMN_{start} \times (-0.296 + 1.2979 / (1 + 0.01841 \times \text{days between urination and 1 November}) \tag{5}$$

where
SMN_{start} = amount of N in kg ha^{-1} directly after deposition in a grazing or in the middle of a period.

SMN decreases very fast immediately following urine deposition. Although Cuttle & Bourn (1993) also reported high initial losses of N, they assume that denitrification, ammonia volatilization and very fast leaching could not fully explain the observed losses. Whitehead & Bristow (1990) assume rapid loss via soil micropores; they measured about 18% ammonia volatilization in about two weeks. Fraser *et al.* (1994) and Clough *et al.* (1996) did not measure these losses, but calculated them via ammonia volatilization (16–56%) and denitrification (28%), to complete the N balance.

Under dry conditions and in case of urine scorch the uptake of N from fertilizer and urine is reduced and the N not taken up is fully added to the SMN.

The relationship between SMN and nitrate concentration

The following equation is applied to calculate nitrate concentration in the groundwater (expressed in mg l^{-1}) from SMN on sandy soils.

$$NO_3^- \text{ concentration} = 62/14 \times SMN \times DNF / \text{Precip.} \times 10^4 \tag{6}$$

where
SMN = Soil Mineral Nitrogen in the 0–100 cm soil layer (kg ha^{-1}),
DNF = denitrification factor, according to Boumans *et al.* (1989),
Precip. = precipitation (mm) during the winter period, according to Van Drecht & Scheper (1998).

As the model focuses on grassland management, no attention is paid to variation in precipitation surpluses among years or to the distribution of the surplus over the winter period.

On lighter sandy soils, Goossensen & Meeuwisen (1990), Barraclough *et al.* (1992) and Cuttle & Bourn (1993) have found good relationships between SMN and nitrate leaching. On sandy soils, SMN in autumn is completely leached during the following winter period (Rück & Stahr, 1996; Holshof & Willems, 2001). On the other hand Lord *et al.* (1995) and Rück & Stahr (1996) hardly found any relationship between SMN and leaching over a range of soil types and crops.

The denitrification factor only corrects for denitrification losses during the winter period. On dry sandy soils little denitrification occurs during that season (Boumans *et al.*, 1989; Corré, 2000) but on moist soils denitrification can be strong (Boumans *et al.*, 1989).

Validation and uncertainty analysis

So far the different steps of the model have been validated. Despite satisfactory agreement between the model formulae and the data from literature, a large variation was sometimes found and validation of the complete model is still necessary.

The number of data sets for validation is limited. However, the monitoring programme carried out by RIVM (Fraters *et al.*, 1998) is based on measurements at about 80 farms over 4 years. Data from 'De Marke' are based on a 6-year period (Boumans *et al.*, 2001). Data are also available for two commercial farms on dry sandy soils.

To show the effects of the variation in the different processes, an uncertainty analysis is carried out by randomizing all essential parameters in the farm approach. Since many data and formulae are derived from other models, it is difficult to give standard deviations for the formulae and parameters used. Instead, for most of them simply a range of + or – 25% was assumed, except for urine scorch and denitrification (Table 5). It is known that the variation in urine scorch can be large and that this variation strongly depends on weather conditions (Lantinga *et al.*, 1987), so a range of + or – 100% was used. As denitrification in grassland also shows large variations (Velthof, 1997), a range of + or –50% was assumed. Standard deviations of precipitation are 30 to 35% of the total precipitation over a 3-month period and 20% over one year. For the leaching period November-March we assumed a range in precipitation of 25%.

To show as clearly as possible the effects of a very high N return via urine, day-and-night grazing with dairy cows and young stock was simulated. N rate was at recommended levels, but no drought was assumed. The model was run 200 times, randomizing the parameters listed in Table 5.

Table 5. Ranges of the parameters used for the uncertainty analysis of the NURP model.

Formulae/parameters	Process	Range
N uptake by grass from fertilizer and slurry	A	+/– 25 kg N ha^{-1} (Schils *et al.*, 1997)
N uptake by grass from urine spots	A	+/– 25 %
N surplus in the animals ration	B	+/– 25 %
Size urine spot	C	+/– 25 %
Urine scorch	C	+/– 100 %
$SMN_{cutting}$	D	+/– 25 %
$SMN_{grazing}$	D	+/– 25 %
Precipitation surplus in the leaching period	E	+/– 25 %
Denitrification correction	E	+/– 50 %

Results and discussion

Model validation

Comparison of the farm model with results of extensive measurements by the National Institute of Public Health and the Environment (RIVM; Fraters *et al.*, 1998) is shown in Table 6 and Figure 7. The method of Fraters *et al.* (1998) is based on N surpluses, so the fertilizer levels from NURP were translated into N surpluses. It was assumed that up to a fertilizer level of 340 kg N ha^{-1} per year, 1 kg increase in N-fertilizer leads to an increase of 0.7 kg N surplus. This is in agreement with the data from Willems *et al.* (2000). For fertilizer levels above 340 kg N ha^{-1} per year it was assumed that each kg fertilizer N increases the N surplus by 1 kg, because at such levels additional dry matter yield production on dry sandy soils is very low. In their regression model, Fraters *et al.* (1998) neither defined a grazing system nor a stocking rate. We calculated the effect of day-and-night grazing and of day grazing with a fixed stocking rate of two cows per ha, with associated young stock (ratio dairy cows:young stock = 1:1).

For day-and-night grazing, the model calculates equal or higher nitrate concentra-

Table 6. Input data for the NURP model to calculate the nitrate concentration in the upper groundwater for 'De Marke' and for dairy farms on dry sandy soils, according to Fraters *et al.* (1998), and the calculated nitrate concentration for 'De Marke'.

	'De Marke'			Fraters *et al.* (1998)		
Area (ha)	31			20		
Fertilizer level (kg ha^{-1})	250			80–450		
Groundwater table depth (m)	1.20–2.00 (min–max)			–		
Yield reduction by drought (%)	15			21		
Animals:	Dairy cows	Heifers	Calves	Dairy cows	Heifers	Calves
Number	65	21	22	40	19	20
Milk production (kg cow^{-1} year^{-1})	8500			6500		
Grazing regime						
April	H[1]	H	H	H	H	H
May	D+6[2]	DN	H	DN/D+4[3]	H	H
June	D+6	DN	DN	DN/D+4	DN	DN
July	D+6	DN	DN	DN/D+4	DN	DN
August	D+6	DN	DN	DN/D+4	DN	DN
September	D+6	DN	H	DN/D+4	DN	H
October	H	DN	H	DN/D+4	DN	H
November	H	DN	H	H	H	H
Calculated NO_3^- conc. (mg l^{-1})	65			See Fig. 7		
Measured NO_3^- conc. (mg l^{-1})	63			See Fig. 7		

[1] Housed.

[2] Day grazing with 6 kg DM of maize silage as supplement.

[3] Day-and-night or day grazing, with 4 kg DM of maize silage as supplement.

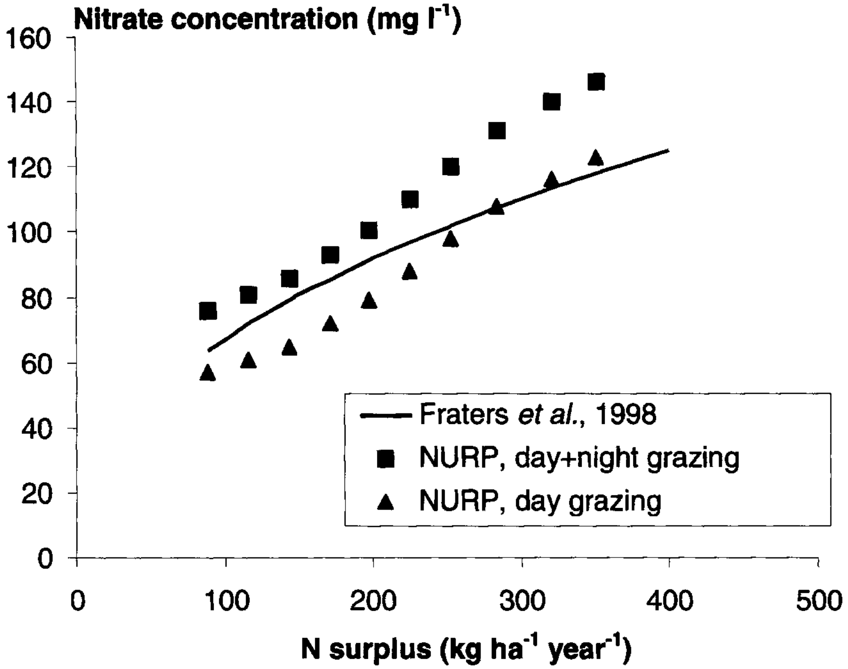


Figure 7. Nitrate concentration in the upper groundwater as affected by the N surplus at farm level. Measurements by Fraters *et al.* (1998) compared with data calculated by the NURP model for two grazing systems on dry sandy soils.

tions than found by Fraters *et al.* (1998) for the complete range of fertilizer levels, while for day grazing equal or lower values are calculated (Figure 7).

The regression model of Fraters *et al.* (1998) shows that the relation between fertilizer level and nitrate concentration levels off. This could be associated with a change in grazing system. Extensive farms – with low surpluses – probably prefer day-and-night grazing, whereas intensive farms – with high surpluses – prefer day grazing. Another reason could be that in the lower surplus range increasing surpluses are related to increasing stocking rates, but this is not the case in the higher surplus range.

It can be concluded that the steeper slope of our model (Figure 7) is not in contradiction with the results of the RIVM measurements.

Using characteristics of the 'De Marke' dairy farm (Table 6), the NURP-calculated nitrate concentration on grassland is on average 65 mg l^{-1}. The measurements described by Boumans *et al.* (2001), and corrected for weather conditions, show an average nitrate concentration of 63 mg l^{-1}. Reported average values for the different years at 'De Marke' are affected by changes in the paddocks used (Boumans *et al.*, 2001; Aarts *et al.*, 2001). This can lead to somewhat lower nitrate concentrations. The results of our model thus appear in good agreement with measured data. Model calculations by Hack-Ten Broeke *et al.* (1999) show similar results, with an average nitrate concentration for grassland of 67 mg l^{-1}.

In the autumn of 1999, SMN was measured on two dairy farms on slightly to moderately dry sandy soils near Mander, in the vicinity of the Dutch-German border. The necessary farm characteristics used as input for the NURP model, and the calculated and measured SMN are shown in Table 7. Calculated and measured SMN on grassland are virtually identical for both farms, although there is variation among paddocks.

Uncertainty analysis

The uncertainty analysis shows that the nitrate concentrations are normally distributed with an average of 94 mg l^{-1} and a standard deviation of 24.9 mg l^{-1}. This large deviation makes that effects of changes in management are difficult to measure, which is confirmed by experiments of Holshof & Willems (2001). The day-and-night grazing of dairy cows causes a large contribution of $\text{SMN}_{\text{grazing}}$ to the nitrate concentration. Similar large variations have been found by Fraters *et al.* (1998).

If the range of individual parameters is reduced to 0, the standard deviations decrease only slightly. Only if a range in precipitation or denitrification is omitted, the standard deviation is reduced to 18–19 mg l^{-1}. If both parameters are kept constant, the standard deviation is reduced to about 10 mg l^{-1}.

Table 7. Input data for the NURP model to calculate Soil Mineral Nitrogen (SMN) at the end of the growing season, and the measured and calculated SMN values for two dairy farms in Mander.

	Farm A			Farm B		
Area (ha)	25.5			21.4		
Fertilizer level (kg ha^{-1})	282			296		
Groundwater table depth (m)	0.40–1.20 (min–max)			0.60–1.50 (min–max)		
Yield reduction due to drought (%)	5			11		
Animals:	Dairy cows	Heifers	Calves	Dairy cows	Heifers	Calves
Number	49	19	20	45	15	15
Milk production (kg/animal/year)	8000			8000		
Grazing regime						
April	H[1]	H	H	H	H	H
May	DN+3[2]	H	H	D+5[3]	H	H
June	DN+3	DN	DN	D+5	DN	DN
July	DN+3	DN	DN	D+5	DN	DN
August	DN+3	DN	DN	D+5	DN	DN
September	DN+3	DN	H	D+5	DN	H
October	D+5	H	H	D+5	H	H
November	H	H	H	H	H	H
Calculated SMN (kg ha^{-1})	74			62		
Measured SMN (kg ha^{-1})	78			61		

[1] Housed.

[2] Day grazing with 5 kg DM of maize silage as supplement.

[3] Day-and-night grazing, with 3 kg DM of maize silage as supplement.

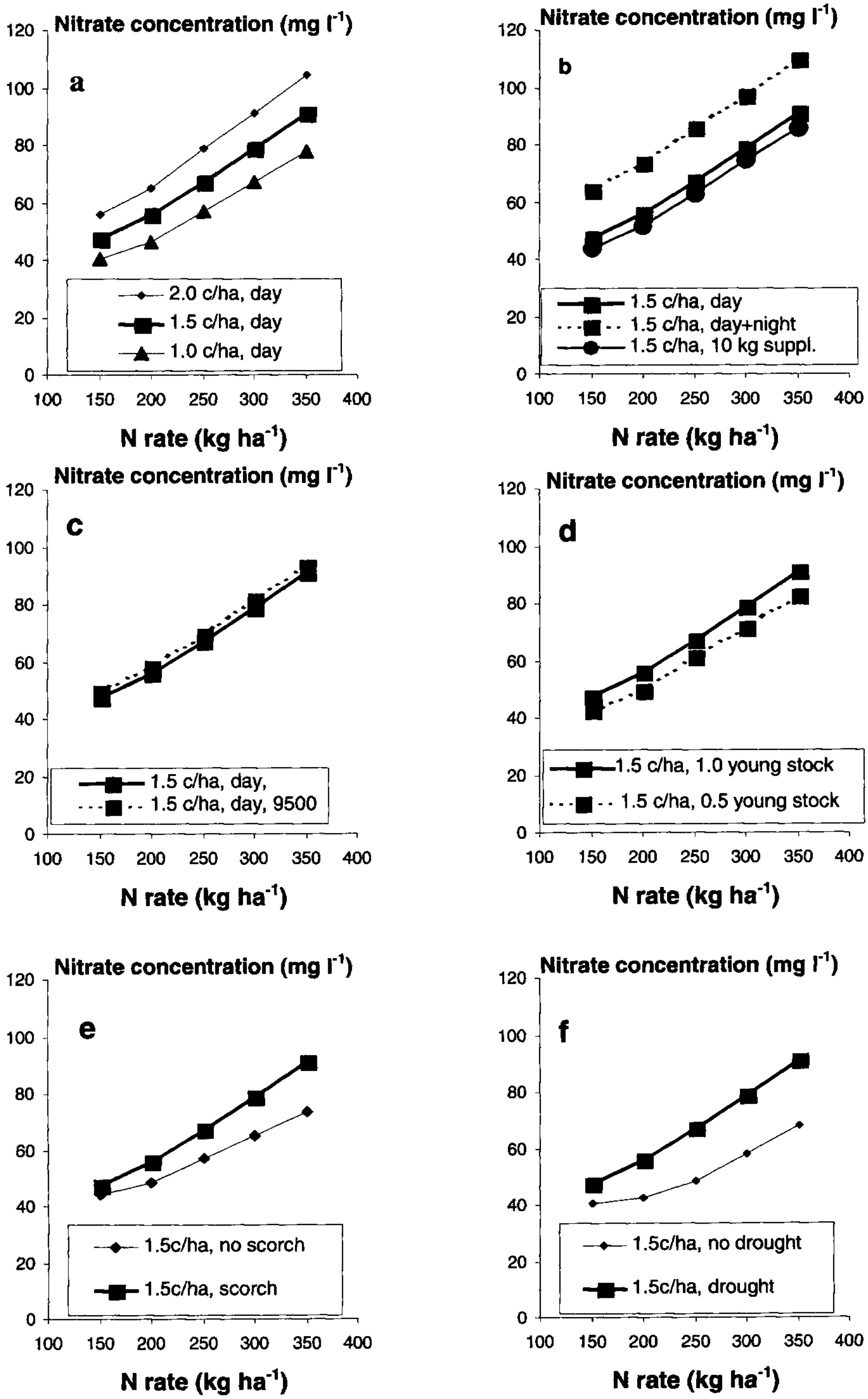
Effect of changes in grassland management

When analysing experiments, the effects of fertilization level and stocking rate are often confounded (Barraclough *et al.*, 1992; Simon *et al.*, 1997). With NURP these effects can be separated (Figure 8a). Calculations were performed for a situation on dry sandy soils comparable with 'De Marke', with dairy cows with an average annual milk production of 7,500 kg, grazing by day only, and with 4 kg DM of maize silage as supplementary feed. The ratio dairy cows:young stock was 1:1. Doubling the stocking rate from 1.0 dairy cow (+ young stock) to 2.0 dairy cows per ha, at N fertilizer levels of 150 and 350 kg N ha^{-1}, results in an increase of the calculated nitrate concentration of 16 and 27 mg l^{-1}, respectively. Increasing N fertilizer level at constant stocking rate leads to doubling of the nitrate concentration, from 39 and 56 to 78 and 105 mg l^{-1} for the low and high stocking rate, respectively. A marked increase in nitrate leaching from 40 to 88 mg l^{-1} as a combined effect of increasing stocking rate (from 1.0 to 1.5 cows per ha) and – to meet fodder demand – increasing fertilizer application (from 150 to 350 kg N ha^{-1}), is also found in literature (Vertès *et al.*, 1997). This suggests that extensification is an effective way to reduce nitrate leaching.

The importance of grazing is also shown in Figure 8b. Increasing grazing time from 8 to 20 hours per day and reducing protein-poor supplements, leads to a strong increase of urine N and consequently to a strong increase in nitrate concentration in the upper groundwater. Reduction of grazing time has been mentioned as an effective way to reduce nitrate concentrations (Aarts *et al.*, 1992). Increasing low-protein supplementation to 10 kg dry matter per cow per day leads to only a very small reduction in nitrate concentrations.

Increased milk production per cow at the same stocking rate slightly increases nitrate concentrations (Figure 8c) and seems an ineffective way to reduce nitrate concentrations. But with a fixed milk quotum per ha, increased milk production will lead to lower stocking rates and thus to lower nitrate concentrations. Keeping less young stock is another way to reduce grazing and also is an effective way to reduce nitrate leaching (Figure 8d). On many dairy farms in the Netherlands the ratio dairy cows:young stock is high, i.e., between 0.8 and 1.0. On these farms reducing young stock is effective. On farms with low replacement ratios, like organic farms, further reduction is not possible.

Vellinga & Hilhorst (2001) have discussed operational grassland management. Farmers tend to graze at low dry matter yields, and growing periods between cuts are short. The effect on nitrate leaching, however, is small. At N rates of about 200 kg N ha^{-1} more cuts per year hardly affect N uptake, but herbage N contents are increased and annual dry matter yield is decreased (Vellinga & André, 1999). The higher herbage N content leads to higher N uptake by grazing animals and to higher urine N returns. So $SMN_{grazing}$ is expected to increase. In many cases dairy cows are offered low-protein supplements and the effect of the increased herbage N content is limited because of the lower herbage intake. In case of grazing by day only, half of the excreted N is not returned to the paddock. So in general the effect of grazing at low dry matter yields will lead to a limited increase in SMN and in leaching.


Nitrate concentration (mg l^{-1})
N rate (kg ha^{-1})
0
20
40
60
80
100
120
100
150
200
250
300
350
400
a
2.0 c/ha, day
1.5 c/ha, day
1.0 c/ha, day
b
1.5 c/ha, day
1.5 c/ha, day+night
1.5 c/ha, 10 kg suppl.
c
1.5 c/ha, day,
1.5 c/ha, day, 9500
d
1.5 c/ha, 1.0 young stock
1.5 c/ha, 0.5 young stock
e
1.5c/ha, no scorch
1.5c/ha, scorch
f
1.5c/ha, no drought
1.5c/ha, drought

The main disadvantage of grazing at low dry matter yield is that low yields force the farmer to apply extra N or to buy extra forage. As was shown, extra N will lead to increased nitrate leaching.

In the foregoing the importance of reduced grazing was demonstrated. Following the introduction of automatic milking, many farmers tend to house the dairy cows permanently. As a reaction, the Ministry of Agriculture, Nature Management and Fisheries and the farmers organizations want to stimulate grazing. From this point of view it is interesting to know whether reduced grazing at the end of the growing season will be more effective in reducing nitrate concentrations than reduced or no grazing during the whole season. On most dairy farms in the Netherlands grazing is continued until 1 November. Grazing of dairy cows at 'De Marke' already stops on 1 October, and from the year 2000 onwards the dairy cows are kept indoors after 1 September. Simulation results with NURP (Figure 9) show that if dairy cows are housed one month earlier and heifers are also housed on 1 September instead of 1 December – under otherwise similar conditions – nitrate concentration will decrease from 65 to 54 mg l^{-1}. Titchen *et al.* (1993), Lord (1993) and Holshof & Willems (2001) have reported similar effects of earlier housing.

To realize a further reduction in nitrate concentration, grazing should be further restricted or fertilizer level should be reduced. Decreasing the fertilization level from 250 to 200 kg N ha^{-1} will reduce nitrate concentration from 54 to 42 mg l^{-1}. Zero grazing of all animals will reduce the nitrate concentration to 32 and 26 mg l^{-1} at fertilization levels of 250 and 200 kg N, respectively. These results show that with a judicious combination of reduced fertilizer inputs and restricted grazing, a nitrate concentration below 50 mg l^{-1} in the upper groundwater can be realized.

Effect of scorch and drought on nitrate leaching

The contribution of urine scorch to the fertilizer effect on nitrate concentrations is substantial. If the fertilizer level is increased from 150 to 350 kg N ha^{-1}, nitrate concentration increases from 48 to 91 mg l^{-1} (Figure 8e). If no urine scorch would occur, nitrate concentration would increase from 45 to 74 mg l^{-1}, i.e., about one third of the concentration increase is associated with urine scorch.

Both urine scorch and drought affect N uptake from urine spots. Drought reduces grass growth, so less N is taken up and more nitrate is leached. In the standard situation of 1.5 cow per ha at N rates from 150 to 350 kg ha^{-1}, the nitrate concentration increases from 48 to 91 mg l^{-1} when drought reduces growth, and from 40 to 68 mg

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Figure 8. Nitrate concentration in the upper groundwater on a farm with dry sandy soils as affected by N fertilizer levels. The thick line in all figures (a-f) represents day grazing dairy cows with 4 kg DM silage maize as supplementary feed, a milk production level of 7500 kg per cow per year, a stocking rate of 1.5 cows per ha, and a dairy cows:young stock ratio of 1:1 on a dry sandy soil with occurrence of urine scorch. The figures a-f represent combinations of the basic situation with: a. Stocking rates of 1.0 and 2.0 cows per ha. b. Day-and-night grazing dairy cows without supplementary feeding and day grazing with a supplement of 10 kg DM from silage. c. A milk production level of 9500 kg per cow per year. d. A dairy cows:young stock ratio of 1:0.5. e. A situation without urine scorch. f. A situation without drought.

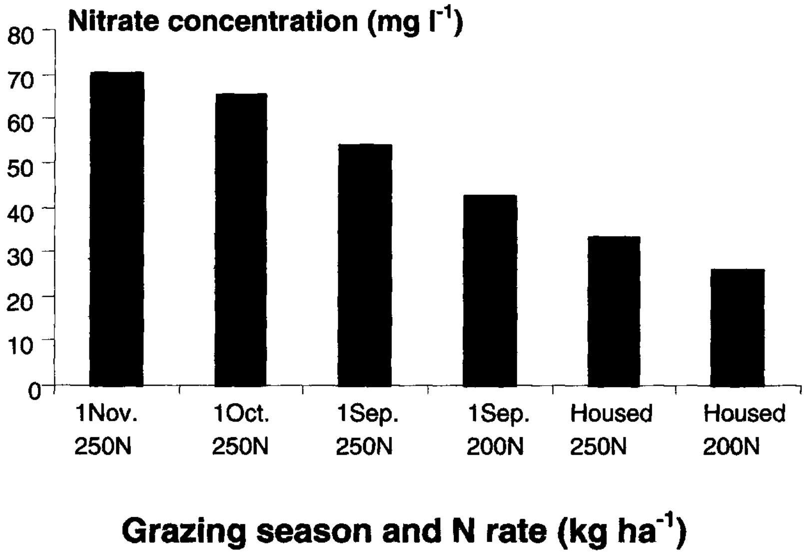

Figure 9. Nitrate concentration in the upper groundwater of dry sandy soils for different combinations of grazing season and N fertilizer rate. Cows and heifers housed all the time (Housed) or housed from 1 November, 1 October or 1 September.

l^{-1} when grass production is not reduced (Figure 8f). Without drought, the increase in nitrate concentration is only two thirds of the increase in case of drought.

Aspects of other models versus NURP

The model NURP provides the possibility to simulate every dairy farm. The model emphasizes a wide range of strategic, tactical and operational grassland management. To reduce nitrate leaching, independency of management factors is important for the development of management strategies for many types of dairy farms. Many models have paid attention to the technical aspects and very clearly showed the impact of fertilization and grazing on nitrate leaching (e.g. Van Der Meer & Meeuwissen, 1989). In our model we also incorporated the effect of the time of urine depositions on accumulation of SMN and on subsequent leaching. In the UK, Scholefield *et al.* (1991) developed a broadly oriented model that incorporated soil type, climate and some management factors, but also changes in land use by the use of leys.

Some authors developed relationships between N fertilizer level and nitrate leaching (Kolenbrander, 1981; Van Der Meer & Meeuwissen, 1989). But Prins (1983) and Tyson *et al.* (1997) for instance showed that it is better to work with non-harvested N from fertilizers and urine N. The use of non-harvested N as input for SMN also made it possible to pay attention to N uptake reduced by drought and urine scorch. As was shown, the effects of drought and urine scorch on nitrate leaching are substantial and cannot be neglected.

Other models (Scholefield *et al.*, 1991; Decau *et al.*, 1997; Delaby *et al.*, 1997) have incorporated the effect of white clover on the N contribution to the sward and on nitrate leaching. Cuttle (1992) and Cuttle *et al.* (1992) found little difference in nitrate leaching between clover- and fertilizer-based swards of similar stock carrying capacity. According to Cuttle & Scholefield (1995), the advantage of clover-based swards is more associated with less intensive grassland systems than with a lower nitrate leaching at comparable levels of N flow in clover- and fertilizer-based swards. Although it is a simplification, the contribution of white clover, i.e., N fixation, to nitrate leaching in the NURP model can be estimated on the basis of its contribution to total N input. However, Cuttle & Jarvis (1995) modify this statement by assuming a feed-back system, which reduces N fixation in urine spots – thus preventing a 'double load' of N – and leads to lower values of nitrate leaching than would be the case with fertilizers.

Grassland renovation can result in small losses due to enhanced mineralization caused by ploughing, which in turn can lead to a small increase in nitrate leaching. Ernst & Berendonk (1991) measured nitrate-leaching values of 5–15 kg N ha^{-1} following grassland renovation in spring, increasing nitrate concentration from 18 to 21–29 mg l^{-1}. Nitrate leaching following grassland renovation in autumn was more than three times higher (exceeding 50 kg N; nitrate concentrations of 53–60 mg l^{-1}). Possibly, the small losses are the result of a combination of increased leaching during the renovation phase, increased N uptake by the new grass sward and increased immobilization. If 10% of the grassland area is renovated every year, nitrate concentration will increase by about 1 to 4 mg l^{-1}, following renovation in spring and autumn, respectively. Although the effect of grassland renovation is not as strong as that of grazing and fertilizer level, it should not be neglected.

Ploughing grassland for arable crops can lead to substantial increases in nitrate leaching (Whitmore *et al.*, 1992; Hoffman, 1999). N losses are higher under older grassland than under young grassland (Whitehead *et al.*, 1990). Under young grassland and under ley–arable crop rotations, immobilization levels are higher and consequently nitrate leaching lower (Scholefield *et al.,* 1993). N losses associated with grassland renovation and ley-arable crop rotations are not incorporated in NURP. Especially if grassland is renovated in autumn, and older grassland is ploughed up to grow silage maize, the effects on nitrate concentrations can be substantial, and thus have to be incorporated in the model.

Summarizing, the model NURP is a useful tool in research and extension work to reduce nitrate leaching. A wide range of management factors can be varied independently and attention is paid to interactions between the various factors. The conclusion that fertilizer input and grazing are important factors is not new, nor surprising. However, the largest advantage of the model is its possibility to develop effective combinations of management measures to realize the reduction in nitrate leaching. The model validation showed satisfying results. The uncertainty analysis made clear that, although promising management strategies to reduce nitrate leaching can be developed, there is no guarantee that this will always happen in practice.

Acknowledgements

We would like to thank the Research Institute for Animal Husbandry (PV) in Lelystad and Plant Research International in Wageningen for their permission to use the data for this publication.

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