Nitrate leaching from dairy farming on sandy soils

Case studies for experimental farm De Marke

Promotor: Dr.Ir. J. Bouma
hoogleraar in de bodeminventarisatie en landevaluatie

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ABSTRACT

The main problem with nitrogen (N) at dairy farms on sandy soils in the Netherlands is the leaching of nitrate to the groundwater. Experimental farm De Marke was set up in 1991 on poor sandy soils with the objective to develop a prototype of an economically feasible farming system with acceptable nutrient losses. For the quantification of the inputs and outputs of the De Marke farming system, measurements have been carried out on subsystems of the farm. This thesis uses the data collected for assessing the performance of the crop-soil-nitrogen subsystem.

Monitoring of soil moisture conditions and nitrate concentrations was carried out during the years 1991-1995 at six experimental sites. With these data, studies were carried out on nitrate leaching affected by land use in relation to the occurring soils at the farm and the groundwater regimes, using simulation models. The use of simulation models can only be valid when the right input data are used. Soil physical characteristics are important input parameters and for the monitoring sites a comparison was made using soil physical characteristics from either laboratory measurements or from the Staring series as input. It was found that simulation results were not significantly different, implying that the Staring series could be used in studies like these for simulating the unsaturated water flow regime in sandy soils.

Cattle grazing at the experimental farm was reduced to eight hours per day, but urine-affected areas had great influence on the nitrate measurements. At one 'wet' site the probability of exceeding the EC-directive for drinking water (11.3 mg/l nitrate-N) under a urination deposited in either July or September was respectively 10 and 25%. At the dry site the directive will be exceeded under any urine patch in almost 100% of the years, affecting the field average concentration. In this field careful grazing management would result in less nitrate leaching, but the environmental goals would not be reached.

A precision agriculture technique which allows adapting fertilization to urine-affected areas resulted in considerable reductions of simulated nitrate concentrations. A rise of the water table usually also resulted in a decrease in simulated nitrate concentrations. The combined effect of non-fertilization of urine patches and the raising of groundwater levels usually resulted in higher simulated reductions of nitrate concentrations than the single options.

Supplementary irrigation management options for grazed grassland were selected. A change in application volume from 25 to 15 mm per irrigation event resulted in higher irrigation efficiencies, lower annual water use and only small changes in the transpiration ratio T_a/T_p. The different irrigation strategies had no significant effect on nitrate concentrations of the two dry fields studied (fields 9 and 11). For the evaluation of environmental effects it was advised to assess the actual nitrate concentrations and not only the water fluxes, which potentially cause solute leaching (i.e. the leaching potential).

For the upscaling of the data collected at six sites within the farm to whole farm level, the information of the soil survey of De Marke was used. The probability of exceeding the threshold value of 11.3 mg/l nitrate-N (EC-directive) during the period of summer 1991 - spring 1995 was 63% for the whole farm with marked differences between years, crops and hydrological conditions. Considering temporal variability due to weather conditions, the average simulated nitrate-N concentration at a depth of 1 m for the whole farm was 15.1 mg/l and the probability of exceeding the EC-directive for drinking water (11.3 mg/l) at the same depth was 67%. It would be easier to meet both the environmental and agricultural goals of De Marke on most other sandy soils than those of De Marke itself. Allocation of land use with the highest nitrate leaching risk to the least vulnerable soils within one farm and vice versa could well reduce the farm average nitrate losses to the groundwater.

VOORWOORD

Dit proefschrift is tot stand gekomen door interactie met veel mensen en vooral collega's. In mijn beleving is het belangrijk om onderzoek en het schrijven van publicaties niet geïsoleerd uit te voeren, maar erover met anderen van gedachten te wisselen en bij voorkeur samen te werken. Het is prettig dat het voorwoord gebruikt kan worden om al deze mensen te bedanken.

Mijn promotor, Johan Bouma, heeft het in zich om mensen enthousiast te maken voor hun werk. Johan leek er altijd in te geloven dat het mij zou lukken om dit proefschrift te schrijven, ook in de periode dat ik zelf dacht dat het er niet meer van zou komen. Na een gesprek met Johan had ik altijd het gevoel dat ik het uiteindelijk wel zou klaren. De samenstelling van dit proefschrift is mede een resultante van de discussies met Johan, die mij vaak op nieuwe gedachten brachten.

Henny van Lanen en Peter Finke zijn mijn paranimfen en dat is niet voor niets. Vanaf mijn allereerste werkdag was Henny voor mij het ideale afdelingshoofd. Ik heb van hem in korte tijd meer geleerd dan tijdens mijn studie aan de LU, ook vanwege zijn inspirerende manier van leiding geven. Het meest uitgebreide commentaar op concept-versies van de artikelen in dit proefschrift was altijd van Henny afkomstig, ook al was hij intussen verhuisd naar de LU en werkzaam op een ander terrein. Dankzij Peter ben ik weer in mezelf gaan geloven als onderzoeker. Misschien was mijn proefschrift er wel nooit gekomen als ik niet bij SBI was verwelkomd.

Natuurlijk heb ik veel gehad aan de samenwerking met de (overige) co-auteurs van de artikelen. Jos Hegmans, Willy de Groot, Janet Mol-Dijkstra, Toon van der Putten en Tom Schut: ieder van jullie bracht een andere vorm van prettige samenwerking in en dat maakte het iedere keer uniek en leerzaam.

Mijn allereerste werkervaring was bij de afdeling Bodemgebruik, waar ik nog altijd met veel plezier aan terugdenk. Het woord collegialiteit heeft toen voor mij betekenis gekregen. Met alle afdelingsgenootjes van toen heb ik gelukkig nog wel eens contact. Vooral mijn kamergenoot in die jaren, Frans Wopereis, verdient een ereplaats in dit voorwoord. De namen van Henny van Lanen en Willy de Groot zijn al eerder genoemd, maar bij die eerste afdeling hoorden ook Kees Hendriks, Gerard van Soesbergen en Wim van der Voort.

Een dankwoord aan de directie van DLO-Staring Centrum (tegenwoordig Alterra) is hier op zijn plaats. Een deel van het werk heb ik mogen uitvoeren op instituutskosten. Met name Ben van der Pouw heeft voor mij seo-geld geregeld in de periode 1997-1998. Vóór die tijd was het werk voor De Marke ondergebracht in verschillende projecten. De laatste jaren is Oscar Schoumans in zijn rol als programmaleider financieel bijgesprongen voor een klein deel van de laatste loodjes. Omdat er verder geen instituutsbijdrage meer mogelijk was, heb ik in 1999 en 2000 vooral mijn vrije tijd aan dit proefschrift gespendeerd. Ook de layout heb ik dankzij enkele nuttige wenken

van Henny Michel zelf uitgevoerd. Voor de figuren zijn Henk van Ledden en Martin Jansen verantwoordelijk en Karel Hulsteijn schilderde op mijn verzoek een aquarel met gras, water en koeien in een milieu-vriendelijke omgeving voor de kaft.

In de loop van de tijd heb ik met veel mensen mogen samenwerken en aan veel werkgroepen en commissies deelgenomen. Het gaat te ver om alle mensen te noemen, die ik daarbij heb ontmoet, maar een aantal van hen heeft zeker bijgedragen aan mijn gedachtenvorming voor dit proefschrift. Natuurlijk komen de collega's op en rond De Marke hier op de eerste plaats. Frans Aarts (PRI) is een heel bijzondere en enthousiaste collega en ik heb veel aan hem te danken. Helaas lukte het niet om op dezelfde dag te promoveren, maar Frans, nu hebben we twee keer feest! Ook van Gerjan Hilhorst en Carel de Vries, beiden werkzaam op het proefbedrijf, heb ik veel geleerd, vooral over de complexiteit van de melkveehouderij. Via de Nederlandse Vereniging voor Weide- en Voederbouw, het FOMA-stikstofprogrammateam en de projecten rond voedergewassen en 'beregenen op maat' is die kennis verder uitgebreid en de contacten die ik daaraan heb overgehouden bij collega-instituten zoals PRI, PAV en PV zijn mij zeer dierbaar.

Although Jeff Wagenet is no longer with us, I want to express my gratitude to him for inviting me to come to Cornell. I spent three months at SCAS and learnt a lot about the American way of research, soil science and especially modelling. At that time, John Hutson and Mary Ellen Niederhofer provided all I needed, being the much appreciated colleagues of the 10th floor.

De huidige collega's binnen Alterra verdienen hier ook een plek. Voor mij is een goede werksfeer een eerste vereiste om te kunnen functioneren. Het team GIST, bestaande uit Marc Bierkens, Dick Brus, Peter Finke, Willy de Groot, Jaap de Gruijter, Kees Hendriks, Tom Hoogland, Martin Knotters, Ellis Leeters, Reind Visschers, Folkert de Vries, Dennis Walvoort en voorheen ook Henk van het Loo, Harm Rosing en Dick Groot Obbink (toen het nog SBI was), heeft daar enorm aan bijgedragen. Op het gebied van veldbodemkunde heb ik veel geleerd van Henk Kleijer en Koos Dekkers, die er helaas niet meer is. De collega's van de toenmalige afdeling Regionale Milieu-Effectstudies hebben mij wegwijs gemaakt op het gebied van stikstof en ANIMO: Koen Roest, Piet Groenendijk, Joop Kroes, Gert-Jan Noij en Jan Roelsma. Daarvoor had ik al wat van stikstof opgestoken via Hans Jansen en Jan Kragt in het EU-project 'Nitrate in soils'. Voor mijn allereerste werk in 1987 klopte ik aan bij de afdeling agrohydrologie (met name Barend van den Broek, Pavel Kabat en Jan Wesseling) voor SWATREN, later gevolgd door SWATRE, SWACROP en tegenwoordig SWAP.

Conny van den Broek en Kirsten Verburg, een vriendin dichtbij en een vriendin op afstand: het is fijn dat jullie er altijd zijn om te luisteren naar de verhalen in levende lijve, via de telefoon of per e-mail. Jeaan Bruggeman heeft per e-mail vanuit Syrië nog wat redactionele tips voor mijn Engelse teksten gegeven!

Mijn ouders hebben mij van jongs af aan gestimuleerd om te blijven leren en ze leven altijd in bijzondere mate mee met al mijn verrichtingen. Ook mijn schoonouders toonden interesse voor mijn vorderingen, vooral de laatste jaren, ook als er geen schot in leek te zitten.

De beroemde laatste loodjes waren echt geen lolletje, waarbij ik thuis zodra Eline sliep achter de PC zat. Maarten zei wel eens: "als het maar een goed feest oplevert!", dus laten we daar dan maar van uit gaan.

De totstandkoming van dit proefschrift heeft ruim zeven jaar geduurd als je bedenkt dat het eerste artikel (hoofdstuk 2) is gepresenteerd op een congres op Cornell University in augustus 1992. Gemiddeld heb ik één artikel per jaar geschreven, meestal in de zomer als het binnen andere projecten even rustig was en de laatste jaren dus in mijn vrije tijd. Voor mij persoonlijk was het goed dat ik geen AIO was en dat ik mij zodoende met verschillende onderwerpen heb kunnen bezighouden. Die verschillende projecten brachten mij ook vaak weer op ideeën voor de artikelen van dit proefschrift. Bij het herlezen van de hoofdstukken uit dit proefschrift realiseerde ik mij dat ik sommige dingen nu anders zou doen. Het was desalniettemin van begin tot eind voor mij de moeite waard en ik hoop dat dit uit de bladzijden van dit proefschrift valt af te lezen.

Mirjam Hack-ten Broeke
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Stellingen

1. De maximale MINAS-overschotten of de voorgestelde aanvoernormen, waarmee LNV beoogt om in Nederland te voldoen aan de EU-nitraatrichtlijn voor grondwater, zullen er niet toe leiden dat overal in Nederland de gewenste nitraatconcentratie in het bovenste grondwater wordt bereikt. *(Oenema et al., 1997; dit proefschrift)*

2. Minder waterverbruik voor beregening van grasland, door bijvoorbeeld gebruik te maken van beregeningsadviessystemen, is op droge zandgronden mogelijk zonder gevolgen voor de gewasopbrengst, maar ook zonder gevolgen voor de nitraatuitspoeling naar het grondwater. *(Boland et al., 1996; Hoving et al., 1998; dit proefschrift)*

3. Eén van de doelstellingen van proefbedrijf De Marke is het demonstreren van een bedrijfsopzet voor grondgebonden melkproduktie op zandgrond die voldoet aan stringente milieunormen. Het is echter op bijna alle andere zandgronden in Nederland makkelijker om te voldoen aan normen voor nitraatuitspoeling dan op De Marke zelf. *(Biewinga et al., 1992; dit proefschrift)*

4. In de jaren tachtig werd al geconstateerd dat nitraatuitspoeling onder beweid grasland hoger is dan onder niet beweid grasland. Dit blijkt op zandgronden met name te worden veroorzaakt door urineplekken die onstaan tijdens beweiding na augustus, dus het is aan te raden om daar vanaf 1 september geen beweiding meer toe te staan. *(Ball & Ryden, 1984; Steenvoorden et al., 1986; dit proefschrift)*

5. Bij de opschaling van gekwantificeerde milieu-effecten van punt naar perceel, van perceel naar bedrijf en van bedrijf naar regio worden bodemkundige gegevens onvoldoende benut.

6. Het gebruik van simulatiemodellen wordt vaak met argwaan aanschouwd. Het toepassen van wiskundige formules of rekenregels wordt veelal wel acceptabel gevonden. Omdat een simulatiemodel niets anders is dan een set rekenregels is de argwaan onbegrijpelijk. *(naar een uitspraak van J.L. Hutson, Cornell University, 1992)*

7. Het landbouwkundige bedrijfssystemenonderzoek, zoals dit ook op proefbedrijf De Marke plaatsvindt, heeft een grotere bijdrage geleverd aan het oplossen van de problemen van landbouw en milieu dan het traditionele onderzoek naar de deelsystemen.

8. Zonder watertransport vindt in de bodem geen stoftransport plaats, maar voor de juiste voorspelling van nitraatuitspoeling is meer nodig dan alleen een schatting van het stikstofoverschot en het watertransport naar het grondwater.

9. Bodemkundigen zouden er goed aan doen om zich niet af te vragen wat de toekomst van de bodemkunde is, maar om mee te denken over en bijdragen te leveren aan de maatschappelijke vraagstukken voor de toekomst. (*NBV, 123e wetenschappelijke bijeenkomst 'De toekomst van de bodemkunde'*)

10. Wee degene die kennis uit meerdere disciplines probeert te vereenvoudigen: je zult door de specialisten de grond in worden geboord.

11. Wie goed is in het brengen van goed nieuws is meestal niet goed in het voeren van slecht-nieuwsgesprekken en vice versa.

12. De van bovenaf opgelegde wens voor samenwerking binnen de kenniseenheden van Wageningen Universiteit en Research Centre in te vormen divisies is zo moeizaam en gekunsteld, dat het beter zou zijn om middelen beschikbaar te stellen om de huidige samenwerkingsvormen van onderaf te verbeteren.

13. Er zijn goede gronden om aan te nemen dat op goede gronden de milieuproblemen wel meevallen.

14. Grondgebonden is beter dan ongegrond.

Stellingen behorend bij het proefschrift van M.J.D. Hack-ten Broeke *Nitrate leaching from dairy farming on sandy soils; case studies for experimental farm De Marke*, Wageningen, 21 juni 2000

CONTENTS

SUMMARY

The main problem with nitrogen (N) at dairy farms on sandy soils in the Netherlands is the leaching of nitrate to the groundwater. In the eighties it was found that this was caused by high N-surplusses of more than 400 kg N per ha at farm level, of which a large amount is transported to the groundwater. The nitrate concentration in the shallow groundwater is often compared with the EC-directive for drinking water of 50 mg/l (=11,3 mg/l nitrate-N). With an average rainfall surplus of 300 mm for grassland in the Netherlands this concentration corresponds with a maximum load of approximately 35 kg N per ha. Because of other losses, like denitrification and ammonia volatilization, the N-surplus at farm level may be allowed to exceed these 35 kg N per ha, depending on the local conditions. In the Netherlands farmers are keeping records of their N-losses and N-use within the so called Minerals Accounting System (MINAS). The maximum allowed N-loss from grassland in 2008 for dry sandy soils will be 140 kg N per ha.

Experimental farm De Marke was set up in 1991 in the east of the Netherlands on poor sandy soils with the main objective to develop a prototype of an economically feasible farming system with acceptable nutrient losses. The aim for the N-surplus of the De Marke system was 128 kg N per ha. The sum of leaching to groundwater and denitrification should be 82 kg N per ha, assuming that on average about half of this amount would leach to the groundwater. This should be achieved through a farm management strategy, based on principles such as high milk production per cow, on-farm production of feed crops, reduced fertilization, reduced cattle grazing etc. The progress and results of the farm showed great improvement for the environment compared to conventional farms. The average N-surplus of De Marke for the period 1993-1996 was 166 kg N per ha and the calculated average N-leaching in that period was 52 kg N per ha. The N-losses to the groundwater at six monitoring sites within fields of De Marke ranged from 0 to 73 kg N per ha per hydrological year (1 April – 31 March) and the corresponding nitrate-N concentrations ranged from 3 to 64 mg/l nitrate-N.

This thesis

For the quantification of the inputs and outputs of the De Marke farming system, measurements have been carried out - and are being carried out still - on subsystems or components of the farm. The crop-soil-nitrogen system is one of those subsystems and this thesis uses the data collected for assessing the performance of this subsystem. Monitoring of soil moisture conditions and nitrate concentrations was carried out during the years 1991-1995 at six different experimental sites. With these data, studies were carried out on nitrate leaching affected by land use in relation to the different occurring soils at the farm and the prevailing groundwater regimes. Simulation models, calibrated and validated using these data, were used to study effects of changes in land use or changes in soil and groundwater characteristics, within the ranges of model validity.

Of all the chapters in this thesis only chapter 2 is not directly related to De Marke. For the quantification of soil-specific land use effects on solute leaching a certain characteristic is needed for the purpose of comparison between, for instance, two different land use options. Therefore, an environmental land quality was proposed in chapter 2 within the land evaluation concept, derived from the water flux leaving the root zone, taking inert solutes and compounds like nutrients along on its way to the groundwater. This environmental land quality was called the 'leaching potential'. The data and simulations with the SWANY model in this chapter are related to a number of irrigation strategies for potatoes on a coarse-textured sandy soil (Humic Podzol) and to a set of different groundwater regimes on a loamy soil (Calcaric Fluvisol) cultivated with potato. The simulation results showed that irrigation increased crop yields for the sandy soil, but also increased the leaching potential. Restricted irrigation resulted in similar crop production levels, but reduced the downward flux from the root zone. For the loamy soil, drainage provided higher crop yields and a slightly lower leaching potential due to an increased water uptake by the crop. The usefulness of a 'leaching potential' for the quantification of environmental effects of management strategies, dealing with temporal variability in probabilistic terms, was demonstrated.

The use of simulation models can only be valid when the right input data are used. Soil physical characteristics are important input parameters for simulation modelling of unsaturated flow in soils and associated solute flow. This issue is addressed in chapter 3. The determination of soil water retention and hydraulic conductivity curves in the laboratory is laborious and expensive. For modelling studies that require characteristics for many soil horizons, such as regional studies or scenario studies, it may be impossible to measure all the necessary characteristics. An alternative would be to use characteristics inferred from readily available soil data by class-pedotransfer functions. For the six monitoring sites at De Marke such a comparison was made using the soil-water model SWACROP with soil physical characteristics from either laboratory measurements or from a standard series (Staring series) as input. For this the simulated pressure head values and moisture content values were compared with measured values using statistical criteria. Furthermore, the number of workable days and the number of days with possible drought were calculated from simulated pressure head values and again the different results were compared. It was found that simulation results were not significantly different, implying that standard series or class-pedotransfer functions (Staring series) could be used in studies like these for simulating the unsaturated water flow regime in sandy soils on field/farm level or regional level. Differences for specific criteria for individual sites were sometimes substantial and in such cases (at field level) it will make a difference which soil physical characteristics are used. Thus, the specific goal and scale of a study determines whether the Staring series can be used or not. When measurements are available, it is naturally preferable to use them. In the following chapters measured soil characteristics were used, which were determined from the laboratory measurements as used in chapter 3 combined with field measurements.

Chapters 4, 5 and 6 focus on different management options for grazed grassland at De Marke. Cattle grazing at the experimental farm was reduced to eight hours per day. Yet, during these eight hours, cattle still produce faeces and urine. Especially urine patches are responsible for peak concentrations of nitrate in soil water. An extra experiment for assessing within-field spatial variability of nitrate concentrations in groundwater was conducted and the statistical analysis of the data of this experiment told us that indeed the variability was high at short distances and that extremely high peak values were found at random places within the field. This indicated that urine-affected areas had great influence on the nitrate measurements. Data on water and nitrogen flows in the unsaturated zone, collected in two grazed pastures of De Marke during the years 1991 to 1994 were used in chapter 4. First, these data provided a basis for calibration and validation of the simulation models SWACROP and ANIMO. The differences in the levels of nitrate-N concentrations of the two plots could largely be explained by differences in crop uptake and simulated denitrification as influenced by different groundwater levels. The irregular distribution of excreta was taken into account by a simulation study quantifying the variability of nitrate-N concentrations under a grazed field. The resulting distribution of simulated nitrate-N concentrations explained the average and peak values of the measured concentrations. Temporal variability of weather was used to assess the nitrate leaching risk under urine patches deposited in either July or September. At site A (in field 17) the probability of exceeding the EC-directive for drinking water (11.3 mg/l nitrate-N) under a urination deposited in either July or September was respectively 10 and 25%. The average field concentration at this site will hardly ever be a high risk for the environment under current farm management. At site B (in field 9) the EC-directive will be exceeded under any urine patch in almost 100% of the years, affecting the field average concentration. In field B careful grazing management would result in less nitrate leaching, but the environmental goals would not be reached.

At experimental farm Droevendaal a site-specific technique was developed, which allowed adapting fertilization to the existing pattern of urine-affected areas. The environmental effects of such a technique for De Marke were studied in chapter 5. In this chapter also a rise of the water table is studied as an option for improving moisture supply to the crops. Whereas in chapter 4 especially temporal variability was addressed, in this study within-field spatial variability received special attention. Simulations were again performed with SWACROP and ANIMO to quantify the effects of management options on nitrate leaching to the groundwater in grazed pastures, this time using the data of the years 1991-1995. The simulations showed that the precision agriculture technique, which can identify urine-affected areas in the field and then subsequently omit fertilizing such areas, resulted in considerable reductions of simulated nitrate concentrations in the soil water, especially on an intensively grazed and relatively dry site (in field 9) with groundwater levels between 0.5 and 2.8 m. On the wetter site (in field 17), the maximum calculated reduction in nitrate concentrations was 11%, but for the relatively dry site the maximum calculated reduction was as high as 41%. The simulated raising of groundwater levels usually also resulted in a decrease in simulated nitrate concentrations. Under wet conditions, the groundwater level increase may, however, cause water excess and a deterioration in conditions for crop growth and thus, less N-uptake by the crop, which would ultimately lead to increased nitrate leaching. The combined effect of non-fertilization of urine patches and the raising of groundwater levels usually resulted in higher simulated reductions of nitrate concentrations than the single options. When the effect of within-field soil variability was also considered, the raising of groundwater levels was most effective in reducing nitrate concentrations on the wet site, while on the relatively dry and intensively used site, the non-fertilization of urine-affected areas had the dominant effect.

Chapter 6 pays attention to another aspect of land management for grazed grassland, namely supplementary irrigation. Several strategies can be defined that aim at reducing both water use and nitrate leaching. Six supplementary irrigation management options for grazed grassland were selected and their effects on both agricultural production and nitrate leaching to the groundwater were studied. SWACROP and ANIMO were used to calculate the effects on crop transpiration, water fluxes and nitrate concentrations for three fields of the farm. Comparisons with the common practice at the farm were made. A change in application volume from 25 mm to 15 mm per irrigation event resulted in higher irrigation efficiencies and lower annual water use for supplementary irrigation with only small changes in the transpiration ratio T_a/T_p. The advisory system 'irrigation planner' generally also resulted in high irrigation efficiencies combined with a reduction of water use and a small effect on the transpiration ratio. The different irrigation strategies had no significant effect on nitrate concentrations of the two dry fields studied (fields 9 and 11). For the relatively wet field in this study (field 17) an increase of irrigation water use would improve agricultural production conditions and reduce nitrate concentrations at 1 m depth. For the evaluation of environmental effects of irrigation management options it was advised to assess the actual nitrate concentrations and not only the water fluxes, which potentially cause solute leaching (i.e. the leaching potential).

Chapters 7 and 8 deal with extrapolation, either from site to farm level or even to other soils. For the upscaling of the data collected at six sites within the farm to whole farm level, the information of the soil survey of De Marke was used, again showing the importance of spatial variability. Using more than 200 soil profile descriptions, frequency distributions of model output were generated, allowing a risk assessment for the total farm. The probability of exceeding the threshold value of 11.3 mg/l nitrate-N (EC-directive) during the period of summer 1991 - spring 1995 was 63 % for the whole farm with marked differences between years, crops and hydrological conditions.

Finally, chapter 8 deals with the extrapolation of De Marke to other soils. The land use system of the experimental farm was standardized to allow extrapolation to other sandy soils by means of again a simulation study. This standardization is a description of the land use system as a set of decision rules. Three parcel types were distinguished on the farm: permanent pastures and two different rotations with grass and silage maize. Land use of these three parcel types was thus described with decision rules for fertilization, grazing and cutting of grassland and supplementary irrigation. The effect of temporal variability due to weather conditions was taken into account by using a 30-year record of weather data for the simulations. The decision rules were applied to the actual fields and soils of De Marke for these 30 years as well as to five representative soils for major soil mapping units of the sandy areas of the 1 : 50 000 Soil Map of the Netherlands in order to explore the possible effects of introducing this land use at farms in other areas with sandy soils. The profile descriptions of the representative soils were formed from all available soil survey information for the mapping units. The average simulated nitrate-N concentration at a depth of 1 m for the De Marke farm as a whole was 15.1 mg/l and the probability of exceeding the EC-directive for drinking water (11.3 mg/l) at the same depth was 67%. The probabilities of exceeding this value ranged from 3 to 73% for the five major mapping units. The average actual transpiration of the land use system was higher than at De Marke for all five soil map units, which implies a potential for higher crop yields. This means that it would be easier to meet both the environmental and agricultural goals of De Marke on most other sandy soils than those of De Marke itself. The three parcel types resulted in different levels of nitrate leaching, and it would therefore be worthwhile locating permanent pastures, which are used most intensively, on soils which show the least environmental risk, and vice versa.

Additional to all these results and conclusions some final remarks are presented in the last chapter.

- The powerful combination of a comprehensive dataset and simulation modelling, as used in this thesis, allows for scenario studies and extrapolation in space and time. When promising options for future land use or management have thus been identified, it is always necessary to evaluate the effects of implemented scenarios by measuring the actual behaviour of the system.
- The impact of spatial and temporal variability is an important factor when studying environmental effects of land use. The output of simulation models in which variation in space and time is accounted for, can be presented as frequency distributions and as probabilities or risks. For development and implementation of environmental policies differentiation according to soil conditions is recommended.
- Changes in land use are not only necessary at the most vulnerable locations with respect to nitrate leaching. It was found that at relatively wet locations at experimental farm De Marke, where nitrate concentration levels in the shallow groundwater were already low, changes in groundwater regime or irrigation management could lead to a further reduction of nitrate leaching.
- After eight years of data gathering in the shallow groundwater of De Marke it was found that the average nitrate concentrations at the farm level were above the required level of 50 mg/l. On the basis of four years of data and simulation modelling that same conclusion was drawn some years earlier. This method with simulation models can therefore be used as a suitable tool for early warning.
- The average N-surplus of De Marke of 166 kg N per ha (including atmospheric deposition and N-fixation by clover) does not yet result in an acceptable nitrate leaching level according to the EC-directive. Based on model simulations, it was found that on other soils this N-

surplus will lead to acceptable average nitrate concentrations in the shallow groundwater. A further differentiation according to soil and groundwater conditions should be considered for such legislation as MINAS.

- For the majority of the sandy soils in the Netherlands the land use system of De Marke will lead to acceptable nitrate leaching levels. Allocation of land use with the highest nitrate leaching risk to the least vulnerable soils within one farm and vice versa could well reduce the farm average nitrate losses to the groundwater. The proposed method was used for identifying environmentally suitable soils for the land use system of De Marke. In principal, the agricultural and environmental suitability for a given land use type can thus be quantified for all soil map units.

SAMENVATTING

Het belangrijkste stikstofprobleem van de melkveehouderij op de Nederlandse zandgronden is nitraatuitspoeling naar het grondwater. In de jaren 80 van de afgelopen eeuw is geconstateerd dat dit werd veroorzaakt door de hoge stikstofoverschotten van meer dan 400 kg stikstof (N) per ha op bedrijfsniveau. Een groot deel van dit overschot komt in het grondwater terecht. De nitraatconcentratie in het bovenste grondwater wordt vaak vergeleken met de EU-nitraatrichtlijn van 50 mg/l (=11,3 mg/l nitraat-N) voor drinkwater. Bij een gemiddeld neerslagoverschot van 300 mm voor Nederlands grasland komt deze concentratie overeen met een N-belasting van ongeveer 35 kg N per ha. Omdat er ook andere verliezen optreden, zoals denitrificatie en ammoniakvervluchtiging, mag het totale N-overschot op bedrijfsniveau hoger zijn dan die 35 kg N, afhankelijk van de omstandigheden. Binnen het nu geldende Mineralen Aangifte Systeem (MINAS) bedraagt het maximale N-overschot op bedrijfsniveau nog 275 kg N, maar in het jaar 2008 slechts 140 kg N per ha voor grasland op de droge zandgronden.

De belangrijkste doelstelling van proefbedrijf De Marke is de ontwikkeling van een prototype voor een economisch rendabele en tegelijkertijd milieuvriendelijke melkveehouderij. De Marke is in 1991 van start gegaan nabij Hengelo in de Achterhoek op schrale, droogtegevoelige zandgronden. Voor het N-overschot op bedrijfsniveau werd 128 kg N per ha als doel gesteld. Uitspoeling naar het grondwater en denitrifcatie zouden samen 82 kg N per ha bedragen. Ongeveer de helft hiervan zou volgens de berekeningen naar het grondwater verdwijnen. De bedrijfsstrategie om dit te bereiken bestaat onder andere uit hoge melkproductie per koe, eigen productie van krachtvoer, lage mestgiften, lage beweidingsdruk etc. Het oorspronkelijke logo van De Marke met de gesloten kringloop rondom de koe gaf de doelstelling nog eens duidelijk aan. De intussen bereikte resultaten van De Marke geven aan dat er grote vooruitgang is geboekt voor het milieu in vergelijking met de gangbare melkveehouderij. Het gemiddelde N-overschot in de jaren 1993-1996 was 166 kg N per ha en de berekende gemiddelde N-uitspoeling in die periode was 52 kg N per ha. De verliezen naar het grondwater op zes meetlokaties, gesitueerd op zes verschillende percelen van het proefbedrijf, varieerden in diezelfde periode van 0 tot 73 kg N per ha per hydrologisch jaar (1 april - 31 maart) en de bijbehorende nitraatconcentraties in het bodemvocht en/of het bovenste grondwater op 1 m - mv. varieerden van 3 tot 64 mg/l nitraat-N.

Dit proefschrift

Om alle inputs en outputs op en rond het bedrijfssysteem De Marke te kunnen kwantificeren worden veel metingen verricht aan onderdelen van het systeem. Het bodem-stikstof-gewassysteem is één van die onderdelen. In dit proefschrift worden de gegevens gebruikt die zijn verzameld om de balans voor juist dit onderdeel te kunnen opmaken. Gedurende de jaren 1991-1995 zijn de bodemvochttoestand en nitraatconcentraties gemeten op zes verschillende meetlokaties binnen De Marke. Met deze gegevens zijn studies uitgevoerd om de effecten van landgebruik of van bijvoorbeeld gewijzigde grondwaterstanden op de nitraatuitspoeling te bepalen in relatie tot de verschillende voorkomende bodems en grondwaterregimes. Hiertoe zijn simulatiemodellen gebruikt, die eerst zijn gecalibreerd en gevalideerd met de genoemde gegevens.

Van alle hoofdstukken in dit proefschrift gaat het alleen in hoofdstuk 2 niet over De Marke. Om het effect van veranderingen in landgebruik op het milieu per bodemtype te kunnen kwantificeren en om bijvoorbeeld verschillende scenario's onderling te vergelijken is een bepaalde doelvariabele of beoordelingsfactor nodig. Voor dit doel werd in hoofdstuk 2 een landhoedanigheid geïntroduceerd binnen het landevaluatie-concept. Deze zogenaamde 'potentiële uitspoeling' is een functie van de hoeveelheid water die de wortelzone verlaat, waarmee opgeloste stoffen in de richting van het grondwater worden meegenomen. In dit hoofdstuk gaat het om gegevens en modelsimulaties met het model SWANY die betrekking hebben op een aantal beregeningsopties voor aardappelteelt op een grofzandige bodem (Humic Podzol) en op een aantal verschillende grondwaterregimes voor een zavelgrond (Calcaric Fluvisol) met eveneens aardappelteelt. De modelresultaten gaven aan dat gewasopbrengsten op de zandgrond hoger werden als gevolg van beregening, maar datzelfde gold voor de potentiële uitspoeling. Een optie met beperkte beregening resulteerde in vergelijkbare gewasopbrengsten, terwijl de extra hoeveelheid water die de wortelzone verlaat als gevolg van beregening minder wordt. Bij de zavelgrond zorgde drainage voor hogere gewasopbrengsten en voor een enigszins lagere potentiële uitspoeling als gevolg van verbeterde vochttontrekking door het gewas. Hiermee werd het gebruik van de 'potentiële uitspoeling' gedemonstreerd, waarbij aandacht werd besteed aan variabiliteit in de tijd door uitspraken te doen in de vorm van kansen.

De toepassing van simulatiemodellen is alleen zinvol als de juiste invoergegevens worden gebruikt. Voor het simuleren van de waterhuishouding in de onverzadigde zone en het daaraan gekoppelde stoftransport zijn bodemfysische parameters belangrijke invoer-parameters. Daarover gaat het in hoofdstuk 3. Bepaling van waterretentie- en onverzadigde doorlatendheidskarakteristieken in het laboratorium is arbeidsintensief en dus duur. Voor sommige regionale of scenariostudies is het ondenkbaar dat voor alle relevante bodemhorizonten de benodigde karakteristieken gemeten worden. Het gebruik van pedotransferfuncties om karakteristieken te schatten met behulp van beschikbare bodemkundige gegevens is dan een veel toegepast alternatief. Voor de zes monitoringlokaties van proefbedrijf De Marke kon een vergelijking worden gemaakt tussen de resultaten van de toepassing van bodemfysische karakteristieken als invoer voor het model SWACROP die enerzijds waren bepaald met behulp van laboratoriummetingen en anderzijds afkomstig waren van de Staringreeks. Statistische criteria werden gebruikt om de berekende en gemeten drukhoogten en vochtgehalten onderling te vergelijken. Daarnaast werden ook het aantal werkbare dagen en het aantal dagen met mogelijk vochttekort voor het gewas (beide berekend uit de gesimuleerde drukhoogten) onderling vergeleken. De modelresultaten bleken niet significant verschillend te zijn, zodat geconcludeerd werd dat voor vergelijkbare studies als deze voor het simuleren van de waterhuishouding in de onverzadigde zone van zandgronden op perceels- of bedrijfsniveau, pedotransferfuncties of de bouwstenen uit de Staringreeks kunnen worden toegepast. Voor een aantal specifieke criteria waren de verschillen in bepaalde situaties echter aanzienlijk en dan maakt het dus wel degelijk uit welke bodemfysische gegevens worden gebruikt. Het doel van de studie en de schaal waarop het model wordt toegepast bepalen of de Staringreeks al dan niet toepasbaar is. Als er metingen beschikbaar zijn, is het altijd raadzaam deze te gebruiken. In de volgende hoofdstukken zijn steeds de 'gemeten' bodemfysische karakteristieken gebruikt. Deze karakteristieken zijn een functie van de al eerder genoemde laboratoriummetingen en van veldwaarnemingen.

In de hoofdstukken 4, 5 en 6 wordt aandacht besteed aan verschillende managementopties voor beweid grasland op De Marke. Beweiding is op het proefbedrijf gereduceerd tot acht uur per dag, maar ook gedurende deze acht uren produceren de koeien urine en faecaliën. Vooral urineplekken zorgen voor piekconcentraties van nitraat in het bodemvocht. Om de variabiliteit van nitraatconcentraties in het grondwater binnen een perceel te kunnen kwantificeren is een extra experiment uitgevoerd. Uit de statistische analyse van de gegevens bleek dat de variabiliteit op korte afstand inderdaad erg hoog kon zijn en dat de piekconcentraties willekeurig verdeeld waren over het perceel. Dit wees erop dat urineplekken een grote invloed hadden op de nitraatmetingen. In hoofdstuk 4 zijn gegevens gebruikt over water en stikstof in de onverzadigde zone, gemeten op twee beweide graslandpercelen in de periode 1991-1994. In eerste instantie vormden deze gegevens een basis voor calibratie en validatie van de simulatiemodellen SWACROP en ANIMO. De verschillen in de gemeten N-concentraties op de twee lokaties konden grotendeels worden verklaard uit verschillen in water- en N-opname door het gewas en de gesimuleerde denitrificatie. Beide factoren worden sterk beïnvloed door het grondwaterniveau. Voor het kwantificeren van de variabiliteit van de nitraat-N-concentraties onder een beweid perceel werd een simulatiestudie uitgevoerd, waarbij de onregelmatige verdeling van urineplekken werd verdisconteerd. Het resultaat van deze modelstudie was een verdeling van gesimuleerde nitraat-N-concentraties, waarvan het gemiddelde en de piekwaarden overeen kwamen met die van de gemeten concentraties. Voor urineplekken, gedeponeerd in juli of in september, werd het nitraatuitspoelingsrisico ingeschat als functie van variabiliteit in de tijd veroorzaakt door het weer. Op lokatie A (perceel 17) was de kans op overschrijding van de EU-richtlijn voor drinkwater (11,3 mg/l nitraat-N) onder een urineplek, gedeponeerd in juli of september, respectievelijk 10 en 25%. Bij de huidige bedrijfsvoering zal de gemiddelde concentratie voor deze lokatie waarschijnlijk nooit een risico voor het milieu vormen. Voor lokatie B (perceel 9) is de kans op overschrijding van de EU-norm onder een urineplek bijna 100% en dit heeft ook effect op de perceelsgemiddelde concentratie. Voor perceel B geldt dat reductie in beweiding de nitraatuitspoeling zal verminderen, maar de milieudoelen voor N zullen daarmee niet worden gehaald.

Op proefboerderij Droevendaal is een pleksgewijze techniek ontwikkeld, waarmee de bemesting kan worden aangepast aan het aanwezige patroon van urineplekken. Het milieu-effect van de toepassing van zo'n techniek op De Marke wordt besproken in hoofdstuk 5. Daarnaast komt het verhogen van grondwaterstanden aan bod als een mogelijkheid om de vochtvoorziening voor de gewassen te verbeteren. Variabiliteit in de tijd was onderwerp van studie in hoofdstuk 4, maar in dit hoofdstuk krijgt ruimtelijke variabiliteit binnen een perceel speciale aandacht. Voor het kwantificeren van de effecten van managementopties op nitraatuitspoeling naar het grondwater onder beweid grasland zijn opnieuw de modellen SWACROP en ANIMO toegepast. In dit geval zijn meetgegevens gebruikt uit de periode 1991-1995. Het resultaat van de modelsimulaties was dat de techniek uit de precisielandbouw, waarmee urineplekken kunnen worden gesignaleerd en vervolgens bij de bemesting deze plekken worden overgeslagen, een substantiële verlaging van de gesimuleerde nitraat-concentraties in het bodemvocht bewerkstelligde. Dit gold vooral voor de intensief beweide en relatief droge lokatie (in perceel 9) met grondwaterstanden tussen 0,5 en 2,8 m - mv. Voor de nattere lokatie (in perceel 17) was de maximale berekende reductie van nitraatconcentraties 11%, maar voor de drogere plek was de maximale reductie maar liefst 41%. Ook de gesimuleerde verhoging van grondwaterstanden resulteerde meestal in een verlaging van de gesimuleerde nitraatconcentraties. Onder vochtige omstandigheden kan een verhoging van de grondwaterstanden ook leiden tot wateroverlast en natschade voor het gewas. Daardoor wordt ook de N-opname door het gewas lager en dit leidt uiteindelijk tot meer nitraat-uitspoeling. De combinatie van beide opties, dus het niet bemesten van urineplekken plus het verhogen van grondwaterstanden, resulteerde in een grotere reductie van nitraatuitspoeling dan de opties afzonderlijk. Als we rekening houden met de bodemvariabiliteit binnen percelen, blijkt dat het verhogen van grondwaterstanden het meest effectief was voor verlaging van nitraatuitspoeling voor het natte perceel, terwijl het niet bemesten van urineplekken het meest effectief was voor het relatief droge en intensief beweide perceel.

In hoofstuk 6 wordt aandacht besteed aan een heel ander aspect van management voor beweid grasland, namelijk beregening. Voor de verlaging van zowel waterverbruik als nitraatuitspoeling zijn verschillende strategieën te bedenken. In dit geval zijn zes beregenings-varianten gedefinieerd en is het effect op enerzijds landbouwkundige productie en anderzijds nitraatuitspoeling naar het grondwater bestudeerd. De modellen SWACROP en ANIMO werden toegepast om voor drie percelen binnen het bedrijf de effecten op gewasverdamping, bodemvochthuishouding en nitraatconcentraties te berekenen. Een vergelijking werd gemaakt met de werkelijk uitgevoerde beregening op De Marke. Een verandering in de beregeningsgift per keer van 25 mm naar 15 mm resulteerde in een hogere beregeningsefficiëntie en tegelijkertijd minder waterverbruik op jaarbasis en slechts kleine veranderingen in de transpiratiecoëfficiënt T_a/T_p. Het adviessysteem dat bekend staat als de 'beregeningsplanner' leverde over het algemeen ook een hogere beregeningsefficiëntie op, gecombineerd met een vermindering van het waterverbruik en een gering effect op de transpiratiecoëfficiënt. Voor de twee droge percelen (percelen 9 en 11) leverden de verschillende beregeningsvarianten geen significant verschillende nitraatconcentraties op. Voor het nattere perceel (perceel 17) zou meer beregening leiden tot een verbetering van de omstandigheden voor gewasproductie en tot lagere nitraatconcentraties op 1 m - mv. Om de milieu-effecten van beregeningsopties te evalueren wordt geadviseerd om voor onderlinge vergelijking de nitraatconcentraties te gebruiken en niet alleen de 'potentiële uitspoeling', gebaseerd op de waterstroming die transport van opgeloste stoffen teweeg brengt.

Extrapolatie van plek naar bedrijfsniveau of zelfs naar andere bodemtypes wordt besproken in de hoofdstukken 7 en 8. Bodemkundige gegevens, verzameld voor de bodemkartering van De Marke, zijn gebruikt voor het opschalen van de gegevens van de zes meetplekken binnen het bedrijf naar bedrijfsniveau. Het belang van ruimtelijke variabiliteit wordt hiermee nog eens benadrukt. Modelberekeningen voor meer dan 200 beschreven bodemprofielen resulteerden in frequentieverdelingen van de modeluitvoer, die vervolgens werden gebruikt voor het inschatten van risico's. De kans op overschrijding van de EU-norm van 11,3 mg/l nitraat-N voor De Marke als geheel was 63% voor de periode zomer 1991 - voorjaar 1995. Verschillende jaren, verschillende gewassen en verschillende hydrologische omstandigheden leveren verschillende overschrijdingskansen op.

Tenslotte wordt in hoofdstuk 8 gesproken over extrapolatie van De Marke naar andere bodemtypen. Om een vertaling van het bodemgebruik van De Marke naar andere zandgronden mogelijk te maken moest het worden beschreven op een eenduidige wijze, die als modelinvoer voor een simulatiestudie gebruikt kon worden. Deze gestandaardiseerde beschrijving van het bodemgebruik bestaat uit een set beslisregels. Drie verschillende kaveltypes worden op het bedrijf onderscheiden: permanent grasland en twee verschillende rotaties van gras en maïs. Het bodemgebruik voor elk van deze drie kaveltypes is zodoende beschreven met beslisregels voor bemesting, beweiding, maaien en beregening. Voor de simulaties is rekening gehouden met het effect van verschillende weerjaren door gegevens van een reeks van 30 jaar te gebruiken. In eerste instantie zijn de beslisregels voor bodemgebruik voor deze 30 weerjaren in een modelstudie toegepast op de percelen van De Marke met de werkelijk voorkomende bodemgesteldheid. Vervolgens zijn dezelfde berekeningen uitgevoerd met karakteristieke bodemprofielen voor de vijf meest voorkomende kaarteenheden binnen de zandgronden van de bodemkaart van Nederland, schaal 1 : 50 000. Het doel van deze verkennende berekeningen was om te onderzoeken welk effect de introductie van het bodemgebruik van De Marke op andere landbouwbedrijven op zandgrond zou kunnen hebben. De karakteristieke profiel-beschrijvingen zijn samengesteld uit alle beschikbare informatie voor de betreffende kaart-eenheden. De berekende bedrijfsgemiddelde nitraat-N-concentratie op 1 m - mv. voor De Marke was 15,1 mg/l en de kans op overschrijding van de EU-norm voor drinkwater (11,3 mg/l) op die diepte was 67%. Voor de vijf meest voorkomende kaarteenheden varieerde deze overschrijdingskans van 3 tot 73%. De gemiddelde berekende gewasverdamping bij het beschreven bodemgebruik was voor alle vijf zandgronden hoger dan op De Marke en dit impliceert hogere gewasopbrengsten dan op De Marke. Dit zou betekenen dat het op bijna alle andere zandgronden dan die van De Marke zelf, makkelijker zou zijn om de voor De Marke gestelde milieu-doelen en landbouwkundige doelen te verwezenlijken. De nitraatuitspoeling is verschillend voor de drie onderscheiden kaveltypen. Het zou daarom de moeite waard zijn om als lokatie voor de meest intensief gebruikte permanente graslanden de percelen te kiezen met de minst uitspoelingsgevoelige grond en vice versa.

In het allerlaatste hoofdstuk worden nog enkele slotopmerkingen gemaakt.

- De in dit proefschrift toegepaste combinatie van een uitgebreide dataset met modelsimulaties maakt het mogelijk om enerzijds scenariostudies uit te voeren en anderzijds te extrapoleren in zowel ruimte als tijd. Als er op deze manier veelbelovende toekomstmogelijkheden voor landgebruik of management zijn geïdentificeerd, blijft het altijd noodzakelijk om opnieuw te meten hoe het systeem zich in werkelijkheid gedraagt.
- Bij het bestuderen van milieu-effecten van landgebruik dient terdege rekening te worden gehouden met de belangrijke invloed van ruimtelijke variabiliteit. Als er bij modelberekeningen rekening is gehouden met variatie in ruimte en tijd kunnen de simulatieresultaten worden gepresenteerd als frequentieverdelingen en in de vorm van kansen of risico's. Differentiatie naar bodemgesteldheid wordt bij de ontwikkeling en uitvoering van milieubeleid raadzaam geacht.
- Aanpassingen aan het landgebruik zijn niet alleen noodzakelijk voor uitspoelingsgevoelige gronden. Voor relatief natte omstandigheden op proefbedrijf De Marke, waar de nitraatconcentraties in het bovenste grondwater toch al laag waren, bleken veranderingen in grondwaterstanden of beregening te kunnen leiden tot een verdere verlaging van de nitraatuitspoeling.
- Op basis van meetgegevens in het bovenste grondwater van De Marke gedurende acht jaren werd geconstateerd dat de bedrijfsgemiddelde nitraatconcentratie boven de vereiste 50 mg/l ligt. Diezelfde conclusie was al enkele jaren eerder getrokken op basis van meetgegevens van vier jaar, gecombineerd met modelberekeningen. Simulatiemodellen zijn een geschikt instrumentarium voor het vroegtijdig vaststellen van mogelijke risico's.
- Het gemiddelde N-overschot van De Marke van 166 kg N per ha (inclusief atmosferische depositie en N-fixatie door klaver) resulteert niet in een acceptabel niveau voor nitraatuitspoeling volgens de EU-richtlijn. Modelberekeningen wijzen uit dat dit N-overschot op andere zandgronden wel zal leiden tot acceptabele nitraatconcentraties in het bovenste grondwater. Voor wetgeving zoals MINAS lijkt een differentiatie naar bodemgesteldheid en grondwaterstanden dus gewenst.
- Voor de meest voorkomende Nederlandse zandgronden zal het bodemgebruik van De Marke acceptabele nitraatuitspoelingsniveaus bewerkstelligen. Toewijzing van landgebruik met het hoogste uitspoelingsrisico aan de minst uitspoelingsgevoelige grond binnen een bedrijf en vice versa betekent zeer waarschijnlijk een verlaging van de bedrijfsgemiddelde stikstofverliezen naar het grondwater. Milieukundig geschikte gronden voor het landgebruik van De Marke zijn geïdentificeerd volgens de in dit proefschrift voorgestelde methode. Het is in principe mogelijk om voor alle kaarteenheden van de bodemkaart de landbouwkundige en milieukundige geschiktheid voor een gegeven landgebruik te kwantificeren.

1. INTRODUCTION

Nitrate leaching

Is there a problem with nitrate leaching from dairy farming on sandy soils in the Netherlands? When this question is raised, often the work of Aarts et al. (1992) is referred to. The answer is of course yes, there is a problem, because high nitrate concentrations are found in surface waters and in groundwater and this N can be traced back to agricultural activities with high nitrogen (N) surplusses. In sandy areas these surplusses are mostly transported to the groundwater. Aarts et al. (1992) calculated a N-balance for an average dairy farm in the period 1983-1986 on Dutch sandy soils. The N-surplus of this average farm was 486 kg N per ha, part of which will have disappeared through ammonia volatilization as NH_3 (approximately 110 kg NH_3-N) and through denitrification as N_2 and NO_x (depending largely on soil moisture conditions) and the remaining N will have ended up in the groundwater. In 1990 a Dutch working group on nitrogen (Goossensen en Meeuwissen, 1990) had come to similar conclusions on the N-surplus (more than 400 kg N per ha) and leaching to groundwater for Dutch agriculture as a whole.

The nitrate concentration in the shallow groundwater is often compared with the EC-directive for drinking water of 50 mg/l (=11,3 mg/l nitrate-N). On average, with an average annual rainfall surplus of about 300 mm, a loss to the groundwater of about 35 kg N per ha will result in such a concentration of 50 mg/l nitrate in the shallow groundwater. It is obvious that an average dairy farm on sandy soils in the eighties would not be able to meet this average directive. This directive for drinking water is also used as the environmental goal for groundwater at 2 m below the groundwater level. This depth is, however, not easily determined, because it may change daily with the changing groundwater level. It is also not clear whether this directive should be compared with average concentrations or should the groundwater be of drinking water quality at any time? Droogers (1997) suggested that a critical threshold value should include an associated time-aggregation level. Considering that groundwater usually mixes on its (often long) way to the drinking water pumping stations in the Dutch sandy areas, in this thesis the average annual concentration in the shallow groundwater is taken as the relevant concentration which should meet the environmental goal. Goossensen and Meeuwissen (1990) proposed that the average farm level should be used, where a farm is defined as consisting of a number of fields. This proposed average farm level concentration is also used in the last two chapters of this thesis.

Van Eck and Meijs (1995) reported on N-losses in Dutch agriculture for a set of future land use and management scenarios for different soils. On the one hand, calculations resulted in a maximum allowed N-loss per soil type considered and on the other hand the land use scenarios resulted in N-losses that were considered acceptable from the agricultural point of view. For grassland within dairy farming it was concluded that on clay soils, peat soils and sandy soils with high groundwater levels it should be difficult but possible to meet the environmental goals. For grassland on sandy soils in dry areas the calculated environmentally acceptable N-loss ranged from 70 to 130 kg N per ha. The lowest N-loss, calculated for the different management scenarios for dairy farming, was 180 kg N per ha, showing that the problem of nitrate leaching from dairy farming on sandy soils would not be easy to solve.

In other northern European countries similar problems with N-losses from dairy farms have been found (e.g. Jarvis, 1993; Weissbach and Ernst, 1994, Verbruggen et al., 1994). The calculated N-surplusses reported for Germany and Belgium ranged from 300 to 400 kg N per ha, whilst for the UK the calculated sum of N-losses for a model dairy farm through leaching, denitrification and volatilization was up to 200 kg N per ha. Various changes in grassland management have been suggested to reduce N-losses and experiments have been set up for developing (prototypes of) environment-friendly dairy farming systems (e.g. Laws and Pain, 1994; Peel et al., 1997, Lantinga and Rabbinge, 1997).

At this moment in the Netherlands farmers are keeping records of their N-losses and N-use within the so called Minerals Accounting System (MINAS). This system requires records of the amount of minerals used, the mineral input and output at farm level and the losses to the environment. The maximum allowed N-loss from grassland in 2000 is 275 kg N per ha and in 2008 the maximum allowed N-loss for dry sandy soils will be 140 kg N per ha. It is expected that implementation of MINAS will lead to a drastic decrease in nitrogen losses (Oenema et al., 1997). In 1999 an extra constraint was proposed by the government with maximum fertilization levels, derived from the European nitrate directive. For grassland this would include a maximum amount of 300 kg N per ha from animal manure in 2002 en in 2003 this would be reduced to 250 kg N per ha. For all other crops the maximum application would be 170 kg N per ha from animal manure.

De Marke

Experimental farm De Marke was officially set up in 1991 in the east of the Netherlands on poor sandy soils with the main objective to develop a prototype of an economically feasible farming system with acceptable nutrient losses. An important goal of De Marke was to show that the problem of nitrate leaching from dairy farming on sandy soils in the Netherlands could be solved. The aim of the N-surplus of the De Marke system was 128 kg N per ha (Biewinga et al., 1992). Aarts et al. (1992) calculated that for this farm the sum of leaching to groundwater and denitrification should be 82 kg N per ha, assuming that on average about half of this amount would leach to the groundwater. This should be achieved through a farm management strategy, based on principles like high milk production per cow, on-farm production of feed crops, reduced fertilization, reduced cattle grazing etc. (Biewinga et al., 1992).

In 1990 I became involved in the De Marke project. A project proposal 'Analysis of feed production at experimental farm De Marke on the basis of moisture supply, nitrogen management and crop growth' was written in which I was responsible for measurements of soil moisture conditions and nitrate in soil water. A design for experimental sites was included in this proposal as well as the monitoring and research plan. Funding by FOMA (Financierings-overleg Mest- en Ammoniakonderzoek), a fund for research on fertilization and ammonia, was applied for. The original plan involved measurements on the soil-water-crop system combined with model simulations in order to allow extrapolation of the system to other locations. The assessment of the relation between land use and nitrate leaching was the main purpose of this research proposal. The Winand Staring Centre contribution would focus on water and nitrogen and the Institute for Agrobiology and Soil Fertility on crops and crop modelling. FOMA decided that the simulations should be omitted and instead a separate simulation model project was initiated with the purpose to finally integrate all those existing nitrogen models into one model. This excellent initiative resulted after a few years in an attempt, which is known as the never finished model 'Ntegratie'. For simulating the soil-water-crop interactions at the sites of De Marke we waited for this model and therefore we did not perform soil-water-crop modelling for De Marke.

De Marke was set up in 1991 and the progress and results of the farm, especially considering N, have been thoroughly reported (e.g. Aarts, 1995; Aarts et al., 1996, Hack-ten Broeke and Aarts, 1996; Aarts et al., 1999a). The average N-surplus of De Marke for the period 1993-1996 was 166 kg N per ha and the calculated average N-leaching in that period was 52 kg N per ha (Aarts et al., 1999a). Based on nitrate measurements in soil moisture at 1 m depth during the years 1991-1995, the N-losses at six monitoring sites within fields of De Marke ranged from 0 to 73 kg N per ha per hydrological year (1 April – 31 March) and the corresponding nitrate-N concentrations ranged from 3 to 64 mg/l nitrate-N (Hack-ten Broeke and De Groot, 1996)

Nitrate leaching in relation to soil and groundwater

The majority of the research and publications on performance of De Marke in relation to N consider the farming system as a whole (e.g. Aarts et al., 1996; Aarts et al., 1999a; Aarts, 2000), because the aim of the De Marke research is 'whole farm system research' (Aarts et al.,1992), enabling the development of a prototype for sustainable dairy farming. For the quantification of the inputs and outputs of this farming system, measurements have been carried out -and are being carried out still- on subsystems or components of the farm. The crop-soil-nitrogen system is one of those subsystems. The data gathered for assessing the performance of this subsystem can be used extraordinarily well for other purposes than 'only' linking them to the data of the whole farm. The data on soil water and nitrogen, gathered during the period 1991-1995 on six different sites of the farm, allow a study on nitrate leaching affected by land use in relation to the different occurring soils at the farm and the prevailing groundwater regimes. The use of simulation models, calibrated and validated using these data, allows a study on effects of changes in land use or changes in soil and groundwater characteristics, within the ranges of model validity.

During the monitoring years, several aspects of the crop-soil-nitrogen system were studied in relation to weather conditions and differences in soil characteristics and groundwater regimes.

Some of these aspects seemed to be more important in relation to the possible effect on nitrate leaching to the groundwater than was realized when the De Marke farm started. Examples for grassland are the random distribution of urine-affected areas during cattle grazing and supplementary irrigation. For three chapters of this thesis the main objective was to quantify the importance of these two aspects for nitrate leaching in relation to temporal and spatial variability.

Thus, measurements on different sites during a period of more than four years in combination with simulation modelling can be utilized for assessing effects of management options or land use changes for these sites on nitrate leaching, but for De Marke it is important to quantify N-losses to groundwater for the whole farm. Extrapolation from point to field to farm was needed to assess the nitrate leaching for the farm level crop-soil-nitrogen system. This aspect is also addressed in this thesis.

An important goal of De Marke is the demonstration of sustainable dairy farming. In the period of September 1992 until the end of 1994 18,000 people visited the farm and several aspects of the farm management were copied by dairy farmers all over the country (Aarts et al., 1996). Most visitors are farmers, but researchers, policy makers, students, extension workers and visitors from other countries come as well. The question often arises how De Marke would perform at other locations, e.g. on other soils and with other groundwater levels. In this thesis we describe one method to assess the performance of the land use system of De Marke on other soils using simulation models. In another research project ('Cows and Challenges') the strategy of De Marke is extrapolated to 12 real farms (Aarts et al., 1999b), bringing the opportunity to develop the prototype for a great variety of Dutch conditions.

Chapters of this thesis

This thesis deals with 'nitrate leaching from dairy farming on sandy soils; case studies for experimental farm De Marke'. Only *chapter 2* is not directly related to De Marke. For the quantification of soil-specific land use effects on nitrate leaching a certain characteristic is needed for the purpose of comparison (e.g. between different soils and land use options). Therefore an environmental land quality was proposed within the land evaluation concept, derived from the water flux leaving the root zone, taking inert solutes and compounds like nutrients along on its way to the groundwater. This environmental land quality was called the 'leaching potential' and the definition and use of this land quality is described in chapter 2. The data and simulations in this chapter are related to a number of irrigation strategies for potatoes on sandy soils and to a set of different groundwater regimes on loamy soils with again potato growing. Although these examples have no direct relation to the De Marke farm, the methods used, namely modelling, dealing with temporal variability and interpretation of model results in terms of frequency distributions and probabilities, are used in many other chapters of this thesis. More specifically, the leaching potential and partly also the definition of irrigation strategies is used again in chapter 6.

Chapters 3-8 are all based on data gathered at De Marke. Monitoring of soil water at six sites within the farm started in 1991 and the first data analysis was performed in 1992. The first modelling attempts for characterizing soil water and nitrogen dynamics were then carried out as well. The assessment of the right input data for modelling activities is very important and, especially for modelling unsaturated water flow, the soil physical characteristics are crucial (*chapter 3*). Therefore we took samples at De Marke for measuring these characteristics, but we also wanted to find out if we could just as well use the already available characteristics of the Staring Series (Wösten et al., 1993). Because measurements are time-consuming and thus more expensive than the use of available characteristics, we considered it worthwhile to compare the effect on model results. Using the data of a little more than one year of monitoring at De Marke, a first calibration of the SWACROP model was performed. For chapter 3 this calibrated model was run using either measured or standard soil physical characteristics and the model results were compared using statistical criteria and graphs of simulated and measured values.

Chapters 4, 5 and 6 focus on different management options for grazed grassland at De Marke. Cattle grazing at the experimental farm was reduced to eight hours per day. Yet, during these eight hours, cattle still produce faeces and urine. Especially urine patches are responsible for peak concentrations of nitrate in soil water (*chapter 4*). An extra experiment for assessing within-field spatial variability of nitrate concentrations in groundwater was conducted and the statistical analysis of the data of this experiment told us that indeed the variability was high at short distances and that extremely high peak values were found at random places within the field. This indicated that urine-affected areas had great influence on our nitrate measurements. Again, simulation models were utilized and this time we used the models SWACROP and ANIMO to help explain the measured variability in nitrate concentrations. Then the soil-specific nitrate leaching risk was assessed by simulating all possible conditions with or without urine during the growing season, taking the effect of weather variability into account. The nitrate leaching risk in chapter 4 was defined as a land quality within land evaluation, similar to the leaching potential of chapter 2.

At experimental farm Droevendaal a site-specific technique was developed, which allowed adapting fertilization to the existing pattern of urine-affected areas (Van der Putten et al., 1996). We wondered how much difference this strategy would make in terms of nitrate leaching at De Marke. In that same period we first learned about the hydrological plans for the area around De Marke. As compensation for the drought caused by the pumping station for drinking water nearby, a so-called wetting scheme was planned. The soils of De Marke are very drought susceptible and a rise of the water table could be very welcome for moisture supply to the crops. It is therefore that we wrote *chapter 5* on effects of management options on nitrate leaching considering site-specific fertilization omitting urine-affected areas on one hand and raising the groundwater levels on the other. Again using simulation models, within-field spatial variability gets special attention in this chapter in order to define field-specifically which option is more promising for lowering nitrate leaching, whilst maintaining or improving crop productivity: site specific fertilization or the raising of groundwater levels?

Chapter 6 pays attention to another aspect of land management for grazed grassland, namely supplementary irrigation. Several strategies can be defined that aim at reducing both water use and nitrate leaching. Using the modelling concepts of the previous chapters, the optimal strategy is assessed from both the environmental and the agricultural point of view. Within-field spatial variability is accounted for in the same manner as in chapter 5. The use of the nitrate leaching risk as defined in chapter 4 is compared with the use of the leaching potential as defined in chapter 2.

Chapters 7 and 8 deal with extrapolation, either from site to farm level or even to other soils. For the upscaling of the data gathered at six sites within the farm to whole farm level, the information of the soil survey of De Marke was used, again showing the importance of spatial variability. Using more than 200 soil profiles as input resulted in more than 200 different model results, allowing a simple analysis as is presented in *chapter 7*. The model results are used for assessing the nitrate leaching risk for the farm (i.e. the sum of all farm fields), but also differentiated per year, per crop and groundwater conditions.

Finally, *chapter 8* deals with the extrapolation of De Marke to other soils. For this, we translated all soil use management activities into decision rules. We thought that grassland management with rotational grazing and cutting would depend on weather conditions and on grass growth, but this was not the case. The decision rules ended up as being rather simply determined by a standard number of days between grazing and cutting. We were then able to perform an extrapolation of De Marke to other areas as had been the intention at the beginning of the project. For this, the simulation models SWACROP and ANIMO were used as well as the manner of dealing with temporal variability as was already adopted for chapter 4. We 'replaced' the soils of De Marke by other major soils in sandy areas of the Netherlands to find out how the land use systems of De Marke would perform on other locations within the sandy areas of the Netherlands.

2. THE LEACHING POTENTIAL AS A LAND QUALITY OF TWO DUTCH SOILS UNDER CURRENT AND POTENTIAL MANAGEMENT CONDITIONS

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THE LEACHING POTENTIAL AS A LAND QUALITY OF TWO DUTCH SOILS UNDER CURRENT AND POTENTIAL MANAGEMENT CONDITIONS

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Abstract

Within the field of land evaluation, crop productivity as well as environmental effects should be investigated for specific land use types. The leaching potential is introduced as an environmental land quality and is expressed in terms of a downward flux from the root zone. The frequency distribution and the amount of this downward flux were calculated for each period of the year using the SWANY model, which simulates soil water flow, evapotranspiration and crop growth. Two examples for the use of this land quality are presented for potato production under different irrigation regimes on a coarse-textured Humic Podzol and under different groundwater control regimes on a median-textured Calcaric Fluvisol in the Netherlands.

The simulation results showed that irrigation increases crop yields for the Humic Podzol, but also increases the leaching potential. Restricted irrigation resulted in similar crop production levels, but in only part of the additional downward flux from the root zone. For the Calcaric Fluvisol, drainage provided higher crop yields and a slightly lower leaching potential due to an increase in crop uptake.

Introduction

It is being recognized nowadays that research on modern agricultural systems should not only aim at increasing crop production, but must also seek to decrease environmental impacts. Measures to minimize negative environmental effects, such as means to reduce nutrient and pesticide losses or soil erosion, have to be investigated.

Sustainable agricultural systems which consider both crop production and environmental effects can be investigated with land evaluation methods. Land evaluation is the process of assessing the suitability of land for a specified type of land use and starts with a physical evaluation phase, followed by a socio-economic analysis in the integral land evaluation phase. Physical land evaluation involves an analysis of natural resources, implying an evaluation of attributes of land such as climate, soil, hydrology and topography for defined agricultural production systems.

Different types of technical procedures are available for physical land evaluation, ranging from qualitative methods using expert knowledge to quantitative methods based on computer simulation (Van Lanen et al., 1992). A comparison of a qualitative and a quantitative land evaluation procedure for the assessment of soil-water related land qualities was carried out by Van Lanen and Bouma (1989), clearly showing that quantitative methods produce more detailed information, including temporal variability, and are better suitable for evaluating alternative scenarios.

Quantitative physical land evaluation has thusfar mainly been occupied with the assessment of quantitative expressions for crop productivity as affected by, for example, water deficit and excess, workability in spring and harvestability in autumn, and nutrient availability (e.g. Van Wijk and Feddes, 1986; Bouma and Van Lanen, 1987; Van Lanen et al., 1987; Van Diepen et al., 1989; Hack-ten Broeke et al., 1990). Recently, environmental effects such as expressions for the leaching potential of land have been introduced (Wösten et al., 1990b; Petach et al., 1991; Vereecken et al., 1991). None of these methods use an integrated approach, in which both crop production and environmental aspects have been incorporated. In this study, the leaching potential is introduced as a land quality, indicating the possibility of water and solutes leaching to groundwater. Computer simulation is applied to obtain water-associated land qualities (for example soil water deficit and workability) related to crop growth for two contrasting Dutch soils. In addition, the leaching potential, which is also a water-associated land quality, is assessed for both soils. The study involves current as well as potential management conditions, specifically supplemental irrigation for a coarse-textured soil and increased drainage for a median-textured soil. At this stage solute behaviour is not included, although it is recognized that for many solutes not only water fluxes are determining the leaching potential. However, without water movement leaching would not occur at all and therefore we focus on water fluxes in this study.

The purpose of this paper is twofold: (1) to introduce the leaching potential as a land quality within the concept of land evaluation, and (2) to illustrate its usefulness through two practical examples of its determination and interpretation in relation to other land qualities and crop growth.

Materials and methods

Leaching potential

Within the field of quantitative land evaluation computer simulation models and short-term experiments are applied to obtain quantitative expressions of land qualities. For example, workability can be described in terms of a number of days within a specific time period during which the soil is workable, often expressed as a frequency distribution (Van Lanen et al., 1987; Hack-ten Broeke et al., 1990). Water deficit during the growing season can be used as a measure for the water supply capacity of a specific soil type under the prevailing groundwater and climatic conditions. When a great number of growing seasons are simulated, a frequency distribution can be produced showing how often a specific water deficit will be exceeded.

Likewise, it is possible to define the leaching potential in quantitative terms. In this paper, the soil water flux from the root zone is taken as the determining factor for the leaching potential, because soil water movement largely determines the leaching of solutes. Leaching is directly related to water flux for inert solutes. Water flowing downward from the root zone is not necessarily lost to root water uptake, because of possible capillary rise, and this should be taken into account.

The leaching potential is defined as the occurring downward flux from the root zone, possibly causing solute leaching and is therefore expressed in terms of the number of days during the year with a downward flux from the root zone as well as in terms of the flux itself. Frequency distributions are provided that are based on calculations from periods of at least 20 years for the particular land utilization type. Simulation provides the information to define this frequency distribution and the amount of water involved. For this purpose the model SWANY, based on the SWACROP model, was used.

Model description

SWACROP

The quantitative procedure is based on the model SWACROP, which consists of a soil water flow model (SWATRE) and a crop production model (CROPR). The soil water flow model SWATRE (Soil Water Actual Transpiration Rate Extended) describes one-dimensional (vertical), transient, unsaturated water flow in a heterogeneous soil-root system using Richard's equation (Belmans et al., 1983; Feddes et al., 1988), which is solved numerically by a finite-difference scheme. The soil is divided into compartments and the term for root water uptake (sink term) is calculated as a function of the maximum transpiration rate and a reduction factor, which depends on the pressure head in the root zone (Feddes et al., 1988). The rooting depth can vary with time. In the SWACROP model, the rooting depth is not directly linked to the daily crop growth rate.

The boundary condition at the top of the soil profile is the maximum evapotranspiration flux. This upper boundary condition is calculated from daily meteorological data. At the bottom of the soil profile, a lower boundary condition has to be defined, for which a water table, soil water potential or flux can be used.

The crop production model CROPR computes the daily actual and potential dry matter production as a function of actual and potential transpiration respectively (Feddes et al., 1978). The daily growth rate is expressed as a function of transpiration and vapour pressure deficit. Optimum nutrient supply is assumed, and the effects of weeds or diseases are not taken into account.

The output of SWACROP contains potential and water-limited yields which are assumed to be representative for high input agricultural systems, daily values of moisture content and pressure head, root water uptake for each soil compartment within the root zone, fluxes between the nodal points (and so also the flux from the root zone to the underlying soil), and potential and actual transpiration

SWANY

SWACROP allows for simulation of only one growing season. SWANY (SWAcrop for a Number of Years) was developed to allow for multiple-year simulations to obtain frequency distributions of events. SWANY simulates both winter and growing season. The start of the growing season, being the sowing or planting date, is simulated by the soil-water model (Fig. 2.1) by considering the calculated number of workable days and the required number of days for field operations. The simulated pressure head and the air temperature after sowing or planting determine the crop emergence date. This procedure is crop specific. From emergence onwards, the soil-water and crop model simulates daily soil-water flow and crop growth (Van Wijk and Feddes, 1986; Hack-ten Broeke et al., 1989). At the end of the growing season the crop is harvested and the model returns to the soil-water simulations for the next winter period. The output of SWANY is used to present quantitative measures for crop productivity, workability, water deficit, aeration and leaching potential. In this paper the emphasis will be on the leaching potential.

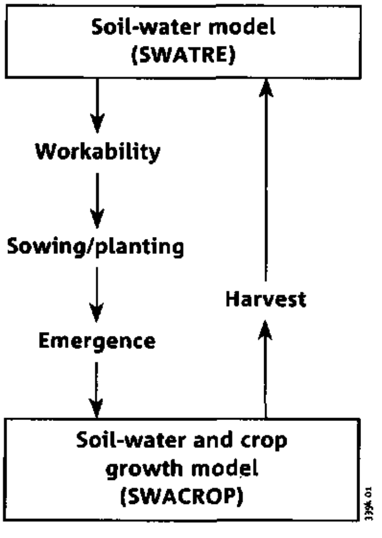

Fig. 2.1 Yearly simulation procedure within SWANY

When calibration and validation of SWANY is successful, i.e. an acceptable agreement is found between measured and simulated values, it is assumed that the model is valid for long-term weather data (number of years). Daily meteorological data for 30 years from the meteorological station De Bilt in the Netherlands were used to calculate the upper boundary condition for the simulations. Usually, for soils with a relatively shallow water table (influencing transpiration rates), groundwater depth can be used as a boundary condition, but these data are generally not available for 30 years. Therefore, a relation between groundwater level and flux through the bottom-boundary of the simulated profile was used. The groundwater depths, simulated with this relationship, were compared with the expected distribution of groundwater levels (Van der Sluijs and De Gruijter, 1985). The expected levels can be calculated with the known mean highest and lowest water table at the sites, which are determined from soil surveys. For soils with deep groundwater tables, a fixed pressure head or free drainage is used as the lower boundary condition.

Sites and simulated experiments

The sites were located at two different experimental stations in the Netherlands. The soils at the Sinderhoeve site consist of sandy, fluvioglacial, mostly gravelly sediments with deep groundwater. These soils are depicted as Humic Podzols on the 1 : 1,000,000 EC soil map (CEC, 1985) and are classified as Plaggeptic Haplohumods according to Soil Taxonomy (Soil Survey Staff, 1975). The crop involved in the simulation and in the experiment, used for calibration and validation, was potatoes. Moisture stress is the main yield limiting factor for the potato crop at this site and irrigation is often used to provide additional water.

Three irrigation options were simulated using the SWANY model: no irrigation (option 1), conventional irrigation (option 2) and reduced irrigation (option 3). Irrigation was applied when the simulated pressure head at a specified depth in the root zone drops below a critical value (Wesseling and Van den Broek, 1988). For option 2, this critical pressure head was h = -400 cm at 25 cm below the soil surface and the amount of water applied was 2.5 cm. The interval between individual applications, usually dictated by availability of equipment and labour, was minimally 7 days. This option represents normal practice in the Netherlands. In many areas in the Netherlands legislation is being developed to decrease irrigation, due to concerns about lowered water tables. Option 3 represents a reduced irrigation scheme of 1.0 cm water when the pressure head at 25 cm below the surface falls below h = -400 cm. The minimum interval between irrigation events was reduced to 5 days.

It should be pointed out that potatoes are in reality never grown for thirty years in succession. However, these simulations were performed to include temporal variability due to changing weather conditions.

A second site was located on an experimental farm near Lelystad in the IJsselmeerpolders. The soils here have a loamy texture and a groundwater regime characterized by a mean highest water table of 60 cm and a mean lowest water table of 160 cm below the surface. These soils are classified as Calcaric Fluvisols according to the 1 : 1,000,000 EC soil map and as Typic Fluvaquents in Soil Taxonomy (Soil Survey Staff, 1975). The crop involved in the experiment and simulation was again potatoes. At this site moisture stress rarely occurs, but spring workability can be a problem resulting in a shorter growing season. Lowering of the groundwater table might be considered through drainage or by artificially lowering of the surface water levels in the polders. Three options were simulated using the SWANY model: the current groundwater regime (option 1) and two optional regimes (options 2 and 3). Option 2 represented a mean highest water level of 80 cm below soil surface and a mean lowest water level of 180 cm below the soil surface. The third alternative assumed no groundwater influence at all. This can not be achieved in the polder, but was included in this study to enable a comparison of soil water behaviour in case of presence and of absence of groundwater.

For both sites data on soil water and crop production of one year were used for calibration and similar data of a second year for validation. Only the parameters determining crop water uptake were used as calibration parameters.

Data of 1981 were used to calibrate and data of 1982 were used to validate the SWANY model for the Sinderhoeve site. Measured moisture storage in the upper 40 cm of the soil, pressure heads at 15 and 25 cm below the soil surface and average potato tuber yields were used to compare with the simulation results. For the Lelystad site, data for calibration and validation were available from a different experiment conducted in the years 1986 and 1987 respectively. Pressure heads were measured at 35 and 45 cm below the soil surface.

Results

In Figure 2.2 some of the calibration results for the Sinderhoeve site are presented. Figure 2.2A shows measured and simulated moisture storage for 1981 and Figure 2.2B measured and simulated tuber yield for 1981. Figure 2.3 shows calibration results for the pressure head at 45 cm below the soil surface (A) and the tuber yield (B) of 1986 at the Lelystad site. More details on calibration and validation of the model are provided by Feddes et al. (1988), Wesseling and Van den Broek (1988) and Hack-ten Broeke et al. (1990). The calibration and validation results were considered satisfactory enough to proceed to simulations with the SWANY model.

<u>Sinderhoeve site</u>

Figures 2.4 and 2.5 show the simulation results for the Sinderhoeve site for crop production and the leaching potential respectively. Without irrigation (option 1), a tuber yield over 10,000 kg/ha dry matter was not exceeded in about 38% of the years (Fig. 2.4). Furthermore, the simulated average dry matter yield was 10,040 kg/ha. The frequency distributions of the number of days with a downward flux (Fig. 2.5A) are based on daily values, but are presented as averages for ten-day periods. Figure 2.5A shows that during the first days of July the number of days with a downward flux was 3 out of 10 when no irrigation was applied. The average number of days with a downward flux during a year was 259 in that case and the total amount of water flowing downward during those days was 42.8 cm.

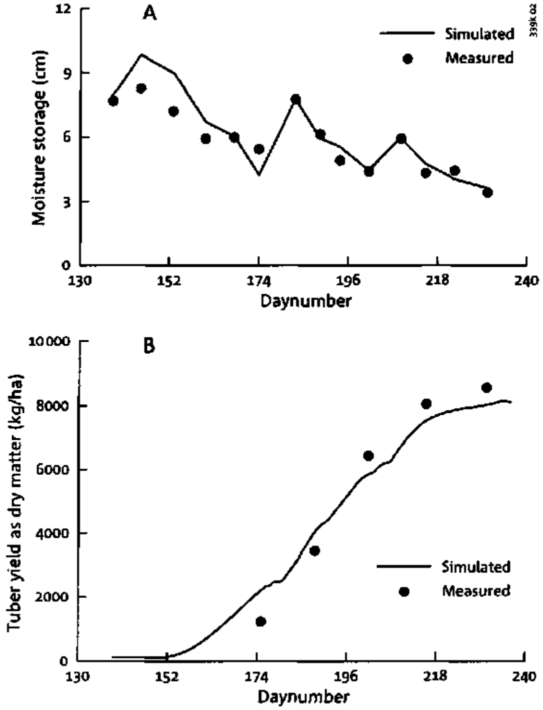

Fig. 2.2 Simulated and measured moisture storage of the upper 40 cm (A), and tuber yields (B) in 1981 for the Sinderhoeve site

Additional water supply yielded a higher crop production level and also a higher amount of leaching water for both irrigation options (Figs. 2.4 and 2.5). For both options 2 and 3 the dry matter yield was always higher than 10,000 kg/ha. The average tuber yield for option 2 was 13,326 and for option 3 12,549 kg/ha dry matter. These yields were obtained with an average annual irrigation of 13.6 cm and 9.6 cm respectively. The differences in yield between irrigation option 2 and 3 were not as spectacular as the differences in irrigation amounts showing that the two types of management can result in similar crop production levels: between 11,000 and 16,000 kg/ha for option 2 and between 10,000 and 14,500 kg/ha for option 3. Considering that the production range without irrigation varied from 6000 to 13,500 kg/ha dry matter, this also means that supplementary irrigation reduced the production range, which is relevant for a risk analysis.

No differences in leaching potential existed during the winter (Fig. 2.5), but during the first 10 days of July over 50% of the days showed a downward flux under option 2 and 40% under option 3. From the end of May to August the two options yielded about 10 to 20% more days with downward leaching from the root zone than option 1. The average number of days with a

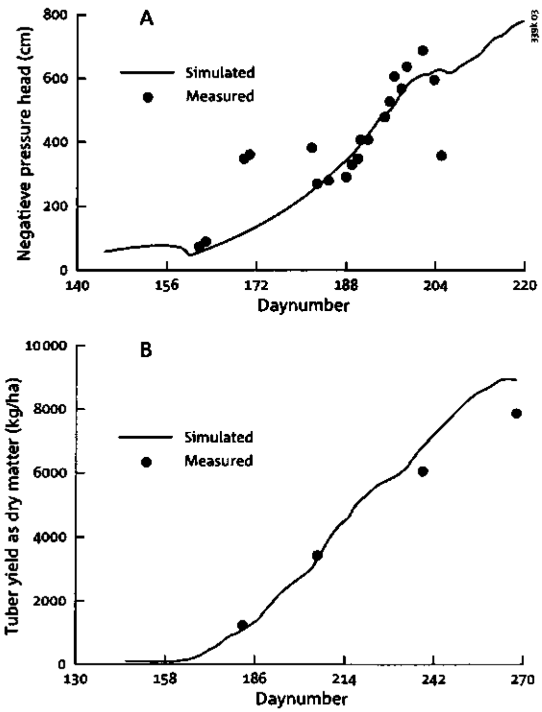

Fig. 2.3 Simulated and measured pressure head at 45 cm below the soil surface (A), and tuber yield (B) in 1986 at the Lelystad site

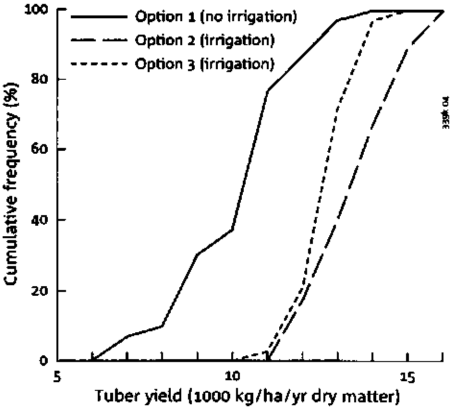

Fig. 2.4 Cumulative frequency distribution of potato tuber yield at the Sinderhoeve site for three irrigation options

downward flux during a year was 277 for option 2 and 271 for option 3. Figure 2.5B shows the cumulative amount of water flowing downward for each ten-day period of the hydrological year. Obviously, this amount was higher as irrigation increased. On the average irrigation option 3 produced 45.7 cm water as a cumulative downward flux during a year and option 2

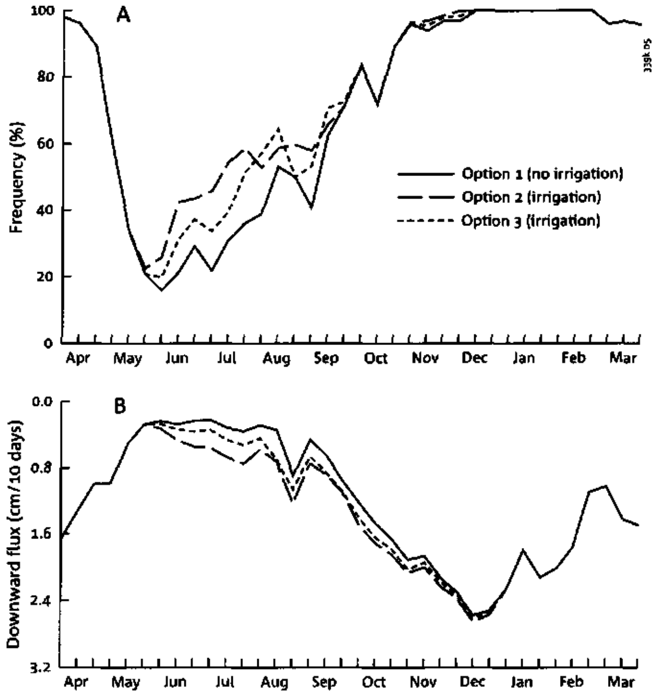

Fig. 2.5 The leaching potential: frequency distribution of the occurrence of a downward flux from the root zone (A), and cumulative downward flux at the bottom of the root zone for each ten-day period (B) at the Sinderhoeve site for three irrigation options

produced 47.5 cm water. Although irrigation option 3 produced only half the additional downward flux of option 2, this difference in downward flux was certainly not as big as the difference in applied irrigation water.

Lelystad site

The simulated effects of the three different groundwater regimes on soil workability, crop production and leaching potential are presented in Figures 2.6, 2.7 and 2.8 respectively.

The workability of the soil is the most important problem due to water excess when growing potatoes at the Lelystad site. In Figure 2.6 the workability is presented as the frequency distribution of workable days. The 60-160 (mean highest and mean lowest water table) regime is the prevailing one at the site (option 1). In that case, 2 out of 10 days were workable during the first ten days of March. The average total of workable days in March and April was 11. Figure 2.7 shows the frequency distribution of tuber yields. The dry matter yield was higher than 12,000 kg/ha in 40% of the years under the current groundwater regime. The simulated average yield was 11,381 kg/ha dry matter. The leaching potential is presented in Figure 2.8. In the last ten-day period of May a downward flux from the root zone occurred in 5 out of 10 days for the prevailing groundwater regime. Figure 2.8B shows that there was also an upward flux. The total number of days with a downward flux during a year was on the average 244 with 45.4 cm water moving downward. The total average upward flux was 6.8 cm water.

Figure 2.6 shows that relevant differences in workability for field operations under Dutch weather conditions mainly occurred in the spring period. The drainage option (80-180), option 2, doubled the amount of workable days during the first ten days of March to approximately 4 out of 10 and no groundwater influence (option 3) resulted in 5 out of 10 workable days. The total number of workable days in March and April was 23 for the 80-180 option and was 29 in case of "no groundwater". For both options this implies a longer growing season and as a result, frequency distributions of tuber yields for both alternative groundwater regimes showed higher yields compared to the current groundwater regime (Fig. 2.7). For example, the tuber yield was more than 12,000 kg/ha dry matter in 60% of the years under the alternative regimes, with an average dry matter yield of 12,243 kg/ha for option 2 and 11,921 kg/ha for option 3. The differences in yield between options 2 and 3 were negligible, because the longer growing season for option 3 (without groundwater influence) was compensated by moisture deficits.

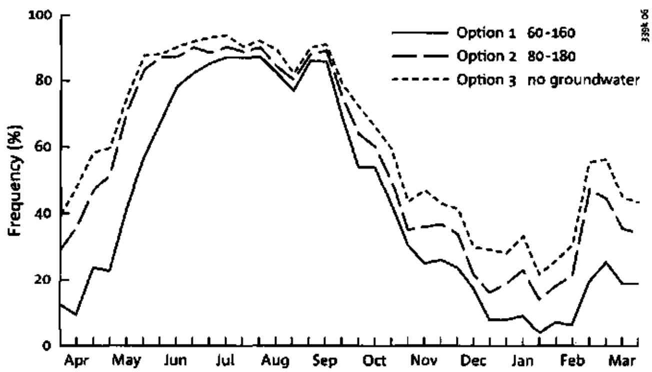

Fig. 2.6 Frequency distribution of workable days at the Lelystad site for three groundwater regime options

The most obvious differences for the leaching potential (Fig. 2.8) were found in May and June. When crop development started earlier in the season (for both options 2 and 3), more water was taken up from the root zone, resulting in a decrease in downward flux. In the last ten-day period of May a downward flux from the root zone occurred in only 2 out of 10 days for the two alternative regimes (Fig. 2.8A). Differences between options 2 and 3 occurred later in the growing season and in the winter period. During the winter (especially February and March), downward fluxes always occurred when there was no groundwater influence. From Figure 2.8B it can be concluded that in May and June the downward flux was decreased due to the earlier crop development. This diagram also shows that lower groundwater decreased capillary rise in summer. The total average number of days with a downward flux for the 80-180 regime (option 2) was the same as for the prevailing regime (244 days) involving 43.3 cm water flowing

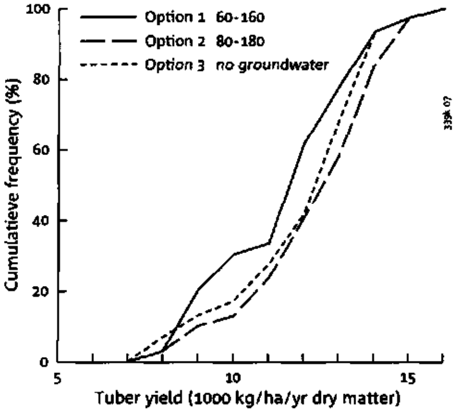

Fig. 2.7 Cumulative frequency distribution of potato tuber yield at the Lelystad site for three groundwater regime options

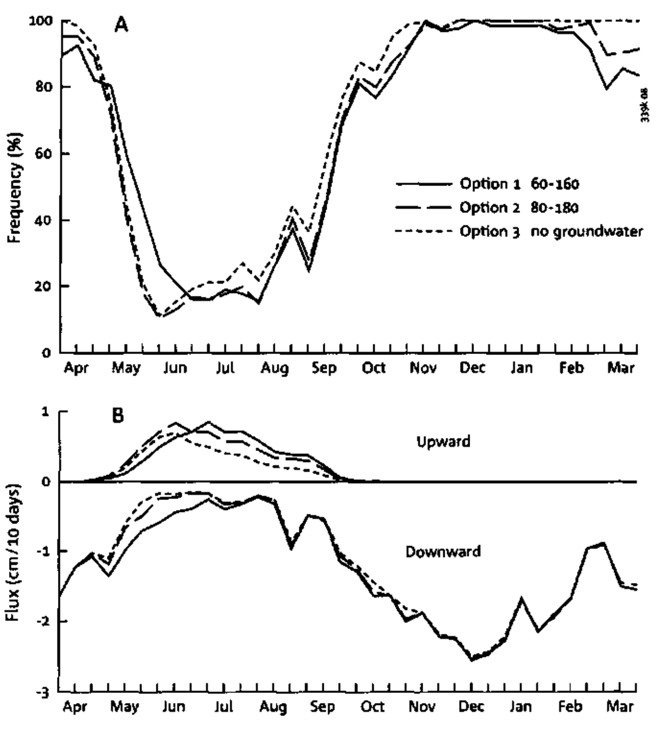

Fig. 2.8 The leaching potential: frequency distribution of the occurrence of a downward flux from the root zone (A), and cumulative downward and upward water flux at the bottom of the root zone for each ten-day period (B) at the Lelystad site for three groundwater regime options

downward and the total upward flux was then 6.7 cm water. Thus, increased drainage did not only increase crop yields, but also decreased leaching. Without groundwater influence (option 3) the number of days with a downward flux increased to 258 at this site with a flux of 42.2 cm downward and 4.9 cm upward.

Comparison of the sites

At the Sinderhoeve site with the sandy soil and very deep groundwater the main problem for agricultural use is the moisture deficit. The potato tuber yield ranged from 6000 to 13,500 kg/ha dry matter with an average of 10,040 kg/ha dry matter. At the Lelystad site with the loamy soil and groundwater influencing the moisture regime, a restriction for agriculture is workability in spring. The potato tuber yield at the Lelystad site ranged from 7000 to 16,000 kg/ha dry matter with an average yield of 11,381 kg/ha dry matter. Through management options, involving irrigation at the Sinderhoeve site and drainage at the Lelystad site, yields could be increased.

The differences between the sites concerning the leaching potential were most obvious in Figures 2.5A and 2.8A, showing the frequency distribution of days with a downward flux from the root zone. During the months July and August, for instance, the number of days with a downward flux at the Sinderhoeve site ranged from 5 to 6 days out of 10 and at the Lelystad site only from 2 to 3 days out of 10. The total average number of days during a year with a downward flux ranged from 259 to 277 with 42.8 to 47.5 cm water flowing downward at the Sinderhoeve site and from 244 to 258 with 42.2 to 45.4 cm water at the Lelystad site. Furthermore, the most important difference between the sites that can be read from Figures 2.5B and 2.8B is that at the Sinderhoeve site there was no upward flux at all. This clearly shows the importance of the water holding capacity of the soil.

Conclusions and discussion

The leaching potential can well be used as a land quality within quantitative land evaluation to evaluate the effects of current and possible future management practices, such as plans for irrigation schemes or adapting groundwater regimes. Besides, crop productivity of land in relation to the environmental impact can now be estimated. These and similar assessments can be used for land-use policy making. When decisions have to be made, for instance in case of conflicting objectives, the assessment of the impact of changes in management or legislation on both crop productivity and environment is needed.

From the simulation results it can be concluded that restricted irrigation at a site with a Humic Podzol can provide similar production levels as the conventional irrigation regime, decreasing the leaching potential. Next, increased drainage at a Calcaric Fluvisol will increase crop production and decrease the leaching potential.

In this study only two examples were elaborated for irrigation and for drainage. However, the procedure can readily be extended to simulate more options or scenarios to support decision makers.

In this study the flux from the root zone is considered as determining the leaching potential. Any other flux at any depth below the root zone could also be used for this purpose. In the Netherlands often the level of 1 m below soil surface is considered. This could easily be adopted in the presented procedure.

The proposed procedure only provides a first estimate of the environmental impact of inert solutes and focuses only on the flow from the root zone. For most solutes the involved processes in the soil, such as adsorption or transformation, should be included in the model to simulate their leaching potential. There are enough existing (sub-)models, describing chemical processes (e.g. ANIMO, Rijtema and Kroes, 1991 and LEACHM, Hutson and Wagenet, 1992), that can be incorporated in quantitative land evaluation methods to provide information for such purposes.

Acknowledgements

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3. USE OF SOIL PHYSICAL CHARACTERISTICS FROM LABORATORY MEASUREMENTS OR STANDARD SERIES FOR MODELLING UNSATURATED WATER FLOW

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USE OF SOIL PHYSICAL CHARACTERISTICS FROM LABORATORY MEASUREMENTS OR STANDARD SERIES FOR MODELLING UNSATURATED WATER FLOW

M.J.D. Hack-ten Broeke and J.H.B.M. Hegmans

Abstract

Soil physical characteristics are important input parameters for simulation modelling of unsaturated flow in soils and associated solute flow. The determination of soil water retention and hydraulic conductivity curves in the laboratory is laborious and expensive. For modelling studies that require characteristics for many soil horizons, such as regional studies or scenario studies, it may be impossible to measure all the necessary characteristics. An alternative would be to use characteristics inferred from readily available soil data by class-pedotransfer functions. In this study such a comparison was made for six sites on sandy soils in the Netherlands using the soil-water model SWACROP with soil physical characteristics from either laboratory measurements or from a standard series as input. For this the simulated pressure head values and moisture content values were compared with measured values at eight different depths using statistical criteria. Furthermore two functional criteria, i.e. the number of workable days and number of days with possible drought, were inferred from simulated pressure head values and again the different results were compared. It was found that simulation results were not significantly different, implying that standard series or class-pedotransfer functions could be used in studies like these for simulating the unsaturated water flow regime in sandy soils on field/farm level or regional level. Differences for specific criteria for individual sites were sometimes substantial and in such cases (at field level) it will make a difference which soil physical characteristics are used.

Keywords: Soil-water modelling; Soil hydraulic characteristics; Pedotransfer functions

Introduction

Soil physical characteristics are important input parameters for all dynamic deterministic models, describing unsaturated soil water flow. In most models a few homogeneous soil layers can be distinguished and for each layer soil water retention and hydraulic conductivity curves are used for the simulations. There are various methods for measuring these soil characteristics, but these measurements are time-consuming. The use of available soil characteristics of a standard series, referred to as class-pedotransfer functions, is a possibility to avoid the measurements (Bouma and Van Lanen, 1987). In the Netherlands such a standard series exists (Wösten et al., 1987; Wösten et al., 1994), the so-called 'Staring Series'. Procedures using different pedotransfer functions for deriving soil hydraulic characteristics have also been published by Vereecken et al. (1989), Vereecken et al. (1990), Vereecken et al. (1992) and Tietje and Tapkenhinrichs (1993).

Wösten et al. (1990a) compared the accuracy of four different methods to generate soil hydraulic functions by comparing the simulated water storage of the upper 50 cm of three soil profiles over a period of seven years. These four methods comprised directly measured data and the already mentioned Staring Series for the Netherlands. The differences in model performance were not significant, but the directly measured hydraulic functions seemed to produce slightly better simulation results than the pedotransfer functions.

In land evaluation studies land qualities are often derived from simulated pressure head or moisture content values at specific depths. For instance soil workability is often derived from the simulated pressure head at 5 cm depth and aeration from soil moisture content values in the root zone (e.g. Van Wijk and Feddes, 1986; Van Lanen et al., 1987; Bouma and Hack-ten Broeke, 1993; Hack-ten Broeke et al., 1993). Studies to calculate the leaching of solutes often depend on the simulated flux at a certain depth and this calculated flux is again the result of simulated pressure head values. Therefore the objective of this study is to compare the use of different soil hydraulic characteristics focused on simulated pressure head and moisture content values. For this purpose data for six different sites on sandy soils were used.

Materials and methods

Experimental sites

This study was performed for six different sites at De Marke, experimental farm for sustainable dairy farming. The farm is located on dry sandy soils in the east of the Netherlands. The farm area (55 ha) was used to grow grass (56%), silage maize (33%) and fodder beet (11%). About one third of the area was permanent grassland, situated near the farm buildings, the rest of the area had a rotation of grass and fodder crops. Supplementary irrigation was only permitted if urgently needed to ensure grazing possibilities. The farm was set up with the main objective to develop and demonstrate a prototype of a farming system which minimizes nutrient and pesticide losses to the environment while remaining economically feasible (Aarts et al., 1992). A comprehensive monitoring plan for various components of the farming system started in 1991. One of the purposes of this data gathering is the evaluation of the success of the farming system considering the environmental goals. This implies in this case the need for assessment of solute transport to the groundwater and therefore a thorough understanding of unsaturated flow phenomena.

A soil survey of the farm was carried out in 1990 (Dekkers, 1992). The information on soils and groundwater levels from this survey was used together with the land use on the farm to choose six monitoring sites (Tables 3.1 and 3.2). Three sites were located on relatively dry spots and three sites on spots with shallower groundwater levels. The different crop rotations of the sites are given in Table 3.2. These six sites gave an overall insight in the soil water behaviour of the farm. The soil profile characteristics of the six sites (referred to with field numbers) are given in Table 3.1. Sites 2, 9 and 11 were the relatively dry sites with groundwater levels varying on

Table 3.1 Soil profile characteristics of six monitoring sites at 'De Marke'

Soil horizon	Depth below soil surface (cm)	Organic matter content (%)	Loam content (%)
Site 2			
Ap	0-27	3.7	11.4
Ah/EBp	27-36	3.0	9.8
BCg	36-48	2.8	9.8
Cg1	48-66	0.5	9.5
Cg2	66-120	0.5	9.2
Site 9			
Ap	0-30	6.1	11.7
Bhe	30-45	3.0	9.8
Cg1	45-80	1.6	8.8
Cg2	80-120	0.8	3.3
Site 11			
Ap	0-30	4.0	12.0
Bw	30-60	0.8	4.4
Cu	60-85	0.6	2.7
Cg	85-120	0.2	2.6
Site 17			
Ap	0-30	3.0	15.7
Bhe/BCe	30-40	3.0	16.0
Bhe	40-55	3.0	13.0
Bce	55-75	1.5	17.4
Ce	75-100	0.3	20.0
Site 19			
Ap	0-30	3.9	24.1
Bhe	30-40	2.4	13.9
BCe1	40-55	1.6	14.0
BCe2	55-75	1.3	17.7
Ce	75-110	0.2	20.0
Site 21			
Ap	0-34	5.0	16.0
Ahb	34-38	4.0	18.0
Cg1	38-50	0.2	18.0
Cg2	50-90	0.2	19.0
Cr	90-120	0.1	22.0

average from 1.20 to 2.50 or 3.00 m below soil surface and the relatively wet sites 17, 19 and 21 had groundwater levels between 0.30 and 1.70 m.

In each of the six fields there was one monitoring site of 20 x 20 m, where all crop and soil monitoring took place. In one strip of about 10 m length and 1 m width tensiometers, time domain reflectometry (TDR-) probes and soil suction cups were installed. In a central location in this equipment strip the TDR probes were installed at eight depths, namely 10, 20, 30, 40, 60, 90, 120 and 150 cm below soil surface. The tensiometers were installed on either side of the TDR equipment within the equipment strip at the same depths. For the pressure head measurements within the root zone (10, 20, 30 and 40 cm below soil surface) there were three replicates per site. A piezometer was available for measuring the groundwater depth. Volumetric moisture contents, pressure heads and groundwater depths were measured every two weeks.

Table 3.2 Classification of monitoring sites according to hydrological condition (dry/wet) and crop rotation (1. permanent pasture, 2. 2/3 of the years grass, 1/3 of the years silage maize and fodder beet, 3. 1/3 of the years grass, 2/3 of the years silage maize and fodder beet)

Site number	Hydrological condition	Field type	Crop	
			1991	1992
2	dry	rotation 1/3 grass	fodder beet	maize
9	dry	permanent pasture	grass	grass
11	dry	rotation 2/3 grass	grass	grass
17	wet	permanent pasture	grass	grass
19	wet	rotation 2/3 grass	grass	fodder beet
21	wet	rotation 1/3 grass	maize	maize

Soil physical characteristics

In a pit, dug just outside each 20 x 20 m monitoring site, soil columns were taken at three different depths for determination of soil water retention and hydraulic conductivity characteristics in the laboratory. In these pits the same soil horizons were distinguished as in the equipment strip which was located at 6 m (permanent pasture) or only 3 m (other sites) distance from the pit. In the laboratory the one step outflow method (Doering, 1965; Kool and Parker, 1987) and the crust method (Bouma et al., 1983) were used to determine the physical characteristics. For the comparison between these laboratory curves and curves from the standard series, curves were taken from the Staring Series (Wösten et al., 1987). The choice of the curves from these series depends on soil texture class, organic matter class and whether the soil layer is within the topsoil or the subsoil. For sandy soils the loam content (see Table 3.1) is the major determining factor. This method is referred to as a class-pedotransfer function relating soil horizons or other class data such as texture class to associated physical parameters (Bouma and Van Lanen, 1987). The allocation of physical parameters of the Staring Series is based on texture classes as used in the Dutch soil survey.

Simulation

The different soil physical characteristics for each of the six experimental sites were used as input parameters for the model SWACROP. SWACROP is a dynamic deterministic model describing one-dimensional (vertical) unsaturated water flow in a heterogeneous soil-root system using Richard's equation (Feddes et al., 1978; Belmans et al., 1983; Feddes et al., 1988). Besides water retention and hydraulic conductivity input data are needed to define the upper and lower boundary of the soil profile and the initial moisture status. For the upper boundary meteorological data could be used that were measured on the farm itself. These data comprised rainfall, temperature, global and net radiation (for grass and bare soil), relative humidity and wind speed. From these data potential transpiration was calculated on a daily basis according to Monteith (1965) and Rijtema (1965). Crop data, such as soil cover or leaf area index, rooting depth and sowing and harvest dates, are needed to determine actual transpiration with the model (Feddes et al., 1988). These data were all available from the regular research program of the farm (Hack-ten Broeke et al., 1992). Groundwater levels, measured on all sites, were used to determine the bottom boundary of the profile and initial soil moisture status was derived from measured pressure head values. No calibration took place, so besides the different soil physical characteristics, all input data and model parameters were kept constant during the simulations. Two simulation runs, comprising two years, were carried out for each site: one simulation used only physical characteristics determined in the laboratory for all soil horizons and the other simulation only used curves of the Staring Series. Model output includes for each day actual and potential evapotranspiration, root water uptake, moisture content and pressure head values for each soil compartment and fluxes between the soil compartments.

Table 3.3 Statistical criteria for comparing model performance

$$ME = Max\left|P_i - O_i\right|_{i=1}^{n}$$

$$RMSE = 100 \cdot \left(\sum_{i=1}^{n} (P_i - O_i)^2 / n \right)^{1/2} / \overline{O}$$

$$CD = \sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2 / \sum_{i=1}^{n} \left(P_i - \overline{O}\right)^2$$

$$EF = \left(\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{n} (P_i - O_i)^2 \right) / \left(\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2 \right)$$

$$CRM = \left(\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i \right) / \left(\sum_{i=1}^{n} O_i \right)$$

ME = maximum error, *RMSE* = root mean square error, *CD* = coefficient of determination, *EF* = modelling efficiency, *CRM* = coefficient of residual mass

P_i = simulated value i
O_i = observed value i

Statistical criteria

From all six experimental sites, pressure head and moisture content measurements of 1991 and 1992 were used for the evaluation. The simulated pressure head and moisture content values at the eight depths of measurements were compared with these measured values. This model output for each experimental site, resulting from the simulations with two different sets of soil physical characteristics, was compared using statistical criteria and visual interpretation of the time series graphs. Firstly, statistical criteria were calculated according to Loague and Green (1991). This assessment comprised five criteria: maximum error *(ME)*, root mean square error *(RMSE)*, coefficient of determination *(CD)*, modelling efficiency *(EF)* and coefficient of residual mass *(CRM)* (Table 3.3). These criteria were only used for the comparison of the model results of the two different simulations. Several of these statistics are sensitive to a few large errors. The *CD* (in Table 3.3) as defined by Loague and Green (1991) is not the same as the classical coefficient of determination. The *CD* used here rather expresses the ratio of the scatter of the simulated values and the scatter of the measured values. When *EF* becomes negative the mean of the measurements is a better estimate than the simulations. Positive values for *CRM* indicate that the model underestimates the measurements and negative values for *CRM* indicate a tendency to overestimate. Loague and Green (1991) also mention that statistical criteria have serious limitations and that graphical displays can be useful for showing trends, types of errors and distribution patterns. Therefore simulated and measured pressure head and moisture content values were plotted against time and these graphs were also used for comparing the results.

Functional criteria

Besides the statistical criteria and visual interpretation of the fit between simulated and measured pressure head and moisture content values at eight different depths, we also used functional criteria as are used in land evaluation studies or other regional studies.

The criteria should allow a comparison of the simulation results for wet and dry periods. Therefore we chose on the one hand workability as an important land quality in the spring during a relatively wet period of the year and on the other hand drought stress as a typical land quality for the dry summer period.

Workability is often expressed as the number of workable days, derived from pressure head values at 5 cm depth. This number of workable days is easily calculated for a sandy soil as the number of days with a pressure head value of $h < -70$ cm (Van Wijk and Feddes, 1986; Van Lanen et al., 1987; Hack-ten Broeke et al., 1993). This was carried out for the months April and May of both 1991 and 1992 using the pressure head values simulated with the two different sets of soil physical characteristics. A similar approach was followed for days with possible drought stress. If a pressure head value within the root zone (in this case a root zone of 40 cm was assumed for all sites and all crops) reached a value of $h < -500$ cm (corresponding with a pF-value of approximately 2.7) it was considered as a drought day. The number of such days was assessed from the simulations for both years for the months June, July and August.

Results and discussion

Statistical criteria

The results for the statistical criteria for all six sites and the two sets of soil physical characteristics are presented for pressure head values and moisture content values in Table 3.4 and Table 3.5 respectively. When comparing the data pairs in both Tables, it is obvious that the differences between the values of the statistical criteria for the two simulations are often not striking. With a *t*-test for paired observations to compare the two sets of criteria per site we found that none of the differences were significant. This would mean that in this case model performance is similar using either the laboratory measurements or the Staring Series.

Table 3.4 Results for the statistical criteria (see Table 3.3) considering simulated and measured pressure head values

	ME	*RMSE*	*CD*	*EF*	*CRM*
Optimum	0	0	1	1	0
Site 2					
laboratory	742.0	-114.8	2.8	-0.02	-0.02
Staring Series	778.5	-112.2	3.1	0.02	0.20
Site 9					
laboratory	706.1	-93.9	2.1	0.29	0.06
Staring Series	742.2	-96.9	1.8	0.24	0.15
Site 11					
laboratory	722.0	-129.6	1.0	-0.53	-0.13
Staring Series	722.9	-128.9	1.1	-0.54	0.01
Site 17					
laboratory	603.9	-101.9	2.3	0.19	0.23
Staring Series	616.9	-100.3	1.1	0.21	0.10
Site 19					
laboratory	772.1	-150.7	0.4	-1.31	-0.01
Staring Series	758.7	-119.4	0.7	-0.45	0.10
Site 21					
laboratory	824.3	-136.9	3.4	0.03	0.57
Staring Series	810.6	-128.5	3.8	0.14	0.36

Table 3.5 Results for the statistical criteria (see Table 3.3) considering simulated and measured moisture content values

	ME	*RMSE*	*CD*	*EF*	*CRM*
Optimum	0	0	1	1	0
Site 2					
laboratory	0.13	55.6	0.5	-1.40	-0.32
Staring Series	0.18	85.0	0.2	-4.59	-0.68
Site 9					
laboratory	0.30	44.9	0.6	-0.96	-0.32
Staring Series	0.33	42.6	0.4	-0.77	-0.24
Site 11					
laboratory	0.17	43.3	0.4	-1.23	-0.05
Staring Series	0.17	41.6	0.4	-1.06	-0.08
Site 17					
laboratory	0.30	33.2	0.8	-0.77	-0.18
Staring Series	0.26	23.0	1.3	0.15	0.01
Site 19					
laboratory	0.30	34.0	0.7	-0.73	-0.15
Staring Series	0.28	32.1	0.9	-0.55	0.04
Site 21					
laboratory	0.16	21.7	1.6	0.52	-0.07
Staring Series	0.11	23.5	1.7	0.43	0.06

The numbers in both Tables are valid for total soil profiles and the total simulation period. The criteria were thus calculated because those conditions are usually also of interest for regional studies for which we would want to use class-pedotransfer functions. In this study we also compared simulated and measured values for specific layers and specific parts of the year. Especially visual interpretation of the results showed in which cases differences between the simulations occured and how important that may be. Differences can be expected when some of the individual data pairs in Table 3.4 and Table 3.5 are examined. As an example the simulated and measured pressure head values at 20 and 40 cm below soil surface for one of the sites (site 17) are presented in Figure 3.1. With the laboratory curves (Fig. 3.1A) the pressure head at 20 cm depth during the dry summer periods was not simulated well and with the Staring Series (Fig. 3.1B) this obviously improved. The difference between the simulated pressure head values at 40 cm depth (Fig. 3.1C and 3.1D) was small. There was still a difference during the first summer period, but it was less pronounced.

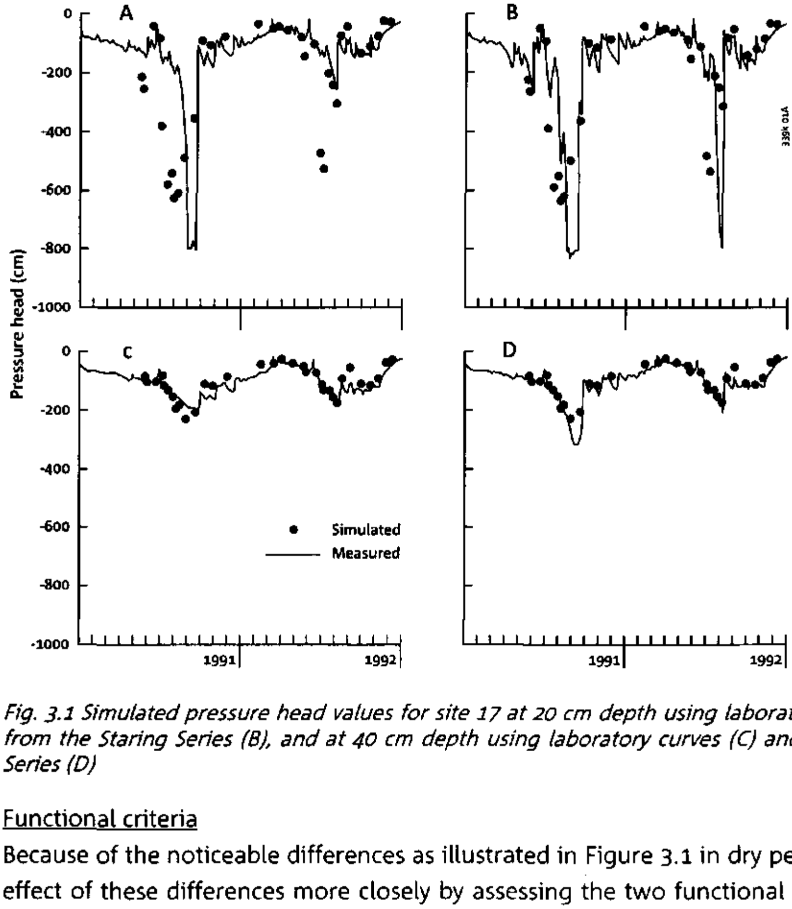

Fig. 3.1 Simulated pressure head values for site 17 at 20 cm depth using laboratory curves (A) and curves from the Staring Series (B), and at 40 cm depth using laboratory curves (C) and curves from the Staring Series (D)

Functional criteria

Because of the noticeable differences as illustrated in Figure 3.1 in dry periods we examined the effect of these differences more closely by assessing the two functional criteria: the number of workable days and the number of days with possible drought (Tables 3.6 and 3.7). For all data in both Tables the *t*-test for paired observations, carried out for each site, indicated that the differences between laboratory curves and Staring Series were neither significant for workable days nor for days with drought. Individual differences between data pairs can be substantial, e.g. the simulated number of workable days in April '92 at site 21 was nineteen when the Staring Series was used and there were no workable days left when the measured curves were used. Because the *t*-test was carried out for only six data pairs at a time relatively large differences are needed to make them significant. Differences in workability (Table 3.6) were most pronounced in 1992, especially for sites 19 and 21. These sites were relatively wet sites and in 1992 at both sites there was bare soil, followed by fodder beet and silage maize respectively. At the sites with permanent grassland (9 and 17) and the other two sites with deeper groundwater levels (sites 2 and 11) the pressure head at 5 cm depth was almost always below the threshold value h = -70 cm.

Table 3.6 Results for functional criteria considering workability

	Number of workable days			
	April '91	May '91	April '92	May '92
Site 2				
laboratory	30	31	30	31
Staring Series	29	31	28	30
Site 9				
laboratory	30	31	30	31
Staring Series	30	31	28	29
Site 11				
laboratory	30	31	30	31
Staring Series	30	31	28	30
Site 17				
laboratory	30	31	21	29
Staring Series	30	31	17	27
Site 19				
laboratory	30	31	14	22
Staring Series	30	31	23	29
Site 21				
laboratory	25	26	0	15
Staring Series	29	31	19	25

Table 3.7 also shows the different effects of crops in this case considering pressure head values within the root zone affected by root water uptake. Especially fodder beets can extract water from a very dry soil, whereas grass often shows limited transpiration already at pressure head values in the root zone between h = -200 cm and h = -500 cm (De Jong and Kabat, 1990). For the determination of drought days in Table 3.7 the latter limit was used, which might mean an overestimation of drought stress for fodder beet. At site 2 fodder beet was grown in 1991 and at site 19 in 1992 (see Table 3.2). Especially the difference at site 2 between the two years 1991 (fodder beet) and 1992 (maize) was obvious. The differences in simulated pressure head values in the summer, as illustrated in Figure 3.1, are causing these differences in drought days between simulations with laboratory curves and Staring Series. The differences between sites and between years were larger than the differences between the simulations with the two sets of physical characteristics. It was not possible to distinguish the relatively wet and dry sites using these data because the dry sites (9 and 11) were irrigated.

Table 3.7 *Results for functional criteria considering drought stress*

	Number of days with possible drought					
	June '91	July '91	Aug. '91	June '92	July '92	Aug. '92
Site 2						
laboratory	1	20	31	0	1	11
Staring Series	0	21	31	0	0	12
Site 9						
laboratory	7	0	0	0	0	0
Staring Series	18	9	8	1	0	0
Site 11						
laboratory	15	21	27	15	31	13
Staring Series	17	9	28	10	31	14
Site 17						
laboratory	0	0	1	0	0	0
Staring Series	0	0	17	0	3	9
Site 19						
laboratory	12	1	31	2	31	15
Staring Series	0	0	13	4	24	13
Site 21						
laboratory	0	0	8	0	15	15
Staring Series	0	0	8	0	1	11

Conclusions

Soil water pressure head and moisture content values, measured at six sites and eight different depths in sandy soils, were simulated well with the model SWACROP either using soil physical characteristics measured in the laboratory or using standard soil physical characteristics from the Staring Series. Small differences between five statistical criteria calculated to assess the difference between measured and simulated values for total soil profiles and total simulation periods, were found to be not significant. Visual interpretation of graphs of simulated and measured values against time were helpful to find the reason for these small differences in the statistical criteria, which turned out to occur mainly during the growing season. Calculated functional criteria, i.e. workable days in April and May and days with possible drought in June, July and August, also showed no significant differences when the two sets of physical characteristics were used for the simulations. Differences for specific criteria for individual sites were sometimes substantial and in such cases (at site level) it will make a difference which soil physical characteristics are used.

The small overall differences imply that use of the Staring Series in modelling studies on field/farm level or regional level like the ones discussed here is a good alternative for expensive time-consuming laboratory measurements. This is of great importance for scenario studies or regional studies in land evaluation or environmental risk assessments where many simulations for a variety of soil types are needed. It should be noticed that this conclusion is valid for sandy soils and the criteria used in this specific study.

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4. IMPACT OF EXCRETED NITROGEN BY GRAZING CATTLE ON NITRATE LEACHING

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IMPACT OF EXCRETED NITROGEN BY GRAZING CATTLE ON NITRATE LEACHING

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Abstract

At De Marke experimental farm, data on water and nitrogen flows in the unsaturated zone were gathered on two grazed pastures on sandy soils during the years 1991 to 1994. These provided a basis for calibration and validation of simulation models. The different levels of nitrate-N concentrations of the two plots could largely be explained by differences in crop uptake and simulated denitrification as influenced by different groundwater levels. The irregular distribution of excreta was taken into account by a simulation study quantifying the variability of nitrate-N concentrations under a grazed field. The resulting distribution of simulated nitrate-N concentrations explained the average and peak values of the measured concentrations. Temporal variability of weather was used to assess the nitrate leaching risk under urine patches deposited in either July or September. At site A the probability of exceeding the EC-directive by drinking water (11.3 mg/l nitrate-N) under a urination deposited in either July or September was respectively 10 and 25%. The average field concentration at this site will hardly ever be a high risk for the environment under the current farm management. At site B the EC-directive will be exceeded under any urine patch in almost 100% of the years, affecting the field average concentration. In field B careful grazing management would result in less nitrate leaching, but the environmental goals would not be reached.

Keywords: Nitrogen; Nitrate; Leaching; Urine; Cattle; Grazing; Models

Introduction

Dairy farming in the Netherlands is facing serious environmental problems. At De Marke experimental farm for sustainable dairy farming, a system is being developed which aims at meeting environmental goals (e.g. for nitrate leaching), whilst being economically viable (Aarts et al., 1992). This paper focuses on the environmental goals for nitrate leaching on grazed grassland at the farm.

Nitrogen is added to the soil by human activities with animal manure, fertilizers, crop residues, through atmospheric deposition, and by grazing cattle. The effect of urine droppings by grazing cattle on nitrogen (N) losses to the groundwater can be of major importance. One urine patch can represent a local application of between 400 and 1200 kg N/ha (Addiscott et al., 1991). It is obvious that, especially in the last part of the growing season, this N cannot be fully utilized by the grass crop and might substantially leach to the groundwater. Various studies have shown that nitrate leaching is indeed greater under grazed grassland than under cut grassland (e.g. Ball & Ryden, 1984; Steenvoorden et al., 1986; White et al., 1987; Macduff et al., 1990; Spatz, 1992). Because movement of N from urine patches occurs mainly in the vertical direction

(Garwood & Ryden, 1986; Spatz, 1992), variability of nitrate-N concentrations in soil water or groundwater under a grazed grassland field is expected to be high. Dung patches hardly affect nitrate leaching, because 65 to 80% of the N excreted is contained in urine, the area covered by dung patches is relatively small and furthermore the organic N in dung patches only slowly degrades (Lantinga et al., 1987; Deenen & Middelkoop, 1992). Therefore dung is not considered in this study.

At two sites within different grazed pastures of the experimental farm, nitrate-N concentrations in soil water or groundwater were measured during the period 1991 to 1994. In one of these fields an extra experiment was carried out in 1992 to assess the degree of variability of the nitrate-N concentrations within the whole field.

In this paper first the results of the monitoring and the extra experiment are presented and discussed. Then the calibration and validation of the simulation models for water and nitrogen are described. The model results were compared with observed soil moisture and nitrate-N concentration data. Next the spatial distribution of excreta was calculated to assess the distribution of nitrate-N concentrations under the two fields. Finally the sensitivity of leaching following urination to different weather conditions was studied. Using these results the nitrate leaching risk of the two fields was quantified in terms of nitrate-N concentrations and the number of days during the year with nitrate-N concentrations exceeding a threshold value (EC directive for drinking water, also used as the limit for the farm).

The objectives of the paper are to try to explain measured variability of nitrate-N concentrations in soil water by simulations including effects of grazing, and to assess the vulnerability of the two fields to different weather conditions following urination, expressed as the nitrate leaching risk.

Materials and methods

Experimental sites

The experimental farm De Marke is located in the eastern region of the Netherlands on sandy soils. The farm area (55 ha) is used to grow grass (56%), silage maize (33%) and fodder beet (11%). About one third of the area is permanent grassland, situated near the farm buildings. A comprehensive monitoring plan for various components of the farming system started in 1991. One of the purposes of this data gathering was to evaluate the progress of the farming system towards achieving environmental goals. This implies the need for quantification of various components of the nutrient cycles, including the effects of grazing cattle. For the nitrate concentration in groundwater the environmental goal was set to the EC-directive for drinking water of 11.3 mg nitrate-N/l (Aarts et al., 1992).

A detailed soil survey of the farm was carried out in 1990 (Dekkers, 1992). The information on soils and groundwater levels from this survey was used to choose the monitoring sites. Within two grazed pastures (A and B) with different groundwater levels and also slightly different soil types two sites were chosen. The main differences between the soil types were the organic matter content in the topsoil and the loam content of the total soil profile. At the relatively wet site A, groundwater depths varied between 0.0 and 2.0 m below soil surface during the monitoring years and at the drier site B between 0.5 and 2.8 m below soil surface. At site A the sum of the silt and clay contents of the sandy soil was about 17% throughout the soil profile down to 1 m and the organic matter content of the topsoil was 3%. At site B the content of silt plus clay of the topsoil was about 12% decreasing to about 3% at 1 m depth. The organic matter content of the topsoil at this site was about 6%. The greater silt plus clay content in field A resulted in a larger water holding capacity and more capillary rise compared to site B. Soil mineral N contents were similar for both sites. In spring, mineral N contents for the upper 20 cm of the soil range from 10 to 20 kg/ha and in the summer peak values of 60 to 70 kg/ha were measured.

At De Marke a rotational grazing system was practised. At site B the grazing density was higher than at site A and at site A intermediate cuts were usually more frequent than at site B. In 1992 the grass was cut three times at both sites, but in 1993 the grass was cut four times at site A and only two times at site B. Grazing periods with 60 to 78 cows on fields of approximately 2 ha

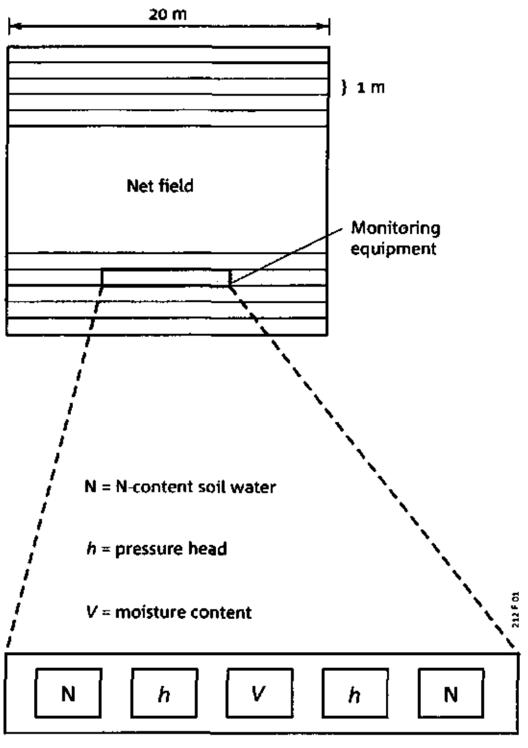

Fig. 4.1 Monitoring site in the grassland fields of De Marke experimental farm

varied from one to five days and was usually followed by grazing with 20 to 30 heifers for one to seven days.

In each field there was one monitoring site of 20 x 20 m (Fig. 4.1), where all crop and soil monitoring took place. As is shown in Figure 4.1 tensiometers, Time Domain Reflectometry (TDR) probes and soil suction cups were installed in one strip of about 10 m length and 1 m width. In a central location in this measurement strip the TDR probes (for measuring soil moisture content) were installed at eight depths, namely 10, 20, 30, 40, 60, 90, 120 and 150 cm below the soil surface. At each depth one probe was installed. The tensiometers (for measuring pressure head) were installed on either side of the TDR equipment at the same depths. There were three replicates per site for the pressure head measurements within the root zone (10, 20, 30 and 40 cm below the soil surface). At depths of 60 to 150 cm only one tensiometer was installed. A piezometer was available for measuring the groundwater depth. Volumetric moisture contents, pressure heads and groundwater depths were measured every two weeks from 1991 to 1994. In two pits at the outer ends of the measurement strip (Fig. 4.1) 20 suction cups (10 cups per pit) were installed at 1 m depth for sampling the soil water. These samples were analysed for nitrate-N concentration in the laboratory. Figure 4.2 shows how the ten cups were installed per pit. At site B it was often not possible to sample soil water from the suction cups at 1 m depth due to dry soil and therefore seven extra piezometers were installed from which groundwater was sampled. The eight piezometers (not shown in Fig. 4.1) at site B were installed 3 m apart and within the monitoring site. In between measurements, the equipment was covered with soil and the grass sward to enable normal field management and grazing and to ensure that soil water movement was not affected by the monitoring.

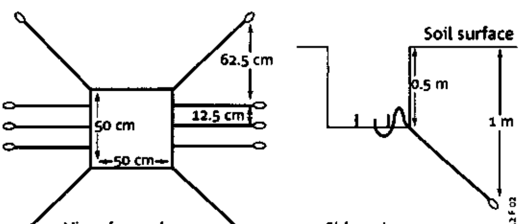

Fig. 4.2 Installation of suction cups for soil water sampling

In addition to the regular monitoring, the groundwater was sampled in field A in April 1992 at 100 grid points, evenly distributed over the field at varying intermediate distances of 1, 5 and 25 m, to obtain data on variability of nitrate-N concentrations under grazed grassland (Dijkstra et al., 1993). At these grid points also a soil profile description was made and the groundwater depth at the time was recorded.

Models

The SWACROP model was used for simulating unsaturated water flow and the ANIMO model for simulating the nitrogen dynamics of the two grazed grassland fields.

SWACROP is a dynamic deterministic model describing one-dimensional (vertical) unsaturated water flow in a heterogeneous soil-root system using Richard's equation (Feddes et al., 1978; Belmans et al., 1983; Feddes et al., 1988). Water retention and hydraulic conductivity characteristics are crucial input data for the simulation of unsaturated water flow. For the experimental sites these characteristics were thoroughly determined and tested for model use (Hack-ten Broeke & Hegmans, 1996). Field data of pressure head and moisture content were used to further improve these curves. Moreover, input data were needed to define the upper and lower boundary conditions and the initial moisture status for simulating soil water movement in the soil profile. For the upper boundary, meteorological data were available from the farm itself. These data comprised rainfall, temperature, global and net radiation (for grass and bare soil), relative humidity and wind speed. From these data potential transpiration was calculated on a daily basis. Crop data, such as soil cover or leaf area index, rooting depth and mowing dates, were needed to determine actual transpiration with the model (Feddes et al., 1988). These data were all available from the regular research program of the farm (Hack-ten Broeke et al., 1992). Groundwater levels, measured at the two sites, were used to determine the bottom boundary of the profile and the initial soil moisture status was derived from measured pressure head values.

The ANIMO model is a dynamic simulation model which describes the carbon and nitrogen cycle in the soil and their interrelations (Rijtema & Kroes, 1991; Jansen, 1991). When the model is used in combination with SWACROP it calculates solute transport in the unsaturated zone and it can then simulate nitrate leaching to the groundwater. Important processes in the model are mineralization and immobilization of nitrogen, crop uptake, nitrification and denitrification. All processes are strongly affected by soil moisture (simulated by SWACROP), pH (input parameter), oxygen supply and soil temperature (both simulated by ANIMO) and also by the simulated decomposition and availability of organic matter. Inputs to the model comprise fertilizer and manure applications, volatilization rates for each application, atmospheric deposition of N and N supply through crop residues and excreta from grazing cattle.

Both models were calibrated and validated by comparing measured and simulated data (moisture content, pressure head and nitrate-N concentration). Calibration was performed using the data of the hydrological years (April-April) 1991/1992 and 1992/1993 and then the remaining data of 1993 and 1994 were used as the validation set. All measured model input parameters were left unchanged during the calibration. Hence for SWACROP only the parameters describing the root water uptake function were used as calibration parameters and for ANIMO only the parameters describing the diffusion of oxygen. During the calibration and validation process the excreta of the grazing cattle were assumed to be distributed evenly over the field as extra animal manure during each day of the grazing periods. This resulted in average nitrate-N concentrations as model output, which were compared with the averages of the measured nitrate-N concentrations. After validation, a simulation study was performed to assess the effects of unevenly distributed urine patches.

Spatial distribution of excreta

Obviously, excreta from grazing cattle are not distributed evenly over the pasture. To quantify the effect of spatial variability of urine patches, first the mean excreta density should be calculated, followed by the spatial distribution. The mean excretal density D_t at time t is defined by (Petersen et al., 1956):

$$D_t = \frac{N_t a}{A}$$

with N_t being the total number of urinations in the pasture at time t, a the area covered by a single excretion and A the total area of the field. Dairy cows tend to urinate twelve times a day (Lantinga et al., 1987) and at De Marke the cows spent eight hours per day in the field. During these hours they are expected to have urinated four times on average. When the number of grazing cattle is known as well, N_t can be calculated. The influenced area a of a single urine patch is assumed to be 0.68 m^2 (Lantinga et al., 1987).

Petersen et al. (1956) found that the Poisson distribution function gave a satisfactory description of the distribution of excreta for what they described as relatively short grazing periods (up to three years) with $D_t < 0.5$. Possible overlap of urine patches is taken into account by this function. The proportion $P_t(r)$ of the total area covered by r urinations at a given time t is (Petersen et al., 1956):

$$P_t(r) = \frac{e^{-D_t}(D_t)^r}{r!}; r = 0,1,2,\ldots,N_t$$

Having thus calculated the area covered by urine patches during a year, the occurrence probability of patches can be used to derive a probability distribution of simulated nitrate-N concentrations in the soil water under the grazed pasture. Excretions can occur only during the grazing periods. On the basis of nitrogen intake of the cattle and excretion of N in animal products and dung, it was calculated that at De Marke on average 455 kg N/ha is excreted per urine patch. With the models it was now possible to simulate the nitrate-N concentrations in the soil water as a result of one urine patch excreted on one particular day, assuming only vertical movement of N under a urine patch. For all possible days, e.g. all days within the grazing periods, such simulations were performed. Each simulated nitrate-N concentration of each possible situation was then multiplied with the calculated occurrence probability of that situation. When necessary, i.e. when a considerable area is not covered by just one but by more urine patches (overlap), this exercise was repeated for higher values of *r*. One simulation was carried out without excreta (r = 0). The resulting frequency distribution of nitrate-N concentrations was compared with measurements to examine to what extent this type of modelling was able to simulate the effects of excreta on nitrate-N concentrations for the two grazed pastures.

Temporal variability and potential leaching

Leaching of solutes to the groundwater strongly depends on weather conditions, so as a next step we wanted to explore the temporal variability of nitrate leaching from urine patches due to different weather conditions following a urination. Therefore two grazing options for both sites A and B were used: (1) option 'July' with one urination on 1 July 1992 and (2) option 'Sept.' with one urination on 1 September 1992. Then the weather data of 1992 after deposition of the urine patch were replaced 30 times by different weather data. For these simulations daily weather data for 30 years from the De Bilt meteorological station (1959-1989) were used. Each simulation run started in 1991 and up to the urination the weather was not changed (1991 and part of 1992), so as not to influence the initial conditions. The weather data of 1993 were kept the same.

To quantify the differences in leaching risk between the two sites, the results from these simulated grazing options were used. Hack-ten Broeke et al. (1993) defined the leaching potential as a land quality within the concept of land evaluation. Using simulation results of the soil water flow model SWACROP, the leaching potential was expressed in that study in terms of the number of days during the year with a downward water flux and by the magnitude of the water flux itself. Following that concept the nitrate leaching risk is expressed in this paper by the number of days during the hydrological year (April-April) with a nitrate-N concentration at 1 m depth exceeding 11.3 mg/l (EC directive for drinking water, also adopted as the limit for the farm) and the level of the annual average nitrate-N concentration itself. The frequency distribution of both this number of days and the concentration, defining the leaching risk, is calculated as a result of the 30 different simulations per grazing option.

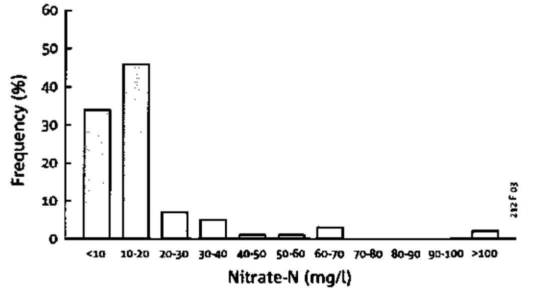

Fig. 4.3 Frequency distribution of nitrate-N in 100 groundwater samples, taken in April 1992 in field A

Results and discussion

Measured concentrations and variability

Spatial variability within field A

The average, minimum and maximum concentrations of the data presented in Figure 4.3 were 17.0, 0.0 and 109.7 mg/l nitrate-N respectively. The extreme values occurred at random locations within the field. No correlation was found between the measured concentrations and soil parameters, such as organic matter content, soil texture and groundwater depth (Aarts et al., 1994). As expected this implies that the variability is predominantly caused by urine patches, deposited in the last months of the growing season of the previous year.

The nitrate-N concentrations were found to be lognormally distributed (Dijkstra et al., 1993) and after log transformation of the data the spatial dependence of the measured nitrate-N concentrations was examined. Figure 4.4 shows the semi-variogram with calculated semi-variance values for more than 30 data pairs. The diagram indicates no spatial dependence for the examined intermediate distances of the data points, which again leads to the conclusion that under grazed grassland the randomly located urine patches may be the cause of the variability of the nitrate-N concentrations. White et al. (1987) found that for soil nitrate all variance for grazed grassland was found within a distance of less than 4 m. The semi-variogram presented in Figure 4.4 is in accordance with these results.

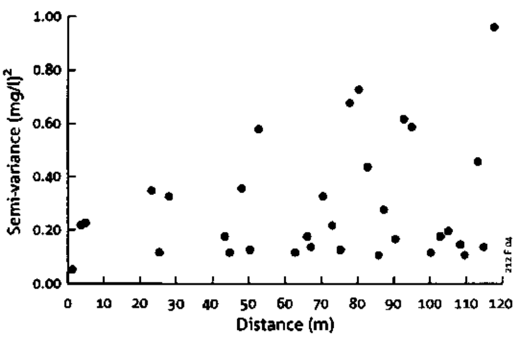

Fig. 4.4 Semi-variance of nitrate-N concentration in groundwater, sampled in April 1992 in field A

Monitoring at sites A and B

The bars in the diagrams of Figure 4.5 represent the standard deviation of the replicate samples of the 20 suction cups of site A. Considering that the EC directive for drinking water is 11.3 mg/l nitrate-N, the concentrations at this site were on average not alarming. Figure 4.6 shows that nitrate-N concentrations and associated standard deviations for site B were clearly higher. In the Figure nitrate-N concentrations in the groundwater are also given. 1993 was a year of high rainfall and it was possible to obtain both groundwater and suction cup samples. The

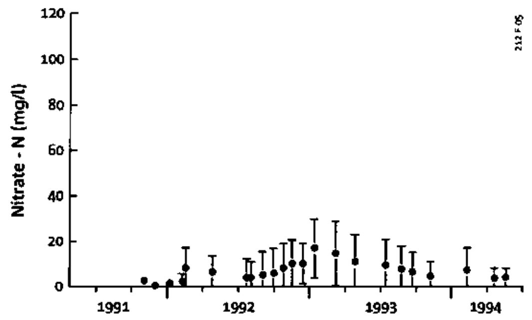

Fig. 4.5 Measured nitrate-N concentrations (average and standard deviation) at 1 m depth fo site A, 1991-1994.

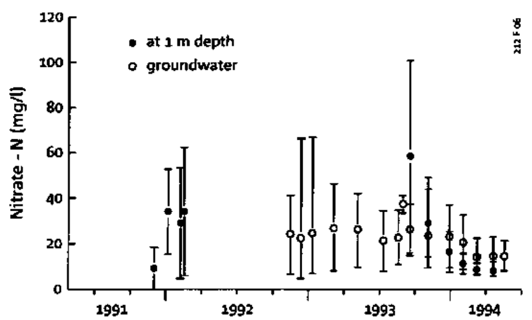

Fig. 4.6 Measured nitrate-N concentrations (average and standard deviation) at 1 m depth and in groundwater for site B, 1991-1994

differences between the concentrations in groundwater and the soil water at 1 m depth were not significantly different due to the large standard deviations.

<u>Model validation</u>

Before modelling of nitrogen dynamics could start, the water flow in the unsaturated zone had to be modelled with sufficient accuracy, so the first validation concerned the model SWACROP. Soil water pressure heads were measured from three tensiometers per depth within the root zone and the homogeneous results of these replicates indicated no preferential flow. In Figures 4.7 and 4.8 some results are presented for site A and B respectively. The results imply that the Darcy flow concept, used in SWACROP, is indeed valid for both sites. Pressure head values less than h = -900 cm cannot be measured, but lower simulated values are possible. In 1991 for site B levels less than h = -1000 cm were calculated for 20 cm depth (Fig. 4.8A); during part of that period the soil was too dry for measurements. For site A pressure head values above h = 0 cm (saturation) were simulated in the winter of 1993/1994 (Figs. 4.7A and 7B). This winter was very wet and we had no access to the field because of ponding. Measured pressure head and moisture content values for that period were therefore missing. Pressure head was considered to be of more importance than moisture content, because water fluxes in the model were directly derived from pressure head values. Water fluxes were subsequently used in ANIMO to

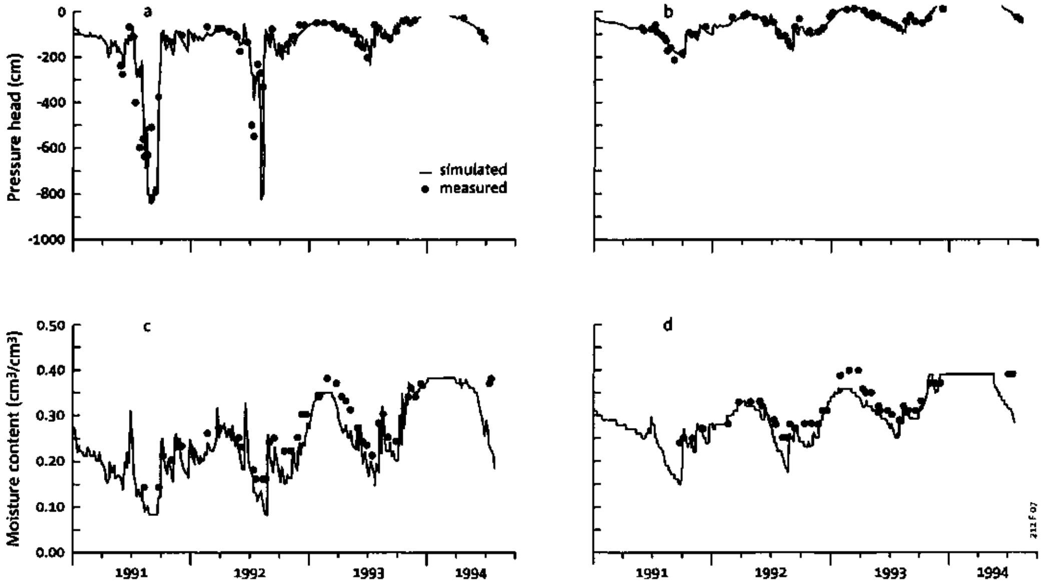

Fig. 4.7 Measured (average) and simulated pressure head values at 20 (a) and 40 (b) cm depth and measured (average) and simulated moisture content values at 20 (c) and 40 (d) cm depth at site A

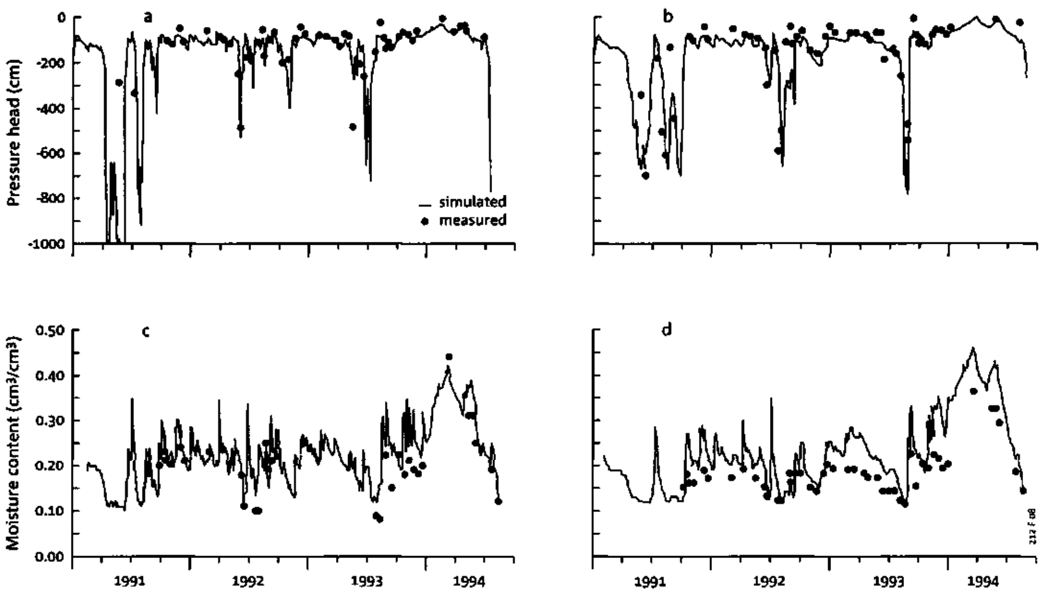

Fig. 4.8 Measured (average) and simulated pressure head values at 20 (a) and 40 (b) cm depth and measured (average) and simulated moisture content values at 20 (c) and 40 (d) cm depth at site B

calculate solute fluxes. The simulation results of SWACROP were considered sufficiently accurate to start simulation runs with ANIMO.

Calibration and validation of the ANIMO model for nitrogen flows was carried out by comparing measured and simulated nitrate-N concentrations at 1 m depth and/or in the groundwater (for site B). The presented average values of the measurements (Table 4.1) were all calculated as the arithmetic mean of the observations. The different methods to calculate mean values for skewed data sets as proposed by White et al. (1987) gave similar results. The measurements at 1 m depth represent concentrations in soil water samples from around the ceramic cups. Therefore the simulated values used for the comparison with the measurements were in this case average values for two of the soil compartments used in the model: 0.9-1.0 m depth and 1.0-1.1 m depth. The groundwater samples were taken from the upper 50 cm of the groundwater. For the comparison between measured and simulated nitrate-N concentrations the simulated values were therefore averaged for the upper 50 cm of the (dynamic) groundwater.

Table 4.1 Comparison of average simulated and measured nitrate-N concentrations

Simulation period	Average nitrate-N concentration (mg/l)	
	Measured	Simulated
Site A		
per hydrological year (1 April-1 April)		
1991/1992	4.7	5.5
1992/1993	7.5	6.2
1993/1994	8.4	8.5
per hydrological season		
winter 1991/1992	4.7	10.3
summer 1992	4.6	6.8
winter 1992/1993	8.9	5.5
summer 1993	10.6	13.0
winter 1993/1994	5.2	3.8
Site B		
per hydrological year (1 April-1 April)		
1991/1992 (1 m)*	27.6	27.0
1992/1993 (grw.)	33.3	28.2
1993/1994 (grw.)	24.5	24.4
per hydrological season		
winter 1991/1992 (1 m)	27.6	27.0
winter 1992/1993 (grw.)	33.3	28.2
summer 1993 (grw.)	25.2	28.6
winter 1993/1994 (1 m)	29.3	30.7
winter 1993/1994 (grw.)	23.9	24.4

* (1 m) = at 1 m depth, (grw.) = in the groundwater

Measurements started in the autumn of 1991, so the first comparison per season (see Table 4.1) is possible from winter 1991/1992. For site A sampling from the suction cups was always possible. As shown in Figure 4.6, the measurements at site B were irregular. In the winter of 1993/1994 concentrations in samples from both the cups and from groundwater were measured at site B (Table 4.1). The main differences between measured and simulated values occurred in the first simulated seasons (especially winter 1991/1992 for site A). This might be due to difficulties with defining initial conditions for N in the soil profile. For later periods the model ANIMO was able to simulate the differences between sites and years relatively well, indicating that the model was accurate enough to perform further simulations with the various grazing options and weather conditions.

The difference between the two sites was mainly caused by the different prevailing groundwater levels. The higher groundwater levels in combination with the higher clay plus silt content of the soil at site A induced better soil moisture supply to the crop as a result of capillary rise. According to the models the grass crop could therefore also take up more nitrogen, leaving less nitrogen in the profile for leaching. Another important effect of the wetter conditions at site A was a larger simulated level of denitrification than at site B, again leaving less nitrate in the profile for leaching. Grazing densities at site B were greater than at site A. The combination of these effects largely explained the higher measured and simulated higher concentrations at site B.

Distribution of nitrate leaching as a function of urine patches

In the simulation of nitrogen flows thus far, it was assumed that N from urine and dung was distributed evenly over the field. Taking the uneven distribution of excreta into account requires calculation of the mean excretal density D_t for the actual grazing periods, followed by the proportion $P_t(r)$ of the total area covered by r urinations. For the two fields the results for all three growing (and grazing) seasons and the different years are shown in Table 4.2.

Table 4.2 Mean excretal density D_t and area $P_t(r)$ covered by r urine patches in 1991-1993

Period	D_t (m^2/m^2)	$P_t(0)$ (% of the field)	$P_t(1)$	$P_t(2)$
Field A				
1991	0.056	94.6	5.3	0.2
1992	0.137	87.2	11.9	0.8
1993	0.129	87.9	11.3	0.7
1991-1993	0.322	72.5	23.3	3.8
Field B				
1991	0.081	92.2	7.5	0.3
1992	0.187	82.9	15.5	1.5
1993	0.270	76.3	20.6	2.8
1991-1993	0.538	58.4	31.4	8.5

During the three growing seasons the distribution function suggested that 23.3% of the area of field A was covered by one urination and 3.8% by two overlapping urinations. Field B, which was more heavily grazed, showed 31.4% of the area covered by one urination and 8.5% by two overlapping ones. Similar values were calculated for every grazing period and were used for the calculation of frequency distributions of annual average nitrate-N concentrations as shown in Figures 4.9 and 4.10. The shape and skewness of these distributions resemble the measured distribution in field A (Fig. 4.3) and are in accordance with distributions found by White et al. (1987). The concentrations at site B (Fig. 4.10) were much greater than at site A (Fig. 4.9). The graphs only show results for the hydrological years 1992/1993 and 1993/1994, because grazing in 1991 was negligible (due to initial problems of the farm). The high nitrate-N concentrations, on the right hand side in both graphs, were caused by a combination of late grazing periods (in September or later) and overlapping urinations. In Table 4.3 the simulated (weighted) average, minimum and maximum concentrations of the frequency distributions are compared with measured data. For site B only simulated and measured values at groundwater level are given in Table 4.3. Average and maximum values were simulated relatively well, but the minimum values were not. These minimum measured values obviously do not correspond with absence of urine patches (causing low simulated nitrate-N concentrations), but must be caused by other factors, such as soil spatial variability.

The simulated average values in Table 4.3 show no improvement over the simulated values in Table 4.1, for which an even spreading of urine-N was assumed. This implies that for the given circumstances of the farm, the calculation of an average field concentration assuming uniform daily distribution of excreted N, is acceptable. It also shows the need for taking into account the distribution of excreted N when the variability of nitrate-N concentrations under a grazed grassland field is studied.

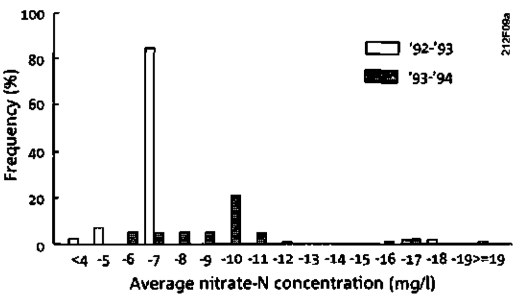

Fig. 4.9 Frequency distribution of simulated nitrate-N concentrations at 1 m depth as a function of the spatial distribution of excreta for site A

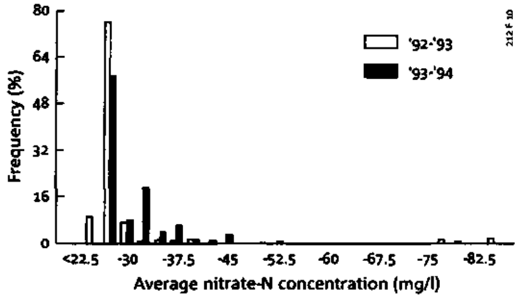

Fig. 4.10 Frequency distribution of simulated nitrate-N concentrations in groundwater as a function of the spatial distribution of excreta for site B

Table 4.3 *Simulated and measured average, minimum and maximum nitrate-N concentrations*

Simulation period	Nitrate-N concentration (mg/l)		
	Average	Minimum	Maximum
Site A			
measured 1992/1993	7.5	0.9	28.4
simulated 1992/1993	6.4	3.9	19.0
measured 1993/1994	8.4	0.9	22.3
simulated 1993/1994	9.4	5.3	16.3
Site B			
measured 1992/1993	33.3	7.6	79.6
simulated 1992/1993	28.9	23.6	82.9
measured 1993/1994	24.5	8.9	48.1
simulated 1993/1994	29.5	26.5	54.9

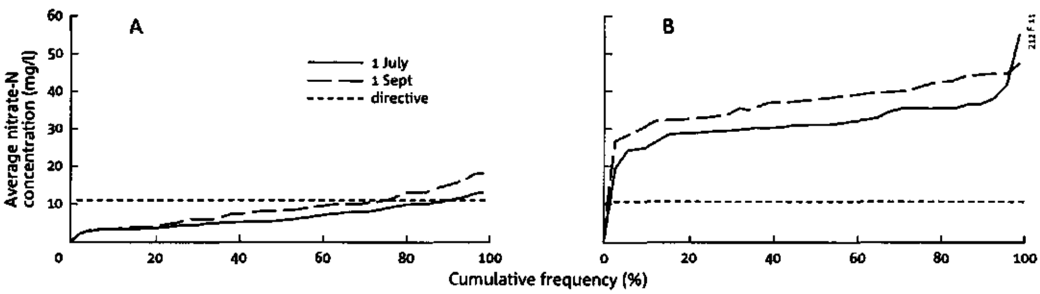

Fig. 4.11 Occurrence probability of nitrate-N concentrations at 1 m depth as a function of temporal variability of weather and following a urination on either 1 July or on 1 September for site A (A) and site B (B)

The nitrate leaching risk as a function of excreta

Figures 4.11 and 4.12 show both components of the nitrate leaching risk as defined in this paper. Figure 4.11A shows that in less than 10% of the years the annual average nitrate-N concentration under a urine patch deposited on 1 July at site A exceeded the EC-directive. For a urination on 1 September the EC-directive was exceeded in less than 25% of the years. For 50% of the years (Fig. 4.12A) the number of days during the whole hydrological year, on which this threshold value was exceeded under a patch at site A, was approximately 60 days (2 months) following a urination in July and approximately 90 days (3 months) following the excretion in September.

At site B (Figs. 4.11B and 4.12B) the nitrate leaching risk is much higher than at site A for the reasons given earlier. The average concentration resulting from a 'July patch' at site B reached a level between 25.0 and 35.0 mg/l nitrate-N in most years and in only a very few years with extreme weather conditions the concentrations reached the level of 55.0 mg/l under a urine patch (Fig. 4.11B). A urine patch deposited in September resulted in nitrate-N concentrations between 30.0 and 40.0 mg/l. Figure 4.12B shows that the probability that throughout the year nitrate-N concentrations at 1 m depth under a urine patch were higher than 11.3 mg/l was almost 100 % for both the 'July' and 'Sept.' option. For environmental goals it is therefore important that grazing at a site like B is restricted to the earlier months of the growing season or that grazing densities are decreased.

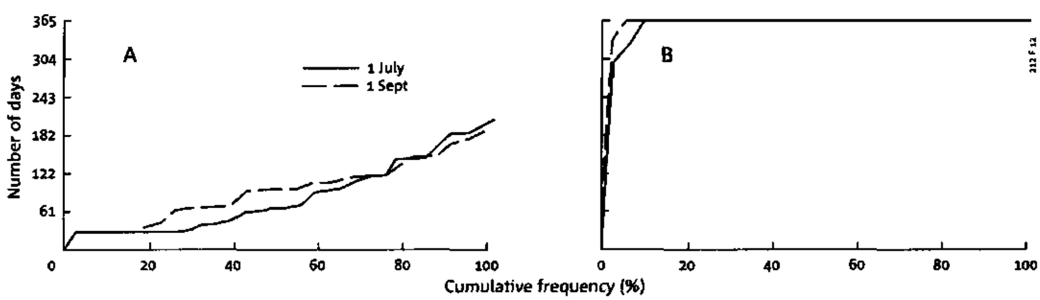

Fig. 4.12 Occurrence probability of the number of days with nitrate-N concentrations exceeding 11.3 mg/l (EC directive for drinking water) as a function of temporal variability of weather and following a urination at either 1 July or 1 September at site A (A) and B (B).

Conclusions

Variability of nitrate-N concentrations was found to be high under grazed grassland with peak values at random locations within the field. All variance seemed to occur within a distance of 5 m, indicating the importance of the uneven distribution of excreted N.

The model SWACROP was successfully used to simulate soil water pressure head and moisture content in the unsaturated zone of the monitored sandy soil profiles and the model ANIMO predicted the average nitrate-N concentrations at the two grazed grassland plots well.

relatively small and the organic N in dung degrades only slowly (Lantinga et al., 1987; Deenen and Middelkoop, 1992). The urine-N is deposited patchwise, resulting locally in high N-inputs (ranging from 300 to 1200 kg/ha N), increased further by subsequent applications of either chemical fertilizer or manure during the remaining part of the growing season. Generally, the recovery of excreted urinary-N is poor on well-fertilized grassland in terms of herbage yield (Deenen and Middelkoop, 1992; Cuttle and Bourne, 1993), implying that a significant part of the excreted N is lost through ammonia (NH_3) volatilization (e.g., Jarvis et al., 1989; Bussink, 1992), nitrous oxide (N_2O) and dinitrogen (N_2) emissions (e.g., Monaghan and Barraclough, 1993; De Klein and Van Logtestijn, 1994) and nitrate (NO_3) leaching to groundwater and drains.

Farm management practices, such as lower fertilization levels and timing and length of grazing periods, are being explored in order to achieve environmentally acceptable nitrate concentration levels in the groundwater on the experimental farms 'De Marke' and 'Droevendaal'. At the 'De Marke' experimental farm for sustainable dairy farming, a system is being developed which aims at meeting both environmental and economic objectives (Aarts et al., 1992). At 'Droevendaal', research has focused on the definition of grassland management strategies in order to reduce nitrogen losses, mainly by investigating the fate of N in the excreta returned to the pasture by grazing cattle. In this paper, the experience of research done at 'Droevendaal' regarding the fate of urine-N is used in the simulations of nitrate leaching on the grazed grassland sites of 'De Marke'.

At 'De Marke', soil water and nitrogen behaviour was monitored intensively on two grazed pastures during the years 1991 - 1995. Simulation models describing water and nitrogen flow were validated using these data (Hack-ten Broeke et al., 1996a). Management options considering, for instance, the effects of urine from grazing cattle on nitrate leaching can be studied using these validated models. Hack-ten Broeke and Dijkstra (1995) reported on such simulations used to quantify effects of urine patches deposited in specific periods of the year on nitrate leaching. They defined five grazing management options with urine depositions ranging from June to October. Concentration levels increased dramatically with the later deposition of urine, with a more pronounced effect in the second simulated year. For the site with relatively high groundwater levels (site A), the EC-directive of 11.3 mg/l nitrate-N was barely exceeded, even under the urine patches, but for the other drier site (site B) all options produced nitrate levels under the urine patches that exceeded the EC-directive. The differences between the sites were largely due to reduced capillary rise, lower net N-uptake by the crop and less denitrification on site B compared with site A. Avoidance of late grazing periods (represented by options with urine deposition in September and October) under such conditions would represent better management in terms of environmental effects.

Hack-ten Broeke et al. (1996a) also indicated that there should be no grazing after August in order to avoid high peak values for nitrate concentrations. In this paper, the emphasis will be on options that might result in the further reduction of nitrate concentration levels with a special focus on the 'hot' spots for nitrate leaching in grazed grassland, the urine-affected areas. The purpose of this paper therefore is to explore the effects on nitrate concentrations in the groundwater of: (i) *A type of precision agriculture which omits fertilization on urine patches* and (ii) Raising of groundwater levels in the area. The ultimate aim of this study is to explore the possibility of defining management options through simulation modelling, dealing with urine-affected areas and groundwater levels for grazed grassland at 'De Marke', which are environmentally acceptable in terms of nitrate leaching to the groundwater and which do not decrease crop yields.

Materials and methods

Experimental sites

The experimental farm 'De Marke' is located on drought-susceptible sandy soils in the eastern part of the Netherlands. About one third of the farm is used for permanent grassland, the rest is used for a rotation of grass and fodder crops. A soil survey of the farm was carried out in 1990 (Dekkers, 1992). The resulting soil map was based on approximately 250 soil profile descriptions on a 50 x 50 m grid. The information on soils and groundwater levels from this survey was used together with the land use of the farm to choose six monitoring sites, two of which were located in permanent pastures. Of these two sites one was located in a relatively dry field (field B) and one in a field with shallower groundwater levels (field A) (Hack-ten Broeke et al., 1992; 1996a). On the relatively wet site A, groundwater depths varied between 0.0 and 2.0 m during the monitoring years and on the drier site B between 0.5 and 2.8 m. On site B in particular, due to drought susceptibility, supplementary irrigation was required to ensure adequate crop growth.

The size of a monitoring site was 20 x 20 m, on which all crop and soil monitoring took place. In one strip of about 10 m length, tensiometers, Time Domain Reflectometry (TDR) probes and soil suction cups were installed (Hack-ten Broeke and De Groot, 1995; Hack-ten Broeke et al., 1996a). Soil moisture samples for measuring nitrate concentrations were taken from the suction cups approximately once a month. Volumetric moisture contents, pressure heads and groundwater depths were measured every two weeks. In another pit, dug just outside the 20 x 20 m monitoring site, undisturbed soil columns were taken to determine soil water retention and hydraulic conductivity characteristics (Hack-ten Broeke and Hegmans, 1996).

For this study monitoring data from the spring of 1991 to May 1995 were used. The weather conditions in these years were quite variable, ranging from dry in 1991 to very wet in 1993. In 1991, the annual rainfall at 'De Marke' was only 658 mm, whereas 1992 was an almost average year with 781 mm. Both 1993 and 1994 were wet years, with 997 and 996 mm rainfall respectively, but the main difference was that a large rainfall surplus in 1993 occurred from July onwards, whereas in 1994 the winter months were wet and the summer was dry until September.

The grassland of site A was cut three times in 1991 and four times per year in 1992, 1993 and 1994, with 233, 290, 272 and 189 full grazing days per year in 1991, 1992, 1993 and 1994, respectively. Site B, which is located near the farm buildings, was cut four times in 1991, three times in 1992, twice in 1993 and only once in 1994. The number of full grazing days on this site was 211, 244, 388 and 373 for 1991, 1992, 1993 and 1994, respectively. The cattle grazing on the farm were dairy cows, heifers and calves, in three separate groups.

A monitoring programme for quantification of the nitrogen inputs and outputs of the soil-crop system was carried out during the years 1992-1994. For the two grazed pastures nitrogen budgets were determined based on measurements and estimates of these inputs and outputs (Hack-ten Broeke et al., 1996b). For the wet site A the N-inputs for these years were on average 195 kg/ha N with animal manure, 85 kg/ha N during grazing (excreta), 115 kg/ha N as mineral fertilizer, 20 kg/ha N through N-fixation by clover and 50 kg/ha N with atmospheric deposition, so the total average N-input to the field was 465 kg/ha N. N-outputs were ammonia volatilization (estimated annual average was 11 kg/ha N), N in harvested grass (cutting and grazing, in total 308 kg/ha N on average), denitrification (27 kg/ha N on average, based on measurements) and nitrate leaching (22 kg/ha N). The sum of N-outputs amounted to 368 kg/ha N on average. For the relatively dry site B the annual N-inputs with animal manure, grazing, mineral fertilizer, N-fixation and deposition were, respectively, 170 kg/ha N, 137 kg/ha N, 150 kg/ha N, 35 kg/ha N and 50 kg/ha N on average. The total average N-input to this field was 542 kg/ha N. The N-inputs at field B were higher than at field A because field B was more intensively used. Average N-outputs through ammonia volatilization, harvested grass, denitrification and nitrate leaching amounted to, respectively, 15 kg/ha N, 280 kg/ha N, 10 kg/ha N and 83 kg/ha N (in total 388 kg/ha N). As expected, denitrification was higher at the wet site and leaching was higher at the relatively dry site, both caused mainly by the difference in groundwater depths. The differences between N-input and N-output for both fields were explained by changes in N-amounts in the crop (mainly grass roots and stubble) and soil organic matter (Hassink et al., 1996).

<u>Within-field variability</u>

Apart from data from the monitoring sites, additional soil information was available from the soil survey. For the relatively wet field A and the relatively dry field B there were, respectively, 16 and 13 soil profile descriptions available within the soil survey grid of the whole farm. Soil physical characteristics for these 29 soil profiles were derived from the data of the monitoring sites. The soil physical characteristics of the six monitoring sites comprised data for a total of 17 distinguished soil horizons, some of which were not significantly different according to the approach used for identifying functional layers (Finke and Bosma, 1993). The remaining 14 sets of soil physical characteristics were linked to all soil horizons of the profile descriptions of the soil survey grid, and the soil physical characteristics could be assigned for each horizon of each described soil profile within fields A and B. Using these data, simulations were performed and a within-field distribution of model results obtained.

The main differences between the 29 soil profile descriptions of fields A and B were the number of distinguished horizons, the clay and silt contents, the median size of the sand fraction (M50) and the organic matter content. Table 5.1 shows the soil characteristics of the used set of layers, and Figure 5.1 shows the sequences of these horizons for the upper 120 cm of the 16 soil profiles of field A and the 13 soil profiles of field B for which simulations were performed. Profiles A0 and B0 are the soil profiles of the monitoring sites.

Table 5.1 *Characteristics of the used soil horizons*

Horizon label	Clay + silt content (%)	Organic matter content (%)	M50 (μm)
Topsoils			
top1	9	3.0	155
top2	9	3.5	155
top3	15	4.0	155
top4	15	3.0	160
top5	20	4.0	140
top6	20	3.0	145
Subsoils			
sub1	9	< 0.5	160
sub2	9	< 0.5	155
sub3	15	< 0.5	160
sub4	17	0.5	155
sub5	40	3.0	120
sub6	35	<0.5	120
sub7	25	<0.5	145
sub8	30	<0.5	155

<u>Simulation models</u>

The models SWACROP and ANIMO were used for simulating unsaturated water flow and nitrogen dynamics, respectively. SWACROP is a dynamic deterministic model describing one-dimensional (vertical) unsaturated water flow in a heterogeneous soil-root system using Richard's equation (Feddes et al., 1978; Belmans et al., 1983; Feddes et al., 1988). Besides soil water retention and hydraulic conductivity characteristics, input data are needed to define the initial conditions and boundary conditions of the soil profile. For the upper boundary, rainfall, temperature, global and net radiation, relative humidity and wind speed, were measured on the farm itself. Groundwater levels, measured on the two sites, were used for the lower boundary of the profile and initial soil moisture status was derived from the measurements. Crop data, such as soil cover, rooting depth and mowing dates, were all available from the standard research programme of the farm (Hack-ten Broeke et al., 1992; Aarts et al., 1994).

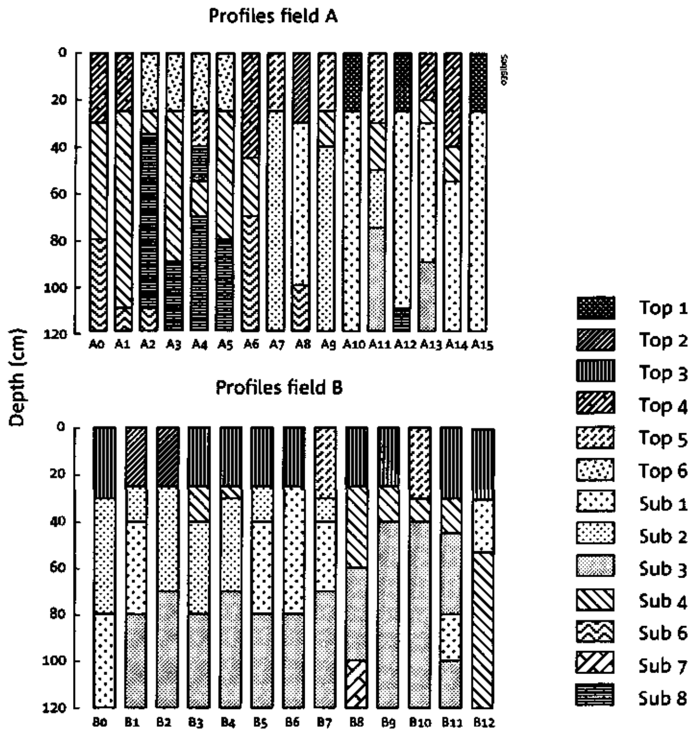

Fig. 5.1 Soil profiles of field A and B

The nutrient model ANIMO is a dynamic simulation model which describes the carbon and nitrogen cycles in the soil and their interrelations (Rijtema and Kroes, 1991; Jansen, 1991). When the model is used in combination with SWACROP, it calculates solute transport in the unsaturated zone and also nitrate leaching to the groundwater. Important processes in the model are mineralization and immobilization of nitrogen, crop uptake, nitrification and denitrification. All processes are strongly affected by soil moisture (simulated by SWACROP), pH (input parameter), oxygen supply and soil temperature (both simulated by ANIMO) as well as the simulated decomposition and availability of organic matter. Additional inputs to this model include fertilizer and manure applications, deposition of N, N supply through crop residues and excreta from grazing cattle, and volatilization rates.

Both models were validated using the measured data (moisture content, pressure head and nitrate-N concentration) for comparison with the model output. Calibration was performed using the data of the hydrological years (April - April) 1991/1992 and 1992/1993. The rest of the data (April 1993 - April 1995) were used as the validation set. Model validation for the monitoring sites was reported by Hack-ten Broeke et al. (1996a). It was found that when simulating average annual nitrate-N concentrations in the soil water or groundwater an even spreading of urine-N over the field could be assumed.

Management options

Omitting fertilization of urine-affected areas

The first option under consideration in this paper involves a simulation study on the possibility of using an advanced technology which omits urine-affected areas during all subsequent fertilizations in the growing season. This option can be considered as a detailed kind of site-specific management or precision agriculture (Robert, 1993). Urine can be regarded as a solution with a high concentration of minerals, and so a urine patch will have increased electrical conductivity compared with the surrounding soil. Techniques for surveying soil electrical conductivity (Rhoades and Corwin, 1981) can therefore, also be used for locating urine patches in pastures. In several experiments at 'Droevendaal' the possibility of detecting urine patches by measuring soil electrical conductivity was successfully demonstrated (Van der Putten et al., 1996). Implementing this technique together with machines for site-specific fertilization offers the possibility of omitting fertilizer and manure applications on urine-affected areas. The possible impact of this non-fertilization of urine-affected areas on nitrate concentrations under these 'hot' spots was calculated for the actual grazing periods in the two pastures (fields A and B) in the years 1991 - 1994. For these actual grazing periods, a urine deposition on the first day of each period was assumed and simulations of water and nitrogen flows under this urine patch were performed with and without subsequent fertilizer and/or manure applications.

The importance of the reduction in nitrate-N concentrations under urine patches depends on the area of the field that is influenced by urine and thus, on the grazing density. Using the distribution function of Petersen et al. (1956) it is possible to calculate the affected area as a function of cattle density. Cows tend to urinate twelve times per day on average and the influence area of a urine patch is 0.68 m^2 (Lantinga et al., 1987). At 'De Marke', dairy cows spend eight hours a day in the field, corresponding with only four urinations. For example, with 60 cows grazing on a field of 10,000 m^2, the area influenced by one urine patch at 'De Marke' would only be 1.6% of the field. During two days of grazing this would be 3.2% of the field. If the cattle were to be in the field for the whole day, the area influenced by one urination in one day would become 4.7% and for two days it would be as high as 8.9%. Then, two overlapping urinations would cover 0.4% of the field area. Obviously, the effect of the non-fertilization of urinations on the average field concentration of nitrate will be much higher with higher grazing densities, indicating that this option is most interesting for intensive grazing systems.

Rising groundwater levels

The second simulated management option discussed here considers the raising of groundwater levels. In many areas in the Netherlands such options are being designed and a so-called 'wetting scheme' is also under consideration for the area around 'De Marke'. First, the possible effect of higher groundwater levels during the monitoring years was simulated for the two sites with rises of 10 cm up to a maximum of 50 cm. In this case, the assumption of the even spreading of urine-N over the field is used to obtain average nitrate concentrations (Hack-ten Broeke et al., 1996a). The rise in groundwater levels for these fields is not expected to exceed these 50 cm (Grontmij, 1993). This, of course, will not only affect nitrate leaching and denitrification, but, for instance, also the moisture supply to the crop. It is expected that higher groundwater levels will improve conditions for agricultural production under previously dry circumstances, but in relatively wet fields higher groundwater levels may result in conditions that are too wet causing, for instance, problems with trafficability in the spring. These effects on agricultural conditions are, therefore, also studied by considering impact on trafficability and actual transpiration of the sward during the whole growing season. Transpiration is part of the output of the SWACROP model. Trafficability was quantified in terms of the number of trafficable days during a specific period with pressure head values at 5 cm depth below a certain threshold value (e.g., Wösten and Bouma, 1985; Bouma and Van Lanen, 1987). In this case the considered period for trafficability was the month of March in each simulated year and the threshold value for the pressure head was $h = -50$ cm (derived from Peerboom, 1990) for these sandy soils.

Table 5.2 Simulated average nitrate-N concentrations (1 April - 31 March) at 1 m depth following deposition of urine with or without subsequent fertilization for site A

Simulated date of urination	Fertilization (kg/ha N)	Nitrate-N concentration (mg/l) with	without	Reduction (%)
7 July 1992	25 (1x)	4.0	3.9	3
18 June 1993	50 (3x)	5.2	5.1	2
16 July 1993	30 (2x)	5.6	5.6	0
22 July 1993	10 (1x)	6.1	6.1	0
4 July 1994	58 (2x)	7.0	6.2	11

Combination of options

Finally, the most relevant options of rising groundwater levels were combined with the option of non-fertilization of urine patches, resulting in six combined options. The effects of these six options were calculated for all monitoring years. For the single management options simulations were performed using soil data of the monitoring sites, thus, offering information for specific sites on the farm. However, environmental objectives are defined for field or farm levels. Therefore, in this paper the within-field variability of soil characteristics of fields A and B was taken into account for these final simulations. Using the soil profile descriptions of the soil survey, the within-field variation resulted in frequency distributions of model output per field. These results were then used in an analysis of variance to quantify the success of the simulated options in reducing nitrate leaching whilst not endangering crop productivity.

Table 5.3 Simulated average nitrate-N concentrations (1 April - 31 March) at 1 m depth following deposition of urine with or without subsequent fertilization for site B

Simulated date of urination	Fertilization (kg/ha N)	Nitrate-N concentration (mg/l) with	without	Reduction (%)
3 June 1991	131 (3x)	18.6	13.5	27
22 June 1991	131 (3x)	19.3	14.5	25
19 July 1991	79 (2x)	22.2	18.1	18
29 May 1992	113 (4x)	29.2	26.1	11
11 June 1992	94 (3x)	37.1	33.5	10
29 July 1992	20 (1x)	28.9	28.5	1
23 May 1993	117 (4x)	39.6	33.1	16
13 June 1993	69 (3x)	41.8	36.3	13
11 July 1993	42 (2x)	35.1	32.5	7
10 May 1994	191 (6x)	18.7	13.7	27
13 May 1994	156 (5x)	18.7	11.1	41
25 June 1994	79 (3x)	21.8	18.0	17
20 July 1994	51 (2x)	27.6	25.0	9
29 July 1994	35 (1x)	27.1	27.1	0

Results and discussion

Non-fertilization of urine-affected areas

In Tables 5.2 and 5.3, the resulting nitrate concentrations of the simulations for urine patches deposited on the first day of each actual grazing period (followed by fertilization) of sites A and B, respectively, are shown with and without subsequent fertilizations. In the Tables this is indicated by date, amount of N applied and 'with' or 'without'. The number of N-applications for the simulation with fertilization is given in brackets. The reduction in nitrate-N concentration at 1 m depth by this non-fertilization option is given as a percentage. Not all grazing periods are relevant for this simulation study, because especially the grazing periods in the last part of the growing season are not followed by fertilizations. Table 5.2 shows that for site A, where nitrate concentrations were already low, only slight reductions under urine patches could be achieved. The highest calculated reduction was 11% for a urine deposition on 4 July 1994. Table 5.3 shows that at site B the effect of this management option was much greater. The highest achieved reduction was calculated for urine deposition on 13 May 1994 and amounted to 41%, resulting in a concentration level below the EC-directive of 11.3 mg/l nitrate-N even under a urine patch. Overall, reduction by this type of management depends on the date of deposition of the urine, the weather conditions, the original level of the nitrate-N concentration (with actual fertilizations) and the amount of N actually applied with fertilizer or manure after urination.

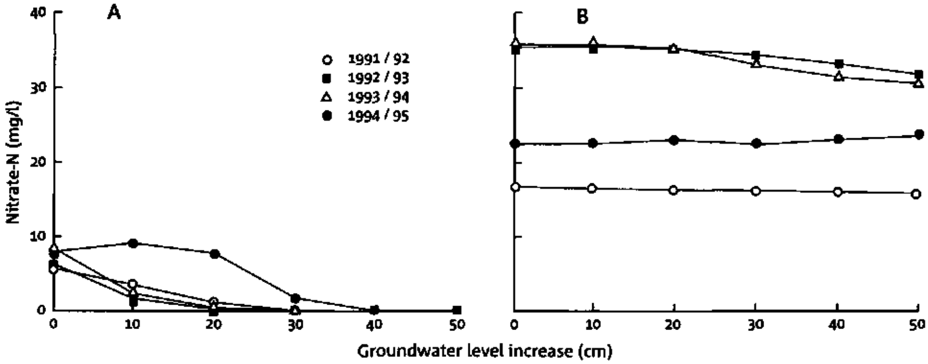

Fig. 5.2 Simulated average annual nitrate-N concentrations at 1 m depth as a function of raising groundwater levels at sites A (A) and B (B)

<u>Rising groundwater levels</u>

One of the major reasons for the differences in nitrate-N concentrations between sites A and B is the difference in groundwater levels, resulting in different amounts of denitrification and capillary rise affecting crop uptake of water and nutrients. Therefore, the proposed raising of the groundwater was expected to be especially interesting for site B. Figure 5.2A shows that the nitrate concentrations at site A could be reduced by raising the groundwater levels, whereas at site B (Fig. 5.2B) the effect was less pronounced. For all years (1991-1994) the same increments for increasing groundwater levels were assumed, so all groundwater levels throughout the years were raised 10 cm per situation for the simulations. This is a rather static procedure, leading to long periods with groundwater levels near the soil surface for site A. The simulated nitrate concentrations at site A even reached values of 0.0 mg/l, which was a result of the static way of dealing with the options. The conditions for the options of 40 and 50 cm groundwater level increase at site A resulted in periods in winter with no simulated water movement at 1 m depth and with no nitrate then reaching that depth. The result of such options for these periods was largely increased run-off which would result in nitrate flows to the ditches, but as an unrealistic option, this is not further considered here. For site B, none of the simulated options were unrealistic and thus the results are more interesting. The differences between the years in Figure 5.2B were obviously caused by the weather conditions. The low levels in 1991/1992 were also caused by the low grazing densities. Small reductions in nitrate concentrations could be achieved by raising groundwater levels except in the year 1994/1995. The reason for this is expressed in Figure 5.3, showing the changes in transpiration. At site B (Fig. 5.3B), transpiration increased with rising groundwater levels as a result of improved moisture supply, except in 1994, when water excess caused deterioration in growth conditions reducing transpiration and increasing nitrate leaching (Fig. 5.2B). Trafficability in March was not affected in the years 1991 - 1993, but the simulated number of trafficable days in March 1994 was reduced from 31 (with actual groundwater levels) to 0 at 50 cm groundwater level increase. For site A, such negative effects were simulated for almost all years except the dry year of 1991. In 1991 transpiration at site A was increased by the options (Fig. 5.3A), whereas in 1993 and 1994 transpiration was reduced, but in 1992 it depended on the level of increase. For 1992 simulated transpiration increased up to a groundwater level rise of 30 cm, but with further rises of the groundwater level negative effects (caused by water excess) became dominant, reducing the transpiration. Again some of the latter model output resulted from unrealistic water movement, but it clarifies the direction of the possible effects.

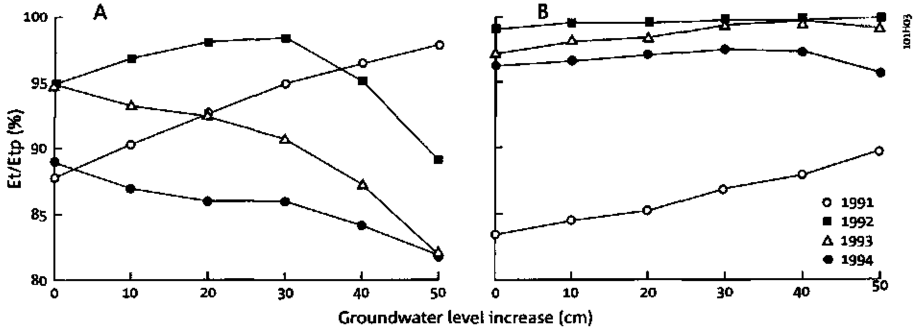

Fig. 5.3 Simulated annual actual/potential transpiration rate (Et/Etp) as a function of raising groundwater levels at sites A (A) and B (B)

Combined effects for urine patches

From the previously mentioned options, six combined scenarios were defined and calculations were performed for these scenarios for all soil profiles in the two pastures (16 in field A and 13 in field B). Considering that groundwater level increase should be realistic for both fields a raise of 20 and 30 cm was considered. Because omitting fertilizer applications from urine patches was most effective for patches deposited in the early growing season, calculations were performed for urine patches deposited on 15 May of each simulated year. This resulted in the following six combinations:

(I) Groundwater levels as measured; fertilizer as actually applied.
(II) Groundwater levels as measured; no fertilizer or manure after 15 May.
(III) Groundwater levels raised 20 cm; fertilizer as actually applied.
(IV) Groundwater levels raised 20 cm; no fertilizer or manure after 15 May.
(V) Groundwater levels raised 30 cm; fertilizer as actually applied.
(VI) Groundwater levels raised 30 cm; no fertilizer or manure after 15 May.

For each scenario and each year, a frequency distribution as a function of within-field variability could be produced. In Figures 5.4 and 5.5, examples of nitrate concentrations for fields A and B, respectively, are shown and in Figure 5.6 for the number of trafficable days. Figure 5.4 shows that there were more or less two groups of soil profiles in each field. There was a relatively small number of soil profiles in field A with high nitrate concentrations under the simulated urine patch, while the majority of the profiles (more than 70%) had nitrate concentrations in

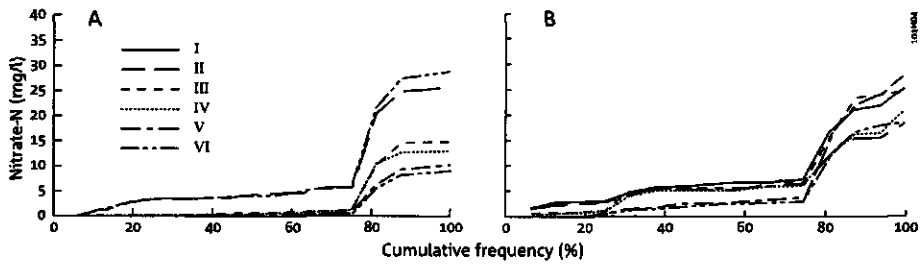

Fig. 5.4 Cumulative frequency distribution of simulated average annual nitrate-N concentrations (1 April-31 March) at 1 m depth as a function of within-field variability per scenario in the years 1992/1993 (A) and 1994/1995 (B) for field A

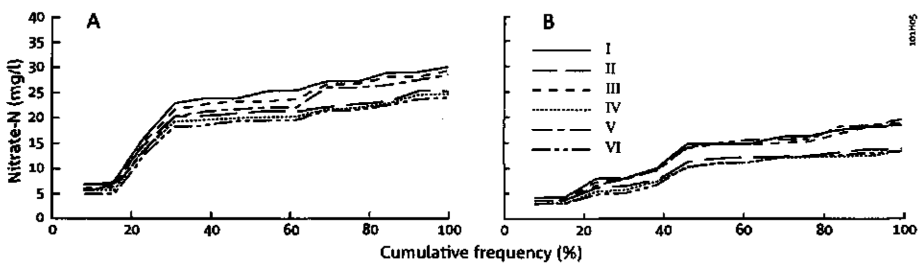

Fig. 5.5 Cumulative frequency distribution of simulated average annual nitrate-N concentrations (1 April-31 March) at 1 m depth as a function of within-field variability per scenario in the years 1992/1993 (A) and 1994/1995 (B) for field B

both 1992/1993 (Fig. 5.4A) and 1994/1995 (Fig. 5.4B) below the EC-directive. In the two presented years, the scenarios had quite a different effect on nitrate concentration. In 1992/1993 (Fig. 5.4A) the results of scenarios I and II were quite similar, whereas the other four scenarios clearly showed reduced concentrations compared with I and II. This implies that raising groundwater levels in this year had a greater effect on concentrations than non-fertilization of the urine patch. The differences between scenarios III - VI were not so great as the difference between this group of scenarios III - VI and scenarios I and II, implying that the further raising of groundwater levels had less effect than the first rise of 20 cm. In this case, the lines in the graph are virtually parallel, whereas in Figure 5.4B, this is not the case, so there seemed to be a mixed effect in the wet year of 1994/1995.

For field B (Fig. 5.5) there was a relatively small number (about 30%) of soil profiles with nitrate concentrations below the EC-directive of 11.3 mg/l nitrate-N. Again in Figure 5.5A the lines in the graph are parallel, but in this case each single scenario seems to have an almost similar decreasing effect on the simulated nitrate concentrations. In 1994/1995 (Fig. 5.5B) the lines cross each other and two groups of lines can be distinguished, implying that in this case, the effect of non-fertilization of the urine patch had a greater effect than the change in groundwater levels.

Table 5.4 Average simulated nitrate-N concentration (mg/l) per scenario and per year

Scenario	1991/92	1992/93	1993/94	1994/95	
Field A					
I	10.58	9.21	11.38	8.73	
II	8.65	8.60	10.05	6.75	
III	6.71	3.71	4.78	8.46	
IV	5.18	3.41	4.09	6.65	
V	4.89	2.26	3.36	6.48	
VI	3.66	2.00	2.70	4.90	(lsd = 1.78)
Field B					
I	13.10	22.74	26.52	12.90	
II	10.09	19.48	22.85	10.05	
III	12.79	21.78	26.12	12.54	
IV	9.76	18.65	22.82	9.35	
V	12.64	20.75	25.60	12.76	
VI	9.52	17.97	22.28	9.27	(lsd = 1.84)

The average simulated concentrations are presented in Table 5.4. The results of the analysis of variance, performed for all simulated nitrate concentrations and taking the simulations for different soil profiles as replicates, showed that for the data in Table 5.4 the least significant difference for fields A and B was 1.78 and 1.84, respectively. For field B there was no interaction between the factors scenario and year. That means that for field B the differences between the scenarios were similar in each year. The least significant difference of 1.84 for field B implies that the non-fertilization of urine patches (scenarios II, IV and VI) resulted in a significant reduction in the nitrate concentrations in all the years.

For field A the results of the scenarios were different for each year (interaction between the factors scenario and year). In 1991/1992, all scenarios II - VI showed a significant reduction in nitrate concentrations compared with scenario I, whereas in 1992/1993 and 1993/1994 this was only the case for scenarios III - VI, so with changes in groundwater levels. In 1994/1995 only scenarios II and IV - VI were significantly different from I, so then, non-fertilization of the urine patch always had a significant effect. Differences between scenarios IV, V and VI were not significant in any of the years, so for field A the further raising of groundwater levels to 30 cm did not result in a further reduction in nitrate leaching.

The different soil profiles did not result in large differences in transpiration rates. Table 5.5 shows the average simulated values. For field B in particular, differences between the scenarios were small. The analysis of variance for the simulated transpiration values for field A showed that raising groundwater levels always had a significant effect on transpiration compared with scenarios I/II. In 1991, the increase from 20 to 30 cm also had a significant effect on transpiration, and in 1994 the difference between scenarios III/IV and V/VI was also significant, although in this case water excess resulted in reduced transpiration. In both 1992 and 1993, differences between III/IV and V/VI were not significant. For field B there were no differences for the years 1992 and 1993 (Table 5.5), but in 1991 the scenarios with groundwater level increase

Table 5.5 Average simulated actual transpiration (cm) per scenario group and per year

Scenario	1991	1992	1993	1994
Field A				
I/II	34.5	42.5	29.6	33.1
III/IV	36.6	44.2	27.9	26.5
V/VI	37.8	44.6	27.2	24.6
Field B				
I/II	36.4	45.7	32.1	40.1
III/IV	37.1	45.7	32.1	39.8
V/VI	37.6	45.7	32.1	38.6

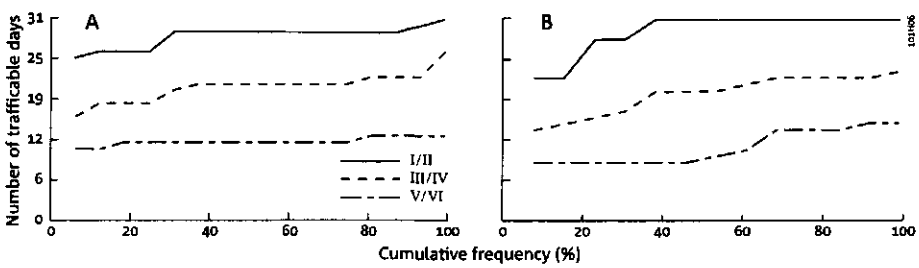

Fig. 5.6 Cumulative frequency distribution of the simulated number of trafficable days in March 1992 for field A (A) and March 1994 for field B (B)

resulted in significantly higher transpiration compared with scenario I/II. In 1994, this was only true for scenario V/VI in comparison with I/II.

In most years, there were no differences between the scenarios in the number of trafficable days in March. Differences were found for 1992 and 1993 for field A, and only for 1994 for field B, and these differences were quite clear as shown in Figure 5.6.

Conclusions

1. Non-fertilization of urine-affected areas, deposited early in the growing season, appears to be a promising method to decrease nitrate concentrations in the soil water under grazed grassland. The simulated effect of this management option for the two sites largely depended on weather conditions, date of deposition of urine, and the amount of N applied in subsequent fertilizations. On the relatively wet site, the maximum calculated reduction was 11%, but for the dry site, where grazing densities were also higher than on site A, the maximum reduction was 41%. The impact of this site-specific management on field average nitrate concentration will become greater with increasing areas affected by urine, indicating that this method is most promising for intensive grazing systems.

2. Raising groundwater levels on the sites will result in reduction of nitrate concentrations in the soil water under dry or average weather conditions, due mainly to increased N-uptake by the crop and increased denitrification. In wet years there may be water excess as a result of rising groundwater levels, which could lead to higher nitrate leaching levels as a result of deteriorating conditions for crop productivity (lower N-uptake). Under dry and average weather conditions the simulations with increased groundwater levels for the dry site resulted in improved growth conditions and higher transpiration levels and consequently increased crop production, due to increased capillary rise.

3. The combination of non-fertilization of urine patches and raising groundwater levels by 20 or 30 cm showed that in most cases the simulated reduction of nitrate concentrations in groundwater was higher when both options were realized. For the 16 soil profiles of the relatively wet field the effect of increased groundwater levels was predominant, except in an already wet year when the non-fertilization of urine patches was more important. The change from 20 to 30 cm groundwater level increase had no further significant effect on the nitrate concentrations for the 16 soil profiles of the wet field. In a wet summer, each separate rise of groundwater levels for this field caused water excess and deteriorating growth conditions and thus, reduced transpiration, and in a wet spring trafficability in March was also reduced significantly. For the dry pasture, for which 13 soil profiles were available, both the non-fertilization of urine-affected areas and the groundwater level increase by 30 cm always resulted in a significant reduction in nitrate concentrations. The 20-cm groundwater level raise was not sufficient for such effects. The groundwater level rise for this dry site also resulted in higher transpiration rates, except in years when drought stress at this site had already been sufficiently compensated for by supplementary irrigation.

4. The promising results of this simulation study suggest the need for application and further study of site-specific management options for grazed grassland as a tool for reducing nitrate leaching. This study also clarifies that wetting schemes can be advantageous for both agriculture and the environment if conditions are not too wet.

Acknowledgements

Part of this work was made possible by funding of the 'Financieringsoverleg Mest- en Ammoniakonderzoek' of FOMA-projects 3.44 and 3.45. Comments by Prof. J. Bouma, Dr. P.A. Finke, Ir. C.A. van Diepen and Dr. H.A.J. van Lanen to earlier versions of the text were gratefully used to improve this paper. Suggestions of Drs. J.H. Oude Voshaar considering the analysis of variance are thankfully acknowledged.

6. IRRIGATION MANAGEMENT FOR OPTIMIZING CROP PRODUCTION AND NITRATE LEACHING ON GRASSLAND

Also: submitted to Agricultural Water Management, October 1999

simulation of the carbon and nitrogen cycles in the soil (Rijtema and Kroes, 1991). When ANIMO is used in combination with SWACROP it also simulates nitrogen transport in the unsaturated zone and to the groundwater. The combined models need input data for the description of the initial situation, the upper and lower boundaries and also parameter values for the simulation of the different soil processes. Meteorological data for defining the upper boundary were registered on the farm. These data comprised daily rainfall, temperature, global and net radiation, relative humidity and wind speed. The lower boundary was defined using the measured groundwater levels. Water retention and hydraulic conductivity characteristics were determined for undisturbed soil columns for all monitoring sites (Hack-ten Broeke and Hegmans, 1996). The research program of the farm provided all necessary data on crops, fertilization and grassland management (Aarts et al.,1994; Aarts, 1996). Model calibration was performed using the data of the period of 1991 to spring 1993. The remaining data (1993-1995) were used for model validation (Hack-ten Broeke et al., 1996a; Hack-ten Broeke and De Groot, 1998).

Irrigation management options

The combined simulation models generate daily results, such as crop transpiration, fluxes into and from all soil layers, nitrate concentrations at each defined depth and pressure head and moisture content values for all soil layers. Simulations were performed for six irrigation management options, summarized in Table 6.1. An option with no irrigation (option 0) was needed for calculating the relative effect of the options on crop transpiration and leaching. The first supplementary irrigation management strategy considered (option 1) is the actual management that was carried out on the farm during the monitoring years. This actual irrigation management represents common practice for grassland on sandy soils in the Netherlands considering timing of irrigation and application amount. The irrigation amount on grassland at De Marke was always 25 mm water per application. The efficiency of water use (*IrrEff*) of an irrigation option is defined as the percentage of irrigation water that contributed to the increase of actual transpiration (T_a):

$$IrrEff = 100\% \cdot \left(T_{a,option\_x} - T_{a,option\_0}\right) / \, irrigation$$

where:
$T_{a,option\_x}$ = Actual annual transpiration of option x (mm)
irrigation = Annual irrigation amount (mm)

Based on the validated model, *IrrEff* can be calculated for the three monitoring sites. For sites A, B and C the simulated efficiency of water use for the actual management ranged, respectively, from 0 to 78%, from 44 to 75% and from 51 to 74%. It was considered that more efficient use should be possible and experiences on sandy soils in the Netherlands with a newly developed advisory systems (Boland et al., 1996; Hoving et al., 1997) showed that advised application amounts on these soils were mostly 15 mm or less. The second management option (Table 6.1) therefore considers a change in irrigation amount to 15 mm water per application, whilst the timing of irrigation remained the same as for option 1. Next, it is possible to question the timing of the irrigation. The SWACROP model can simulate irrigation timing as related to the soil water pressure head in the root zone (Wesseling and Van den Broek, 1988; Hack-ten Broeke et al., 1993). For conventional supplementary irrigation for grassland in the Netherlands irrigation is considered when the pressure head in the middle of the root zone drops below h = -500 cm, with an application of 25 mm water and a minimum time lag between applications of 7 days (which allows the farmer to irrigate other fields of the farm). This simulation option is defined as option 3 and the fourth is similar, but aims to reduce water use. Therefore the irrigation amount for option 4 is the same again as for option 2 (15 mm per application). Where the timing of irrigation for options 1 and 2 is based on the farmer's expert judgement, the irrigation timing for options 3 and 4 is defined by the model. The fifth and final option simulates the advisory system called the 'irrigation planner' (Boland et al., 1996). In that case the timing of irrigation is also determined by the model, but the applied irrigation amounts also vary. The applicated amounts are directly related to the groundwater level, assuming that the root zone can never retain more water than the amount that is calculated from the equilibrium status with that groundwater level (e.g. soil water content corresponding with h = -100 cm when the groundwater is at a depth of 1 m). The applied irrigation amount is then calculated as the difference between this maximum soil water content and the actual water content of the root zone. The system then advises the farmer to apply 10 mm less to make sure that water use is restricted to the most necessary amount. When this advise would lead to an application of less then 10 mm this reduction is not advised, so the minimum advised application is 10 mm water. For all simulated irrigation management options the rule was applied that irrigation will not take place in the period of two days before and two days after cutting the grass or cattle grazing.

Table 6.1 Simulated supplementary irrigation management options

Option	Application size	Irrigation timing
0 no irrigation	0	-
1 actual management	25	decided by farm manager
2 actual reduced	15	decided by farm manager
3 simulated conventional	25	h = -500 cm in root zone
4 simulated reduced	15	h = -500 cm in root zone
5 irrigation planner	site dependent	h = -500 cm in root zone

Simulations and evaluation criteria

The model results were used to calculate both the 'leaching potential' and the 'nitrate leaching risk'. The leaching potential is defined as the downward soil water flux from the root zone, possibly causing solute leaching, expressed in terms of the number of days during the year with a downward flux together with the cumulative downward flux itself (Hack-ten Broeke et al., 1993). The nitrate leaching risk is expressed in terms of the number of days during the year with a nitrate-N concentration exceeding a predefined threshold value together with the level of the annual average nitrate-N concentration itself (Hack-ten Broeke et al., 1996a). As threshold value for nitrate in groundwater the EC-directive for drinking water is used, i.e. 50 mg/l nitrate (= 11.3 mg/l nitrate-N). The SWACROP model gives water fluxes at any specified depth, for which then the ANIMO model can produce nitrate concentrations. Because the nitrate concentration measurements were carried out at 1 m depth, that same depth is used for all analyses of the model results. The monitoring period with four hydrological years covers a great part of the relevant weather variation of the Netherlands (Hack-ten Broeke and Van der Putten, 1997). The first year was relatively dry, the rainfall in the second year was almost 'normal' and the last two years were both wet with a wet summer in 1993 and wet winter months in 1994. Another important source of variation is spatial variability and this was taken into account by performing simulations for all soil profiles that were described for the fields of the monitoring sites, as was previously carried out by Hack-ten Broeke and Van der Putten (1997). In the fields of sites A, B and C there were 16, 13 and 13 soil profiles available, respectively. For each of these, groundwater levels were determined using the measured levels at the six monitoring sites and the soil surface altitude (Hack-ten Broeke and De Groot, 1998). These combinations of soil profiles and groundwater depths are considered to be a respresentative set per field, so the results of modelling for 16 soil profiles within the field of monitoring site A will be referred to as the results for field A, etc. Taking within-field spatial variability into account by performing simulations for all these soil profiles, frequency distributions of the results were calculated, allowing for instance a calculation of the probability that a certain threshold value will be exceeded within a field. Furthermore, the simulations for the soil profiles give site-specific results, which were briefly evaluated as well.

Supplementary irrigation aims at improving crop production through increased transpiration. The success of the irrigation management options in achieving this was therefore evaluated by comparing the ratios of actual and potential transpiration (T_a/T_p) of the simulated management options. These were also compared with the T_a/T_p ratio calculated for a simulated situation with no irrigation (option 0). The irrigation efficiency was also used for comparing the relative success of the various management options.

Results and discussion

Model validation

For the simulated irrigation management options each water application is directly linked to the pressure head in the root zone, so the model performance for especially these pressure head values is important. Figure 6.1 shows the pressure head values for monitoring site B in the root zone. For the intensive monitoring periods in 1994 and 1995 (daynumbers 1265-1371 and 1527-1582, respectively) measured values at midday are shown in the graph, which indicates that the model simulations agree well with measurements for the whole monitoring

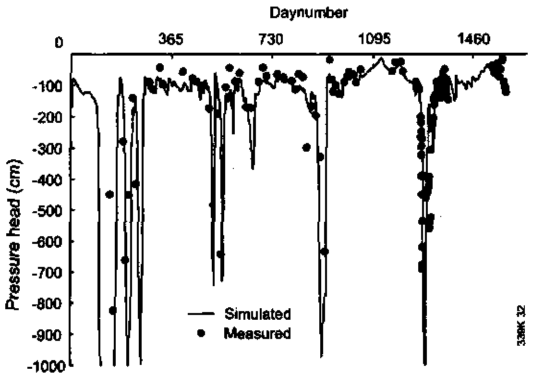

Fig. 6.1 Measured and simulated pressure head at 30 cm depth for monitoring site B for 1 January 1991 (daynumber 1) until 31 March 1995 (daynumber 1582)

period including both the calibration and validation sets. Statistical criteria were used to quantify the goodness of fit, as described by Loague and Green (1991), for the data shown in Figure 6.1. The root mean squared error *RMSE* = -76.7; the coefficient of determination *CD* (ideally *CD* = 1) = 0.70; the modelling efficiency *EF* (ideally *EF* = 1) = 0.39 and the coefficient of residual mass *CRM* (ideally *CRM* = 0) = -0.01. For modelling pressure head values these criteria indicate again that the model simulations agree well with the measurements (see also Hack-ten Broeke and Hegmans, 1996). The *CRM*-value can hardly be improved and the *EF*-value shows that the model gives a reasonable estimate (negative values indicate that the mean of the measurements gives a better estimate than the model). The simulated condition is a representation of option 1 (actual management, Table 6.1) for the monitoring site. This implies that simulations can be used to assess the hydrological effects of irrigation events and that the simulated pressure head values can be used for the timing of irrigation within the management

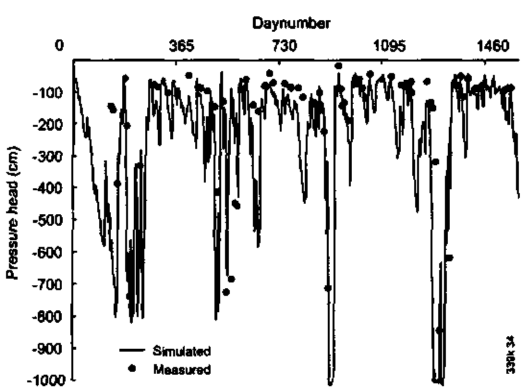

Fig. 6.2 Measured and simulated pressure head at 30 cm depth for monitoring site C for 1 January 1991 (daynumber 1) until 31 March 1995 (daynumber 1582)

options. Model calibration and validation for sites A and B for the monitoring period 1991-1994 were elaborated by Hack-ten Broeke et al. (1996a). For monitoring site C the simulated and measured pressure head values at 30 cm depth are shown in Figure 6.2, similar to the presented results for site B in Figure 6.1. In the evaluation of the simulated irrigation management options annual average nitrate concentrations were used for calculating the nitrate leaching risk. Figure 6.3 shows the simulated versus the measured nitrate concentrations, averaged per season, for the three monitoring sites A, B and C. The calibration and validation was carried out for the monitoring sites. The simulations for the irrigation management options were performed for the fields.

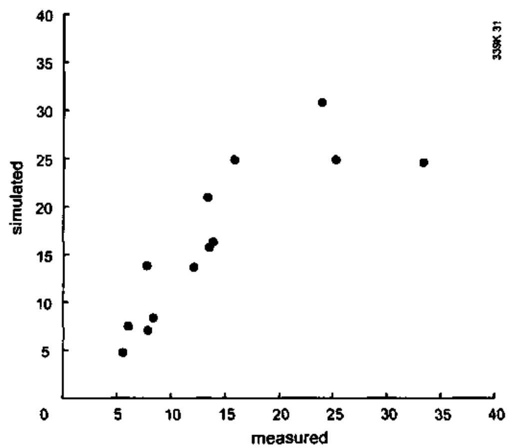

Fig. 6.3 Simulated versus measured seasonal average nitrate concentrations for monitoring sites A, B and C

Simulation results for the irrigation management options

First Figure 6.4 shows the average irrigation efficiencies for options 1-5 for all fields. These field values are averages of the results for all simulated soil profiles (including the soil profiles of the monitoring sites). For field C data are presented for the years with grassland only (i.e. 1991 and 1992) and the farmer decided not to irrigate field A in 1991 (no results for options 1 and 2). The simulated irrigation efficiency was always low in 1993, when the summer was wet. In all cases the change of irrigation amounts from 25 mm (for option 1) to 15 mm (for option 2) caused an increase of the irrigation efficiency. This was also valid for most changes from option 3 to option 4. In several cases the actual management at the farm (option 1) had a much higher irrigation efficiency than the simulated options 3 – 5 (for instance in 1994 at field A and in 1991 at fields B and C). The cause for this is that for the timing of irrigation the farmer was able to take both the actual grassland management (especially cutting and grazing) and the weather forecast into account. In the simulations, irrigation events were never simulated just before or after cutting or grazing of the grassland, but weather forecasts were not considered. Options 3, 4 and 5 are based on similar assumptions and thus comparison is justified. Option 5, representing the advisory system called 'irrigation planner', always resulted in the highest

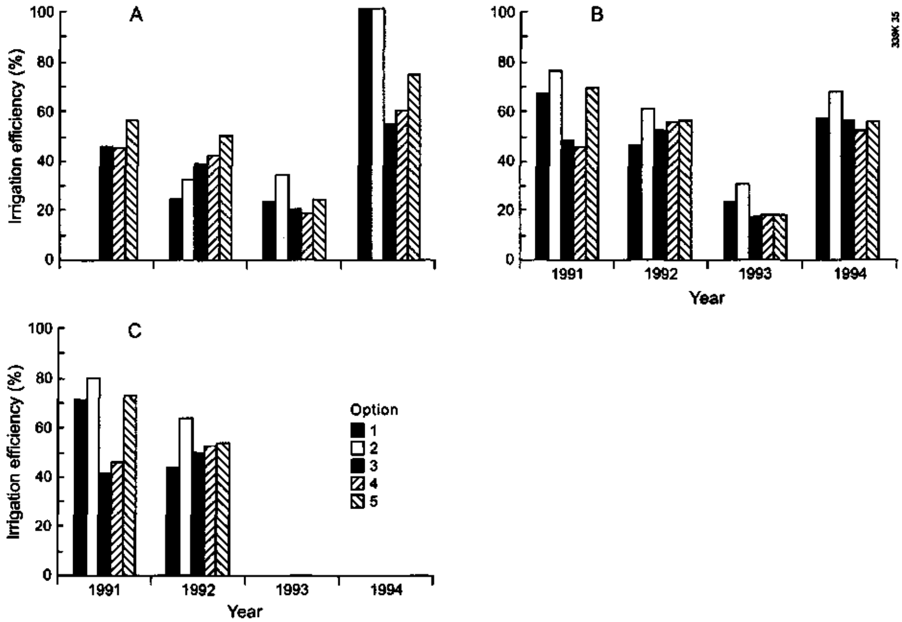

Fig. 6.4 Field average irrigation efficiencies for the irrigation management options per year for field A (A), field B (B) and field C (C).

Table 6.2 Cumulative irrigation amounts (Irr) in mm and the transpiration ratio T_a/T_p per field

Option	Year							
	1991		1992		1993		1994	
	Irr	T_a/T_p	Irr	T_a/T_p	Irr	T_a/T_p	Irr	T_a/T_p
Field A								
option 0	0	0.76	0	0.84	0	0.94	0	0.77
option 1	0	0.76	25	0.85	25	0.96	25	0.82
option 2	0	0.76	15	0.85	15	0.96	15	0.80
option 3	178	0.98	133	0.98	30	0.98	119	0.94
option 4	147	0.95	94	0.95	24	0.97	77	0.89
option 5	129	0.93	85	0.93	22	0.97	70	0.88
Field B								
option 0	0	0.73	0	0.86	0	0.97	0	0.86
option 1	125	0.90	150	0.99	25	0.99	100	0.96
option 2	75	0.85	90	0.96	15	0.99	60	0.94
option 3	173	0.96	106	0.96	40	0.99	83	0.95
option 4	143	0.92	74	0.94	27	0.99	58	0.92
option 5	122	0.90	65	0.93	20	0.99	54	0.92
Field C								
option 0	0	0.66	0	0.82				
option 1	100	0.78	200	0.98				
option 2	60	0.74	120	0.96				
option 3	275	0.94	185	0.99				
option 4	212	0.90	128	0.95				
option 5	155	0.86	89	0.91				

The importance of within-field spatial variability is illustrated in Figure 6.6. For field A options 0, 1 and 2 resulted in similar annual nitrate concentrations and another group of results were produced by options 3, 4 and 5. These differences are similar for all 13 simulated soil profiles. For both fields B and C all simulated options resulted in fairly similar nitrate concentrations per simulated soil profile. As was already visible in Figure 6.5, only the results for option 0 (no irrigation) were obviously higher than the concentrations for all the other options. The shape of the graph for field C suggests that one half of the field is composed of a less vulnerable soil type than the other half of the field. For both fields A and B the different soil profiles resulted in more gradual differences. Considering that for options 1 and 2 the irrigation was kept the same for all soil profiles and that for options 3 - 5 different irrigation amounts resulted from the simulations per profile, Figure 6.6 indicates that site-specific irrigation has no effect on the nitrate-N concentrations at De Marke.

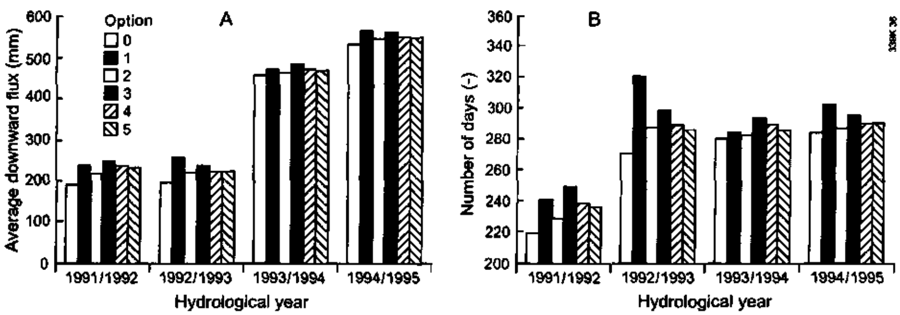

Fig. 6.7 The leaching potential at field B: the field average downward flux at 1 m depth (A) and the average number of days during the hydrological year with a downward flux at that depth (B) for the different irrigation management options per year

Leaching potential

The average results for the leaching potential for field B are shown in Figure 6.7. The diagram with downward fluxes clearly shows that both 1993/1994 and 1994/1995 were wet years with a large rainfall surplus resulting in a downward flux in 1994/1995 of more than 550 mm. The differences between the irrigation management options are small and because of the spatial variability none of the differences are significant. The number of days with a downward flux (Fig. 6.7) again showed no significant differences between the simulated options. The differences between the years were not as obvious as for the downward flux itself. The results for the leaching potential for the other fields were similar.

The simulated extra downward flux compared to option 0 for all three fields is given as a function of irrigation in Figure 6.8. This shows that small annual irrigation amounts of up to 30 mm with low irrigation efficiencies (Fig. 6.4) will cause an extra water flux to the groundwater in the same order of magnitude as the irrigation itself. Furthermore, Figure 6.8 shows that with increasing irrigation the downward fluxes also increase, but for annual supplementary

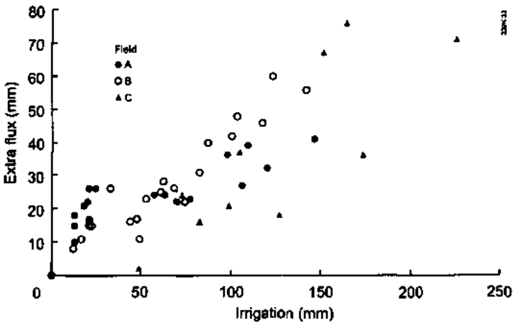

Fig. 6.8 Simulated increase of the downward flux at 1 m depth as a function of simulated cumulative supplementary irrigation per year for the different fields.

Table 6.3 *The annual average nitrate-N concentration (mg/l) at 1 m depth per field (Conc) and the number of Days during the hydrological year with a concentration above 11.3 mg/l nitrate-N*

Option	Year							
	1991/1992		1992/1993		1993/1994		1994/1995	
	Conc.	Days	Conc.	Days	Conc.	Days	Conc.	Days
Field A								
option 0	8.1	98	19.9	274	14.9	201	9.6	134
option 1	8.1	98	19.0	269	12.9	182	8.3	122
option 2	8.1	98	19.1	270	13.2	186	8.5	127
option 3	3.4	42	9.7	151	9.5	127	6.6	73
option 4	3.7	44	10.5	178	10.5	146	7.4	83
option 5	4.1	46	11.1	187	10.3	136	7.7	93
Field B								
option 0	18.8	138	36.6	350	29.3	309	20.6	213
option 1	11.9	128	28.2	318	26.0	304	16.1	198
option 2	13.8	133	28.8	328	26.6	304	16.7	197
option 3	12.9	127	27.8	324	26.0	303	16.2	199
option 4	13.5	131	28.8	326	26.7	305	16.8	199
option 5	14.0	133	29.3	327	27.0	305	17.0	200
Field C								
option 0	20.8	195	32.5	365				
option 1	15.1	198	23.1	296				
option 2	16.1	192	23.5	317				
option 3	16.5	248	21.8	281				
option 4	15.3	200	23.1	312				
option 5	16.5	187	24.4	322				

irrigation between about 50 and 80 mm there is no obvious increase of the downward flux for fields A and B, implying that water use by the crop is then most efficient.

Nitrate leaching risk

The average results for the nitrate leaching risk are presented in Table 6.3 with the field average concentrations at 1 m depth per hydrological year and the number of days within those hydrological years with a concentration higher than the EC-directive for drinking water. The results for field B and C again show that there are no significant differences between the irrigation management options with the exception for option 0. Without irrigation the concentrations were relatively high and in most cases the number of days with an exceedance of the threshold value (11.3 mg/l nitrate-N) was also higher than for the other options (especially in 1992/1993). In this case the downward fluxes (leaching potential) and the nitrate concentrations (nitrate leaching risk) show similar results. For field A, however, options 3, 4 and 5 resulted in lower annual average concentrations in all simulated years in comparison with either the actual and reduced irrigation management options (1 and 2) or the option without irrigation (0). For 1992/1993 this effect was already illustrated in Figure 6.6. For this relatively wet field a different irrigation strategy than the actually applied management would result in better results for the environment, but this is in most simulated cases combined with more supplementary irrigation than was actually applied (see Table 6.2).

Discussion

The simulated results for both downward fluxes from the root zone and for nitrate concentrations at 1 m depth imply that the differences between irrigation management options are small and not relevant for grassland on the drought susceptible soils of the farm. Although a significant environmental effect was expected, the absence of the effect can actually be considered as good news. The optimization of irrigation water use, for which advisory systems are being developed, can be stimulated, knowing that there will be no major effect on the environment considering nitrate leaching. There is a significant effect of the different strategies on total irrigation volumes (see Table 6.2), irrigation efficiencies (Fig. 6.4) and the transpiration ratio (see Table 6.2). Using these criteria, directly related to water use and crop production, a choice for the optimal irrigation magament for dry soils is already possible. When both the timing of irrigation and the application volume are based on the actual soil water conditions (option 5, representing the 'irrigation planner'), water use seems to be most efficient for such soils. However, for relatively wet fields, like field A, the effects on nitrate leaching should not be neglected.

Conclusions

1. The change of application size from 25 mm to 15 mm per supplementary irrigation event generally increases the irrigation efficiency, lowers the total annual water use and only slightly decreases the transpiration ratio T_a/T_p. The same conclusion is valid for the simulated advisory system 'irrigation planner' (Boland et al., 1996), which also results in a higher irrigation efficiency than the actual irrigation managament. When both the timing of irrigation and the applicated amount are determined as a function of soil water conditions ('irrigation planner'), the irrigation efficiency is higher than for the options with simulated timing of irrigation combined with fixed application sizes. For the relatively wet field A, higher irrigation amounts than were actually applied are advised by the simulated options in the dry summers of 1991, 1992 and 1994.

2. Changes in irrigation management, as simulated in this study for five options, have no significant effect on nitrate leaching for dry fields (B and C) in spite of the increase of the downward water flux from the root zone to the groundwater as a function of supplementary irrigation water use. For the relatively wet field A the model advised higher irrigation (options 3, 4 and 5) resulting in lower nitrate concentrations compared to the actual irrigation management at the farm.

3. Considering both the effect on crop transpiration and on nitrate concentrations at 1 m depth, a restriction of water use at the dry fields of the farm is possible without causing either agricultural or environmental problems. At the relatively wet field more supplementary irrigation could improve agricultural production and at the same time reduce nitrate concentrations. Options 3, 4 and 5 each simulate an irrigation advisory system per soil profile within the field. Although this site-specific irrigation management is currently not realistic for grassland and the environmental effects were not clear from this study, it seems worthwhile for optimizing irrigation strategies. Developments within precision agriculture could realize such a strategy considering within-field spatial variability in the future.

4. For the dry fields B and C both the 'leaching potential' and the 'nitrate leaching risk' lead to identical conclusions regarding environmental effects of the irrigation management options. Both the annual downward water flux and the annual average nitrate concentration show no significant effect for the different options. For the relatively wet field A the options also showed no significant changes in the downward flux, whereas the nitrate concentrations were affected by the simulated options. In this case the use of the 'leaching potential' would not lead to the same conclusion about environmental effects as the 'nitrate leaching risk'. For a study like the one presented in this paper, it is therefore not always sufficient when only the potential for leaching is examined.

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7. EVALUATION OF NITRATE LEACHING RISK AT SITE AND FARM LEVEL

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EVALUATION OF NITRATE LEACHING RISK AT SITE AND FARM LEVEL

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Abstract

At experimental farm 'De Marke' a dairy farm was set up with the aim to meet 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 of 11.3 mg/l 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 on 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 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 to meet both environmental and economic goals (Aarts et al., 1992). 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. Management of the farm therefore includes, for instance, 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 (Aarts et al., 1994; Hack-ten Broeke and Aarts, 1996). 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 (Dekkers, 1992). 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 (Hack-ten Broeke and Aarts, 1996; Hilhorst (1995). 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 the 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 (Hack-ten Broeke and Hegmans, 1996) 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 (Hack-ten Broeke and Aarts, 1996; Hack-ten Broeke et al., 1996a). Monitoring was carried out from autumn 1991 to spring 1995.

Modelling

For simulating unsaturated soil water behaviour and nitrogen dynamics, the models SWACROP (Feddes et al., 1988) and ANIMO (Rijtema and Kroes, 1991) 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 (Hack-ten Broeke et al., 1996a).

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.

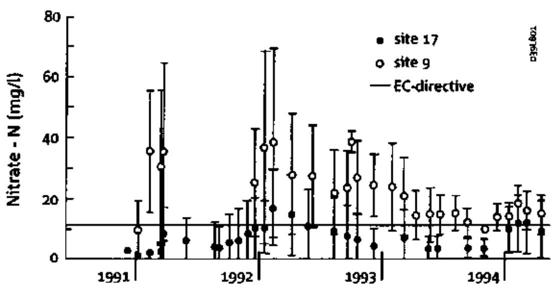

Fig. 7.1 Measured nitrate-N concentrations and standard deviations for two sites in permanent grassland

According to the approach for defining functional layers (Finke and Bosma, 1993) 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 (Dekkers, 1992). Additional required input data per field were supplementary irrigation, crop data and fertilizer and manure applications, including dung and urine from grazing cattle.

have been designed in various countries (e.g. Aarts et al., 1992; Weissbach and Ernst, 1994; Peel et al., 1997).

At the 'De Marke' experimental farm in the Netherlands, a system is under development for sustainable dairy farming on sandy soils (Aarts et al., 1992; Biewinga et al., 1992). In the sandy areas of the Netherlands, especially nitrate leaching to groundwater is of major concern. Therefore, special attention is being given to nutrient management at De Marke, which involves soil aspects, but also animal husbandry, agronomy and economics. For this purpose, a multi-disciplinary team is working on farm development, and researchers from various disciplines have been invited to co-operate for specific research questions (Biewinga et al., 1992). In this paper, we will focus on the land use of the farm, which is part of the design of the farming system as a whole. Land use within the FAO-framework for land evaluation (FAO, 1984) would be referred to as a LUT (Land Utilization Type). In this context a LUT refers to a crop, a combination of crops or a cropping system within a specified technical and socio-economic setting. Most studies describe LUTs for a specific crop or crop rotation (e.g. Rossiter, 1990; Van Lanen et al., 1992; Jansen and Schipper, 1995). For the De Marke farm the design process has resulted in three parcel types with different rotations and specific management. For a land use evaluation of De Marke all these need to be described.

The farm area is approximately 55 ha, and currently 56% of this area is used to grow grass and 44% for silage maize (Biewinga et al., 1996). There are three types of land use: 10 ha of permanent grassland (parcel type A), 30 ha with a rotation of three years grass and three years silage maize (parcel type B) and 15 ha with a rotation of three years grass and five years silage maize (parcel type C). The fields are used less intensively with increasing distance from the farm buildings. The idea behind these three so-called 'parcel types' is that on such a dairy farm the grassland (which is used most intensively) should be located near the farm buildings. This allows rotational grazing, while the silage maize can be grown further away from the farmhouse. The rotation of maize and grassland is important because of the increased mineralization that is expected when the grassland is ploughed, yielding extra nitrogen (N), which can then be used by the maize crop. Of course extra mineralization could also lead to increased N-leaching and therefore in the first years of maize growth after grass, the extra available N is accounted for in the fertilization strategy by slowly increasing the N-fertilization each year. Furthermore, the maize crop is undersown with Italian ryegrass, usually in June, so that after the maize harvest in September the Italian ryegrass sward can establish and take up the remaining N in the soil, as well as the N that is mineralized after harvest. The Italian ryegrass sward is usually ploughed in the next spring, and the mineralization of N from this sward is also taken into account as a source of N. Supplementary irrigation is applied when necessary on the permanent grassland, as well as on the grass in the rotation with three years maize (parcel type B), to ensure grazing. All animal manure produced by the cattle is used on the farm. Mineral fertilizer is used only on the grassland.

The farm is located on sandy soils in the eastern part of the Netherlands. The soils are poor in terms of natural fertility and are susceptible to drought (Dekkers, 1992). This location was chosen for the purpose of showing that both environmental and economic goals can be met even in a 'worst case' setting like this. It is therefore expected that the system will prove to be better from both the economic and environmental points of view on almost any other location with sandy soils. One of the purposes of the present study is to find out whether that is true for the major sandy soils occurring in the Netherlands and to quantify the effects of implementing the De Marke land use system for these soils, on the environment (i.e. nitrate leaching) and on crop productivity. For this an extrapolation of the De Marke land use system is performed using simulation models. Because the De Marke farming system was designed for sandy soils and the model calibration and validation was also performed for these sandy soils, the soils for the extrapolation study were selected from the sandy areas of the Netherlands.

Extrapolation of the De Marke land use system to other soils requires a so-called standardization of land use, implying a description or translation of the farm's land use into a set of management decision rules. In this case, decision rules were needed for fertilization, rotational grazing and cutting and irrigation. Furthermore, the relation to weather conditions had to be defined. Temporal variability of the model results due to weather conditions was quantified by means of simulation runs using long-term weather data over a period of 30 years. The decision rules were applied for these 30 years to the soils occurring at De Marke and to five other major soil map units. For each of these five other units a representative soil profile is used for the model simulations. This leaves spatial variability within mapping units unaccounted for, which may lead to an underestimation of the variability. In an evaluation of the nitrate leaching risk of De Marke (Hack-ten Broeke and De Groot, 1998) with simulations for four consecutive years and more than 200 soil profiles, it was found that the temporal and spatial variability of nitrate concentrations were within the same order of magnitude. In this exploratory study only temporal variability is considered.

Materials and methods

Standardization of the land use of De Marke

The De Marke experimental farm (Aarts et al., 1992; Biewinga et al., 1992) started officially in 1992 and since then all land use activities, such as fertilization and grassland management, have been recorded for each field. The annual variations in circumstances have resulted in differences in these activities per year. It is therefore not feasible to use these real land use data for the fields for a specific year as being representative for the farm. Extrapolation requires generalization of activities, so decision rules for these land use activities were therefore defined, in close co-operation with researchers responsible for the soil/crop system at De Marke.

All animal manure of De Marke is used on the farm. On the basis of N demand, the first allocated amount of manure is reserved for silage maize. The N demand is a function of crop demand, soil moisture supply capacity and expected availability of N from mineralization of previously ploughed grass swards. The animal manure applied per maize field may therefore vary from 0 to 35 m^3/ha (i.e. 0 to 154 kg ha total N). The second portion of animal manure is allocated to permanent grassland (parcel type A in Fig. 8.1) on the basis of phosphorus demand, again a function of crop demand and moisture supply capacity of the soil. The average amount applied per permanent grassland field then becomes 50 m^3/ha, given in two applications during the growing season. All remaining animal manure (75 m^3/ha) is then applied to the grassland fields of the other parcel types (B and C in Fig. 8.1), in three separate manure applications per field. Figure 8.1 schematically shows the decision rules and the timing for fertilization, grazing and cutting of the grassland for the three different parcel types.

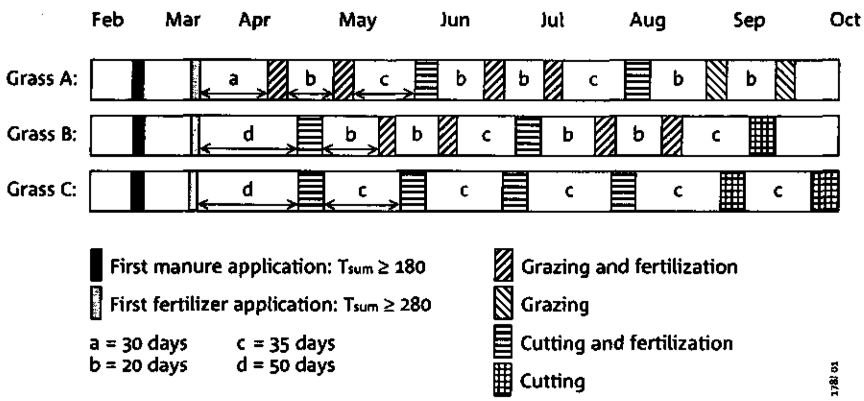

Fig. 8.1 Schematic representation of decision rules for fertilization, cutting and mowing of grassland (A = permanent pasture, B = rotation of 3 years grass and 3 years maize, C = rotation of 3 years grass and 5 years maize

The total sum of N-fertilization with animal manure and mineral fertilizer for grassland amounts to an annual N-application of 250 kg/ha as defined by Agterberg et al. (1993). The first animal manure application takes place when the temperature sum has reached 180 °C and when the soil moisture pressure head at 5 cm depth is lower than the threshold for trafficability (in this case h = -70 cm) as defined by Van Wijk & Feddes (1986) and Bouma & Van Lanen (1987), but in any case between 15 February and 1 March. The second animal manure application on the permanent pastures comes after the second grazing period. On other grassland (types B and C), the second animal manure application is after the first cut. For these fields the final amount of manure is applied after the second grazing period on type B grassland and after the second cut on type C grassland. The first mineral fertilizer is applied when the temperature sum has reached 280 °C and the soil is again defined as trafficable, but always between 15 and 30 March. Then after each grazing period or cut before 15 August, mineral fertilizer is applied according to the fertilizer recommendations for grassland (Agterberg et al., 1993). The N-fertilization with mineral fertilizer according to these decision rules amounts to an average of 141 kg/ha for permanent pastures and 164 kg/ha for other grassland at De Marke. On maize fields the animal manure is applied before sowing. The sowing date for silage maize is 25 April and the harvest date is 25 September.

Grass of the rotation of parcel type C (Fig. 8.1) is not used for grazing, but is only cut in the standardized land use. All other grassland is used for rotational cutting and grazing with dairy cows, heifers and calves in separate groups. The rotational grazing starts on the permanent pastures (parcel type A, Fig. 8.1), 30 days after the first mineral fertilizer application. When all fields of the permanent pastures have been grazed twice, the cattle is moved to the grassland of parcel type B. In the meantime, this grassland has already been cut once. These first cuts take place 50 days after the first mineral fertilizer is applied. In the rest of the growing season, 20 days of grass regrowth is assumed for each grazing period and 35 days of regrowth for each cut. No relation was found between the grazing and cutting scheme and the weather conditions, so this aspect of the grassland management is the same for each year. The urinary-N excretion by grazing cattle was assumed to be evenly distributed over the field on each day of the grazing periods, as proposed by Hack-ten Broeke et al. (1996a).

Supplementary irrigation is applied only on permanent pastures and on the grass and silage maize of parcel type B when the pressure head in the middle of the root zone drops below h = -500 cm (= -50 kPa). Irrigation does not take place during grazing nor during the two days before each grazing period. When the grass is cut, there is no irrigation from two days before until two days after this cut.

Simulation modelling

The simulation models SWACROP and ANIMO were used to simulate unsaturated soil water and nitrogen dynamics, respectively. SWACROP is a dynamic deterministic model describing one-dimensional (vertical) unsaturated water flow in a heterogeneous soil-root system using Richard's equation (Feddes et al., 1978; Belmans et al., 1983; Feddes et al., 1988). The nutrient model ANIMO is a dynamic simulation model which describes the carbon and nitrogen cycles in the soil and their interrelations (Rijtema and Kroes, 1991; Jansen, 1991). When ANIMO is used in combination with SWACROP, it calculates nitrogen transport in the unsaturated zone as well as nitrate leaching to the groundwater on a daily basis. For this the relevant processes affecting nitrogen in the soil (e.g. mineralization and denitrification) are all simulated in relation to soil moisture conditions, temperature, pH, oxygen supply and organic matter.

From autumn 1991 until spring 1995, a monitoring program was carried out at De Marke to quantify soil moisture and nitrogen dynamics. 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: one in a relatively wet field (groundwater levels varied from 0.0 to 2.0 m depth) and the second in a dry field (groundwater levels varied from 0.5 to 2.8 m depth). Similarly two sites were chosen in the rotation with three years of silage maize (parcel type B) and the last two sites were located in fields with the rotation with five years maize (parcel type C). Each monitoring site was 20 m x 20 m, within which all measurements on crops, soil, soil moisture and groundwater were performed (Hack-ten Broeke et al., 1996a). Nitrate concentrations were measured in soil water samples from suction cups at 1 m depth or in groundwater samples, which were taken once a month on average. The monitoring data were used for model calibration and validation. For the two grassland sites this procedure and the results are described by Hack-ten Broeke et al (1996a) and a summary of the validation for all monitoring sites is described by Hack-ten Broeke and De Groot (1998). Figure 8.2 also shows the summarized validation results for all sites. The validation was considered to be satisfactory, and therefore it was concluded that extrapolation studies or scenario studies for De Marke (e.g. Hack-ten Broeke et al., 1996a; Hack-ten Broeke and Van der Putten, 1997) would be allowed. This also implies that the models can be used for the present study, involving extrapolation to 30 years instead of the five monitoring years and extrapolation to other sandy soils than those at the monitoring sites. This extrapolation, which only considers variation in time, is exploratory and relates to average results.

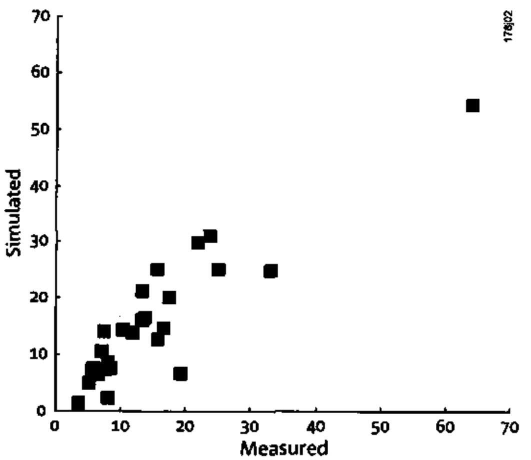

Fig. 8.2 Comparison of measured and simulated seasonal average nitrate-N concentrations for the six monitoring sites at De Marke

The model results comprise the water and nitrogen balances of the soil. For the present study we were interested in nitrate leaching and actual transpiration. Nitrate leaching was quantified using the annual average nitrate concentrations in the soil water at a depth of 1 m. One of the environmental goals of De Marke (Biewinga et al., 1992) is that the nitrate-N concentration in the groundwater should be below the limit for drinking water of 11.3 mg/l, but the groundwater level varies in time and per field. The measurements of nitrate concentrations during the monitoring years, however, were carried out using suction cups at a depth of 1 m (Hack-ten Broeke et al., 1996a) and therefore this depth is also considered for the present study, allowing an easier comparison between fields and years. Furthermore, concentrations at this depth are expected to be more directly related to the soil use than those in the groundwater, because transport and transformation processes in the shallow groundwater may affect concentration levels. Annual average concentrations were calculated for hydrological years (i.e. 1 April - 31 March) from daily simulated nitrate concentration levels. An annual farm average concentration was calculated as the average of all 56 involved fields.

Crop growth was not simulated for this study, but the SWACROP model produces daily potential and actual transpiration, and these values can be translated into crop yields by using transpiration coefficients. This results in maximum yield levels when water availability is considered as the only limiting factor for crop growth.

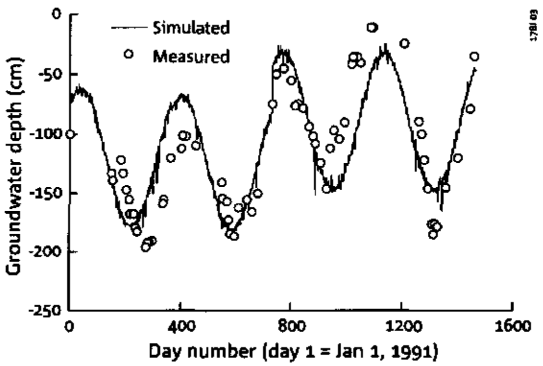

Fig. 8.3 Comparison of simulated and measured groundwater levels at the relatively wet monitoring site of parcel type B; simulations were performed using a sine function

<u>Model input</u>

The required model input for simulating soil water and nitrogen comprises meteorological data, groundwater levels, soil characteristics and data on crop development and on crop and field management. The latter input data were derived from the decision rules for soil use described above. For the monitoring years at De Marke weather data were gathered daily at the farm. For the extrapolation to 30 years, a set of daily meteorological data for the years 1956-1986 was used from the Dutch meteorological station at De Bilt.

For the extrapolation of the results of the monitoring sites of De Marke to the whole farm, the decision rules for land use (Fig. 8.1) had to be applied to all fields. Groundwater levels were observed at the six sites of the farm's monitoring program. These time series of measured groundwater levels could be described using a site-specific sine function. An example of the simulated groundwater levels for one of the sites using this sine function compared with the measured groundwater levels is shown in Figure 8.3. The average annual groundwater level of these functions depended on the annual rainfall. For each 50 mm difference in rainfall, compared to the average annual rainfall of the 30 year period, the average groundwater level required a correction of 5 cm compared to the 30-year average groundwater level. Simulations with SWACROP-ANIMO, using either measured groundwater levels for the six sites or the site-specific sine functions describing groundwater levels, showed that the simulated nitrate concentrations at 1 m depth were the same for both methods (Schut and Hack-ten Broeke, 1997). Furthermore, the groundwater levels were found to be related to soil surface altitude, for which values were available for the whole farm (Dekkers, 1992). This allowed a description of groundwater levels for each field of De Marke for 30 years, using a field-specific sine function.

Soil characteristics for each field were derived from the soil profile descriptions for De Marke (Dekkers, 1992). For the dominant mapping unit per field, the Van Genuchten parameters, describing soil physical characteristics (soil moisture retention and hydraulic conductivity curves), were determined from texture data using the continuous pedotransfer functions developed by Wösten et al. (1995). The predominant soil type at De Marke is a Cambic Podzol (FAO-Unesco, 1988) with an organic matter content of 3 to 5% in the top soil (0-25 or 0-30 cm). Silt + clay contents in the top soil range from 8 to 11% in the southern part of the farm and from 10 to 17% in the northern part. Dystric Gleysols occur on a small portion of the farm area.

Table 8.1 The five major soil map units in sandy areas of the Netherlands selected

Map unit code	Description	Area (ha)
Hn21-VI	Cambic Podzol, Groundwater class VI	119,172
zEZ21-VII	Cumulic Anthrosol, Groundwater class VII	33,331
pZg23-III	Umbric Gleysol, Groundwater class III	36,104
Hn23x-V	Cambic Podzol with boulder clay, Groundwater class V	25,462
pZn21-III	Dystric Gleysol, Groundwater class III	6,580

<u>Five representative soil map units in sandy soils</u>

From the 1 : 50 000 Soil Map of the Netherlands, the five soil series covering the largest area of sandy soils were selected. Next, within each soil series, the groundwater class (i.e. Dutch standard description of the groundwater regime in terms of average highest and average lowest groundwater level) covering the largest area was selected. The five combinations (soil map units) used for simulations are presented in Table 8.1. Soil data needed for deriving model input were obtained for each mapping unit using all available soil profile descriptions for this mapping unit, according to De Vries (1994). This means that for each 5 cm of soil depth a frequency distribution of relevant data (e.g. pH, organic matter content, clay content) was produced using all available profile descriptions for the mapping unit. The average of the most frequently occurring values of these variables for the mapping unit could then be determined. For class data, such as horizon code, the most frequently occurring class per 5 cm of soil depth was selected. The resulting soil profile descriptions are given in Table 8.2. From the texture data, Van Genuchten parameters for describing soil hydraulic characteristics could be calculated for each soil horizon (Wösten et al., 1995). For the groundwater classes, 30-year average groundwater levels and amplitudes were derived from Van der Sluijs (1990) to describe the soil map unit specific sine functions for groundwater depths in a similar way as for De Marke. For

Table 8.2 Soil profile descriptions of the five selected map units (see Table 8.1)

Map unit	Depth (cm)	Horizon	Organic matter content (%)	pH-H_2O	Clay content (%)	Silt+clay content (%)	M50[1] (µm)
Hn21 - VI	0-20	Ap	5.3	4.7	3	11	160
	20-40	Bhe	1.5	4.4	2	7	160
	40-60	BC	1.8	4.4	3	7	160
	60-120	Cg	0.4	4.6	2	9	160
zEZ21-VII	0-25	Aap	4.8	4.1	4	14	160
	25-75	Aa	4.8	4.2	4	12	160
	75-115	Bhe	1.4	4.5	3	10	160
	115-120	Cu	0.7	4.7	3	5	160
pZg23-III	0-25	Aapg	5.2	5.1	6	25	150
	25-35	ACg	2.4	5.0	6	23	150
	35-85	Cg1	0.3	5.4	4	10	150
	85-120	Cg2	0.3	5.7	4	12	150
Hn23x-V	0-20	Ap	5.4	5.1	5	24	160
	20-40	Bhe	2.0	4.4	4	24	160
	40-70	1Cg	0.4	4.3	4	24	160
	70-120	2Cg	0.3	4.1	20	35	160
pZn21-III	0-25	Ap	5.5	4.9	4	12	155
	25-60	Cu	0.4	5.2	3	6	155
	60-115	C2	0.3	5.3	3	6	155

[1]M50 is the median of the sand fraction

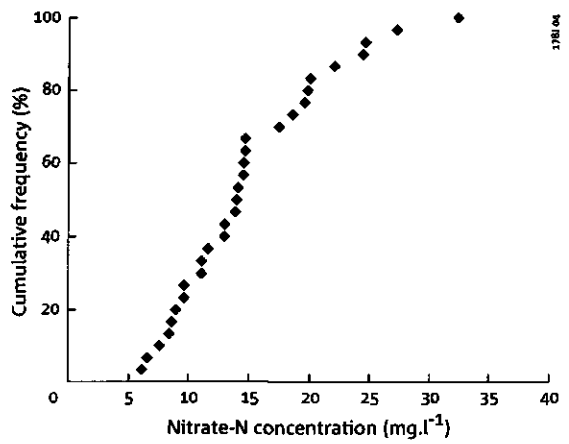

Fig. 8.4 Cumulative frequency distribution of farm average annual nitrate-N concentrations at 1 m depth at De Marke

these five mapping units, groundwater class III represents the highest groundwater levels, described with an average highest level within 40 cm depth and an average lowest level between 80 and 120 cm depth. Groundwater class VII represents the driest soils of these five mapping units and is described as the class with average highest levels between 80 and 140 cm depth and the average lowest level deeper than 140 cm. For the simulations, farms were assumed to be homogeneous, so all fields of all three parcel types had the same soil mapping unit. The standardized soil use of De Marke was then applied to all 56 fields for the same period of 30 years and results for these homogeneous farms were compared with those of the whole-farm simulations for De Marke.

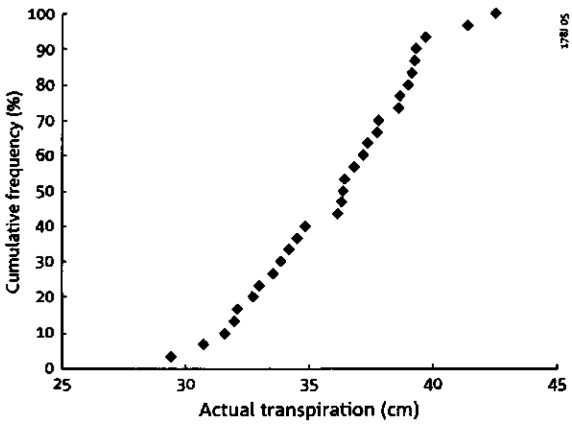

Fig. 8.5 Cumulative frequency distribution of farm average actual transpiration at De Marke

Results

Modelling results for farm average nitrate concentrations for De Marke are presented in Figure 8.4 as a frequency distribution. This frequency distribution is the result of simulation runs for the 56 fields of the farm, each for 30 consecutive years. Particularly dry years caused the high concentrations (up to 32 mg/l), while simulations for wet years were responsible for the lower part of the graph. This is caused by dilution and differences in transformation processes such as denitrification, but also by differences in moisture supply and thus in N uptake by the crops. The differences in moisture supply (including the supplementary irrigation) between the years resulted in the frequency distribution of actual transpiration presented in Figure 8.5. The average annual nitrate-N concentration at De Marke was 15.1 mg/l and the average actual transpiration of the farm was 366 mm. The frequency distribution of Figure 8.4 also tells us how often the predefined threshold value of 11.3 mg/l was exceeded: the probability was 67%. In a study to quantify the effect of soil spatial variability within the De Marke farm during the monitoring years, Hack-ten Broeke and De Groot (1998) found that the probability of exceeding the 11.3 mg/l threshold value for the farm was 63%.

For the five soil map units, the farm level results for nitrate leaching are shown in Figure 8.6 and Table 8.3. The differences in nitrate leaching caused by differences in soils is most obvious in Figure 8.6. The differences between the results for the soil map units were all significant, except for the difference between the Umbric Gleysol (pZg23-III) and the Cumulic Anthrosol (zEZ21-VII), although their similarity resulted from different factors. Applying the same land use system to five different mapping units may result in negligible nitrate leaching in one case (Hn23x-V) and nitrate concentrations exceeding the directive for drinking water (at 1 m depth) in almost 75% of the years in another (Hn21-VI). These differences were caused by differences in moisture supply and the various related nitrogen processes, such as mineralization, denitrification and uptake by the crop. The differences resulting from growing either grass or silage maize were also significant in most cases. In Table 8.3 the average concentrations for grassland (average for parcel types A, B and C) and for silage maize (average of the two rotations with grassland of parcel type B and C) are presented. Grassland is used most intensively and nitrate inputs are higher than on fields with silage maize. The different fertilization and grazing intensities of the three types of grassland (Fig. 8.1) also caused differences in leaching between the parcel types.

Table 8.3 Average nitrate-N concentrations at 1 m depth for five soil map units and probability of exceeding the limit of 11.3 mg/l

Map unit	Nitrate-N concentration (mg/l)			Probability of exceedance of drinking water limit (%)
	average	grassland	sil.maize	
Hn21-VI	17.1	19.4	15.1	73
zEZ21-VII	11.4	12.8	10.2	40
pZg23-III	11.3	13.3	9.3	43
Hn23x-V	3.4	3.6	3.5	3
pZn21-III	6.3	7.0	5.8	17

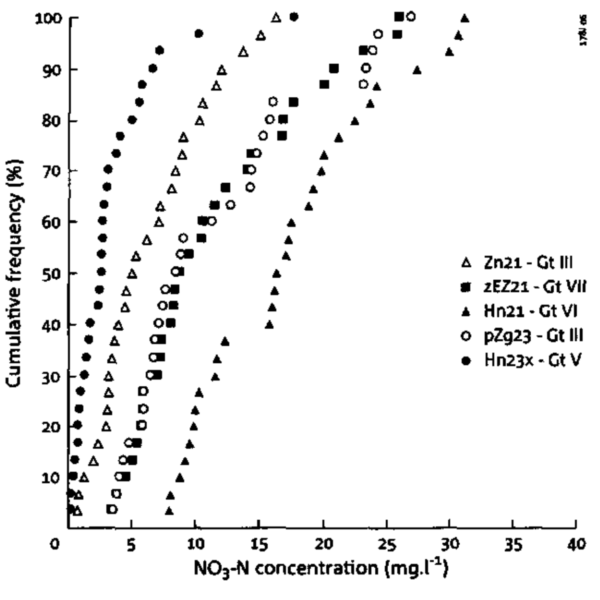

Fig. 8.6 Cumulative frequency distribution of farm average annual nitrate-N concentrations at 1 m depth for five mapping units in sandy soils

The permanent pastures (type A) were responsible for the highest nitrate concentrations at a depth of 1 m, reaching an average of 26.4 mg/l nitrate-N for the Cambic Podzol Hn21-VI. Parcel type C resulted in the lowest concentrations.

Regarding the threshold value for drinking water of 11.3 mg/l, the probability of exceeding this limit at 1 m depth was always less than 50% at farm level, except for Hn21-VI (Table 8.3). As was expected, almost any other location for a farm on sandy soils with the soil use system of De Marke would have resulted in less nitrate leaching than the current location of the experimental farm on poor sandy soils.

For an area near De Marke, a map was produced showing the average nitrate concentrations of Table 8.3 for the relevant mapping units (Fig. 8.7). This means that the map shows the effect of introducing the standardized land use to this sandy area. Three of the five selected soil map units occurred in this area, and these covered as much as 46% of the map area. This method will thus allow, for any region, a soil-specific assessment of the effects of implementing a land use system as described here. In this study spatial variability was not taken into account and only average nitrate concentrations are considered in the legend. It is of course also possible to show probabilities of exceeding the defined threshold value or to consider spatial variability in order to assess leaching risks (e.g. Finke, 1993; Verhagen and Bouma, 1997).

Table 8.4 Increase of transpiration and related increase in crop yield for five soil map units compared with De Marke

Map unit	Transpiration increase (mm)		Maximum yield increase (kg/ha)	
	grassland	silage maize	grassland	silage maize
Hn21-VI	25.5	28.6	1020	1430
zEZ21-VII	16.2	20.7	648	1035
pZg23-III	13.6	20.6	544	1030
Hn23x-V	10.3	8.2	412	410
pZn21-III	15.1	19.8	604	990

The average actual transpiration for all five soil map units was higher than the farm average for De Marke. The increased transpiration may result in an increase of crop yield. A simple calculation with transpiration coefficients for grass and silage maize of respectively 250 and 200 kg water per kg dry matter (Aarts and Grashoff, 1993) resulted in extra crop production values as presented in Table 8.4. On average, each soil series resulted in higher actual transpiration levels than at De Marke, but in some wet years the transpiration was also less. Especially for the mapping units with high groundwater levels, water excess reduced transpiration in wet years. The Cambic Podzol Hn21-VI showed the highest average transpiration compared to De Marke and thus the highest yield potential. For the 'wetter' mapping units, the average was greatly affected by the years with water excess, whereas the relatively high average for Hn21-VI was mainly caused by a few simulated years with high transpiration.

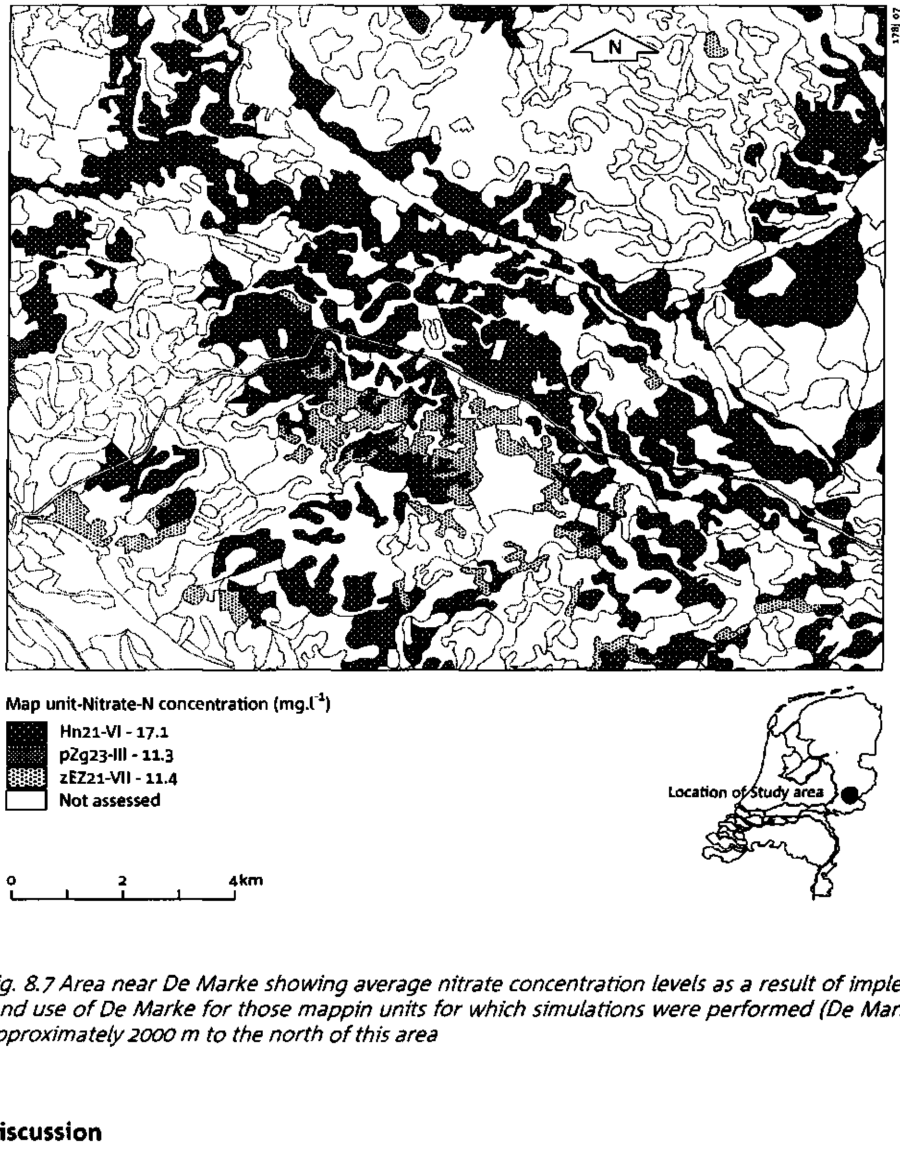

Fig. 8.7 Area near De Marke showing average nitrate concentration levels as a result of implementing the land use of De Marke for those mappin units for which simulations were performed (De Marke is located approximately 2000 m to the north of this area

Discussion

Nitrate leaching at the De Marke experimental farm for sustainable dairy farming, based on simulations for 30 years and for all fields of the farm, resulted in an average nitrate-N concentration at a depth of 1 m of 15.1 mg/l and a probability of 67% of exceeding the directive for drinking water of 11.3 mg/l. The permanent pastures, years with dry weather conditions and the drier parts of the farm contributed most to this exceedance. The threshold value is used for shallow groundwater, and processes like denitrification will likely reduce the concentration in the deeper groundwater compared to the concentrations at 1 m depth. Under the assumption that a probability of exceeding this limit of less than for instance 50% would be acceptable, De Marke would have almost reached the environmental goal for nitrate leaching. A similar conclusion was drawn by Aarts (1996) and Fraters et al. (1997) on the basis of measured nitrate concentrations in the groundwater. However, if the environmental goal would be stricter and the nitrate concentration would have to be below the EC-directive in at least 25% of the years, there is still a lot of work to be done at the farm.

The method used to calculate an annual average for the whole farm is just one of the possibilities. Different ways of averaging over time have been presented by Droogers (1997) and it is also possible to account for spatial variability of nitrate leaching (e.g. Finke, 1993, Hack-ten Broeke and De Groot, 1998). The purpose of the present study, however, was to compare model results for De Marke with those for five simulated 'farms' with different sandy soils. Since all averages were calculated in exactly the same way, this comparison can be considered valid.

Extrapolating the land use system of De Marke to other sandy soils in the Netherlands showed that in four of the five cases, simulated average nitrate leaching would be less than at De Marke. For all five simulated major soil map units the average transpiration and thus the water-limited crop growth would be higher than at De Marke, so compared to De Marke it is easier on almost all these soil map units to meet both the environmental and the agricultural production goals.

Usually, different soil map units occur within a farm. The three parcel types of the De Marke land use system, ranging from permanent pastures to a rotation of three years grass and five years silage maize, result in three different levels of nitrate leaching. Because the nitrate leaching is highest for permanent grassland, which is utilized most intensively, it might be worthwhile locating the land use with the highest leaching on soils which show the least environmental risk and vice versa. Since it is generally preferred to locate permanent pastures near the farm buildings, this may not always be feasible in practice, but it is worth considering.

If a farmer on other sandy soils than De Marke would want to apply the standardized land use system, the farmer would probably want to adapt it to his own circumstances, taking the whole farming system into account. The higher production potential of other sandy soils compared to the soils of De Marke, would already lead to differences in the farming system. Furthermore, in order to reduce the environmental effects of a land use type, other management options such as reducing fertilizer use or changing the grazing system can be considered. It is important to realize that a change in land use will affect the whole farming system, and assessing the implications of such a change requires a multi-disciplinary approach.

The present study demonstrates the use of interdisciplinary farm research in defining a sustainable land utilization type (LUT), which is much more complex than the traditional ones (FAO, 1984), which often only refer to a single crop. In fact, three LUTs were defined, occurring at varying distances from the farm. The study also shows that comprehensive data can be generated for a given soil series, which is useful in databases when assessing the possible effects of land use changes for a particular region.

Conclusions

1. Evaluating environmental effects of the land use on farm level requires a quantitative description of all land use activities, including different crop rotations and management practices. For extrapolation to other locations, the activities have to be described in terms of standardized management decision rules, developed by prototyping. Current descriptions of Land Utilization Types (LUT) in land evaluation are far too simple to adequately express sustainable land management.

2. At the De Marke experimental farm for sustainable dairy farming, the probability that the annual average nitrate concentration at 1 m depth will exceed the goal for nitrate leaching (i.e. a nitrate-N concentration of 11.3 mg/l) is 67 %. On four major soil map units of the sandy areas of the Netherlands implementation of the land use management of De Marke would lead to acceptable leaching levels.

3. Land use with the highest nitrate leaching risk, as characterized in this study for different parcel types, should be located on the least vulnerable soils on a farm and vice versa. Soil survey data can thus contribute towards optimizing land use allocation.

4. Detailed process-oriented studies of nitrogen dynamics in soil are most effective when they follow interdisciplinary prototyping activities by focussing on identified knowledge gaps

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CURRICULUM VITAE

Op 4-4-1964 werd Mirjam Josephine Désirée ten Broeke geboren in Arnhem. Toen ze één jaar oud was verhuisde ze met haar ouders mee naar Maastricht, waar ze leerde praten en een begin maakte met de lagere school. In het begin van de tweede klas verhuisde het gezin naar Zeist. Mirjam voltooide er de lagere school en de eerste drie jaren van de middelbare school op de Katholieke Scholengemeenschap De Breul. De laatste helft van de middelbare school bracht zij door in Apeldoorn op het Katholiek Veluws College. In 1982 behaalde zij haar eindexamen Gymnasium β en verhuisde ze naar Wageningen, waar ze nu nog woont.

Aan de Landbouwhogeschool startte zij in 1982 als één van de proefkonijnen van de tweefasenstructuur en koos voor de studierichting Cultuurtechniek. In maart 1987 studeerde zij af aan de Landbouwuniversiteit met agrohydrologie als afstudeerrichting. 1 Juni 1987 was haar eerste werkdag bij de Stichting voor Bodemkartering (STIBOKA). Haar eerste tijdelijke aanstelling was voor het door de EG gefinancierde project 'Use of modern physical field methods and computer simulation for land evaluation purposes'. Er zouden nog vele verlengingen van de tijdelijke aanstelling bij STIBOKA en later DLO-Staring Centrum volgen. De laatste drie verlengingen waren voor respectievelijk een maand, nog eens een maand en tenslotte twee maanden. Op 1 mei 1991 trad ze in dienst bij de LUW-vakgroep Bodemkunde en Geologie om te werken aan het EG-project 'WASTES' met opnieuw een tijdelijke aanstelling, ditmaal voor de duur van anderhalf jaar. Deze aanstelling duurde uiteindelijk slechts twee maanden, want per 1 juli 1991 kreeg zij eervol ontslag op eigen verzoek en een vaste aanstelling als senior wetenschappelijk onderzoeker bij de afdeling Landevaluatiemethoden van SC-DLO. In 1992 bezocht Mirjam, op uitnodiging van prof. Jeff Wagenet, voor een periode van drie maanden de Department of Soil, Crop and Atmospheric Sciences (SCAS) van Cornell University in Ithaca, New York. Op 1 oktober 1994 verhuisde zij naar de afdeling Systematische Bodemkundige Informatie. Vanaf 1 maart 1998 tot 1 juni 1999 was zij hoofd van die afdeling, op dat moment sectie geheten. Sinds 1 juni 1999 is zij teamleider van het team Geo-informatie, Statistiek en Toepassing (afdeling Bodem & Landgebruik) bij eerst nog Staring Centrum en sinds 1 januari 2000 Alterra. Volgens haar functie-omschrijving is Mirjam sinds de reorganisatie van eind 1998 senior wetenschappelijk onderzoeker op het gebied van de agrohydrologie en de landevaluatie. Op 1 december 1999 was zij 12½ jaar 'in dienst'.

Mirjam trouwde in juni 1987 met Maarten Hack. Maarten en Mirjam hebben één dochter; Eline werd geboren op 4 december 1997.