Management and nitrogen utilisation of grassland on intensive dairy farms

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Abstract
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Increased nitrogen (N) inputs via fertiliser and animal manure have played a large role in the intensification of grassland-based dairy farming in the Netherlands during the second half of the 20th century. However, the increased N inputs have also contributed to large increases in N losses to the environment. In response, the government has implemented a series of environmental legislation to restrict the use of N inputs and thereby to minimise N losses. Consequently, management goals in dairy farming have shifted from mainly economic to a combination of economic and environmental.
The general objective of the research prsented in this thesis was to gain insight into the effects of various management decisions at operational, tactical and strategic levels on herbage DM yield and N content per cut, N losses via leaching and N_2O and CO_2 emissions, using multi-site and many-years experiments, statistical analyses and empirical models. New criteria for environmentally sound N recommendations and tools for operational grassland management were derived, so as to improve the decision making in grassland management on intensive dairy farms.
Relationships between growth time, N application, herbage DM yield and N content and Soil Mineral N (SMN) have been quantified in single cuts during the whole growing season. Using critical levels formarginal N response, herbage N content and unrecovered N, combinations of economically optimum and environmetally sound N applications per cut were established for the complete growing season. Residual effects of the previously applied N may show up as SMN, but results indicate that SMN is not a useful tool for fine-tuning N-application per cut. Growth time per cut has a large effect on herbage DM yield and N use eficiency. It is shown that grazing at a young growth stage leads to low productivity and N use efficiency and to high leaching losses. In practice, grazing at a young stage is probably related to a risk-averse attitude of farmers, which in turn is caused by the lack of accurate data on herbage DM yield and quality during the growing season. A combination of the developed relationships with quick and accurate herbage yield and N content measurements in a 'Dynamic Decision Support System' is suggested to be the way to further improve operational grassland management.

Key-words
Grassland management, N application, nitrate leaching, nitrous oxide, herbage N content, grazing, apparent N recovery, grassland ploughing, field experiments

Voorwoord.

Na ongeveer 2500 uur werk zit het erop, het proefschrift is klaar. Ik kan me nog de discussie herinneren met Willem Prins die mij omstreeks 1987 probeerde over te halen een proefschrift te schrijven. Toen heb ik dat afgehouden met het argument dat er meer is in het leven dan werken en een proefschrift schrijven.
Waarom ben ik dan alsnog aan een proefschrift begonnen? Daar zijn twee belangrijke redenen voor. De eerste is dat wetenschappelijke aandacht en waardering vooral voortkomen uit het schrijven van publicaties in internationale, wetenschappelijke, gerefereerde tijdschriften. Het onderzoek dat is uitgevoerd op het Praktijkonderzoek voor Rundvee, Schapen en Paardenhouderij (PR) betrof onderzoek in bedrijfsverband, wat vaak samenviel met het operationele management op landbouwbedrijven. Soms was het eerder demonstratie dan onderzoek, maar in veel gevallen is degelijk wetenschappelijk onderzoek verricht. De meeste onderzoekers waren echter praktische mensen, voor wie publicatie in de Nederlandse vakbladen en de overdracht van de kennis naar de voorlichting, landbouwonderwijs en boeren een waardige afsluiting vormden van hun noeste werk. Het feit dat veel praktijkonderzoek niet is gepubliceerd in gerefereerde internationale wetenschappelijke tijdschriften heeft geleid tot de verminderde aandacht en waardering voor het praktijkonderzoek in bedrijfsverband en het operationeel management. Hoewel ik geen voorkeur heb voor “Nederengelse” citaten, is het “Publish or perish” duidelijk van toepassing voor het praktijk-onderzoek. Met het schrijven van een aantal publicaties over operationeel graslandmanagement wil ik een stukje van de waardering opeisen die het onderzoek in bedrijfsverband aan het PR verdiende.
Een tweede reden is dat veel van mijn collega’s en vrienden promoveerden. ”Wat zij kunnen, kan ik ook”, was toen mijn gedachte. Enige ambitie is mij niet vreemd.

Het feit dat gras per snede wordt geoogst klinkt als een open deur. Toch is dat een heel belangrijk uitgangspunt geweest in mijn onderzoek. Het is essentieel geweest bij de opzet en uitvoering van proeven en bij het gebruiken van de proefresultaten voor praktijkadviezen. Die adviezen varieerden van het berekenen van stikstofbemestingsadviezen en vergoedingen voor agrarisch natuurbeheer tot de voedervoorziening bij de bedrijfseconomische advisering. Harm Wieling en Hein Korevaar, bedankt dat jullie mij op het spoor hebben gezet van dit uiterst interessante onderzoeksterrein en mij hebben gesteund met stevige discussies en voldoende ruimte om ideeën uit te werken.

Alle hoofdstukken in dit proefschrift zijn geschreven in nauwe samenwerking met anderen.
Goed onderzoek vereist visie, doorzettingsvermogen en statistiek. Deze drie eigenschappen/voorwaarden vond ik bij Geert André. Geert, je bent kort na mij bij het Praktijkonderzoek gekomen en eveneens besmet met het gedachtengoed van Harm. Bijna twintig jaar hebben we samengewerkt aan de opzet, uitvoering en analyse van proeven. Zonder jou waren een aantal van de publicaties in dit proefschrift niet tot stand gekomen. Heel erg bedankt daarvoor. Jouw bijdrage aan de kwaliteit van het praktijkonderzoek kan moeilijk worden overschat.
Oene Oenema en René Schils, als promotor en co-promotor en als mede-auteurs hebben jullie geduldig vele versies van alle hoofdstukken gelezen, actief meegedacht over de hoofdlijnen van het proefschrift en waar nodig zelfs tot in de details de discussie aangegaan. Ik heb het jullie niet makkelijk gemaakt en jullie mij niet. Maar wat mij betreft is het resultaat de inspanning waard geweest.
Het hoofdstukover lachgasemissies was taai. Agnes van den Pol-van Dasselaar en Peter Kuikman, jullie hebben mij als co-auteurs geweldig geholpen om te zorgen dat het verhaal tot een publicatie kwam.
Michiel Mooij, Toon van der Putten, jullie bijdrage aan het model NURP voor de nitraatuitspoeling was onmisbaar door mee te denken, veel rekenwerk te doen en data aan te leveren. Ik heb genoten van de samenwerking.
Teun Kraak en Gerjan Hilhorst, co-auteurs en verantwoordelijk voor het tot stand komen van series gegevens waar ik nu op kan promoveren. Bedankt daarvoor.
Alle leden van de Commissie Bemesting Grasland en Voedergewassen hebben mij gevoed met hun ideeën en discussies. Peter Hoeks, als voorzitter heb jij altijd gezorgd voor een goed klimaat om de discussie te voeren. Het is voor mij een stimulans geweest om in dit proefschrift duidelijk aandacht te vragen voor de stikstofbemestingsadviezen voor grasland.

Aan de zijlijn van een proefschrift staan altijd een aantal mensen. Zij schrijven niet mee, maar zonder hen kun je niet schrijven.
Henk Groen, Jan Hollestelle, Henk van Elten, Otto Broertjes en Peter Muilwijk, al ruim 30 000 kilometers mijn loopvrienden. Samen hardlopen met je vrienden is goud waard.
En als bijna laatsten, maar zeker niet de minsten, mijn ouders. Pa en ma, jullie hebben mij gestimuleerd om te gaan studeren en zijn altijd volop belangstellend geweest tijdens het schrijven van mijn proefschrift.
Carine, Nynke en Jildau, hoewel jullie zeiden dat een vermelding in dit voorwoord niet nodig zou zijn, wil ik jullie bedanken voor je steun, vertrouwen en geduld.

Contents

Chapter 1

General introduction

1 Introduction

1.1 Intensification of agricultural production

Historical background

During the second half of the 20th century, agricultural production in western Europe increased strongly. The intensification of the agricultural production was supported by the Common Agricultural Policy (CAP) of the European Union and consisted of two main routes: increase of the production level per ha and per unit of labour (http://europa.eu.int/scadplus/leg/nl/lvb/l04000.htm). The higher production per ha aimed at a higher level of self-supply in all agricultural products. Increase of labour productivity was necessary to increase farmers' incomes and to release labour for industry.

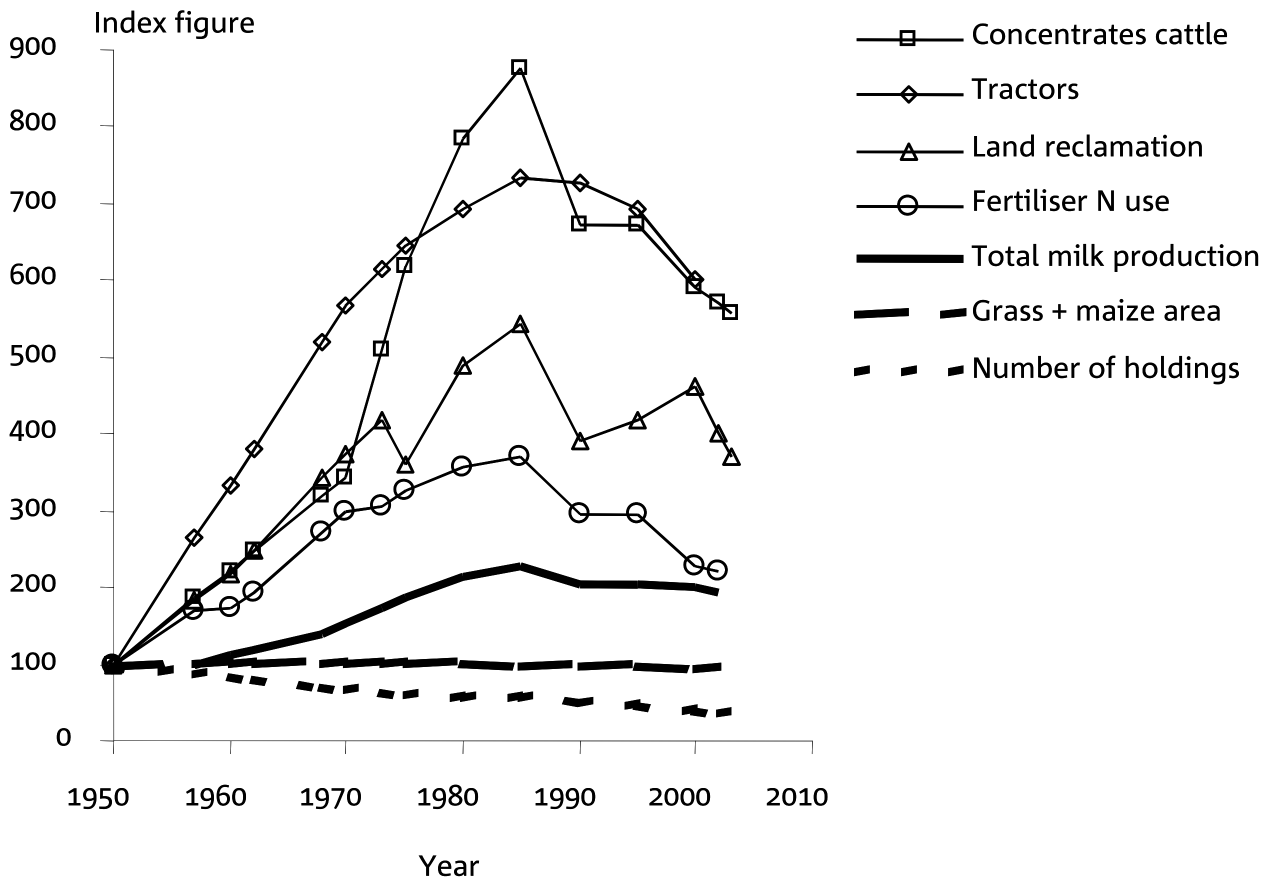

Figure 1-1. Data on agricultural development in The Netherlands between 1950 and 2003, concerning the number of farms, the area of grass and maize, national milk production, fertiliser use, governmental investments in land reclamation, the number of tractors in agriculture and the use of purchased concentrates in dairy farming. All data in index figures (1950 = 100). Sources: Van Der Molen *et al.*, 1980; LEI/CBS, 2004; De Clercq *et al.*, 2001

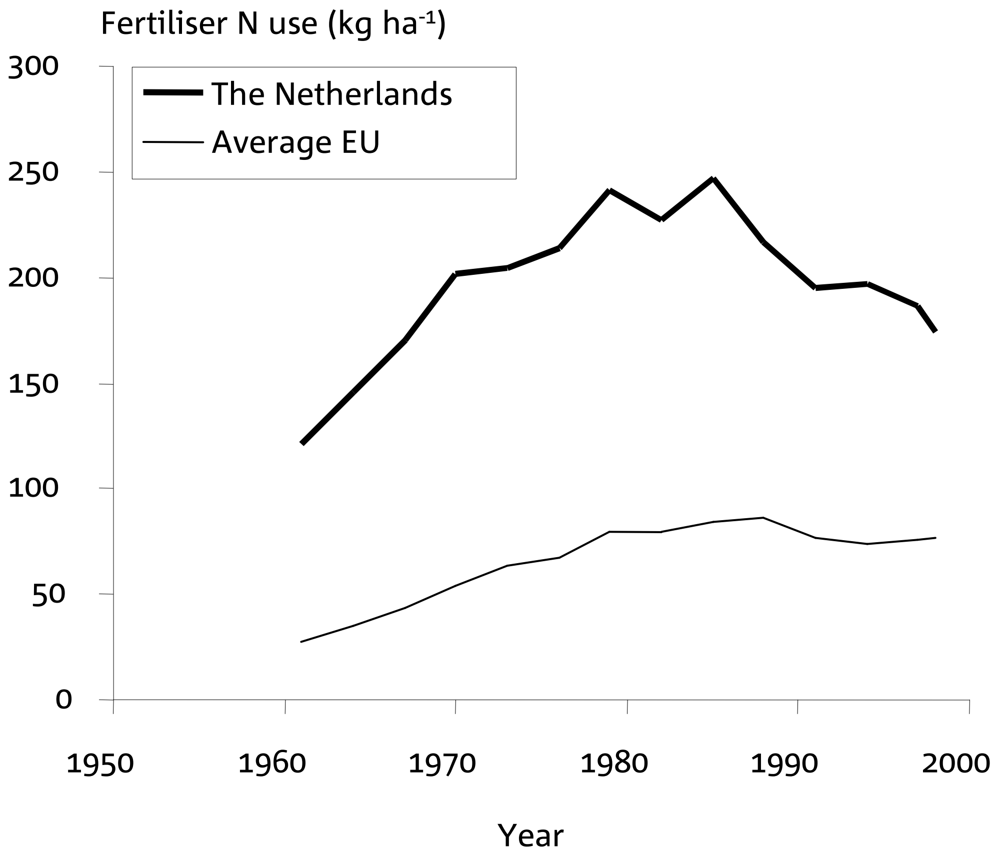

Figure 1-2. Input of fertiliser nitrogen per ha on agricultural holdings in The Netherlands and in the EU-15 between 1960 and 2000. Source: De Clercq *et al.*, 2001.

In The Netherlands, the government promoted the intensification of agricultural production strongly, and subsidised investments in land reclamation (Figure 1-1), with the aim to increase labour productivity and land productivity (Bieleman, 2000). Farmers invested in mechanisation as demonstrated by the increase in the number of tractors. Also the inputs in dairy farming increased sharply as shown for example by the increase in the use of concentrates and fertiliser nitrogen (N). Between 1950 and 2000, milk production doubled while the total area of grassland and fodder crops remained almost constant. In contrast, the number of farm holdings and especially the number of labourers decreased strongly. Between 1950 and 2000, the number of farm holdings decreased almost by a factor three (Figure 1-1).
Fertiliser N input per ha roughly doubled between 1950 and 1985 and was more than a factor two higher in The Netherlands than the average of the 15 member states of the European Union (EU-15) in this period (Figure 1-2). The scarcity of

agricultural land, the good climatic conditions, the presence of a good infrastructure (harbours) and a good export market, all have contributed to the strong intensification in The Netherlands relative to other EU-member states. This holds especially also for dairy farming. However, intensively managed dairy farms can be found also elsewhere in Europe, notably in regions where favourable conditions for high production and a good market are present, like northern Italy, Brittanny (France), United Kingdom and also Portugal (De Clercq *et al*., 2001).
The further intensification of dairy production per unit of surface area was blocked during the 1980's. The milk quota system was introduced by the EU Commission in 1984, so as to reduce the surpluses of dairy products and the intervention costs for the EU. The milk quota capped the total milk production, and as the national milk quota slowly decreased in the years after 1984 while milk production per cow still increased, the number of cows and the inputs of fertilisers and concentrates started decreasing. The strong decrease in the use of fertilisers and concentrates from about 1995 onwards is related to changes in the manure policy, based in part on the obligations of the EU Nitrates Directive (Anonymous, 1991a). The implementation of the Mineral Accounting System (MINAS) in 1998 forced farmers to reduce the input of (N) and phosphorus (P) strongly. The implementation of the EU Water Framework Directive (Anonymous, 2000e) will likely force farmers to decrease N and P inputs even further in the near future.

Changes in grassland use related to intensification
Approximately half of the agricultural area in The Netherlands is grassland used for dairy farming. The strong intensification of dairy farming during the second half of the 20th century has led to large changes in the management and utilisation of grassland. Subsidised land reclamation projects have contributed to drainage of wet grasslands and reparcelling and levelling of grassland fields. Drainage was improved by drains, furrows and ditches, and by lowering the water level in canals and ditches. Workability was improved by increasing paddock size by closing ditches and removing hedgerows. Paddocks were exchanged between farmers to realise shorter distances to farm buildings. Also new roads were built and new farms were established. Farmers invested in mechanisation, sward renovation, soil fertility, animal housing, and in the number and productivity of dairy cows (Van Der Molen, 1980; Bieleman, 2000).

Grassland performance was drastically affected by these investments ('t Mannetje, 1985). Drainage led to an earlier start of herbage production in spring. Irrigation and reseeding grassland with higher yielding and more persistent species led to an increased productivity, especially in spring and summer (Minderhoud, 1960; Boxem & Leusink, 1981; Van Wijk & Reheul, 1991). Drainage improved workability and mechanisation, and allowed harvesting the increased yields (Priester, 2000). Grass quality was affected as well, as perennial ryegrass with a higher production capacity and better nutritive value than most other indigenous species (Korevaar, 1986; Anonymous, 2000a) became the most important grass species in the sward (Dirven & Neuteboom, 1975; Keuning, 1994). It has been indicated that plant breeding efforts in perennial ryegrass continues to result in increased grassland productivity (Wilkins & Humphreys, 2003).

The increase in dry matter yield of grassland and the improvement in herbage quality, especially protein content, were boosted by fertiliser nitrogen (N) applications. Similarly, the availability of soil phosphorus, potassium and other essential nutrients was also improved through application of fertilisers and soil amendments. With time, N fertiliser was increasingly seen as management tool to increase herbage yield and quality, and to realise the planned grazing and cutting cycles. The increased growth rate following N application reduced the growth time for grazing cuts and silage cuts. So, more cuts per year were possible (Van Burg *et al*., 1980, 1981). The reduced distance between farm and paddocks led to an intensive grassland use all over the whole farm area, and the original distinction of intensively used grasslands near the farm and extensively used grasslands at distance from the farm disappeared (Priester, 2000). Because more paddocks could be used for grazing, grazing changed from very intensive grazing on a relatively small area to an intensive grazing system on all paddocks.

The process of intensification in dairy farming is strongly stimulated by the co-operation between research, extension and education (Bieleman, 2000). Nitrogen Pilot farms played an important role in disseminating knowledge amongst farmers, not only in the period of intensification, but also in the subsequent period when N losses had to be reduced (Frankena, 1960; Van Burg *et al.*, 1980; Oenema *et al*., 2001).

Environmental legislation in EU related to grassland use

The concern of the European Union with environmental matters started in 1973 with the adoption of the first Environmental Action Programme. But until the mid 1980's, the EU had no legal means to deal effectively with environmental problems. Convincing scientific evidence of large N losses from animal production systems to the wider environment and it deleterious ecological effects was published in the 1980's (e.g. Ryden, 1984, Van Breemen *et al.*, 1982, Buisman *et al.*, 1987). In response, governmental policies and measures have been developed, at national levels as well as at EU level (De Clercq *et al.*, 2001), concerning water and air quality. Currently, agriculture and especially the use of animal manure and fertilisers is affected by three categories of EU policies and measures (e.g., De Clercq *et al.*, 2001): (i) Agenda 2000 and the reform of the CAP, (ii) Water Framework Directive, and (iii) Air Quality Directive. These are further discussed below.

Agenda 2000

Agenda 2000 is an action program launched in 1999 by the EU to increase competitiveness, to enhance standards of food safety and quality, and to ensure a fair standard of living for the agricultural community. It addresses the reform of the CAP and the structural policy, including the uncoupling of production and income support. Within Agenda 2000 there are two regulations that specifically affect N and P use. Firstly, Regulation No 1259/99 establishes common rules for direct payments to farmers in return for agri-environmental commitments. Secondly, Regulation 1257/99 supports sustainable rural development to restore and enhance competitiveness. The focus of Agenda 2000 is on (i) less-favoured areas and areas with environmental restrictions, and (ii) on agricultural production methods designed to protect the environment and to maintain the countryside. Hence, farmers who apply good farming practices, decrease livestock density, conserve the landscape, and or conserve areas with high nature value, can be granted a compensatory allowance.

Water Framework Directive

The Water Framework Directive (Anonymous 2000e) is the most substantial piece of EU water legislation. It requires all inland and coastal waters to reach good ecological status by 2015. It will do this by establishing a river basin district structure within which demanding environmental objectives will be set, including ecological targets for surface waters. It addresses all compounds that affect the ecological status of surface waters, including N and P from agriculture. The Water Framework Directive also establishes a framework for the Integrated Program on Water Quality Management. It includes (i) water quality standards, (ii) emission limits and (iii) legislation and measures. It encompasses a large number of other directives. So far, most important for agriculture is the Nitrates Directive

(91/676/EC*)*, which has been agreed upon by all member states in 1991 and which must have been implemented by 2003 (Anonymous, 1991a).

The main objective of the Nitrates Directive is "to decrease water pollution caused or induced by nitrates from agricultural sources and prevent further such pollution". For this, all member states have to take various measures (i.e., designate vulnerable zones and establish action and monitoring programs and a code of good agricultural practices for these zones). Nitrate vulnerable zones must be designated on the basis of monitoring results which indicate that the groundwater and surface waters in these zones are or could be affected by nitrate pollution from agriculture. So far, Austria, Denmark, Finland, Germany, Luxembourg and The Netherlands have designated the whole territory as nitrate vulnerable zone, while other member states have only designated parts of the country as nitrate vulnerable zones. The difference in designation between member states is only partly related to the actual pollution with nitrate. Some member states designated the whole territory to keep uniform measures, to avoid unfair competition between different groups of farmers, and to raise environmental awareness among all farmers (De Clercq *et al*., 2001).

The action program must contain mandatory measures relating to (i) periods when application of animal manure and fertilisers is prohibited, (ii) capacity of and facilities for storage of animal manure, and (iii) limits to the amounts of animal manure and fertilisers applied to land. These measures must ensure that for each farm in vulnerable areas the amount of N applied via animal manure, including that deposited by grazing animals, shall not exceed 170 kg ha^{-1} yr^{-1}. Member states are obliged to monitor the nitrate concentrations of groundwater and surface waters, to assess the impact of the measures, and to report the results to the European Commission. So far, there is a wide variation between member states in the interpretation and implementation of action programs and codes of good agricultural practices (De Clercq *et al*., 2001).

The limit of 170 kg ha^{-1} yr^{-1} of N from animal manure on a farm basis has been questioned, as this limits livestock density per farm, and there is no scientific justification for one uniform limit for all agricultural land. A note in the annex of the Nitrates Directive provides a way out; member states may derogate from this limit and may apply more N via animal manure when justified on the basis of scientifically and practically sound data and arguments. A few countries applied for derogation (Denmark, Germany and The Netherlands). Points of discussion are the height (250, 230, 210 kg·ha^{-1}·$yr^{-1}$of N), and the criteria (e.g., surface area, land use, drainage, duration) for derogation. So far, only the requests for derogation of

Denmark and The Netherlands (250 kg·ha^{-1}·yr^{-1} of N) have been approved by the European Commission.

EU Air Quality Directive
The EU Air Quality Directive (1999/30/EC) sets limits to the emission of ammonia and nitrogen oxides, and other gases, mainly from industrial sources and traffic, into the atmosphere, so as to abate acidification, eutrophication, and ground-level ozone. The directive sets targets for emission reduction to be reached in 2010 relative to the reference year 1990. The emission reduction targets for ammonia range between 0 and 43% for individual member states. Mitigation measures for agriculture focus on the use of urea and ammonium-based N fertilisers, manure application, manure storage, animal housing, and an advisory code of good agricultural practice. The strict emission reduction targets necessitate livestock farmers in some member states to use low-protein animal feed and low-emission techniques for the storage, handling and application of animal manures. The Directive does not define specific measures for diary farming.

The increasing concentration of greenhouse gases in the atmosphere is also an international environmental concern. In Kyoto in 1997, governments of 77 countries agreed to reduce the emissions of six greenhouse gases, of which the gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have relevance to agriculture. Agricultural activities are responsible for up to 40% of the estimated global emission of 14 Mton of N_2O into the atmosphere (Prather *et al.*, 1995). The application of N via animal manure and N fertilisers to agricultural land is an important source of N_2O (Freibauer & Kaltschnitt, 2003; Olivier *et al.*, 2003). The EU Directive concerning gaseous emissions (Anonymous, 1999a) is in line with the Kyoto-goals.

1.2 Farm management

Investments in land and labour productivity have consequences for the long term as well as for the day-to-day activities of dairy farms. Increased fertiliser use, land reclamation, increased stocking rates, higher nutritional demands of the herd, economical constraints and the long term and short term decisions needed to be tuned to each other (e.g. Huirne, 1990; Kay & Edwards, 1994; Rougoor *et al.*, 1997). This tuning of inputs, demands, constraints and possibilities on a particular farm is the central item of farm management. Management is defined in many different ways, but always contains three central elements: (i) the need to establish goals or objectives, (ii) the use of resources in order to meet the goals, and (iii) the possibility to use resources in alternative ways (Kay & Edwards, 1994). In the interaction with the environment, four environments have to be distinguished affecting management decisions (Boehlje & Eidman, 1984*)*, i.e., (i) the institutional environment (e.g., infrastructure for inputs and outputs, government policy), (ii) the social environment (e.g., family and religion), (iii) the physical environment (soil, water, wheather, technology), and (iv) the economic environment (markets, prices, risks).

Management views and approaches

The credo "management by objectives" has been introduced by Drucker (1955). Because a farm is an enterprise, set up to realise an income for owner, farmer and labourers, the primary objective is economic and this has been the only goal for a long time. The need to reduce nutrient losses to the physical environment has become an important goal on farms from the 1980's onwards. The introduction of 'nutrient management', the management philosophy to improve nutrient efficiency and to achieve both economic and environmental objectives, reflects this change in objectives (Oenema & Pietrzak, 2002). Management is not only a technical process of allocating resources, the farmers' personal motives and style have to be considered too (Van Der Ploeg, 1994).

Within a farm, subsystems or compartments can be distinguished and these can be subject of special attention in research, extension and the farmers' management efforts (Van Der Ploeg, 1994). Rougoor *et al*. (1999a, 1999b) distinguished pasture use, animal feeding and herd as dominant foci in the management of dairy farms. The nutrient flow chart, which is an important tool in nutrient management (Schröder *et al*., 2003; Figure 1-3), distinguishes four compartments, namely soil, crop, livestock and animal manure. These compartments are linked by conversion factors. These factors are main items of interest in nutrient management.

Grassland management usually aims at efficient production of high-quality herbage with minimal inputs and with minimal losses to the environment. The transformation of harvested herbage to silage and the intake of fresh herbage by grazing livestock are sometimes also seen as part of grassland management (Ondersteijn *et al*., 2002a). The N content of fresh and conserved herbage affects animal N utilisation, and thereby the conversion of herbage energy and protein to animal energy and protein, and the production and composition of animal manure. In some views, grassland management should focus on the production of good quality manure with a low mineral N content (Van Bruchem *et al*., 1999; Verhoeven *et al*., 2003). The approach of looking at the level of subsystems is comparable to what is called “management by discipline” by Drucker (1955). The risk of focusing on sub-systems only is that optimising one sub-system does not automatically lead to optimisation at farm level.

Approaches “management by objectives” and “management by sub-systems/disciplines” are not necessary contradictorily. They can be combined very well. This is visualised by placing the approaches on different sides of the total “field” of management in Figure 1-4. In this thesis, the focus will be on the cross-section of both approaches, on nutrient and grassland management.

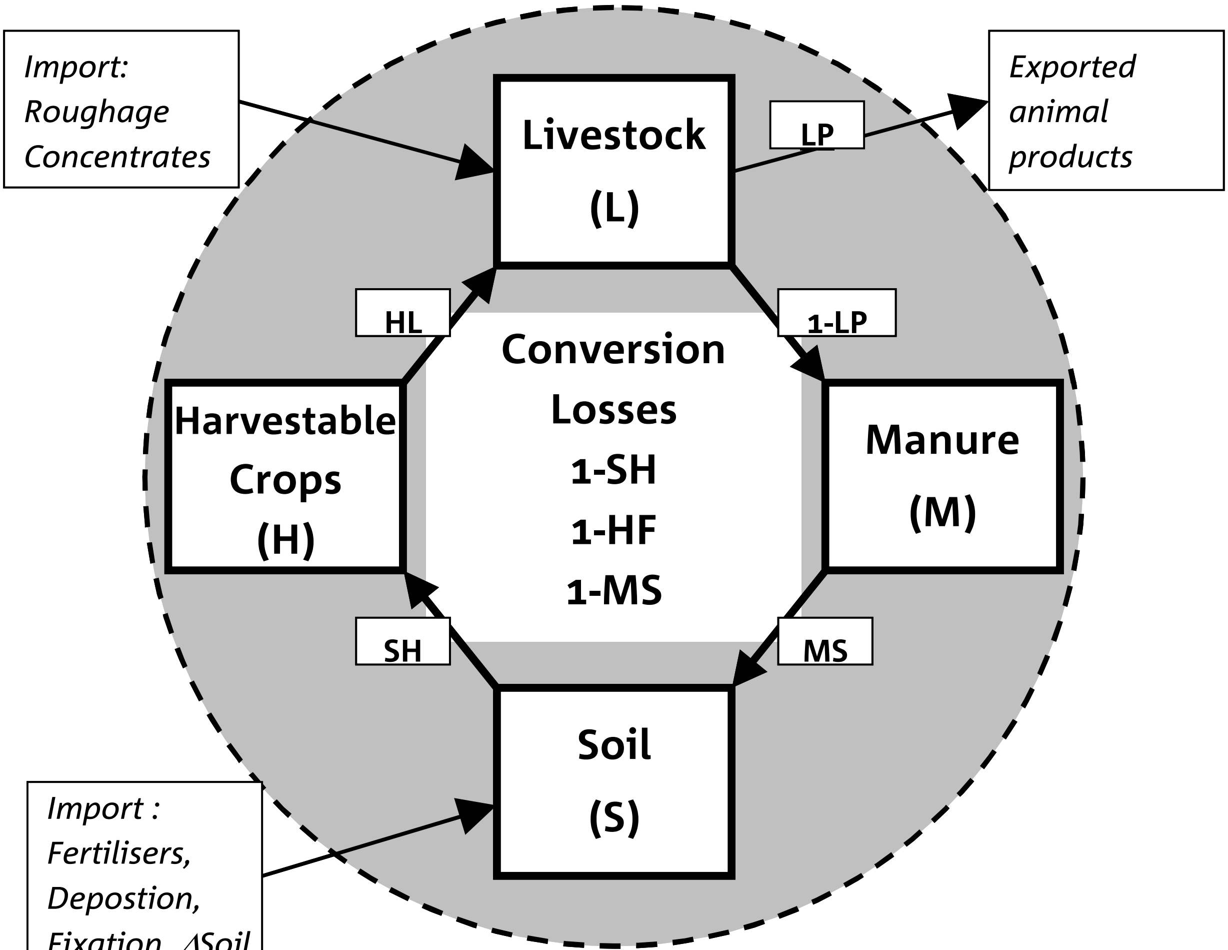

Figure 1-3. The simplified nutrient flow chart according to Schröder *et al*. (2003).

Strategic, tactical and operational management levels
To understand management decisions at different time and spatial scales, strategic, tactical and operational management levels have to be distinguished. These levels address long-term, intermediate-term and short-term decisions, respectively (De Koeijer *et al.*, 2003).

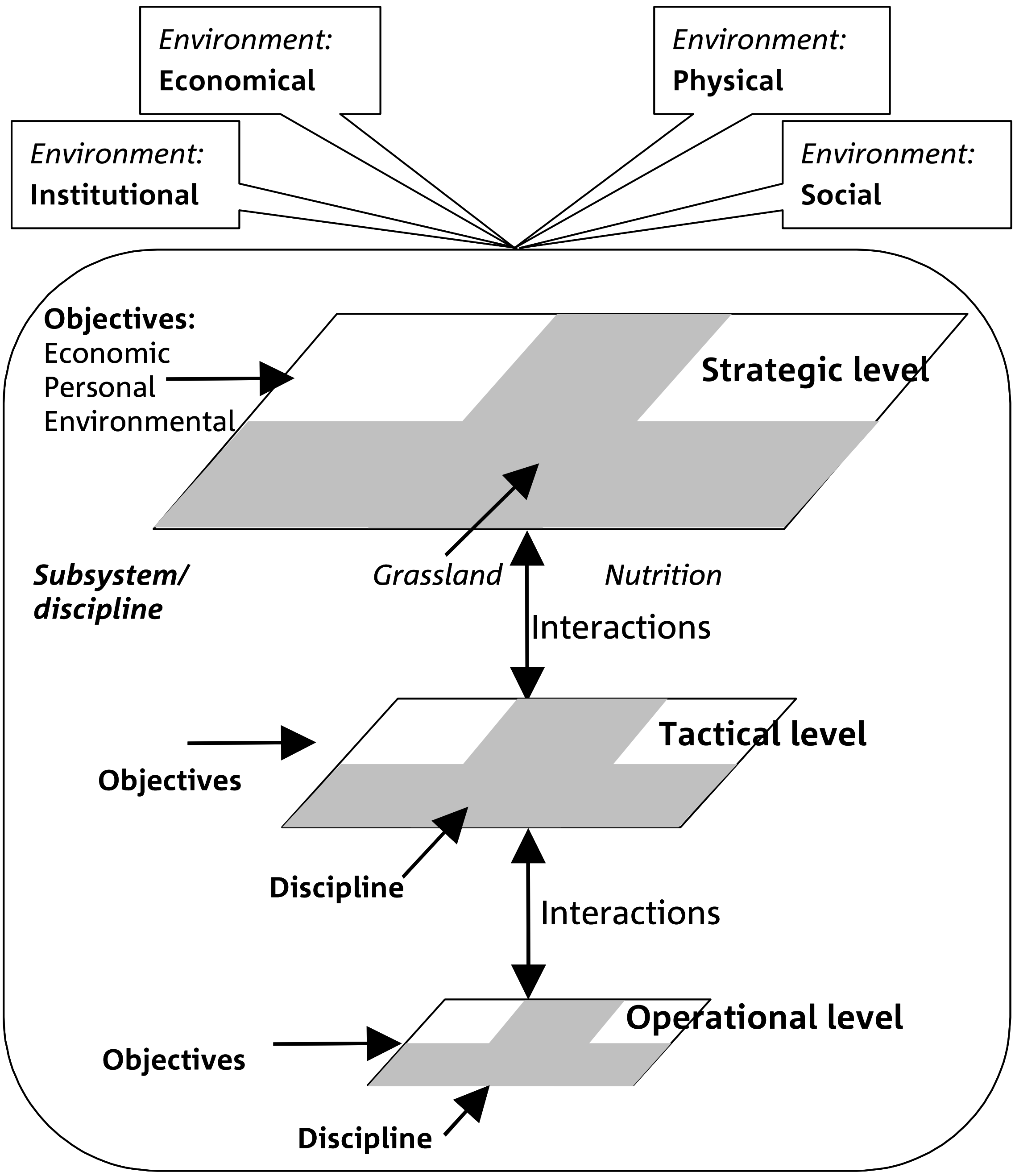

Figure 1-4. Scheme of farm management, with two approaches: objectives and sub-systems/disciplines and three levels: strategic, tactical and operational.

Strategic management deals with the structure and size of the farm, but in part also deals with the farms' institutional, social, economic and physical environments. Strategic management concerns decisions on the ratio between grassland and arable land, their spatial distribution, land reclamation and drainage, stocking density, housing system and farmers' skills. (Ondersteijn *et al.*, 2002a).
Tactical management focuses on annual fertiliser application levels, amount and composition of purchased concentrates, cropping and storage techniques, grazing system, the ratio dairy cows/young stock, the target levels for cutting and grazing, etc. (Ondersteijn *et al.*, 2002a). Its spatial scale is at farm level. Tactical decisions are influenced by the four environments and by decisions on strategic level, as discussed above.
The spatial emphasis of operational grassland management is at paddock level and is focussed on fertiliser and manure application per cut and decisions on the moment of cutting and grazing. The four environments and the strategic and tactical decisions define the room for manœuvre at the operational management level.

Interactions between management levels
Strategic decisions affect the room for manœuvre at tactical and operational management levels. For example, changes in production conditions through land reclamation and mechanisation affect the potential for grassland utilisation, because cutting frequency, DM yields per cut and harvesting periods change. Changes in area of permanent grassland, leys and fodder or arable crops set constraints on the possibilities for grazing. But consequences of decisions are not only "top-down", from strategic to operational. There is also a "bottom-up" process: the possibilities at operational and tactical management levels have influence on the window of opportunities at the strategic management level. For example, desired herbage quality in terms of energy and protein content sets limitations to the ratio between grassland and fodder crops and the choice of the fodder crops. Preference of a specific grazing system sets constraints to the minimum grassland area and the spatial distribution of parcels.
Evidently, there are relationships and possible interactions between the objectives formulated at strategic, tactical and operational management levels. Objectives for the strategic management level are defined for the long term and at farm or catchment scale, as for example for nitrate. These objectives have to be translated to daily (operational) activities and to the field scale. The question is than how?

And what are the effects of fertiliser application rates and harvested herbage in a single cut on water and air quality?
De Clercq *et al*. (2001) mentioned several indicators that are being used in the EU-countries to monitor and control nutrient application and surplusses and to meet the requirements of the EU-Directives. Some of the indicators fit with the demands of the EU Nitrates Directive, like nutrient and manure input at field level. Interestingly, all indicators are defined on strategic or tactical levels, with one year or one growing season as the smallest unit of time. As yet, there are no well-defined and tested indicators for the operational management level.

The management cycle

Management encompasses a set of cyclic and coherent activities, i.e. analysing – decision making – planning – execution – monitoring – evaluation – (improved decision) (Beegle & Lanyon, 1994; De Koeijer *et al*., 2003). The frequency of this cycle is low at strategic level and high at operational level. However, time investment in strategic decisions is often large and relatively detailed scenarios have to be developed before the final decision is taken. The high frequency of operational decisions and activities (sometimes daily) leave little time for monitoring, evaluation, analysis and planning. Complicating factors are more or less unpredictable temporal variations in weather and soil conditions.

The information requirement and data quality is very different at the various management levels. While working with averaged conditions for the strategic management level, decision making at the operational management level requires information about actual conditions and the insights of skilled craftsmen to cope with these conditions directly. Also data availability is very different between the two levels. At strategic and tactical management levels, data availability is much higher than on operational management level. Because decisions in operational grassland management are related to relatively small time steps and because herbage is an intermediate product when seen from the farm perspective, the relationship between decisions at operational management level and farm performance is usually far from clear. This makes the operational management level to be considered sometimes as a ‘forgotten management level’.

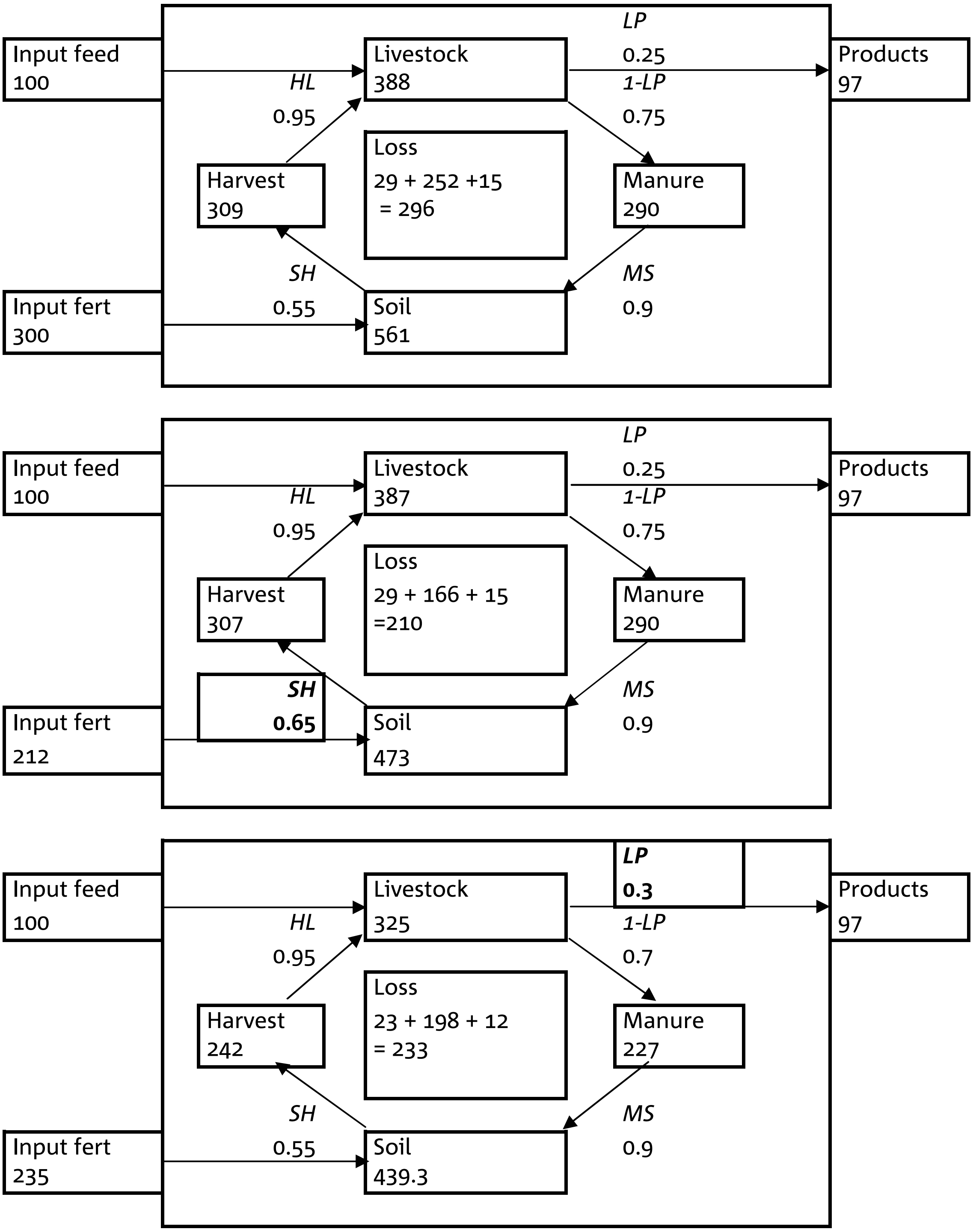

Figure 1-5. Calculated N flows in a dairy farm according to the simple model of Schröder *et al*. (2003), with a standard situation (upper scheme), with an improved conversion factor for Soil to Harvest (SH) of 0.65 (middle scheme) and with an improved conversion factor Livestock to Products (LP) of 0.3 (lower scheme). In the cases with improved conversion factors, the input of N via feed and the output via products is kept constant and the input via fertilisers is reduced.

The importance of grassland management

Calculations with the dairy farm model of Schröder *et al.* (2003) show that improvement of the conversion factors SH (soil to harvestable crop) and LP (from livestock to animal products) are very effective to increase N utilisation at farm level. For the dairy farm shown in Figure 1-5, a relative improvement of the two conversion factors LP and SH by 5 and 10%, lead to decreases in N inputs of 65 to 88 kg N ha^{-1} $year^{-1}$, respectively with the same output per hectare. Hence, relative small improvements in conversion factors have considerable effects on the size of the N flows in dairy farming systems.

The conversion of N from soil, manure and fertiliser to harvestable herbage is the domain of grassland management. The subsequent conversion of herbage to animal products is greatly affected by the quality of the herbage offered to the animals. Hence, grassland management also affects the conversion factor LP. Evidently, grassland management plays a dominant role in nutrient management of dairy farms.

Improving the conversion factors for N (and P) has received considerable attention by the research community as well as by farmers in practice. For commercial dairy farms in The Netherlands, Aarts *et al.* (2000b) estimated the conversion factor SH at 0.53 and stated that this factor could be improved to 0.77. The improvement should be realised through a combination of improved utilisation of slurry N, supplemental feeding, reduced grazing and reduced input of fertiliser N. Experimental dairy farm “De Marke” realised an average value of 0.65 for the SH conversion factor during the period 1993-1996.

The conversion of N in animal feed to N in valuable animal products (LP) ranges between 0.15 and 0.25 on commercial dairy farms. This huge variation is related to the genetic potential of the herd, the herd replacement rate, animal nutrition, and grazing management. Van Vuuren & Meijs (1987) stated that the maximum conversion efficiency of animal feed protein into milk protein is about 0.45. The maximum efficiency can be realised by a high-yielding herd through optimisation of the amino acid composition and hence the protein content of the animal ration, in which the N content of fresh herbage and silage plays an important role.

The challenges of operational grassland management

Improving the operational grassland management is complicated because herbage is an intermediate product at farm level and there is often little factual information on herbage yield and quality. There is a theoretical relationship between good grassland management and a high level of production and

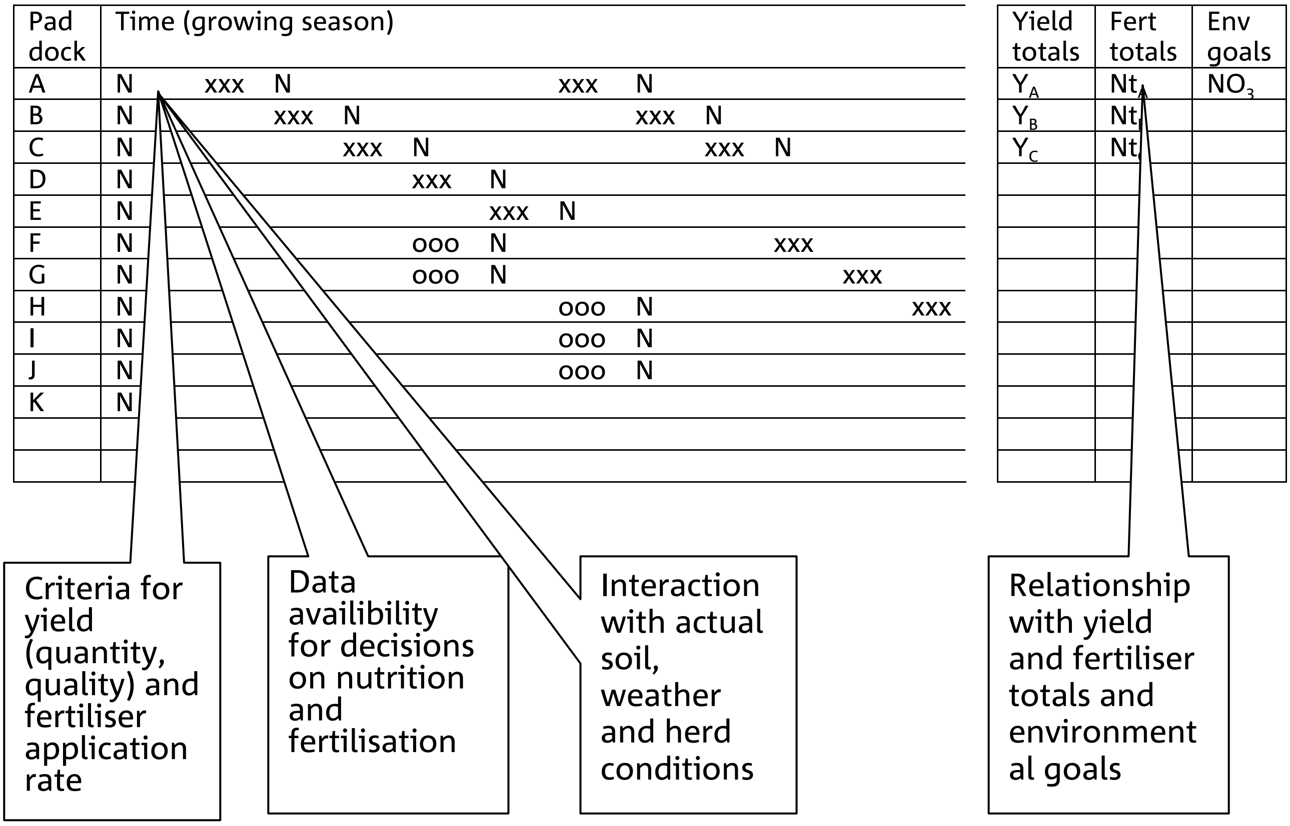

Figure 1-6. Challenges in the decision-action-evaluation cycle in operational grassland management for paddocks A-K. xxx means three days grazing, N is N application, ooo is a three day cutting and wilting period. Only a limited part of the complete growing season is shown.

profitability (e.g. Rougoor, 1999a, 1999b), but this relationship is not very clear and not easy to notice in practice. Farm outputs in the form of meat, milk and arable products are always measured and measurement techniques are very exact. This information is usually sufficient for assessing the effectiveness of the management at strategic (farm) management level. However, this information can not be used for assessing the effectiveness of the management at operational management level

At operational management level, the frequency of the management cycle 'analysis – decision – planning – execution – monitoring – evaluation – (improved decision)' is high and there are many gaps, partly due to incomplete information (Figure 1-6). Major limitations concern:

- Lack of accurate data about herbage yield and quality. In theory, sward height measurements can quickly provide information on herbage yield, but the accuracy is low (Gabriels & Van Den Berg, 1993). Herbage N contents can be measured, but accurate sampling and analysis are time consuming activities and the results become available only after three or more days.

- Lack of clear and specific objectives for the operational management level. The targets at strategic and tactical management levels have not been translated in clear and specific objectives at operational management level. For example, there are no clear criteria for the yield in single cuts in terms of herbage quantity and quality and for decreasing nitrate leaching, based on goals and targets at strategic and tactical levels. What can a farmer do at the operational management level to reduce nitrate leaching? This question can be answered of course in a general way, but it would be helpful to farmers providing clear tools for defining exact fertiliser application rates, N contents of animal rations, grazing time, etc. Likewise, the opposite direction, from operational to tactical and strategic management levels is not elaborated neither. For example, when a single cut is harvested, it is unclear whether or not it contributes sufficiently to achieving the objectives at strategic management level.
- The strong impact of unpredictable incidents, i.e. changing weather conditions and pest and diseases, makes the operational management level complicated like “managing the unmanageable”.

The challenge for operational grassland management is to improve the availability of factual information and to define clear objectives and criteria. I expect that a combination of accurate data, clear objectives and decision support systems for the operational management level, has potential for improving nutrient efficiency on dairy farms. Promising results in fast and accurate measurements of sward quality have been shown by Schut *et al*. (2005). Van Duinkerken *et al*. (2003) developed a prototype in which measurements and models are combined to deal with the large variations that occur in operational nutrition management.

1.3 This thesis

This thesis aims at contributing to improved decision making at the operational management level, by improving the understanding of the relationships between strategic, tactical and operational management and by deriving and underpinning specific objectives and criteria.
Improving the decision making at operational grassland management requires improved understanding of the relationships between N application rates, herbage yield and quality in single cuts and their effect on N use efficiency. This

knowledge is essential for deriving criteria for environmentally-sound fertiliser recommendations, and for the identification of tools for improved operational grassland management.

The specific objectives of this thesis are therefore:
1. to increase the understanding of the relationships between N application rates, herbage yield and quality in single cuts and their effect on N use efficiency;
2. to identify possible objectives and tools for operational grassland management;
3. to increase the understanding of the interaction between operational, tactical and strategic management.

To be able to achieve these objectives, I analysed and reviewed data from existing multi-site and many-years' field experiments using various statistical models, analysed the operational and tactical grassland management of experimental dairy farm "De Marke" using a descriptive technique, and developed and tested two simple simulation models for the analysis of the effects of grassland management on nitrate leaching and nitrous oxide (N_2O) emissions and soil carbon sequestration. The multi-site and many-years field experiments allowed analysing the effects of weather and soil conditions as well.

This study focuses on N fertiliser as a tool in grassland management, but in practice the N from applied fertiliser and N from applied animal manure can be exchanged to some extent. In fact, a large part of the N applied to current grassland systems is from animal manure. For convenience's sake, I chose to use N fertiliser to increase the understanding of N applications in operational and tactical grassland management.

Outline

The chapters 2-4 focus on operational grassland management (Figure 1-7). Chapters 2 and 3 deal with the relationships between N application rates, herbage yield and quality in single cuts and their effect on N use efficiency, and provide the underpinning for decisions on N application rates per cut. Chapter 4 examines the use of the grassland calendar as a planning tool for operational grassland management at the experimental dairy farm "De Marke".
Chapter 5 examines the optimisation of grassland management for minimising nitrate leaching, by using a simple model.

Chapter 6 analyses the impact of changes in grassland management at operational, tactical and strategic level on Apparent Nitrogen Recovery (ANR).

Chapter 7 focuses on decisions at strategic level and discusses the effects of reseeding and of rotations of grassland with arable crops on soil carbon sequestration and emissions of nitrous oxide to the atmosphere.

Finally, chapter 8 summarises the main findings of the thesis, discusses the scientific and practical implications of the findings and provides some suggestions for further research.

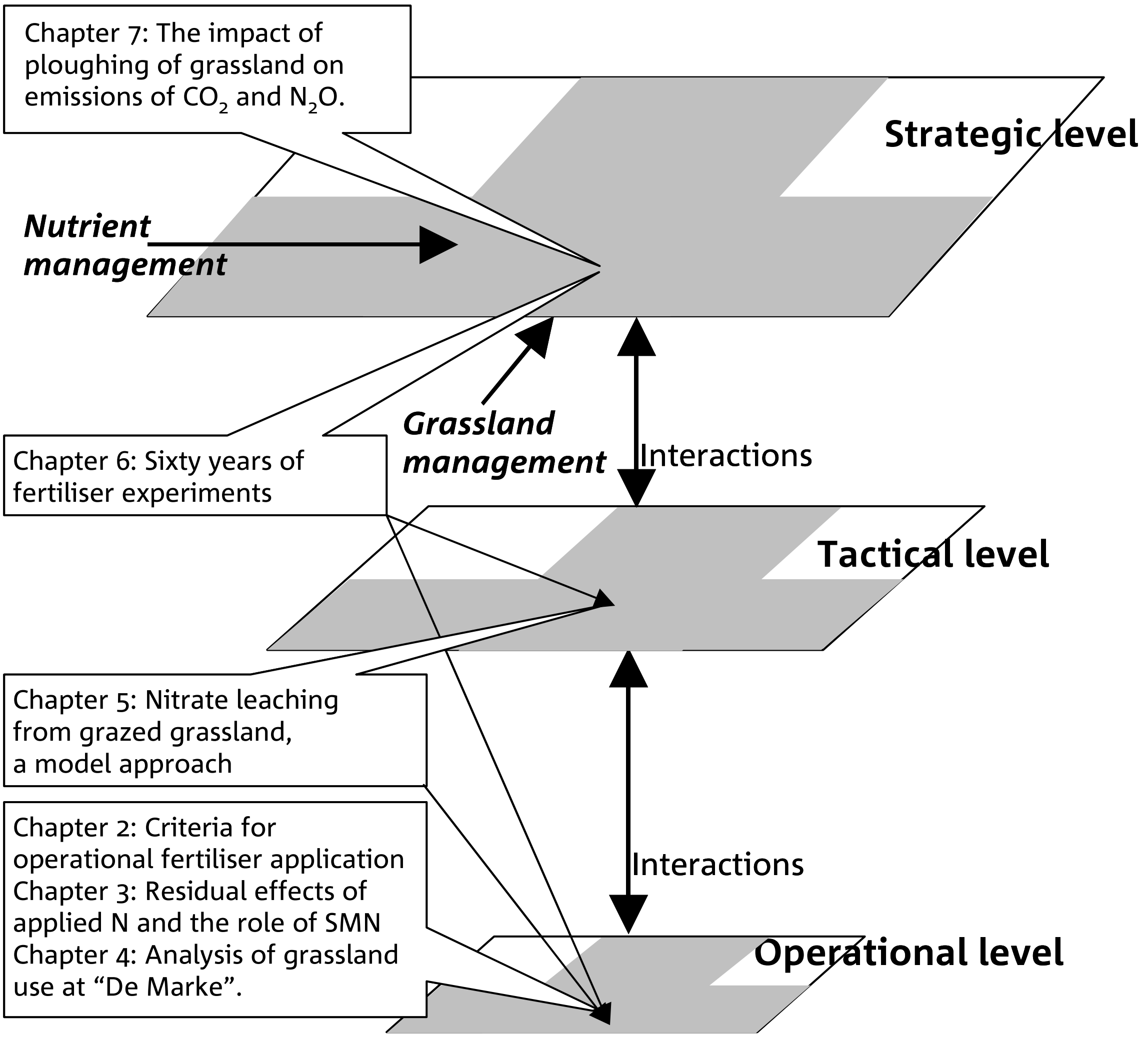

Figure 1-7. The position of the papers of this thesis in the three levels of nutrient and grassland management.

Chapter 2

Operational nitrogen fertiliser management in dairy farming systems: identification of criteria and derivation of fertiliser application rates

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2 Operational nitrogen fertiliser management in dairy farming systems: identification of criteria and derivation of fertiliser application rates

Abstract
Fertiliser nitrogen (N) management is a decisive factor in grass-based, intensive dairy farming, as it strongly influences economic and environmental performance. But little attention has been paid to grounding guidance on N fertiliser management at an operational level to meet these criteria and performance. Essential criteria in operational N fertiliser management were identified as target dry matter yield of herbage (DM), growth period per cut, herbage N concentration (N use efficiency, NUE), amount of unrecovered N and marginal N response. Statistical relationships between fertiliser N application rates per cut and these criteria were derived from field experiments. These relationships were then used to explore the effects of the criteria on optimum fertiliser-N applications. Optimum fertiliser N rates depended strongly on target levels for NUE, amounts of unrecovered N, growth period and DM yield of herbage. Calculations show that target DM yield of herbage and growth period per cut are essential in the calculation of the effect of applied N on marginal N response, NUE and amounts of unrecovered N. The derived relationships can be used to explore the effects of changes in target levels of the criteria on optimum fertiliser-N applications. The study showed that operational fertiliser-N management set constraints to the decisions made at strategic and tactical management levels and vice versa.

2.1 Introduction

Management is often called the ‘fourth production factor’ in agriculture, next to land, labour and capital. It is usually defined as the process of allocating and utilising resources to achieve specific goals through proper analysis, decision-making, planning, implementation, monitoring and control. The importance and complexity of management has increased greatly during the last decades due the changing decision environment.

The management of nutrients has become particularly important for grass-based dairy farming as the nutrient use efficiency strongly influences the economic and environmental performance of this enterprise (Aarts *et al.*, 1992; Jarvis, 1996; Oenema & Pietrzak, 2002). Various integrated nutrient management strategies have been developed to improve nutrient use efficiency and to decrease nutrient losses in a cost-efficient way at the tactical management level, especially for intensively managed dairy farms in Western Europe (e.g. Jarvis, 1996; Sharpley *et al.*, 2000; Ondersteijn *et al.*, 2002b). Tactical management focuses on a complete growing season and includes changes in animal nutrition, animal housing, manure storage and manure application to land, grass and maize production and fertiliser use.

In contrast, operational management focuses on day-to-day activities, with dry matter (DM) yield per cut and growth period as decisive factors. The operational management decisions have to be made within the framework of tactical management decisions. There has been little focus on the decision making at operational level in nutrient management, probably because of the large number of farm-, site-, crop- and climate-specific variables. This holds also for the use of nitrogen (N) fertiliser and, as a consequence, there are few operational guidelines for the application of N fertiliser that take into account both agronomic and environmental targets.

The use of N fertiliser is an important factor in intensive grass-based dairy farming, since it affects DM yield and the crude protein concentration of the herbage, and thereby the amount and crude protein concentration of supplementary feeding, and the size of the N losses through ammonia volatilisation, nitrate leaching, nitrous oxide emission and denitrification (Jarvis, 1996; Whitehead, 2000).

Recommendations for application rates of N fertiliser have been defined at a tactical management level, often as a function of soil type, grassland type and climate (Morrison, 1980; Vellinga & André, 1999). Until about 1990, the criterion for optimum application rates of N fertiliser was merely economic, for example, a marginal N response of 7.5 kg DM per kg N (Unwin & Vellinga, 1994). However, large N losses associated with high application rates of N fertiliser caused a shift in focus from merely an economical goal to a combination of economic and environmental goals and thus constraints on the use of N fertiliser (Aarts *et al.,* 1992, Jarvis,1996). The targets of the European Commission's Nitrates Directive (Anonymous, 1991a), the Dutch mineral accounting system MINAS (Van Den Brandt & Smit, 1997), as well as calculations on nitrate leaching (Scholefield *et al.*, 1991; Vertès *et al.*, 1997; Vellinga *et al.*, 2001), are related to annual amounts of applied and unrecovered N (and phosphorus) at a tactical management level. These targets have to be translated subsequently into day-to-day operational management, as stated by Duru & Hubert (2003). However, there are currently few operational guidelines available (Scholefield & Titchen, 1995; Kowalenko & Bittman, 2000; Di & Cameron, 2002)

It is argued that operational N fertiliser management is strongly related to targets for DM yield of herbage , growth period, herbage N concentration, and amounts of unrecovered N from applied fertiliser. Herbage N concentration or N use efficiency (NUE) is important for optimising ruminant livestock nutrition (Valk, 2003), as herbage N concentration greatly affects total N excretion by the animal and the potential for N losses from manure (Delaby *et al.*, 1997; Astigarraga *et al.*, 2002). In this paper the potential to use target levels for DM yield and growth period per cut, NUE and the amount of unrecovered N as criteria for operational N fertiliser management 'per cut' is explored and a comparison is made with purely economic criteria. Existing data from field experiments and the three-quadrant analysis procedure are used to derive statistical relationships per cut between inputs of N fertiliser, DM yield and growth period per cut, N uptake, NUE and amounts of unrecovered N. Finally, the potential of these relationships to develop guidelines for operational N fertiliser management is explored.

2.2 Conceptual model

Three-quadrant analysis

The three-quadrant analysis was originally developed to analyse the interactions between N-application rate and N utilisation and N recovery on an annual basis (De Wit, 1953; 1992; Van Keulen, 1982). It provides estimates of the apparent N fertiliser recovery in the herbage (ANR), the physiological NUE and the agronomic N use efficiency (ANE). In operational grassland management, growth period per cut is an important criterion. Changes in the relationships between N-application rate, N uptake by herbage and DM yield of herbage with growth period can be analysed by modifying the original three-quadrant figure and replace N-application rate on the axes by growth period per cut (Frankena & De Wit, 1958). With this modified approach (see Figure 2-1), in the lower right quadrant it is shown that total N uptake by herbage increases with increasing N-application rates and with growth period. The relationship between DM yield of herbage and growth period is shown in the upper left quadrant. The differences in DM yield of herbage between the different N application rates increase with time, indicating that the DM yield response increases with time. Finally, in the upper right quadrant, the NUE, the ratio between DM yield of herbage and N uptake by herbage (kg DM (kg N)$^{-1}$) is shown. When N uptake by herbage tends to level off with time (the lower right quadrant), DM yield of herbage still increases almost linearly (upper left quadrant) and the NUE increases. The dotted lines

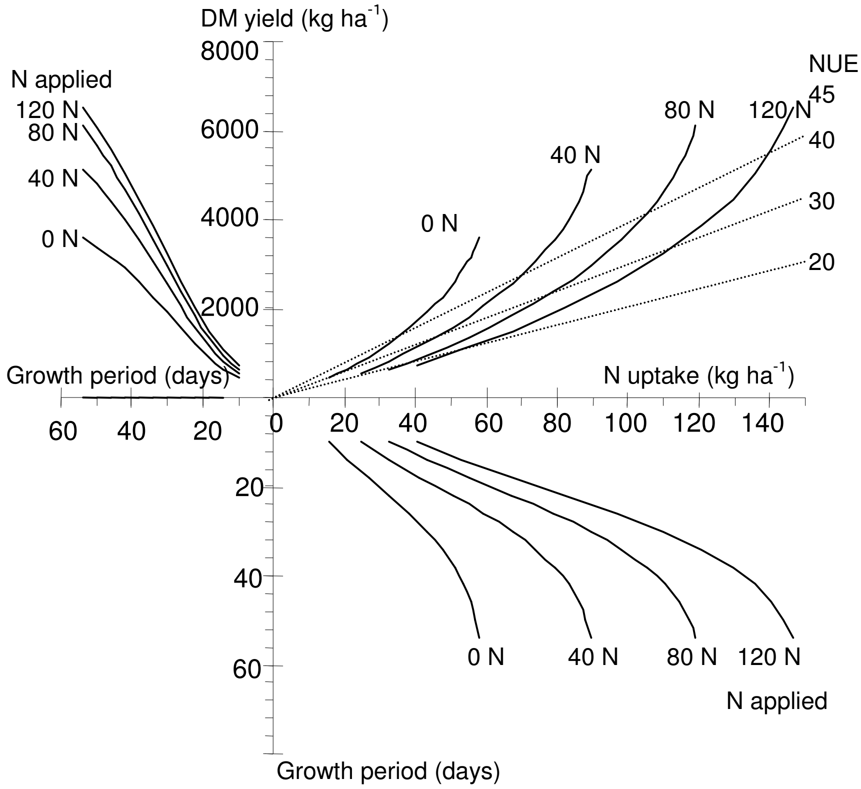

Figure 2-1. The effect of growth period on N uptake, DM yield of herbage and nitrogen use efficiency (NUE) in the second cut, starting on 1 May, at 4 N fertiliser application rates (0, 40, 80, 120 kg ha^{-1}). Output is based on calculations from the N uptake and NUE models.

represent the situations where the ratio between DM yield of herbage and N uptake by herbage is 20, 30 and 40 (kg DM (kg N)$^{-1}$), respectively.
For planning of grazing and harvesting activities, it is important to know the number of days required to attain a certain target DM yield of herbage. Therefore, the three-quadrant figure described in Figure 2-1 is of value in the analysis of operational grassland management.

Criteria: growth period and DM yield of herbage
The growth period 'per cut' influences herbage DM yield, herbage digestibility and N concentration of herbage and subsequent sward quality and regrowth. The growth period should be short enough to avoid a decrease in herbage digestibility (Van Vuuren *et al.*, 1991; Valk *et al.*, 2000) and the presence of dead leaves (Lemaire, 1988), factors that lead to a reduction in voluntary intake of herbage. Herbage digestibility is only to a small extent affected by the rate of N fertiliser application (Valk *et al.*, 2000), indicating that herbage digestibility is not

a suitable criterion for N fertiliser recommendations. A high DM yield of herbage per cut has a negative effect on subsequent sward quality and regrowth (De Wit, 1987a). This means that, even if satisfactory ANR and NUE values can be realised at high N-application rates by a long growth period, negative side-effects make the combination of high N-application rate and long growth period undesirable. Hence, growth period and DM yield of herbage play an important role in operational grassland management and therefore are important criteria in operational N fertiliser management. In this study, target DM yields of herbage for grazing and cutting are set at 2000 and 3000 kg DM ha^{-1}, respectively (Anonymous, 1998b). Growth periods per cut were set 20 and 30 days (Vellinga & Hilhorst, 2001). When target DM yield of herbage is used as criterion, growth period is the result and vice-versa.

Criterion: nitrogen use efficiency

Herbage N concentration influences the crude protein concentration of the ration and N excretion via urine and N losses, irrespective of the level of milk production (Van Vuuren & Meijs 1987; Astigarraga *et al.*, 2002; Sannes *et al.*, 2002). To decrease the crude protein concentration in the ration on grass-based dairy farms, decisions have to be made about herbage N concentration (Valk, 2003) and/or about the protein concentration of purchased roughages and/or concentrates (Van Vuuren *et al.*, 1993; Sannes *et al.*, 2002).

Decreasing herbage N concentration is a useful tactic, especially on grass-based dairy farms with relatively low stocking rates, when low crude protein roughages, such as maize, are not available. Peyraud & Astigarraga (1998) mentioned a critical (minimum) crude protein concentration of 140 g kg^{-1} DM (equivalent to an N concentration of 22.4 g kg^{-1} DM, and an NUE-value of 44.6 kg DM kg^{-1} N) for voluntary herbage intake. Van Vuuren (1993) mentioned critical crude protein concentrations as being in the range of 135 to 150 g kg^{-1} DM (equivalent to an N concentration of 21.6-24 g kg^{-1} DM and an NUE value of 46.3-41.6 kg DM kg^{-1} N) for an optimal efficiency of milk protein synthesis. Combining fresh grass or grass silage with maize silage is a good strategy to adjust the total crude protein concentration of the ration and, thereby, the N utilisation and N excretion via dung and urine by ruminant livestock. When using large proportions of maize silage in the ration, the crude protein concentration of the grass herbage should not be too low. Assuming a ration of 0.5 fresh grass and 0.5 maize silage, and a target crude protein concentration in the total ration of 150 g kg^{-1} DM, herbage N concentration should be 34 g kg^{-1} DM (equivalent to an NUE level of 29.4 kg DM

kg^{-1} N), when the N concentration of the maize silage is 13.3 g kg^{-1} DM (Anonymous, 1998b).
Hence, decisions at strategic management level about grass herbage/fodder crop ratio and the target crude protein concentration in the ration determine the optimal NUE level in the harvested herbage, which may range from 46.3 to 29.4 kg DM kg^{-1} N. In this study, target NUE levels ranged from 30 to 45 kg DM kg^{-1} N.

Criterion: amounts of unrecovered N

Applied N in fertiliser is not fully taken up by the grass. The amount not taken up may be retained in the soil or lost to the environment. The ANR of applied N in fertiliser in the first cut of the year ranges between about 0.30 and 0.70 (Prins *et al.*, 1980), indicating that 0.30 to 0.70 of the N fertiliser applied is either retained in the soil-plant system or lost to the wider environment. Usually, a significant proportion of the unused N fertiliser in first, second and third cut is recovered in subsequent cuts. For example, Hunt *et al.* (1981) found an additional N recovery in the second and third cuts of 0.15-0.20 of the N application at the start of the growing season. However, the amount of unrecovered N in late season cuts is likely to be lost, as uptake is very limited in late autumn and winter in temperate areas. Soil Mineral Nitrogen (SMN) at the end of the growing season has been suggested as a good indicator for N losses via leaching and denitrification (Barraclough *et al.*, 1992; Cuttle & Bourne, 1993), although amount of unrecovered N fertiliser is to a limited extent found as SMN (Vellinga & Hilhorst, 2001). Another complicating factor is grazing. About 0.80 of the herbage N is returned via faeces and urine (Lantinga *et al.*, 1987). The latter contributes significantly to nitrate leaching and reduces the importance of the amount of unrecovered N as an environmental criterion for the application rate of N fertiliser. So, although the criterion of the amount of unrecovered N has been quantified explicitly in a farming system approach and on an annual basis in the Dutch legislation system of MINAS, a clear quantification on operational basis and at field level cannot be made. At the end of the growing season, it might only be an indicator of N losses. In this study, the amount of unrecovered N as a criterion for operational grassland management is chosen instead of SMN, as the amount of unrecovered N is easier to estimate once herbage DM yield and N concentration of herbage are known. Quite arbitrarily, target levels of the amount of unrecovered N in the range of 15 to 30 kg ha^{-1} are used.

Table 2-1. Location, soil properties, botanical composition and experimental lay-out of the growth series experiments, used in parameterising the model.

	Experiments					
Site	Bru-chem	Den Ham	Lutten-berg	Zalt-bommel	Nieuw Leusen	Lely-stad
Year	1972	1972	1973	1973	1974	1975
Soil type	Clay	Sand	Sand	Clay	Sand	Clay
Number of growth series	4	4	6	6	6	6
Maximum N fertiliser application rate*	160	160	120	120	120	120
DM-yield of herbage pretreatment cuts (kg ha^{-1})	2000-3500	2000-3500	2000	2000	2000	2000
Clay content of soil (<16 μm) (%)	78	7	8	42	5	35
Sand content of soil (> 50 μm) (%)	N/A	86	87	53	91	51
Organic matter of soil (%)	14.8	6.7	5.5	3.1	3.6	6.1
Cover percentage (%)						
Perennial ryegrass	N/A	62	90	62	76	98
Timothy	N/A	3	1	37	4	2
Italian ryegrass	N/A	0	0	0	16	0
Tall fescue	N/A	17	0	0	0	0
White clover	N/A	0	0	1	0	0
Additional fertiliser						
P_2O_5 at first cut (kg ha^{-1})	120	120	120	120	120	120
P_2O_5 at each of later cuts (kg ha^{-1})	0	0	0	0	30	50
K_2O at first cut (kg ha^{-1})	140	140	140	140	140	140
K_2O at each of later cuts (kg ha^{-1})	80	80	50	50	50	50

Each experimental site received 80 kg N ha^{-1} per cut prior to the start of the experiment.
Each experiment had six harvesting dates.
N/A, not available
*, N fertiliser application rates were 0, 40, 80, 120, and 160 kg ha^{-1}

2.3 *Material and methods*

Existing data from growth series experiments are used to derive statistical relationships between application rate of N fertiliser, growth period, DM yield of herbage, herbage N concentration and the amount of unrecovered N per cut. A growth series experiment concerns the combination of a number of N-application rates and harvesting times per cut. DM yield of herbage and herbage N concentration are measured for each combination of N-application rate and harvesting date. Data from six experiments with four to six growth series each (Table 2-1) are used. Since both N-application rate and growth period affect the DM yield of herbage of the target and subsequent cuts, plots can only be used once in a growing season, and each growth series must be set up on fresh plots with similar pre-treatment. Detailed information on the experiments can be found in Wieling & De Wit (1987).

Statistical analysis

Herbage N uptake (kg ha^{-1}) was related to N from fertiliser and soil (kg ha^{-1}) and to the number of growing days according to a logistic (Gompertz) curve, using non-linear regression analysis:

$$N_{uptake} = N_{effective} / (1 + \exp(-a * (GD-d)), \quad \textbf{(1)}$$

in which:

$N_{effective}$ = N from soil and fertiliser, GD = growing days within a cut, a = shape parameter, defining the phase of almost linear growth, and d = inflexion point of the logistic curve, where uptake rate starts to decrease.

NUE (kg DM kg^{-1} N) was related to the number of growing days according to a quadratic function after logarithmic transformation:

$$Ln(NUE) = b_0 + b_1 * GD + b_2 * GD^2, \quad \textbf{(2)}$$

in which:

GD = growing days within a cut (d), and b_0, b_1, b_2 = regression coefficients (-)

DM yield of herbage (kg ha^{-1}) is calculated from N uptake and NUE:

$$\text{DM yield of herbage} = \text{N uptake} * \text{NUE (kg ha}^{-1}) \quad \textbf{(3)}$$

Apparent Nitrogen Recovery (ANR) is defined as the proportion of applied fertiliser N taken up by the herbage per cut relative to the N uptake of non-fertiliser herbage:

$$ANR_{Ni} = (Nuptake_{Ni}-Nuptake_{No}) / (N_i-N_o) \quad \textbf{(4)}$$

The amount of unrecovered N fertiliser (kg ha^{-1}), not taken up by the grass is:

$$\text{Unrecovered N} = (1-ANR_{Ni}) * N_i \quad \textbf{(5)}$$

The statistical analysis and the derivation of the statistical models, parameters and coefficients are described in detail in the Annex. The statistical models were validated using independent data from Prins & Van Burg (1979) and Prins *et al.* (1981).

Table 2-2. The calculated nitrogen use efficiency (NUE), the amount of unrecovered N and additional DM yield of herbage in the second and sixth cut after 20 and 40 days growth period with N fertiliser application rates of 0, 40, 80 and 120 kg N ha^{-1}. Calculations are from the N uptake and NUE models.

	Growth period (days)	Second cut N fertiliser applied (kg ha^{-1}) 0	40	80	120	Sixth cut N fertiliser applied (kg ha^{-1}) 0	40	80	120
NUE (kg kg^{-1})	20	35	30	26	23	28	24	21	20
	40	53	47	41	36	34	60	26	23
Amount of	20		24	49	75		30	62	96
Unrecovered N (kg ha^{-1})	40		11	24	43		22	48	77
Additional DM yield of	20		331	219	150		150	65	0
herbage (kg 40kg^{-1} N)	40		1030	641	324		390	155	0

Table 2-3. Growth period, DM yield of herbage, N uptake, the apparent nitrogen recovery (ANR) and the nitrogen use efficiency (NUE) of cuts from 1 May until 1 September, with a N fertiliser application rate of 80 kg ha^{-1}. In the left columns a fixed growth period of 30 days is used and in the right columns, a fixed target DM yield of herbage of 2000 kg ha^{-1} is used. Calculations are from the N uptake and NUE models.

	Date					**Date**				
	1 May	1 June	1 July	1 Aug	1 Sep	1 May	1 June	1 July	1 Aug	1 Sep
Growth period (days)	*30*	*30*	*30*	*30*	*30*	24	26	29	32	36
DM yield of herbage (kg ha^{-1})	2981	2564	2177	1822	1455	*1980*	*2059*	*1957*	*1982*	*1993*
N uptake (kg ha^{-1})	90	76	68	64	61	70	67	64	67	75
ANR	0.58	0.47	0.41	0.37	0.34	0.45	0.41	0.39	0.39	0.41
NUE (kg kg^{-1})	33	34	32	29	24	28	31	31	30	27

2.4 Results

Relationships between applied N fertiliser, N uptake by herbage, DM yield of herbage, apparent N recovery, N use efficency and growing days per cut

Relationships between applied N fertiliser, N uptake by herbage, DM yield of herbage, ANR, NUE and GD are shown for the second cut in Figure 2-1. An increasing N fertiliser application rate leads to decreasing NUE values and response in DM yield of herbage, and to increasing amounts of unrecovered N. Seasonal effects go in the same direction. Later cuts have relatively low NUE values and responses in DM yield of herbage, and relatively high amounts of unrecovered N (Table 2-2). Increasing growth period works in the opposite direction: decreasing amounts of unrecovered N, and increasing NUE values and response in DM yield of herbage. This indicates that growth period per cut is an essential factor in managing NUE, amounts of unrecovered N and responses in DM yield of herbage.

When a fixed growth period of 30 days is used, seasonal effects are strong: both ANR and NUE values decrease towards the end of the growing season (Table 2-3). In contrast, when a fixed DM yield of herbage of about 2000 kg ha^{-1} is chosen, the seasonal effects are much smaller: both ANR and NUE values remain almost constant or decrease only slightly. Hence, seasonal effects are strongly related to an important management decision in grassland use: fixed growth period versus fixed DM yield of herbage.

Calculated N applications per cut

Calculated fertiliser N applications per cut as a function of NUE (30, 35, 40 and 45 kg kg^{-1}), amounts of unrecovered N (15 and 30 kg ha^{-1}), DM yield of herbage (2000 and 3000 kg ha^{-1}) and growth period per cut (20 and 30 days) are shown in Figure 2-2. N application rates vary greatly, depending on the criterion used and the month of the year. Application rates of N fertiliser are relatively high in June and July, and when NUE is low, DM yield of herbage is large and growth period is long. Relatively small changes in NUE greatly affect N application rate, suggesting that NUE is a sensitive criterion. Increasing target DM yield of herbage by 1000 kg ha^{-1} increases application rates by 30 to 50 kg ha^{-1}. Increasing target growth period by 10 days also increases the application rates by 30 to 50 kg ha^{-1}. Increasing the amount of unrecovered N by 15 kg ha^{-1} increases the application rates by 20 to 30 kg ha^{-1}. Application rates based on a fixed DM yield of herbage are slightly lower at the beginning and end of the growing season than in the mid-summer period. In contrast, application rates based on a fixed growth period of 30 days are much lower at the end of the growing season compare to the start and mid-summer growing periods. Hence, seasonal effects on fertiliser applications are much larger with a fixed growth period compared to a fixed DM yield of herbage.

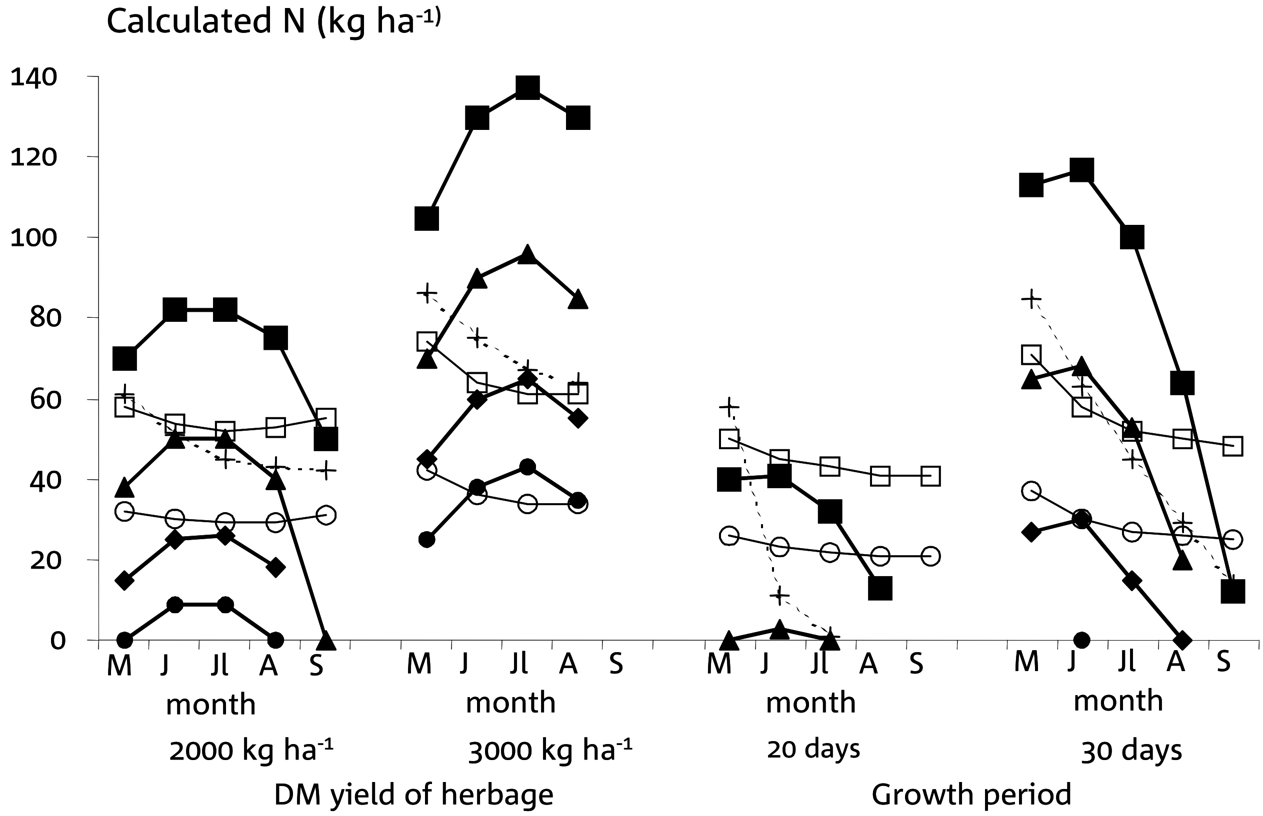

Figure 2-2. The calculated optimal N fertiliser rates (kg ha^{-1}) in May (M), June (J), July (Jl), August (A) and September (S) for two target DM yields of herbage (2000 and 3000 kg ha^{-1}) and two target growth periods (20 and 30 days), using a marginal N response of 7.5 kg kg^{-1} (+, dotted lines), a nitrogen use efficiency of 30 (■), 35(▲), 40(◆) and 45(●) kg kg^{-1} (bold solid lines) and amounts of unrecovered N of 15(○) and 30(□) kg ha^{-1} (normal solid lines).

Calculated growth periods as functions of month of the year, DM yield of herbage, NUE and amount of unrecovered N are shown in Figure 2-3. Growth period exponentially increases with month of the year. Effects of changes in NUE and amount of unrecovered N on growth period are relatively small, but increase as the growing season progresses. This means that target DM yields of herbage cannot be realised in the second half of the growing season, especially when target NUE is high and amounts of unrecovered N are low.

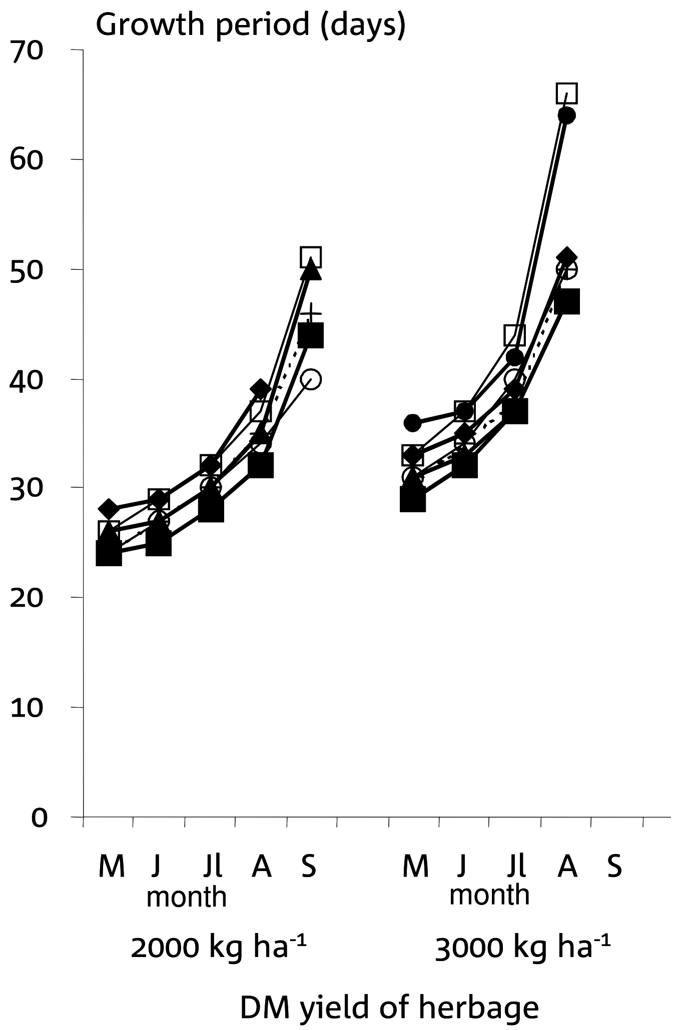

Figure 2-3. The calculated growth period (days) per cut, with applied calculated optimal N fertiliser rates in May (M), June (J), July (Jl), August (A) and September (S) for two target DM yields of herbage (2000 and 3000 kg ha^{-1}), using a marginal N response of 7.5 kg kg^{-1} (+, dotted lines), a nitrogen use efficiency of 30 (■), 35(▲), 40(◆) and 45(●) kg kg^{-1} (bold solid lines) and amounts of unrecovered N of 15(○) and 30(□) kg ha^{-1} (normal solid lines).

Calculated amounts of unrecovered N at the harvest of a cut as functions of month of the year, DM yield of herbage, NUE and growth period are shown in Figure 2-4. Amounts of unrecovered N are relatively large when target NUE is low, DM yield of herbage is high and growth period is long. Relatively small variations in NUE have large effects on amounts of unrecovered N, suggesting again that NUE is a sensitive criterion.

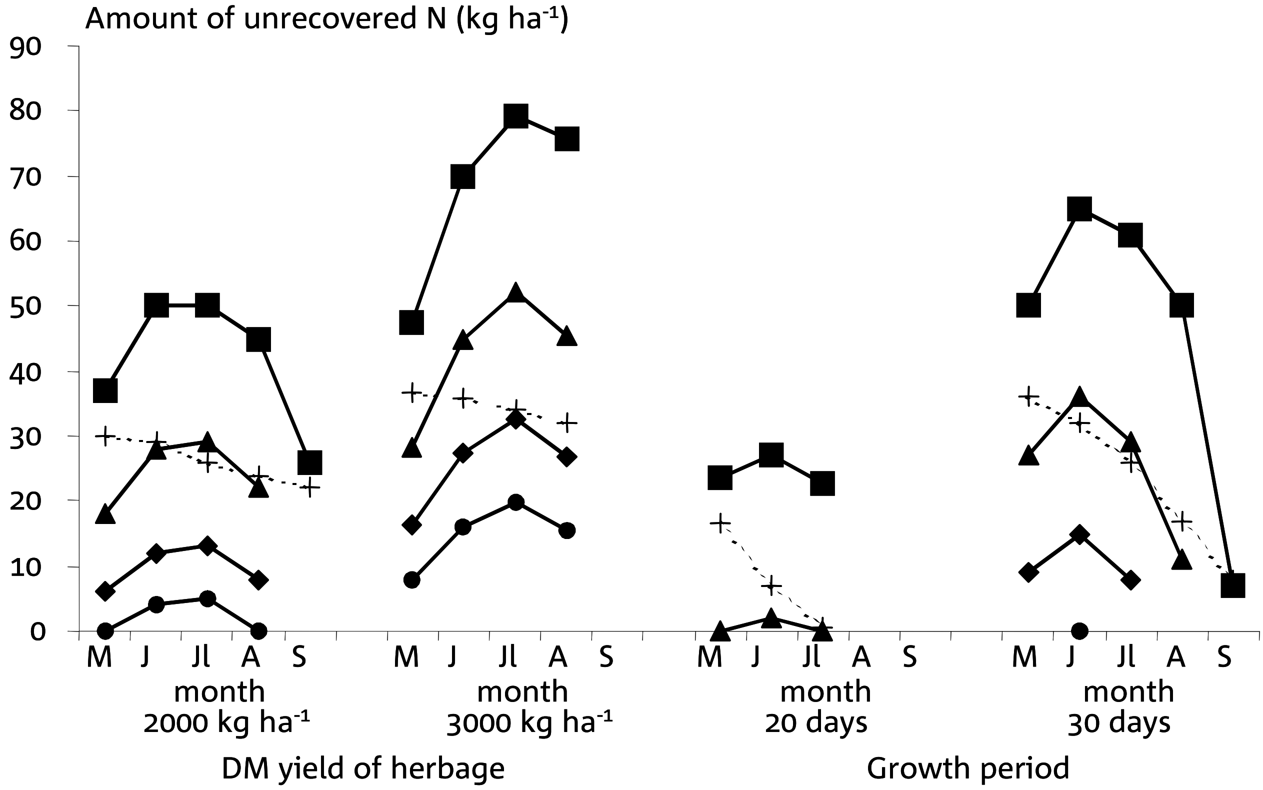

Figure 2-4. The amount of unrecovered N (kg ha^{-1}), with applied calculated optimal N rates in May (M), June (J), July (Jl), August (A) and September (S) for two target DM yields of herbage (2000 and 3000 kg ha^{-1}) and two target growth periods (20 and 30 days), using a marginal N response of 7.5 kg kg^{-1} (+, dotted lines), a nitrogen use efficiency of 30 (■), 35(▲), 40(◆) and 45(●) kg kg^{-1} (bold solid lines).

For reasons of comparison with the economic criterion, application rates of N fertiliser at a marginal N response of 7.5 kg kg^{-1} have also been plotted in Figure 2-2, Figure 2-3, and Figure 2-4. When using this criterion, application rates increase by 30 kg ha^{-1} when target DM yield of herbage increases from 2000 to 3000 kg ha^{-1}, and by 30 and 50 kg ha^{-1} when growth period increases from 20 to 30 days. Seasonal effects are relatively small when DM yield of herbage is used as criterion, but large when growth period is used as criterion. Amounts of unrecovered N increased from 22 to 37 kg ha^{-1} when target DM yields of herbage increased from 2000 to 3000 kg ha^{-1} (Figure 2-4).

The sensitivity of NUE as a criterion is reflected in accumulated annual N fertiliser application rates. Annual application rate were 100 and 400 kg ha^{-1}, for NUE values of 45 and 30, respectively. This implies also a large change in annual DM yields of herbage. Amounts of unrecovered N of 15 and 30 kg ha^{-1} lead to annual application rates of 150 and 300 kg ha^{-1}, respectively. A marginal N response of 7.5 kg kg^{-1} results in an annual application rate of N fertiliser of 300-350 kg ha^{-1}.

2.5 Discussion

In the previous section it has been shown that the "operational decision" of target DM yield of herbage and related growth period per cut is very important. It influences the effect of N fertiliser application rate on the increase of DM yield of herbage, NUE and amount of unrecovered N in single cuts and therefore affects N fertiliser recommendations. The importance of this approach is also clearly demonstrated by Garwood *et al.* (1980) (Figure 2-5). Irrigation led to an increased N uptake at the same growth period (Quadrant IV, lower right) and via the NUE-quadrant (number I, upper right) and a higher DM yield of herbage. ANR and N response are both increased by irrigation. Yet quadrant I shows that the relationship between N uptake and DM yield of herbage (the NUE) is hardly affected by irrigation. This implies that in both irrigated and unirrigated situations, a target DM yield of herbage of for example 2000 kg ha^{-1} is obtained at the same N uptake but, without irrigation more time is needed to realise the target DM yield of herbage. Thus, the interaction between growth period, N fertiliser application rate and N utilisation can be extended to other conditions influencing herbage growth such as water supply.

There are essential differences in N fertiliser application rates derived from a fixed target DM yield of herbage compared to a fixed target growth period. The use of a fixed growth period of 20 days leads to low N fertiliser application rates (Figure 2-2). The use of a fixed growth period of 30 days leads to relatively high N fertiliser application rates in the first half of the growing season and to strongly diminishing N applications in the second half of the growing season, except when the amount of unrecovered N is used as an additional criterion (Figure 2-2).

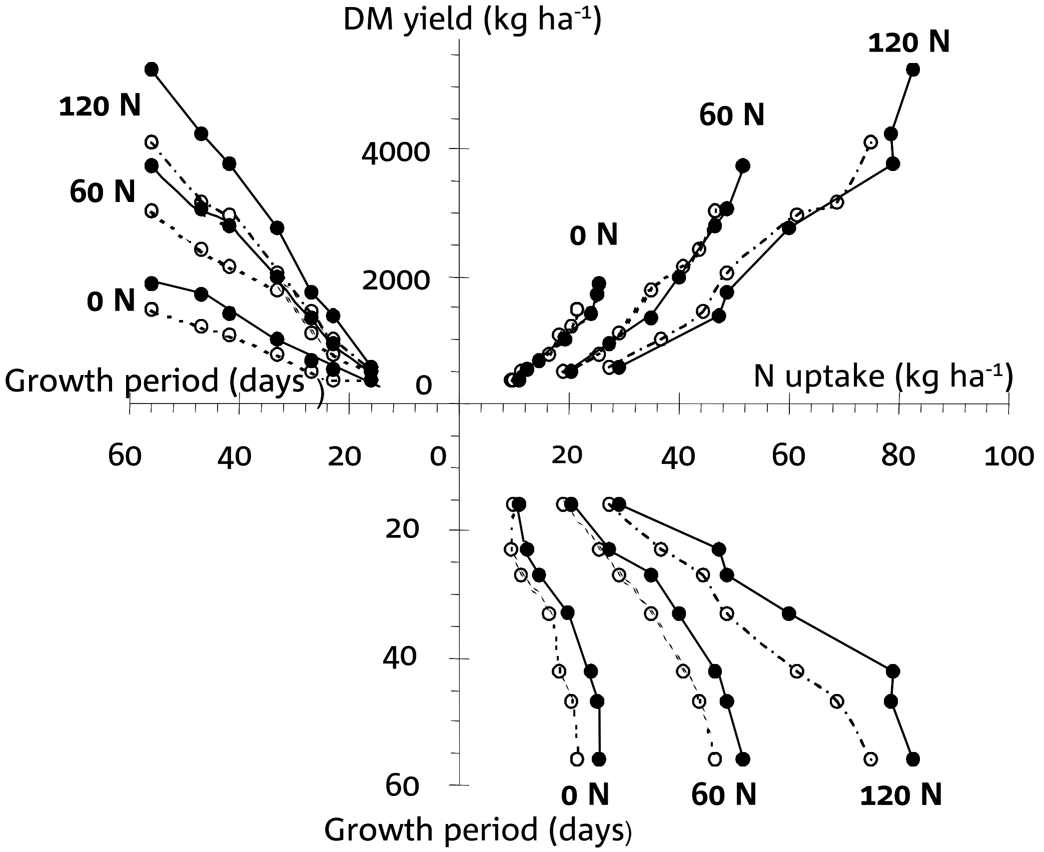

Figure 2-5. The effect of growth period and irrigation on N uptake, DM yield of herbage and nitrogen use efficency at N fertiliser application rates of 0, 60 and 120 kg ha^{-1} in the second cut. Data from Garwood *et al.* (1980). Open dots and dotted lines are unirrigated treatments, closed dots and lines are irrigated treatments.

Inventories indicate that many dairy farmers in The Netherlands do not aim at a target DM yield of herbage but at a target growth period of 15-21 days during the whole season, while N fertiliser application rates are based on target DM yields of herbage of about 2000 kg DM ha^{-1} when used for grazing (Vellinga & Hilhorst, 2001; Holshof, 1997a). Farmers often use a fixed growth period per cut, as this fits within a rotational grazing system. They fertilise for a target DM yield of herbage of 2000 kg ha^{-1} because that is the recommended yield for grazing. The consequence of these choices is that N fertiliser application rates in practice are often high, target DM yields of herbage are not realised, and N concentration in herbage and the amouont of unrecovered N are relatively high. A greater focus on operational grassland management and on the consequences of choosing (and mixing) criteria for establishing 'optimum' N applications can help to improve N use efficiency in practice.

Rougoor *et al.* (1999a) suggested that use of a fixed target yield is the most effective and economic approach, as N fertiliser applied is given time to "work" and low N concentrations in herbage can be realised. But with less favourable growing conditions, the growth period 'per cut' becomes large, although an increase from 20 to about 30-35 days affects digestibility only slightly. A combination of using a target DM yield of herbage in the first half of the growing season and a maximum growth period in the second half of the growing season could be useful to prevent negative side-effects.

The results presented implicitly suggest that high proportions of land used for the production of maize silage relative to grasslands may increase the N fertiliser burden on grassland, when protein-rich herbage is needed to supplement the low protein maize silage. To achieve a high N concentration in herbage (low NUE) at a relatively high target DM yield of herbage, N fertiliser application rates must be high (Figure 2-2), but the amount of unrecovered N will also be high (Figure 2-4) and the marginal N fertiliser response low. Evidently, there are trade-offs between the proportions of land devoted to maize silage and grassland, and between economic (marginal DM yield of herbage and growth period) and environmental criteria (amounts unrecovered N and NUE). Measurement of N in the ration provides information about N utilisation and the potential impacts on the environment. Alternatively, measurement of milk urea concentrations is a simple, fast and accurate tool for assessing the NUE and N utilisation by ruminants indirectly (Ciszuk & Gebregziabher, 1994; Schepers & Meijer, 1998; Van Duinkerken *et al.,* 2005). As such, milk urea is a convenient tool for evaluating operational (and tactical) grassland management, as it provides feedback information to decisions on N fertiliser application rates.

The calculated 'optimum' N fertiliser application rate depends highly on the criterion chosen, i.e., DM yield of herbage, growth period, NUE, and amount of unrecovered N. The developed procedure opens up the possibility for individual farmers to select the criterion and hence the 'optimum' N application rate per cut that best fits within the specific farm conditions. The conditions vary greatly due to differences in, for example, soil type, relative grassland area, stocking density, grazing system and farming style. For some farms, growth period per cut is relevant, while NUE, DM yield of herbage and/or amount of unrecovered N might be relevant for others. The approach presented allows farmers to select their preferred criterion but at the same time provides them with the consequences of their choice. The approach can be extended to include constraints of nitrate leaching, ammonia volatilisation, legislation and farm economics explicitly (Scholefield *et al.*, 1991; Anonymous, 1991a; Vertès *et al.*, 1997; Van Den Brandt & Smit, 1997; Vellinga & Hilhorst, 2001; Ondersteijn *et al.*, 2002b).

2.6 Conclusions

Experimental data of six large field trials were used to derive statistical relationships between N fertiliser application rate, N uptake, DM yield of herbage, growth period, ANR and NUE per cut of intensively managed grassland. The equations selected mimic the fundamental relationships between these parameters, and the proportion of variance explained by the equations was relatively high. The residual variance may be related to short-term seasonal variations between sites and to differences between sites in management. The derived relationships were successfully tested subsequently by using data from three other field experiments. The relationships were used to examine the effects of the choice of a criterion on 'optimum N fertiliser application'. The relationships appear robust and can be used to analyse the complexity and indicate the importance of operational management decisions in intensive grassland farming. However, further testing and improvements of the relationships may be necessary, especially using data from farms, as the relationships will be sensitive to changes in genetic improvements in herbage species, grazing management, including the excretion of urinary N and climatic and environmental conditions. The results presented indicate that greater attention has to be paid to consequences of operational management decision as regards to N fertiliser applications per cut. The complexity on operational management level is too large to presume that decisions at operational management simply follow from decisions at tactical and strategic management levels. The procedure discussed here can help to elucidate the consequences of day-to-day management decisions for the targets set at tactical and strategic management levels.

Acknowledgement

Thanks are due to Agnes Van Den Pol-Van Dasselaar for her critical remarks on previous versions and to Willem Hurkmans for his editorial support.

Annex

Models for N uptake and N use efficiency are described. Although a sequence of growth series covers a complete growing season, the results per series are still discrete, because the pre-treatment always consists of a whole number of cuts. Models provide the possibility to use the starting day, the growth period per cut and the N fertiliser application rate as variables.

The N uptake model

A logistic (Gompertz) curve is chosen for the N uptake model to mimic the increasing N uptake rate at the start of the growth period and decreasing uptake rate at the end. Growth period and N fertiliser application rate per cut are the variables. The parameters are based on the starting day in the growing season and vary per cut. Parameters were estimated by using the REML procedure of Genstat with FITNONLINEAR. Only significant parameters were incorporated in the model ($p<0.05$). Genstat 5, release 5.1 (Anonymous, 2000d) is used.

The general model is:

$$N_{uptake} = N_{effective} / (1 + \exp(-a * (GD - d)), \text{ and} \quad \textbf{(A1)}$$

$$N_{effective} = (N_{appl} + N_{soil}) * (1 - eff) * \exp(-rn * N_{appl}). \quad \textbf{(A2)}$$

The response variable is:

N_{uptake} = the N uptake by the herbage, measured by cutting (kg ha^{-1})

Model parameters are:

$N_{effective}$ = the effective N from soil and fertiliser, depending on the time in the growing season and the applied fertiliser N. (kg ha^{-1}),

a = parameter defining the phase length of almost linear growth (-),

d = the inflexion point at which the growth changes from an increasing growth rate to a decreasing growth rate (day),

(1 - eff) = the effectivity of soil and fertiliser N (-). The parameter eff is calculated using Equation A4 (see below),

rn = parameter defining the response to extra applied N (-), and

N_{soil} = the soil N supply per cut (kg ha^{-1}).

The variables are:

N_{appl} = the applied fertiliser N (kg ha^{-1}) and

GD = the growth period (day).

By using FITNONLINEAR, the parameters a, d, rn, and N_{soil} were described as functions of the starting day (sDay). When sDay had a significant effect on the parameter value, Equation A3a was used:

a = $a_0 + a_1(\text{sDay} - 61) + a_2(\text{sDay}-61)^2$, **(A3a)**

when there was only a significant effect on the first cut versus the later cuts, Equation A3b was used:

a = (if cut .eq. 1) a_3 + (if cut .ge. 2) a_4, **(A3b)**

and when the parameter was not affected by sDay or the order in the first cut/later cuts, Equation A3c was used:

a = a_5, **(A3c)**

when

sDay = starting day of a cut, expressed a Julian day (from 1-365). (for the first cut a minimum value of 61 is used, for the later cuts day 244 (15 September) is used as a maximum, and

$a_0 \ldots a_5$ = the coefficients of the Equation A3.

For eff, the following Equation has been used:

eff = $a_0 / (1 + \exp(-a_1 * (\text{sDay} - 61 - a_2)))$ **(A4)**

The N use efficiency model

The N use efficency (NUE) is defined as the amount of DM of herbage (in kg) that is produced per kg of N uptake. Prior to analysis the NUE data were logarithmically transformed to stabilise residual variance. The relationship between ln(NUE) and growth period was described by a quadratic function with regression coefficients depending on sDay and N fertiliser application rate. Linear and quadratic effects of sDay and N application were taken. Differences between sites were described by taking an additional random effect for the intercept and an additional random effect for different slopes of the linear effect. Random effects of the quadratic effects were tested but were shown to be insignificant. The linear mixed model was:

$$\text{Ln(NUE)} = (\beta_0 + \underline{\varepsilon}_{0S} + \beta_{01}.N_{appl} + \beta_{02}.N^2_{appl} + \beta_{03}.\text{sDay} + \beta_{04}.\text{sDay}^2) + (\beta_{11} + \beta_{12}.N_{appl} + \beta_{13}N^2_{appl} + \beta_{14}.\text{sDay} + \beta_{15}.\text{sDay}^2 + \underline{\varepsilon}_{1S}).GD + (\beta_{21} + \beta_{22}.N_{appl} + \beta_{23}.N^2_{appl} + \beta_{24}.\text{sDay} + \beta_{25}.\text{sDay}^2).GD^2 + \varepsilon_r \quad \textbf{(A5)}$$

where:

β_{0i} = regression parameters of the intercept,

β_{1i} = regression parameters of the linear effect of growth period (GD),

β_{0i} = regression parameters of the quadratic effect of growth period (GD^2),

ε_{0S} = random effect for different intercepts, with $\underline{\varepsilon}_{0s} \sim N(0,\sigma^2_{0s})$,

ε_{1S} = random effect for different slopes of linear effects between sites/ year, with $\underline{\varepsilon}_{1s} \sim N(0,\sigma^2_{1s})$, and

ε_r = residual error with $\varepsilon_r \sim N(0,\sigma^2_r)$.
Estimates of the variance components and the fixed regression parameters were obtained by the REML (Residual Maximum Likelihood method) procedure in Genstat 5, Release 5.1 (Anonymous, 2000d).

Model parameters

Table 2-4. Estimates for the N uptake model of herbage growth per cut of parameters a (length of the phase of linear growth), d (inflexion point), rn (response to applied N fertiliser), eff (efficiency of N from soil and fertiliser) and Nsoil (soil N supply per cut) and standard errors (in parentheses) when different coefficients (a_0, a_1, a_2, a_3, a_4 and a_5) of function A3 are used (see text).

	Coefficients					
Parameter	a_0	a_1	a_2	a_3	a_4	a_5
a				0.04339 (.00275)	0.09947 (.00741)	
d						20.193 (0.517)
rn				0	-0.00001473 (0.00000279)	
eff	0.2832 (.0593)	0.0511 (.0142)	73.35 (6.57)			
Nsoil				125.46 (8.83)	66.11 (5.2)	

a0, a1, a2, a3, a4 and a5 are the coefficients of Equation A3 (see text)

The N uptake model

The estimates and the standard errors of the parameters are shown in Table 2-4. The model explained 0.85 of the total variance, with a standard error of the observations of 13.0. The differences between sites and between years are largely responsible for the large standard error (Figure 2-6).
The model parameter “eff”, defined as the effectivity of N from soil and fertiliser, was dependent upon the starting day of the cut (sDay). The parameters a (length of the phase of almost linear growth), rn (response to applied N fertiliser) and “Nsoil” (soil N supply per cut) had significantly different values for the first and for the later cuts. The inflexion point of the N uptake function, d, had one value for all cuts (Table 2-4).

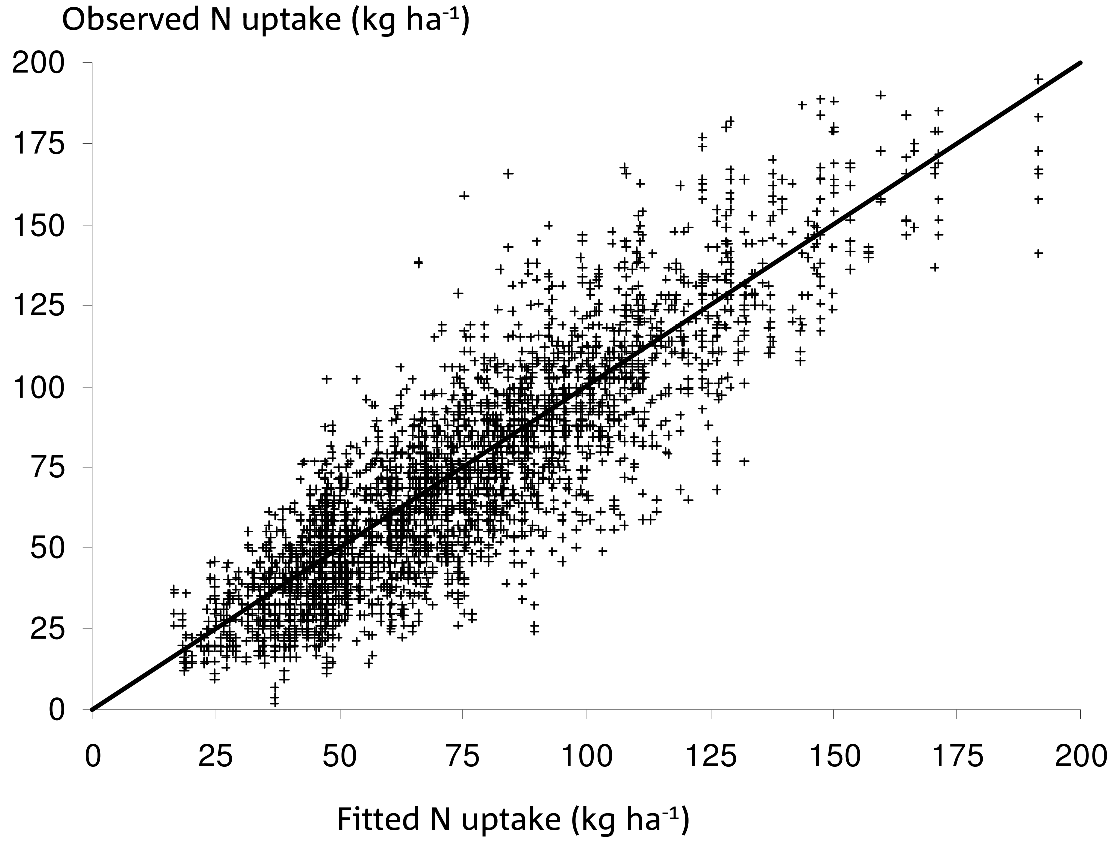

Figure 2-6. Comparison of fitted and observed values of N uptake from the six growth experiments in Table 2-1.

The NUE model

The NUE model is affected by the starting day of the cut, the fertiliser application rate in the particular cut and by the number of growing days. Parameter values are shown in Table 2-5. Figure 2-7 shows the good relationship between fitted and observed values.

Validation

Use of the data from growth series by Prins & Van Burg (1979) and Prins *et al.* (1981) gave similar results in N uptake, NUE and ANR as shown in Figure 2-1, Table 2-2 and Table 2-3.

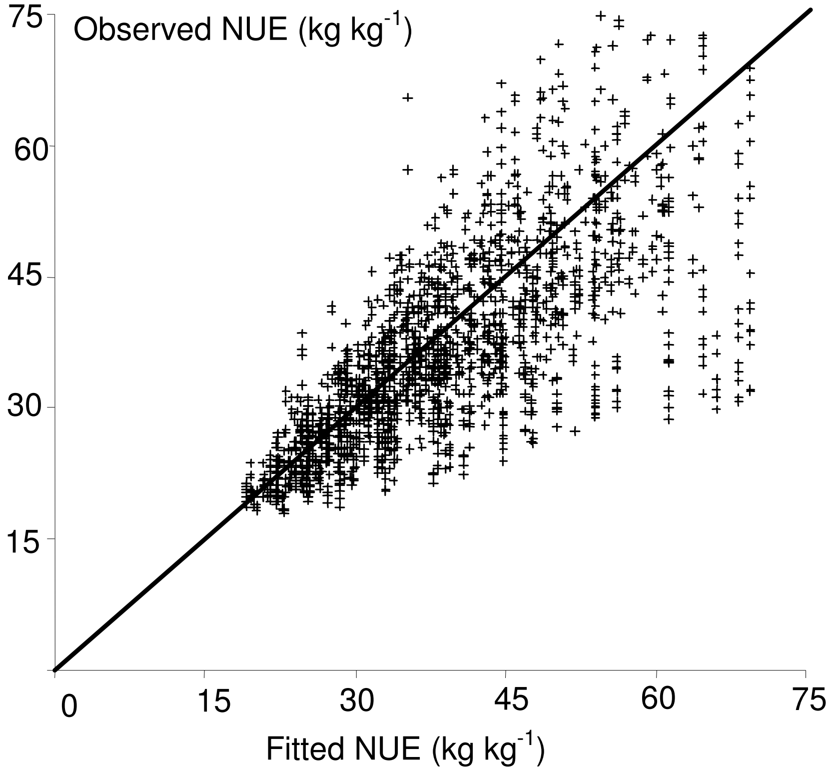

Figure 2-7. Comparison of the fitted and observed values of Nitrogen Use Efficiency from the six growth experiments from Table 2-1.

Table 2-5. Parameter estimates and standard errors (in parentheses) of the model for the nitrogen use efficiency.

Parameter	**Combined with factor**	**Estimate (s.e.)**
β_0	No (intercept)	3.350 (0.2266)
β_{01}	$N_{applied}$	5.352 E-3 (1.256 E-3)
β_{02}	$N^2_{applied}$	1.828 E-5 (8.478 E-6)
β_{03}	sDay	-4.706 E-3 (2.873 E-3)
β_{04}	$sDay^2$	1.354 E-5 (8.789 E-6)
β_{11}	GD	-1.600 E-2 (7.880 E-3)
β_{12}	$GD.N_{applied}$	3.628 E-5 (2.932 E-5)
β_{13}	$GD.N^2_{applied}$	5.187 E-7 (1.650 E-7)
β_{14}	GD.sDay	6.733 E-4 (1.078 E-4)
β_{15}	$GD.sDay^2$	2.156 E-6 (3.460 E-7)
β_{21}	GD^2	2.744 E-4 (7.794 E-5)
β_{22}	$GD^2.N_{applied}$	6.220 E-7 (2.310 E-7)
β_{23}	$GD^2.N^2_{applied}$	Not significant
β_{24}	$GD^2.sDay$	6.512 E-6 (1.201 E-6)
β_{25}	$GD^2.sDay^2$	1.907 E-8 (4.070 E-9)

sDay Starting day of the cut (counting from 1 January)
GD growth period (days; correction in cut 1)
Napplied applied N fertiliser (kg ha-1)

Chapter 3

Accounting for residual effects of previously applied nitrogen fertiliser on intensively managed grasslands

Vellinga, T.V.; G. André, R.L.M. Schils, T.Kraak and O. Oenema, 2005. Accounting for residual effects of previously applied nitrogen fertiliser on intensively managed grasslands. To be submitted to Grass and Forage science.

3 Accounting for residual effects of previously applied nitrogen fertiliser on intensively managed grasslands

Abstract

Intensively managed grasslands annually receive 4 to 8 doses of nitrogen (N) via applications of N fertiliser and animal manure. Usually only 20-70% of the applied N is taken up in the cut directly following application. Residual effects in subsequent cuts can be large, but are poorly quantified and rarely taken into account in current practice. This study aimed at quantifying residual effects of applied N, and deriving a simple tool for the assessment of residual effects.

A simple conceptual framework combined with data from four detailed field experiments on sand, clay and peat soils, and three statistical models allowed analysing residual effects of applied N systematically. The amount of soil mineral N (SMN) and the use of the total amount of previously applied N were compared as possible tools for assessing residual effects.

The results showed that SMN tended to increase with increasing N applications. On peat soils, 15-25% of the applied N was recovered as SMN. On mineral soils this was maximally 8% . There was a clear relationship between SMN and N uptake in the subsequent cut on mineral soils, especially in spring/early summer. However, no relationship between SMN and N uptake by the subsequent cut crop was found on peat soils. Further, there were clear relationships between the amount of previously applied N rate and the N uptake in subsequent cuts, on both soil types and over the complete growing season.

The combination of a low recovery of applied N in SMN on mineral soils, the absence of a relationship between SMN and N uptake on peat soils, the large within field, time and random variation in SMN and the investment time needed to measure SMN, indicates that SMN is not a useful tool in adjustment of N fertiliser application rates.

In contrast, using the amount of applied N in the previous cuts to adjust fertiliser application rates (an “administration system”) is easy to establish and has good accuracy. A simplified statistical model was derived for N uptake and DM yield as function of previously applied N. Results indicate that N uptake and DM yield increased with higher levels of previously applied N. With the help of the simplified statistical model, optimal N application rates have been calculated, using economic and environmental criteria. Optimal N applications are low when preceding N applications were high, and vice versa.

In conclusion, residual effects of previously applied N can be significant and can be assessed using the administration of the previously applied N.

3.1 Introduction

Nearly 40% of the agricultural area in Europe is grassland used to feed ruminant animals. A significant fraction of these grasslands is intensively managed with single-species grass swards receiving nitrogen (N) inputs in the range of 200-400 kg N ha^{-1} yr^{-1} via application of fertilisers and animal manure and through biologically fixed N_2 by clovers, and via atmospheric depositions. The intensively managed grasslands are mainly used for dairy and beef production, which usually involve grazing and mowing cycles. Roughly half of the herbage is harvested via mowing, mainly for the production of silage for use in the winter half year when cattle are housed indoor. During the last decades, the management of grasslands has become more complex following the implementation of series of environmental legislations, limiting the use of N from fertiliser and animal manure, so as to reduce the leaching of nitrate (NO_3^-) to groundwater and surface waters, and the emission of ammonia (NH_3) into the atmosphere (e.g. De Clercq *et al*., 2001; Hatch *et al*., 2005; Oenema *et al*., 2004).

In The Netherlands, grasslands cover about 50% of the agricultural area, and about two-third of this area is intensively managed for dairy production, with annually 2-4 grazing cycles and 2-4 mechanically harvested cuts for silage production and for feeding fresh herbage to housed dairy cattle. Currently, about 10% is zero-grazing grassland (Van Den Pol-Van Dasselaar *et al*., 2002). Grass-based dairy systems are under severe pressure to increase the N use efficiency and to decrease N losses via NO_3^- leaching and NH_3 emissions (Aarts *et al*., 2000; Oenema & Pietrzak, 2002). Various measures have been implemented over the last 20 years which have contributed to a strong decrease in N losses. The main measures taken include a decrease in N fertiliser input, a decrease in protein content of purchased concentrates and the use of low-emission storage and application techniques for animal manure (e.g. RIVM, 2002; 2004). Further improvements in N use efficiency are needed as agreed environmental limits and targets have not been met (RIVM, 2004). Most of the ‘low-hanging fruits’ have been harvested already, suggesting that further improvements in N use efficiency require relatively large efforts.

Here, we focus on improving the N use efficiency of herbage production through improvements in operational management. The main question is ‘how to split annual total N inputs over the various grazing cycles and cuts, and which indicators and criteria should be used for adjustments?’ More specifically the question is here how to adjust for residual effects of previously applied N. The fraction of applied N taken up in the harvested herbage is defined as the

Apparent N Recovery (ANR). Usually, ANR ranges between 20 and 70% in the cut directly following application, suggesting that 30 to 80% of the N applied remains somewhere in the soil-plant-system or has been lost to the environment (Mosier *et al*., 2004; Vellinga *et al*., 2004). Previous studies have indicated that the unrecovered N can lead to considerable residual effects shown up as extra N uptake and DM yield in subsequent cuts (e.g., Hunt *et al.*, 1975; Prins *et al.*, 1981; Kowalenko & Bittman, 2000). It has also been indicated that a part of the unrecovered N is present as soil mineral N (SMN) (Tyson *et al*., 1997, Hack-Ten Broeke *et al*., 1999), and the measurement of SMN has been advocated as an indicator to adjust N applications for residual effects of previously applied N (Cuttle & Scholefield, 1995; Titchen *et al*., 1993; Laws *et al*., 2000; Jarvis, 2000). However, the measurement of SMN is laborious and there is often a huge spatial variation, which limits its applicability.

A systematic analysis of the relationships between previously applied N, the accumulation of SMN and the subsequent effects on N uptake might help in the search for more appropriate indicators for assessing the size of the residual effects and for adjusting N application throughout the growing season. In this paper, we used a combination of a simple conceptual model, a series of detailed four-year lasting field experiments and statistical models to answer the question 'how to use the amounts of previously applied N and unrecovered N as tools to adjust the N application for a next cut, so as to better achieve agricultural and environmental goals simultaneously?' For the sake of convenience, we limit the discussion to residual effects of fertiliser N.

3.2 Material and methods

Conceptual framework

Our conceptual framework is based on the assumption that the residual effects of previously applied N fertiliser are related to the fraction not recovered in harvested herbage. Residual effects are defined here as the 'extra' N uptake and dry matter production in subsequent cuts. The accumulation of Soil Mineral Nitrogen (SMN) is considered to be an "intermediate" residual effect (e.g., Prins & Van Burg, 1977).

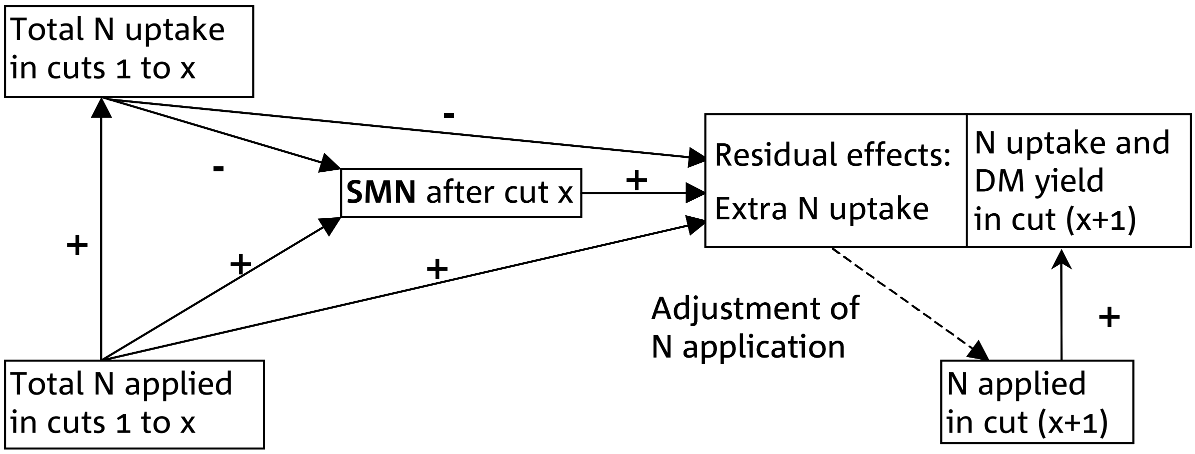

Figure 3-1. The qualitative relationships between applied N in previous cuts 1 to x, the N uptake in previous cuts 1 to x, the accumulation of SMN at the end of cut x, the adjustment of the N application rate at the beginning of cut x+1, the N application rate in cut x+1 and the N uptake and DM yield in cut x+1. A"+" indicates a positive effect, a "-" a negative. "x" can range between 1 and 8, assuming a maximum of 9 cuts in one growing season.

The amount of N applied not recovered simply follows from the difference between N applied and N in harvested herbage. In the conceptual model, the residual effect is positively related to the amounts of applied N and SMN and negatively to total N uptake (Figure 3-1). A fresh N application for the next cut suppresses the residual effect (Prins & Van Burg, 1977). As the fraction of applied N not recovered ranges between 30-80%, and the number of applications ranges between 4 and 8, the summed amount of N not recovered is expected to increase during the growing season.

The simple conceptual framework depicted in Figure 3-1 was tested and quantified statistically using data from four detailed field experiments. The models were used subsequently to derive recommendations per cut for N applications, adjusted for residual effects of previously applied N.

Field experiments
The field experiments were specifically designed to assess residual effects of different N levels and were carried out on sand, clay and peat soil for four subsequent years in the period 1991-1994. An overview of site and soil characteristic is shown in Table 3-1.

Table 3-1. Location and soil properties of the used experiments to estimate residual effects ofpreviously applied N.

Experiment	Lelystad	Heino	Zegveld	Zegveld
Soil type	Clay	Sand	Peat, poorly drained	Peat, well drained
Location code	Wbh	Hn	ZVh	ZVl
Clay (<16 μm) (%)	34	-	26	33
Sand (> 50 μm) (%)	-	87	-	-
Organic matter (%)	10.4	5.9	41	51
pH-KCl (-)	6.8	5.4	4.7	4.5
P-Al (mg P_2O_5/100 g soil	70	87	59	60
K-HCl (mg K_2O/100 g soil)	74	17	43	66
P_2O_5 1st cut (kg ha^{-1})	25	25	25	25
P_2O_5 later cuts (kg ha^{-1})	30	30	30	30
K_2O 1st cut (kg ha^{-1})	0	100-180	0	0
K_2O later cuts (kg ha^{-1})	0	70-100	0	0

- = not determined

The swards on clay and sand soils consisted for more than 80% of perennial ryegrass (*Lolium perenne L.*). Three species were dominant on both peat soils: perennial ryegrass (*Lolium perenne L.,* 30-40%), Rough Meadow-grass (*Poa trivialis L.)* and Couch (*Elymus repens L).* In all swards, little or no white clover (*Trifolium repens L.)* was present.

Experimental design

The set-up and lay out of all four experiments were similar. Residual effects of previously applied N fertiliser were assessed per season in three series: (A) in May, (B) in June/July and (C) in July/August, further indicated as the spring, early summer and late summer series. For each series, there were three basal N fertiliser application rates, i.e. 0, 40 and 80 kg ha^{-1} cut^{-1}, further denoted as low (L), medium (M) and high (H) treatments, respectively. Because N application stimulated herbage production and the herbage was harvested at target yields of 2000 (simulating grazing cut) or 3500 (simulating silage cut) kg DM ha^{-1}, the cutting frequency and the number of cuts in the L, M and H treatments were different (Table 3-2). Residual effects were assessed per L, M and H treatment and per series in experimental cuts receiving fertiliser N at rates of 0, 40, 80 and 120 kg N per ha.

Table 3-2. Number of preceding cuts per treatment (Low, Medium and High) and series (A, B and C) in all four field experiments and in all four experimental years.

Treatment		Series		
		A (spring)	B (early summer)	C (late summer)
Low	(0 kg N per ha per cut)	1	2	3
Medium	(40 kg N per ha per cut)	2	3	4
High	(80 kg N per ha per cut)	2	3	5

Each experiment had 4 replicates, and was repeated in 4 subsequent years. The total number of plots per field experiment equalled 144 in a completely randomised block design (3 series, 3 treatments, 4 levels of fresh N fertiliser and 4 replications). The experimental cut in spring was harvested as silage cut, the late summer cut as grazing cut, and the early summer cut was intermediate between a grazing and a silage cut.

Herbage of all treatments and experimental cuts was mown with a Haldrup cutting equipment with a width of 150 cm and at a stubble height of 6 cm. The length of the cutting strips was 6 meters. Mown herbage was weighed fresh and a representative sample was taken for analysis of dry matter content (DM), crude ash, sand and total N (Van Vuuren, 1993). Only samples from replicates 1 and 3 were analysed for crude ash, sand and total N. Herbage yield is expressed as sand free material. Soil mineral N (SMN) was measured in bulked soil samples (5 samples per plot) from the layer 0-30 cm at the start of all experimental cuts. Samples were analysed within 12 hours of sampling. Mineral N was analysed following 0.01 M $CaCl_2$ extraction according to the description of Houba *et al.* (1997).

Statistical analysis

The conceptual framework shown in Figure 3-1 has been used to define the following statistical models:

1. *Soil Mineral N (SMN)* as function of experimental site, experimental year, season (series) and previously applied N. Initially, N uptake was not included in the model, because this variate appeared to be not significant.
2. *N uptake* as function of experimental site, experimental year, previously applied fertiliser N (in cuts 1 to x in Figure 3-1), N uptake in previous cuts, SMN, and freshly applied N (in cut x+1 in Figure 3-1).

Based on the results of the statistical analyses, we also defined a simplified version of model 2, which is called model 3. In this model, SMN and N uptake in previous cuts were not incorporated as explanatory variates. This model has been used for deriving optimal N application rates, adjusted for residual effects.

3. *N uptake and DM yield* in subsequent cuts as a function of experimental site, experimental year, previously applied fertiliser N, season and freshly applied N.

For all three models, the combined results of all four experiments over four experimental years were analysed statistically, using multi-site analysis. All analyses were carried out using the REML-routine of Genstat 6.1 (Anonymous, 2003). The chosen models consist of a fixed model for the effect of treatments and a random model for other sources of variance. The fixed models describe the expectation of the response as a function of (previously and freshly) applied N, soil type (location) and season (series). The random model accounts for random variation of SMN, N uptake or DM yield due to year, location, replicates within one location (experiment), and series within replicates. There is also a random variation, related to the levels of the continuous functions, e.g. N*previous* in model 1. Finally, there is a term for the residual random effects. Only statistically significant parameters were incorporated in the fixed and random models (P<0.05). The models are briefly described below.

1) Soil Mineral N model

In order to have data with a normal distribution, a log-transformation has been used for previously applied N and for Soil Mineral N.

The fixed model:

$$\begin{aligned} E(Y) = {} & \beta_0 + \beta_1.location + \beta_2.series + \beta_3.year + \beta_{12}.location.series + \\ & \beta_{13}.location.year + \beta_{23}.series.year + \beta_{123}.location.series.year + \\ & \beta_4 \ln(Nprevious) + \beta_5 \ln(Nprevious)^2 \end{aligned} \quad \textbf{(1)}$$

The random model:

$$\begin{aligned} Var(Y) = {} & \sigma^2_{location.replicate} + \sigma^2_{location.replicate.series} + \sigma^2_{location.replicate.year} \\ & + \sigma^2_{location.replicate.series}.\ln(Nprevious)^2 + \sigma^2_{location.replicate.series.year} + \sigma^2_{residual} \end{aligned} \quad \textbf{(2)}$$

2) The N uptake model

In order to have data with a normal distribution, a log-transformation has been used for the N uptake, SMN, for previously and freshly applied fertiliser N. The correlation coefficient between previously applied N, previous N uptake and SMN was low, and we therefore incorporated all three variates in the model.

The fixed model

$$\begin{aligned} E(Y) = {} & (\gamma_0 + \delta_0 + \delta_{01} + \varphi_0) + \\ & (\gamma_1 + \delta_1 + \varphi_1)\ln(prevNuptake) + (\gamma_{11} + \delta_{11} + \varphi_{11}).\ln(prevNuptake)^2 + \\ & (\gamma_2 + \delta_2 + \varphi_2)\ln(Nprevious) + (\gamma_{21} + \delta_{21} + \varphi_{21}).\ln(Nprevious)^2 + \\ & (\gamma_3 + \delta_3 + \varphi_3)\ln(SMN) + \\ & (\gamma_4 + \delta_4 + \varphi_4)\ln(N) + (\gamma_{41} + \delta_{41} + \varphi_{41}).\ln(N)^2 + \\ & (\gamma_{42} + \delta_{42} + \varphi_{42})\ln(N).\ln(SMN) + \\ & (\gamma_{43} + \delta_{43} + \varphi_{43})\ln(N).\ln(Nprevious) \end{aligned} \quad \textbf{(3)}$$

The random model

$$Var(Y) = \sigma^2_{year} + \sigma^2_{location.year} + \sigma^2_{replicate.location.series} + \sigma^2_{replicate.location.year} + \sigma^2_{replicate.location.series}\ln(N)^2 + \sigma^2_{replicate.location.series.year} + \sigma^2_{residual} \quad (4)$$

3) Simplified N uptake model

This model has been derived on the basis of the results of model 2, which showed that N uptake in previous cuts and SMN had a very limited effect on N uptake in subsequent cuts. In the simplified model, only previously applied N, series and year are used as factors. Freshly applied fertiliser N is included as variate, to allow the calculation of optimal application rates adjusted for residual effects. The N uptake and DM yield models were directly based on the experimental data, no transformation was used. The effects of the M and H treatment are described as adjustments of the regression coefficients.

The fixed model

$$E(Y) = (\alpha_0 + \tau_0) + (\alpha_1 + \tau_1)N + (\alpha_2 + \tau_2)series + (\alpha_3 + \tau_3)soil + (\alpha_4 + \tau_4)year + (\alpha_{11} + \tau_{11})N^2 + (\alpha_{12} + \tau_{12})N.series + (\alpha_{112} + \tau_{112})N^2.series + (\alpha_{13} + \tau_{13})N.soil + (\alpha_{24} + \tau_{24})series.year + (\alpha_{14} + \tau_{14})N.year + (\alpha_{34} + \tau_{34})soil.year \quad (5)$$

The random model

$$Var(Y) = \sigma^2_{location.year*} + \sigma^2_{location.replicate.series.year} + \sigma^2_{location.replicate.series.Treat} + \sigma^2_{location.replicate.series.Treat}.N^2 + \sigma^2_{location.replicate.series.Treat.year} + \sigma^2_{residual} \quad (6)$$

with:

E(Y) Expected yield: Models 1, 2: SMN and N uptake respectively, expressed as natural logarithm (ln kg ha^{-1}); model 3 N uptake and DM yield in (kg ha^{-1})

β.. regression coëfficiënts (model 1)

γ.. regression coëfficiënts of the basic function (in spring on mineral soils) (model 2)

δ.. regression coëfficiënts, additional effect to $\gamma_{..}$ of series: early and late summer compared to spring (model 2)

δ_{01} regression coëfficiënt, additional effect to $\gamma_{..}$ of series (spring, early and late summer) with peat soil (model 2)

φ.. regression coëfficiënts, additional effect to $\gamma_{..}$ of soil type: peat soil compared to mineral soils (model 2)

$\alpha_{..}$ regression coëfficiënts with the Low treatment (model 3)

τ.. additional effect to $\alpha_{..}$ of Medium and High treatment (model 3)

Nprevious	cumulative amount of previously applied fertiliser N (kg ha^{-1})
prevNuptake	cumulative N uptake in previous cuts (kg ha^{-1})
SMN	Soil Mineral N at the beginning of the examined cut (kg ha^{-1})
N	freshly applied N (kg ha^{-1})
Treat	treatment-level (Low, Medium, High)
series	period of experimental cut: spring, early summer, late summer (A,B,C)
soil	soil type: mineral soils (sand, clay) and organic soils (poorly and well drained peat)
location	experimental site: Lelystad, Heino and Zegveld (2 sites)
replicate	the experimental replicates
year	experimental year 1991-1994 (in formulae 5 and 6, -92.5 has been used as level correction)
Var (Y)	random variance belonging to E(y)
$\sigma^2_{....}$	variance from source....
Residual	residual variance that cannot be accounted for by experimental random terms

3.3 Results

Accumulation of Soil Mineral Nitrogen as residual effect (model 1)

The relationship between SMN and previously applied N, according the SMN model is shown in Figure 3-2. SMN increased with the total amount of N applied. The increase per kg applied N was much larger for the peat soils than mineral soils (Figure 3-2). The increase differed also between series (growing season). On peat soils, SMN accumulation was higher in spring (24% of previously applied N) than in summer (14-18% of previously applied N). On mineral soils, no differences were found between series in accumulation of SMN; on average 4-8% of the applied N accumulated as SMN.

Increased N uptake as residual effect (model 2)

Effect of previously applied N

The results of model 2 are shown in Figure 3-3. The effects of the previously applied N on N uptake are evident on both mineral and peat soils, irrespective of the application of freshly applied N. The difference in N uptake is smaller between the L and M treatments than between the M and H treatments, especially on peat soils in early spring. In spring, about 6% of the previously applied N on mineral

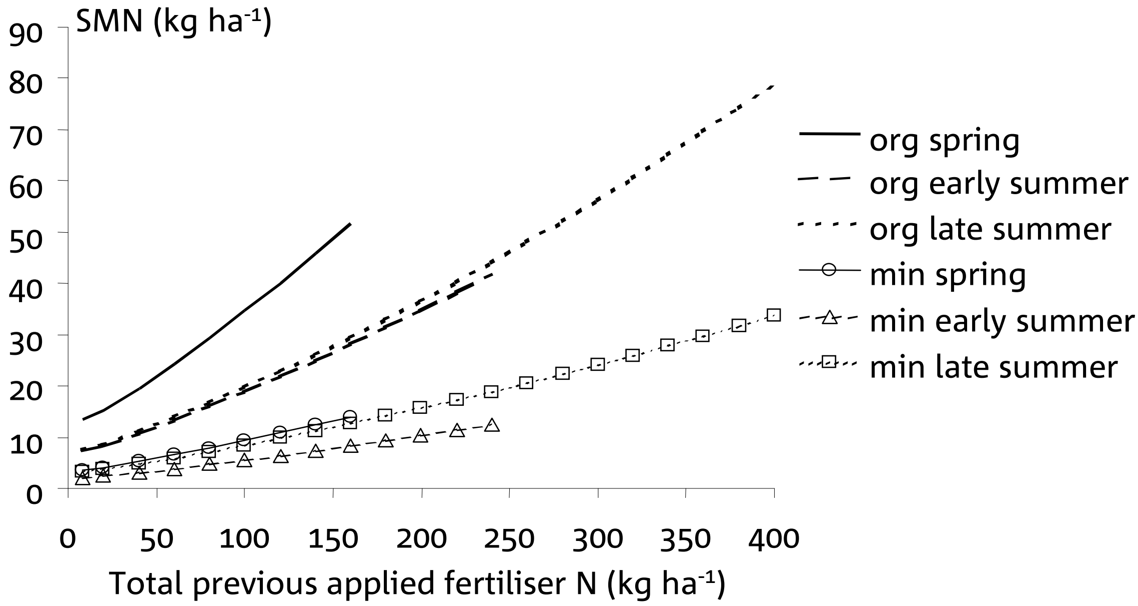

Figure 3-2. The development of SMN in relation to the total previous applied fertiliser N for the three experimental cuts on mineral (min spring, min early summer and min late summer) and organic soils (org spring, org early summer and org late summer). Data averaged over the period 1993-1994. These years are chosen because they represent a more stable situation, which is expected to be more representative for other years.

soils was recovered as N uptake when comparing L and M treatments, and 18% when comparing the M and H treatments. In late summer, about 6% of the previously applied N on mineral soils was recovered as N uptake when comparing L and M treatments, and 8% when comparing the M and H treatments. Residual effects were lower on peat soils than on mineral soils.

Effect of SMN

As indicated before, accumulation of SMN was most evident in the H treatments, and the relationship between accumulation of SMN and N uptake was expected to be most clear in H treatments. Using model 2, we calculated the N uptake after 35 days as function of SMN for the H treatment on peat and mineral soils in spring, early and late summer (Table 3-3). In the calculations, we used a fresh N application of 20 kg ha^{-1} (fresh N applications close to zero led to non-realistic responses). Results in Table 3-3 are presented for the mean SMN values

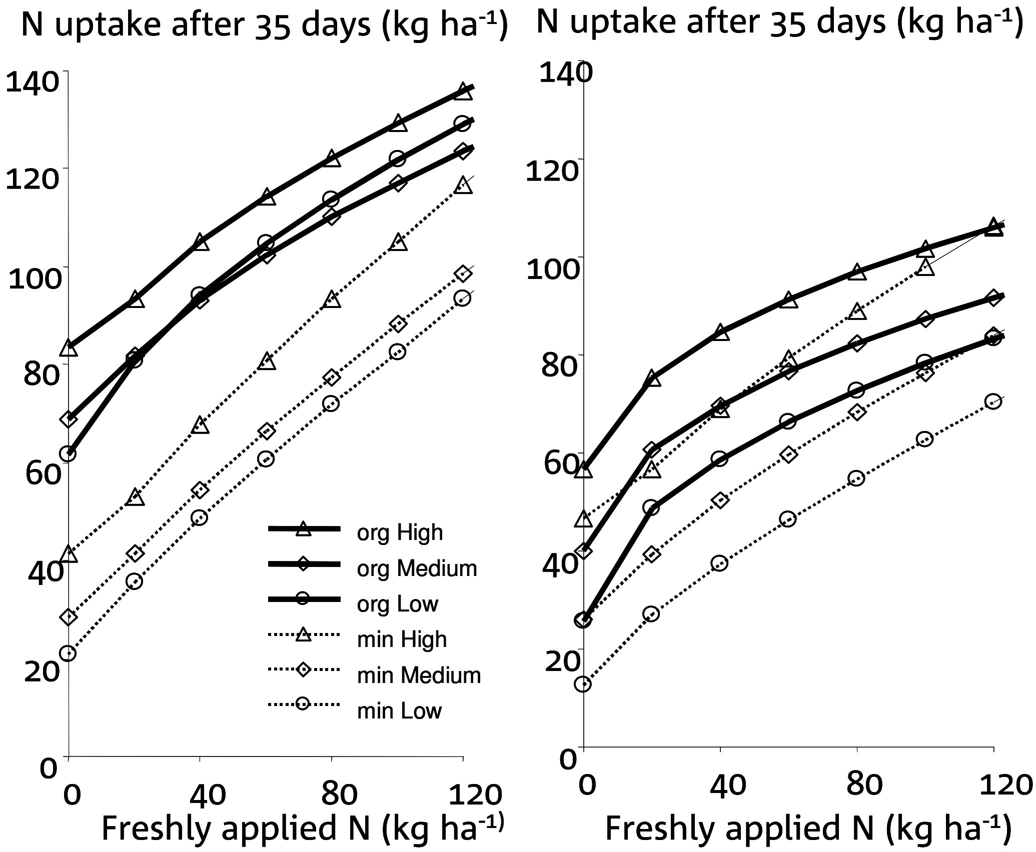

Figure 3-3. The calculated N uptake after 35 days with fresh N applications of 0-120 kg N ha^{-1}, on organic and mineral soils, with treatments Low, Medium and High in spring (left-hand side figure) and late summer (right-hand side figure). Calculations based on model 2.

and for the lower and upper limits of the confidence interval. In general, the variation in SMN was large (mean coefficient of variation ranged between 30 to 40%). The calculated mean lower and upper limits of the confidence of the mean SMN values were 0.2 and 1.8 times the mean, respectively. The results show that the confidence interval for mean SMN values was relatively small on the mineral soils and very large on peat soils (Table 3-3). However, SMN was positively related to N uptake on the mineral soils, but not on the peat soils. The small confidence interval for the mean SMN values on mineral soils led to a significant variation in N uptake, while the large confidence interval for the mean SMN values on peat soils was not associated with systematic variation in N uptake.

Table 3-3. The calculated N uptake in cuts with a fresh N application of 20 kg ha^{-1}in spring, early summer and late summer on mineral and organic soils at high levels of previous N fertiliser application and at average levels of SMN and the minimum and maximum levels of the confidence interval from model 1.

Mineral soils	Spring			Early summer			Late summer		
Previous N fertiliser	160			240			400		
Soil Mineral Nitrogen	5	14	23	4	12	20	10	34	58
N uptake	44	53	58	27	34	39	46	54	58

Organic soils	Spring			Early summer			Late summer		
Previous N fertiliser	160			240			400		
Soil Mineral Nitrogen	10	52	90	8	42	76	16	79	142
N uptake	97	93	92	76	80	81	77	69	60

The results presented in Table 3-3 suggest that on mineral soils the ANR from the SMN was about 50% in spring and early summer and about 15-20% in late summer. ANR is calculated as: (N uptake(SMN_{high}) – N uptake(SMN_{low}))/(SMN_{high}-SMN_{low}). On peat soils, ANR from SMN was nil to negative in spring and late summer and maximal 10% in early summer.

Effect of the N uptake in previous cuts

The effects of the previous N uptake are small, only 1-3 kg N ha^{-1} and are therefore not treated further.

Overview of residual effects (models 1 and 2)

The relationships between N applied, SMN and N uptake as shown in Figure 3-1 were quantified using models 1 and 2. An overview of the results for mineral soils are shown in Figure 3-4, for spring and early summer seasons (left-hand figure) and late summer (right-hand figure). During the first half of the growing season, 4-8% of the applied fertiliser N was recovered as SMN. Approximately 50% of this SMN was recovered in the subsequent cut. In late summer, also 4-8% of the previous applied N was recovered as SMN, but the recovery of SMN in the subsequent cut was on average only 20%. Hence, less than 4% of the previous applied N was recovered as uptake in spring and early summer and less than 1.5% in late summer.

The relationship between previous N uptake and accumulation of SMN and N uptake appeared to be insignificant. The N uptake directly related to previously

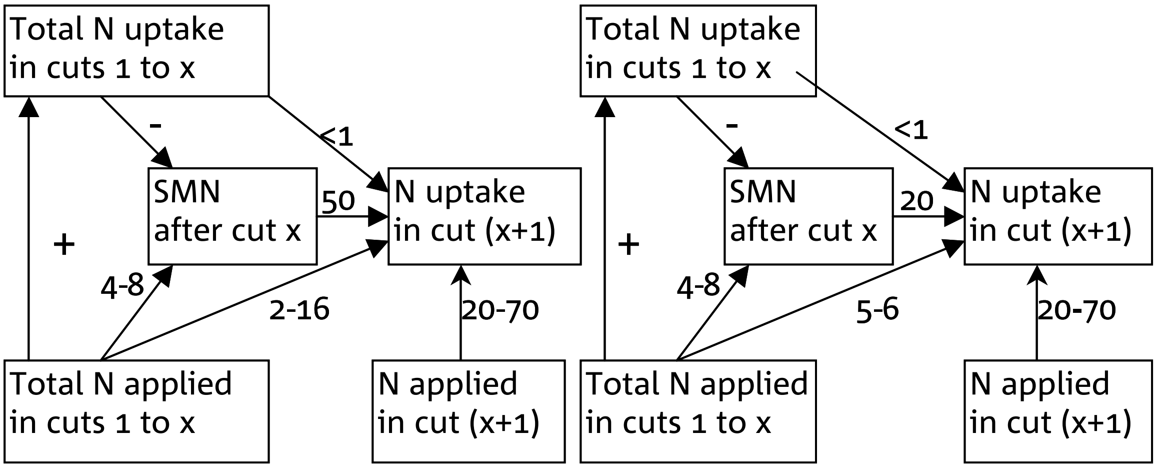

Figure 3-4. The Apparent Nitrogen recoveries from freshly applied N and from previously applied N in spring/early summer (left-hand side figure) and in late summer (right-hand side figure) on mineral soils. Data based on the models 1 and 2 and from chapter 2. The figures represent the Apparent Nitrogen Recoveries.

applied N ranged from 2 to 16% in spring and early summer and from 5 to 6% in late summer. Note that in this case the previously applied N did not result in accumulation of SMN (see Figure 3-1). The ANR of the freshly applied N was arbitrarily set at 20-70% (Vellinga, *et al.*, 2004). More or less similar results were obtained for the peat soils (not shown) with one exception; no estimate was obtained for the recovery of SMN in the subsequent cut because of the large variation in ANR.

Residual effects as N uptake and DM yield (model 3).

The large variations in SMN and the non-response of SMN on N uptake in subsequent cuts in peat soils (e.g. Table 3-3), combined with the complicating results that previously applied N also had a direct effect on the N uptake of subsequent cuts (without accumulation of SMN (Figure 3-4)) led us to derive a simple statistical model (model 3). The simplified model is easier but captures almost the same amount of variance as model 2 (see Annex).

Results of this model for mineral soils are shown in Figure 3-5. Dry matter yield, N uptake and ANR clearly respond to previously applied N, and the responses are clearly affected by freshly applied N. Effects of the L, M and H treatments remained large throughout the growing season.

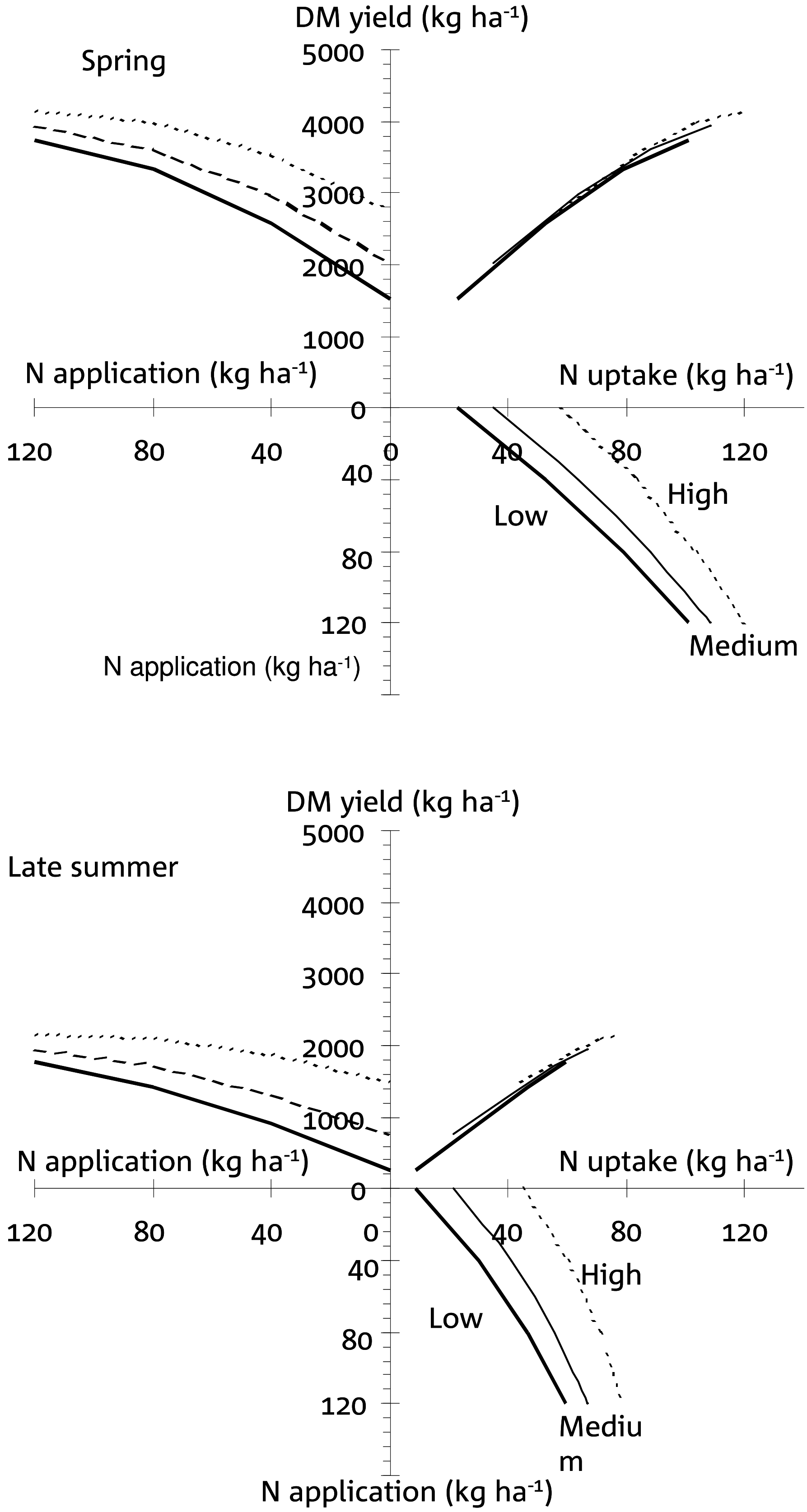

Figure 3-5. The effect of freshly applied N on DM yield, N uptake and the NUE on mineral soils in the spring and late summer series for the treatment Low, Medium and High after a growth time of 35 days.

The effects of freshly applied N on DM yield and N uptake decreased with increasing levels of previously applied N. This effect was significantly different ($P<0.001$) for the L, M and H treatments. This is also a clear indication of residual effects of previously applied N on N uptake and on DM yield. It means that optimal N application rates will be affected by the level of applied N in previous cuts. The physiological N use efficiency (NUE) was not or only marginally affected by the L, M and H treatments, indicating that the amount of DM produced per unit of N taken up remains constant, independent of previously applied N.

The ANR of previously applied N (calculated as the difference in N uptake in cut x+1 between two treatments/ the difference in N applied in cuts 1 to x between two treatments) decreased from 16 and 22% in spring to 6 and 9% in late summer for peat and mineral soils, respectively. Hunt *et al*. (1975), Dawson & Ryden (1985) and Rao *et al*. (1992) showed that residual effects of applied N mainly occur in the first two subsequent cuts, and are very low in the later cuts. When the ANR of previously applied N is based on the previous two cuts, the residual ANR remains constant in all cuts at 16 and 22% on peat and mineral soils respectively.

3.4 Discussion

Results of the four field experiments show marked residual effects of previously applied N during all four experimental years. The magnitude of the residual effects varied with season, year and site, and these effects could be assessed accurately with statistical models. Residual effects of previously applied N have been reported by Hunt (1973, 1974), Prins & Van Burg (1977, 1979), Prins *et al.* (1981), Hunt *et al*. (1981), Reid (1984), Bittman & Kowalenko (1998), Kowalenko & Bittman (2000) and Beckwith *et al*. (2002). Our study is the first one that assesses residual effects during the whole growing season, systematically and quantitatively. The statistical models were based on experimental rigour; they accounted for relevant interactions and provided insight in the dominant controlling factors. The ability to distinguish quantitatively between direct and residual effects of N can improve operational N management. This improvement has agronomic advantages, because the fine-tuning leads to a higher recovery of applied N and preventing applications with a low marginal N response. It has also potential environmental benefits, because the fine-tuning leads to a decrease of the N input, which is expected to reduce the N losses to the environment.

Measurement of SMN of limited value

In many recommendations for N application to arable crops in practice, it is advocated to make corrections for the amounts of SMN at the time of N application (e.g. Germon, 1989; Murphy *et al.*, 2004). Promising experimental results of using SMN as a tool to adjust N application rates in intensively managed grasslands in the UK have been reported by Laws *et al*. (2000) and Jarvis (2000). In these experiments, the adjustment of the N application rate is based on the measured amount of SMN in the soil, In contrast, measurements of SMN in grassland are not yet recommended for correcting N application in practice on a routine basis (Laws *et al.*, 2000; Stienezen, 2002). The findings of our study do also not support the results of Laws *et al*. (2000) and Jarvis (2000).

Our experiments showed that only a fraction of the N applied was recovered as SMN. On mineral soils this fraction was 4-8%. On peat soils more N was recovered as SMN, but no relationship could be established between SMN and N uptake. Meanwhile, residual effects of previously applied N are evident in terms of N uptake and DM yield, on both peat and mineral soils. The lack of relationship between SMN and N uptake in subsequent cuts is probably related to the temporary storage and release of N in other soil pools (Whitehead & Bristow, 1990; Rao *et al*., 1992). This suggests that measurements of SMN do provide only a partial account of the fraction of applied N that is not recovered in herbage. Further, the size and functioning of these pools is related in part to seasonal dynamics, weather conditions and management factors (e.g. Hassink, 1994).
An aspect that might play a role in the different findings between Laws *et al*. (2000) and our experiments is the difference in application frequency. In the UK experiments, a fixed application rate was used, which possibly resulted in SMN accumulation in periods with a poor growth. In our experiments, the cutting and N application frequency depended on chosen target DM yields and high SMN levels hardly occurred. Research on drought sensitive sandy soils indicated that high SMN values under cutting conditions are found only in case of poor growth due to drought, (Vellinga *et al*., 1996).

The wide confidence interval in our experiments indicates that only in the case of relatively high SMN levels adjustment of N application rates should be done. Accurate measurement of SMN on grassland in practice is difficult, because of the large spatial variability, especially on grazed grasslands (Titchen *et al*., 1993; Bogaert *et al.*, 2000). Further, sampling and measurement of SMN is laborious,

especially when spatial variability is high, as can be the case under grazing conditions (Titchen *et al*., 1993).
In conclusion, the assessment of SMN on grassland is laborious (because of number of assessments per season and the spatial variability), has a large confidence interval and it provides only a partial account of the fraction of applied N that is not recovered in herbage. As a result, SMN was poorly related to N uptake and DM yield in subsequent cuts. On peat soils, measurement of SMN had no value at all. Clearly, measuring SMN to adjust N application rates has very little value.

Our results indicate that other indicators should be used as basis for adjusting N application rates. We propose that the amount of previously applied N can be used as suitable indicator, given the relationships between N uptake and dry matter yields and the amount of previously applied N (Figure 3-4 and Figure 3-5).

Deriving optimal N application rates
The simple model (model 3) allows calculating optimal N application rates in a consistent way, taking direct and residual effects of N applications into account. Table 3-4 provides an overview of calculated optimal N calculations after a growth period of five weeks, as function of L, M and H treatments, and as function of three criteria for optimisation, i.e., marginal DM-response, N Use Efficiency and unrecovered N (Vellinga *et al*., 2004). Optimal application rates could not be calculated in all situations, because only one growth period of five weeks was used in this experiment. When growth time would be incorporated, a wider range of target values could be calculated, as is shown in Vellinga *et al*. (2004). The difference in optimal N application rate between the M and the L treatment is 14, 18 and 29 kg N ha^{-1}, when the target is to realise a marginal N response of 7.5 kg DM kg^{-1} N in spring, early and late summer, respectively. Similarly, the difference in optimal N application rate between the H and the M treatment is 22, 30 and 46 kg N, respectively. The differences in optimal N application rates at a marginal N response of 12.5 kg DM kg^{-1} N are almost the same. The residual effects on peat soil are comparable to those on mineral soils. The reduction of the optimal application rate is 16-18% of the amount of previously applied N between the L and M treatment and 19-28% between the M and H treatment, irrespective the level of the marginal N response criterion.

Table 3-4. Calculated optimal fertiliser application rates per cut after a growth time of 5 weeks in spring, summer and late summer on peat soils and mineral soils after fertiliser N treatments of 0 (Low), 40 (Medium) and 80 (High) kg ha^{-1} per preceding cut.

		Peat soil			Mineral soils		
Criterion	Treat ment	Spring	Summer	Late summer	Spring	Summer	Late summer
Marg N= 7.5	Low	95	88	72	115	114	114
	Medium	81	69	43	101	96	85
	High	59	39	-*	79	66	39
Marg N=12.5	Low	70	54	20	90	81	62
	Medium	56	35	-	76	62	32
	High	34	5	-	54	32	<0
Unrec.N = 15	Low	45	34	27	58	41	32
	Medium	40	31	25	51	37	29
	High	33	26	22	40	30	25
Unrec.N = 30	Low	80	63	52	95	73	60
	Medium	72	58	48	86	68	56
	High	60	50	42	72	58	48
NUE = 35	Low	104	36	-	-	114	120
	Medium	95	30	-	-	104	100
	High	77	6	-	-	80	66
NUE = 40	Low	35	-	-	96	57	-
	Medium	34	-	-	88	48	-
	High	0	-	-	66	20	-

*) – means: cannot be calculated

When using unrecovered N as a criterion, the difference in optimal N application rate between the L and the M treatment range from 2 to 9 and between the M and H treatment from 3 to 14 kg ha^{-1}. The effects of the H, M and L treatments decrease from spring to autumn. Residual effects are comparable on mineral and peat soils. The reduction of the optimal application rate ranges from 1-10% and 4-17% between the L and M and the M and H treatments, respectively.
When using NUE as criterion the difference in optimal N application rate between the L and M and between the M and H treatments range from 1 to 20 and from 18 to 34 kg N ha^{-1}, respectively. Results for peat and mineral soils are comparable. The reduction of the optimal application rate ranges from 1- 12% and 14-43% between the L and M and the M and H treatments, respectively.
Clearly, the optimal application rates are low when previous N applications were high, and vice versa. The effect of previously applied N is stronger at higher levels. The relationship between previously applied N and the reduction of the optimal

application rate depends on the chosen criterion, the level of previously applied N and the period of the growing season.
This indicates that administration of the amount of previously applied N can be used as indicator to derive optimal N application rates, depending on the period of the growing season and the chosen criterion (see also Vellinga, 1998; Stienezen, 2002).

Optimal N application rates on peat and mineral soils
Vellinga & André (1999) showed that the optimal annual N application rate on intensively managed grassland is 100 to 125 kg ha^{-1} lower on peat soils than on sand and clay soils. The results presented here are the first in which a comparison can be made of optimal application rates at operational level, i.e., at the level of each cut. With all three criteria, optimal N application rates per cut are significantly lower on peat soils than on mineral soils (Table 3-4).
When the marginal N response is used as criterion, optimal N application rates are 20 to 40 kg ha^{-1} lower on peat soils than on mineral soils. With unrecovered N as criterion, the difference ranges between 5 and 15 kg ha^{-1}. With NUE as criterion, calculated optimal fertiliser application rates differ greatly with NUE target and season. In the early summer with NUE=35 as criterion, this difference amounts 60-80 kg ha^{-1}. So, the difference in optimal N application rates depends on the chosen criterion. This means that derivation of optimal N application rates per cut is different on peat soils than on mineral soils.

3.5 Conclusions

- Application of N leads to residual effects in later cuts. The residual effects depend on N application rate and time, soil type and year.
- Calculated optimal N application rates decrease when previous N application rates are high and vice versa. This holds for marginal N response, NUE and unrecovered N as criteria for optimisation. The residual effects of previously applied N increases stronger at higher levels of applied N.
- The residual effects of previously applied N on optimal N application rates are about similar when using the marginal N response and the NUE as criteria. When unrecovered N is used as criterion, the change of the optimal N application rate is smaller compared to the other two criteria.
- Measurement of soil mineral nitrogen is of little value on mineral soils and of no value on peat soils.

Annex

Accumulation of Soil Mineral Nitrogen as residual effect (model 1)

Table 3-5. Regression coefficients of the fixed model for SMN development of the experiments on sand, clay, poorly and well drained peat in the years 1991-1994.

Factor/variate		coefficient				X^2-prob.
Constant	β_0	3.334				***
		Sand	Clay	Peat, poor	Peat, well	
Location	β_1	0	0.1923	0.7875	0.9629	***
		A	B	C		
Series	β_2	0	0.11914	0.11183		***
		1991	1992	1993	1994	
Year	β_3	0	-0.6163	-1.2518	-1.2163	***
Location.series		A	B	C		
Sand	β_{12}	0	0	0		***
Clay		0	-0.94780	-0.84950		
Peat, poorly drained		0	-1.27090	-0.85860		
Peat, well drained		0	-0.97090	-0.67500		
Location.year		1991	1992	1993	1994	
Sand	B_{13}	0	0	0	0	**
Clay		0	-0.13070	-0.2819	-0.2618	
Peat, poorly drained		0	0.17580	0.47360	0.0247	
Peat, well drained		0	0.21810	0.29820	-0.1096	
Series.year		1991	1992	1993	1994	
A	B_{23}	0	0	0	0	***
B		0	0.16720	-0.3485	-0.4652	
C		0	0.43870	-0.30800	-0.1349	
Location.series.year		1991	1992	1993	1994	***
Sand.A	β_{123}	0	0	0	0	
Sand.B		0	0	0	0	
Sand.C		0	0	0	0	
Clay.A		0	0	0	0	
Clay.B		0	0.2998	0.4163	0.3079	
Clay.C		0	0.1506	0.9193	0.7838	
Peat, poorly drained.A		0	0	0	0	
Peat, poorly drained.B		0	0.4356	1.1155	0.6254	
Peat, poorly drained.C		0	0.1095	-0.0675	0.3023	
Peat, well drained.A		0	0	0	0	
Peat, well drained.B		0	0.1915	0.8319	0.2036	
Peat, well drained.C		0	-0.2611	-0.7976	0.2824	
Ln(*Nprevious*)	B_4	-0.70400				***
Ln(*Nprevious*)^2	B_5	0.16100				***

There were significant (P<0.001) effects of location, year, series (growing season), and previous applied N on the accumulation of SMN (Table 3-5). Surprisingly, the N uptake in previous cuts had no significant effect on the amount of SMN.

For each combination of year, location and series a unique value of the sum of β_0 + ... +β_{123} can be calculated. The effect of previously applied N is the same for all combinations of year, location and series in this logarithmic function. The additional effect of year/location/series-combinations and of previously applied N (linear and quadratic) changes into an interaction effect when the logarithmic function is transformed to normal data.

Results of the random model are shown inTable 3-6. The most important term of variance is the random term, which indicates that the residual variance that cannot be accounted for by the fixed model, does not depend on certain parts of the experimental site or that this variance is larger in the beginning than at the end of the growing season.

Table 3-6. The results of the random model of SMN accumulation of the of the experiments on sand, clay, poorly and well drained peat in the years 1991-1994.

	SMN	
Term	Variance	Relative importance
Location.replicate.year	0.00562	4
Location.replicate.series.level	0.01182	9
Random	0.114	87
Total variance	0.13144	100

Increased N uptake as residual effect (model 2)

Statistical analysis of model 2 showed significant effects of previous N uptake, previously and freshly applied fertiliser N and of SMN (Table 3-7). Although relationships between previously applied fertiliser N and the accumulation of SMN has been developed in the previous section, there was enough variation in the data to use SMN as an independent explanatory variate. Season and previously applied fertiliser N are strongly correlated, caused by the experimental set-up. So, this confounding is not incorporated in the model. Previous N uptake is only partially confounded with season, which allows an interaction in the model. No warnings for confounding of previous N uptake and season were given.

Table 3-7. Regression coefficients of the fixed model for N uptake in relation to previously applied fertiliser N, previous N uptake, SMN and freshly applied fertiliser N. Experiments on sand, clay, poorly and well drained peat in the years 1991-1994.

	γ	X^2	δ (Series B)	δ (Series C)	X^2	φ (Peat)	X^2
Constant	1.61	***	-2.395	-5.777	***	1.6371	***
Peat soil			0.18252	-0.08979	***	-	
PrevNuptake	0.25040	**	0.60200	1.88220	***	-	
PrevNuptake2	-0.01391	***	-0.06334	-0.15994	***	-	
N*previous*	-0.17290	***	-	-		-	
N*previous*2	0.04073	***	-	-		-	
SMN	0.37420	***	0.14377	-0.04961	*	-0.35060	***
Nfresh	0.22050	***	-0.05250	0.42490	***	-0.04399	***
Nfresh2	0.07752	***	0.01514	-0.01622	***	-0.04040	***
Nfresh.SMN	-0.06441	***	-0.03033	0.00210	***	0.04881	***
Nfresh.N*previous*	-0.03771	***	0.02284	-0.06326	***		

The data from Table 3-7 can be read as follows: the constant of the function is 1.61 in the case of series A on mineral soils, for series B and C, the constant has to be adjusted with -2.395 and -5.777, respectively. On peat soils, the three values for the constant have to be adjusted with 1.6371 for series A, B and C and (extra) with 0.18252 and -0.08979 for series B and C respectively, which means that they will be: 3.2471 (=1.61+1.6371), 1.03462 (=1.61-2.395+1.6371+0.18252) and -2.61969 (=1.61-5.777+1.6371-0.08979) for series A, B and C respectively.
The random model is shown in Table 3-8. An important source of variance is the year, as a single term, but also in interaction with the spatial terms location and replicate and with the time (series). Only little variance is present in the terms where the pretreatment level is incorporated. This indicates that the effects of the pretreatment levels were estimated very accurately by the fixed model.

Table 3-8. The results of the random model of N uptake in relation to previously applied fertiliser N, previous N uptake, SMN and freshly applied fertiliser N. Experiments on sand, clay, poorly and well drained peat in the years 1991-1994.

term	N uptake Variance	Relative importance
Year	0.01055	14
Location.year	0.00878	12
Location.replicate.series.level	0.00228	3
Location.replicate.series.year	0.02458	33
Location.replicate.series.level. Nfresh	0.00239	3
Location.replicate.series.level. year	0.00399	5
Random	0.02305	30
Total variance	0.07562	100

A simplified model to calculate residual effects on N uptake and DM yield
The results of the fixed model are shown in Table 3-9 and Table 3-10. The second column, with the α_{ij}-values defines the situation with the low pretreatment. The additional effects of the pretreatments Medium and High are shown in the columns 4 and 5. Effects of treatments, series and freshly applied N on N uptake and DM yield according to model 1 were statistically highly significant.

Table 3-9. Regression coefficients of the fixed model for N uptake of the experiments on sand, clay, poorly and well drained peat in the years 1991-1994. N is freshly applied fertiliser N.

N uptake	α_{ij}		T_{ij}		
Factor/variate		X^2-prob	Treatment M	Treatment H	X^2-prob
Constant	29.34	***	12.62	35.42	***
Series (A,B,C)	-6.756	***			
N	0.9318	***	-0.0423	-0.1368	***
N^2	-0.00134	***			
Soil type	37.15	***	-5.494	-9.311	***
Year	-24.24	**			
Series. N	-0.1178	***			
Series.N^2					
N.soil type	-0.09019	***			
Series.year	9.042	***			
N.year					
Soil type.year					
P<0.001	***				
P<0.005	**				
P<0.01	*				

Also interactions between series and freshly applied N, and between experimental site and freshly applied N were highly significant. There were no significant differences in N uptake and DM yield between sand and clay soils and between well drained and poorly drained peat soils. Therefore, results of the sand and clay soils were combined and are hereafter presented as mineral soils. Results of well-drained and poorly drained peat soils were also combined and are hereafter presented as peat soils. The N uptake and the DM yield were significantly higher (P< 0.001) on peat soils than on mineral soils.

Table 3-10. Regression coefficients of the fixed model for DM yield of the experiments on sand, clay, poorly and well drained peat in the years 1991-1994. N is freshly applied fertiliser N.

DM yield	α_{ii}		T_{ij}	T_{ij}	
Factor/variate		X^2-prob	Treatment M	Treatment H	X^2-prob
Constant	2146	***	518.4	1247	***
Series (A,B,C)	-630.4	***			
N (fresh)	36.8	***	-2.79	-7.21	***
N^2	-0.1266	***			
Soil type	1013.8	***	-207.8	-363	***
Year	-561.5	n.s.	-53.8	-51.5	n.s.
Series. N	-6.121	**			
Series.N^2	0.02621	***			
N.soil type	-4.026	***			
Series.year	176.7	**			
N.year	1.918	***			
Soil type.year	68.79	n.s.	78.47	186.9	*

The results of the random model are shown in Table 3-11. The random variance is 23 and 32% of the total variance for DM yield and N uptake, respectively. Beside the random variance, the most important source of variance is the interaction of location.replicate.series.year. This means that, although soil type and year are incorporated in the fixed model, still a lot of variance is caused by location, within location variation and variations in time within one season and between seasons.

Table 3-11. The results of the random model of N uptake and DM yield of the of the experiments on sand, clay, poorly and well drained peat in the years 1991-1994.

	N uptake		DM Yield	
term	Variance	Relative importance	Variance	Relative importance
Location.year	53.7	14	28 013	6
Location.replicate.series.level	1.1	0	1 276	0
Location.replicate.series.year	168.5	45	280 674	60
Location.replicate.series.level.Nfresh	0	0	13 139	3
Location.replicate.series.level.year	28	8	35 320	8
Random	120.9	32	106 871	23
Total variance	372.2	100	465 293	100

Chapter 4

The role of tactical and operational grassland management in achieving agronomic and environmental objectives; 'De Marke', a case study

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4 The role of tactical and operational grassland management in achieving agronomic and environmental objectives; 'De Marke', a case study

Abstract
Reduction of N losses, especially nitrate leaching, is an important objective for dairy farms in The Netherlands. So far many strategies have focused on changes in strategic and tactical management. Little attention has been paid to operational grassland management. So a conceptual model of operational grassland management was defined, with strong interactions between N rates, realised DM yields, herbage N content, growing days and utilisation per cut. Analysis of data from 'De Marke' and from monitoring projects shows that grassland production and utilisation can be improved by changes in operational grassland management. DM yields for grazing and cutting need to be increased, grazing per paddock must be shorter and slurry must be applied as early as possible. This improved grassland management is able to partially compensate the decrease in DM production caused by a lower N input.

4.1 Introduction
Restriction of nutrient losses to the environment is the main target of the Dutch mineral policy. The aim is reduction of nitrate concentrations in upper groundwater to less than 50 mg l^{-1} (Van Den Brandt & Smit, 1998). Nitrate concentrations in the upper groundwater were too high in the 1990's (Fraters *et al.*, 1998). From literature it is known that on dairy farms fertilisation and grazing have a large impact on nitrate losses (e.g. Benke *et al.*, 1992; Scholefield *et al.*, 1993; Hack-Ten Broeke *et al.*, 1996, 1997, 1999; Vertès *et al.*, 1997; Simon *et al.,* 1997). Although both factors are important, the Dutch mineral policy emphasises a reduction of fertiliser inputs by defining a maximum N surplus per farm varying with farm size (Van Den Brandt & Smit, 1998). The EU policy defines maximum values for animal N excretion per hectare, combined with adjusted fertiliser recommendations (Anonymous, 1991a). The concept of strategic, tactical and operational management (Huirne, 1990; Kay & Edwards, 1994) assigns the reduction of fertiliser inputs to tactical management. The required code of Good Agricultural Practice (Anonymous, 1991a) includes rules for operational management, such as the timing of slurry application and the use of chemical fertilisers, that are based on legislation and the current fertiliser recommendations (Anonymous, 1998a).

At the experimental farm 'De Marke', choices in strategic, tactical and operational management were made in order to combine good agronomic and good environmental performance. On a tactical level, nitrogen (N) input and grazing time were reduced, especially to reduce nitrate leaching (Aarts *et al.*, 1992). Changes in tactical management like reduced fertiliser inputs can lead to changes in technical results and farm profits (Mandersloot *et al.*, 1998; De Haan, 2001). If operational management is improved, inputs can be reduced without changes in economic performance (Zaalmink, 1997). The effects of changes in operational management can be calculated (De Haan, 2001), but are difficult to prove in experiments. However, Rougoor *et al.* (1999a) made plausible that good operational grassland management, i.e. the management of each cut, including N rates, growing days and utilisation, is important for the realisation of good technical and financial results. In their study no effect of operational management on N surpluses could be determined. There are strong interactions between fertilisation, grazing and cutting management (Corrall *et al.*, 1982; Doyle *et al.*, 1983; Hijink & Remmelink, 1987; Rougoor *et al.*, 1999a). Therefore, all aspects should be studied in relation to one another.

Studies of operational grassland management in England and Denmark show that high grazing intensities lead to lower milk productions (Fisher & Dowdeswell, 1995; Fisher & Roberts, 1995; Kristensen, 1997). These results are difficult to compare with Dutch situations. In England and Denmark more emphasis is placed on stock building than on grazing, which means that high grazing intensities lead to low herbage allowance levels. Therefore, an evaluation of tactical and operational grassland management in farming systems is still necessary to determine viable management strategies that can meet environmental and economic goals.

In monitoring programmes on Dutch dairy farms, tactical management has been adjusted to reduce the N surpluses to the MINAS levels by setting targets for the fertiliser inputs per annum and, in some cases, by changing the grazing system (Beldman, 1997b; Oenema *et al.,* 2001). No explicit targets were defined in operational grassland management. At the experimental farm 'De Marke', targets have been defined for grazing and cutting for both tactical and operational management. Since grassland management has been intensively monitored at 'De Marke', data to evaluate tactical and operational grassland management are available. Despite the chosen targets and the efforts in grassland management, the average nitrate concentration still exceeds 50 mg l^{-1} (Boumans *et al.*, 2001). This makes an evaluation of grassland management at 'De Marke' even more interesting as it might lead to suggestions for changes in grassland management at 'De Marke' to reduce nitrate concentrations to 50 mg l^{-1} or less. General conclusions on grassland management might also be reached.

4.2 A framework to evaluate grassland management

Recommendations for tactical grassland management

Tactical grassland management includes decisions about fertiliser levels per hectare per annum and about the grazing system in hours per day and months per annum.

- As MINAS defines the N surpluses for individual farms it is important to define the N fertiliser level for grassland per annum (Van Den Brandt & Smit, 1998; Bresser *et al.*, 1999). Before N inputs were limited by MINAS, N recommendations for grassland were based on economic optimisation only, viz. a marginal N response of 7.5 kg per kg N. These recommendations were defined for each cut and depended on target yield per cut, on season and on indigenous soil N supply (Unwin & Vellinga, 1994; Anonymous, 1998a).
- The grazing system is often based on a combination of available pasture and personal preferences. From an economic point of view as much grazing as possible is recommended, but actual stocking rates and soil conditions define the maximum grazing opportunities (Anonymous, 1997b). Grass production and physical bearing capacity of the soil limit grazing by dairy cows. Calves should not graze before 15 June and should be housed in September. From an environmental point of view, limited grazing is recommended in combination with a supplement of low-protein roughage (Aarts *et al.*, 1992).

A conceptual model and recommendations for operational grassland management

A conceptual model for grassland fertilisation and utilisation has been defined for operational grassland management. It is based on practical grassland use and on recommendations in The Netherlands (Figure 4-1 and Table 4-1). The basis of the model is the single cut in combination with the following management factors: (i) fertilisation, in kg N ha^{-1}, originating from slurry and chemical fertilisers, (ii) DM yield in kg ha^{-1}, (iii) herbage N content in g kg^{-1} DM, (iv) growing period in days, (v) utilisation period, grazing or cutting, in days. Three to ten cuts are realised per annum. The actual fertiliser level and DM yield per annum are the result of N rates and DM yields per cut.

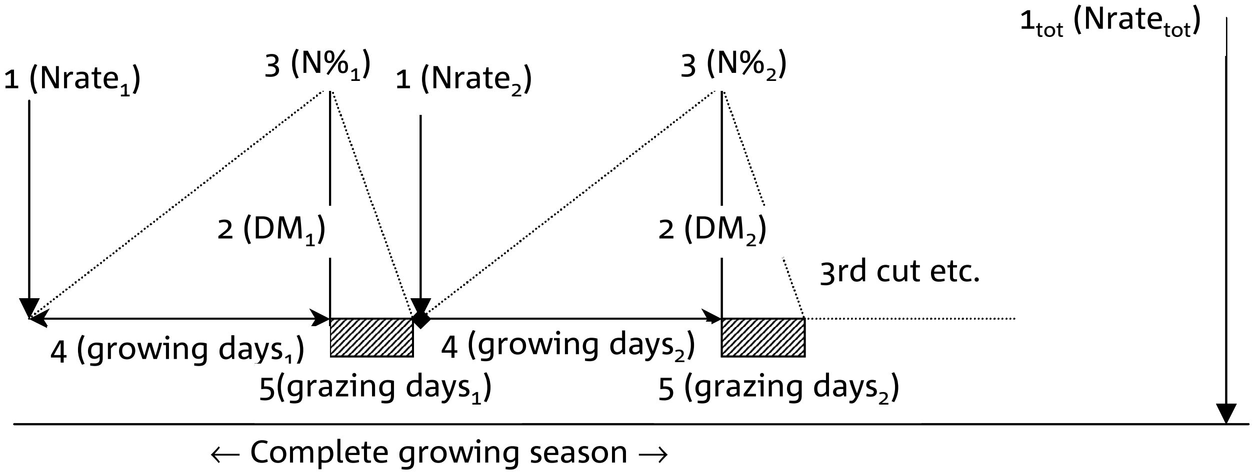

Figure 4-1. Scheme of grassland utilisation with a rotational grazing system, where N rates per cut (1) consist of effective N from slurry and N from chemical fertiliser. DM yields per cut (2) are realised after a number of growing days (4) and are used for grazing or cutting (5). In this scheme the quality of the herbage is expressed by its N content (3). Total N rates per year (1_{tot}) are the sum of all N rates per cut.

N fertilisation

The grassland N fertilisation per cut is based on the tactical target of the N fertiliser level per annum. Slurry is applied two to three times per annum, but the effective N is expressed per cut (Anonymous, 1998a). Chemical fertiliser is applied for every cut. The total N rate per cut is the sum of effective N from slurry and N from chemical fertiliser. There is a strong relationship between recommended N rates and target yields for grazing and cutting. Slurry and chemical fertiliser should be applied within a few days after growth is resumed (Sheldrick *et al.*, 1994). Applications later than one week will hardly contribute to increased growth but do lead to higher herbage N contents (Van Loo, 1993).

Dry matter yield

Although recommended N rates correspond with a wide range of DM yields, recommended DM yields for grazing and cutting are 1700 and 3000 kg ha^{-1} respectively. Moreover, growing periods should not last longer than 4 and 6 weeks respectively (Anonymous, 1997b). This means that the target yields cannot be realised during dry spells or at the end of the growing season. In these cases

Table 4-1. Recommendations for tactical and operational grassland management in The Netherlands.

Management factor	Source	Recommendation
N rates per year	Van Den Brandt & Smit, 1998; Bresser *et al.*, 1999	N surplus = 140 kg ha^{-1}
	Anonymous, 1998a	N rate = 250-350 kg ha^{-1}
N rates per cut	Anonymous, 1998a	See table , part of GAP
	Sheldrick *et al.*, 1994	Within 1 week in new cut
	Van Loo, 1993	
Effective N from slurry	Anonymous, 1998a	4 cuts after application
Timing slurry application	Anonymous, 1998a	Not from 1/9-1/2, part of GAP Within 1 week in new cut
Grazing system	Anonymous, 1997b	Grazing as much as possible
	Aarts *et al.*, 1992	Limited grazing, supplementation
DM yields	Anonymous, 1997b	Grazing 1700 kg DM ha^{-1}, max 4 weeks Cutting 3000 kg DM ha^{-1}, max 6 weeks
Herbage N content	Anonymous, 1998b	See Figure 4-5
Growing periods	Anonymous, 1997b	See Table 4-2
Utilisation	Anonymous, 1997b	Grazing max. 4 days Cutting 2 days

reduced N rates are recommended. The recommended DM yields are based more on practical experience of extension workers than on scientific evidence.

Herbage N content
There is a good relationship between N rate, DM yield and herbage N content. If target yields are not realised, the N rate may have been too high, leading to a lower N recovery per cut (Vellinga *et al.*, 2001), a higher herbage N content and reduced N utilisation by the grazing animal. Consequently, herbage N content is a useful indicator to examine whether fertiliser rate per cut and realised yield are matching. Standard values are based on calculations (Anonymous, 1998b).

Growing period
The length of the growing period for cuts is an indicator that must be used in combination with N rate and realised DM yield to see whether growing conditions were less than perfect, e.g. because of drought, or when the growing periods were too short. Average values have been defined for growing periods in relation to recommended N rates and DM yields per cut and growing season (Table 4-2, Anonymous, 1997b).

Table 4-2. Average number of growing days needed to realise target yields of 1500 and 1700 kg DM ha^{-1} on sandy soils with a high moisture holding capacity, at an annual N rate of 250 kg ha^{-1}. Source: Anonymous, 1997.

	Date of use						
DM yield at grazing (kg ha^{-1})	May I*	June I	June II	July I	July II	Aug. I	Aug. II
1300	20	21	21	22	23	26	28
1700	23	24	24	25	26	30	33
3000	30	32	33	34	36	40	45

* *First or second half of the month.*

Utilisation period

In general, the utilisation period for cuts should be as short a possible. In practice this is defined as a two-day wilting period, with cutting and tedding on the first day, and windrowing and ensilage on the second. Short periods are also preferred for grazing, with a maximum of 4 days (Anonymous, 1997b). Grazing at low DM yields to realise short grazing periods is not recommended.
The factors of tactical and operational grassland management and the recommendations are summarised in Table 4-1. Only the N rates per cut are part of the code of Good Agricultural Practice.

4.3 Material and methods

'De Marke' experimental farm

'De Marke' is located on a drought-sensitive, light sandy soil in the eastern part of The Netherlands. The farm area consists of 55 ha of reclaimed heather with a topsoil containing on average 4.8% organic matter, overlying a layer of sand free from organic matter. 55% Of the area consists of grassland, partly permanent pasture and partly leys. The remainder is used for silage maize and for triticale (Aarts *et al.*, 1999). To create a phosphate buffer in the soil that can be used by the maize following the ley, the amounts of slurry applied on the leys are larger than those on the permanent grassland (Aarts *et al.*, 1999). To maintain a high sward quality, permanent grassland is regularly renovated (Van De Vegte, pers. comm.).

Tactical targets

Fertiliser N rates have been lowered to reduce nitrate leaching on the one hand, but on the other hand they are maintained at levels that just guarantee a sufficient supply of roughage from the farm. Total N fertilisation on grassland is planned at 250 kg N ha^{-1} per annum (Aarts *et al.*, 1999). Grazing time per day has been reduced to 8 hours and energy-rich, low-protein roughage has been supplied. Reduced grazing is managed as a so-called ‘siesta system’, i.e. grazing from about 8–12 a.m. and 6–10 p.m. to balance protein and energy supply during the whole day. Supplements are offered during the indoor periods. (Aarts *et al.*, 1992). Grazing time per day has gradually been reduced from 8 hours in 1997 and 1998 to 6 hours in 1999 and 4 hours in 2000. Dairy cows graze until 1 October. Heifers are grazing day and night and as long as possible during the growing season. Calves are grazing day and night from 15 June till 1 September (Aarts *et al.*, 2001).

Operational targets
Fertiliser N application ceases in late summer instead of in autumn. The target yield for grazing was 1300-1500 kg DM ha^{-1}, the target yield for cutting 2500-3000 kg DM ha^{-1} (Van De Vegte, pers. comm.). The grazing period per paddock was planned at four days with a leader- follower system, i.e. two days grazing by dairy cows followed by two days grazing by non-producing heifers.

Analysis of operational and tactical management
The analysis of grassland management is based on a comparison of the five management factors mentioned above for ‘De Marke’, with norms that partly belong to Good Agricultural Practice. As application of slurry and chemical fertiliser stops after 1 August, only the cuts from before this date will be analysed.

Data collection
Data were collected in the period 1997-2000.

Tactical management
The total N rate per annum was calculated as the sum of the N rates per single cut. The grazing system and grazing period during the growing season were recorded per cut by the farm management. Total grazing period was based on these data.

Operational management
Data were collected on the application (rate and timing) of slurry and chemical fertiliser per paddock and per cut. The amount of slurry applied was measured by weighing each load. It was assumed that the loads were partitioned proportionally over the paddocks where slurry was applied. The amount of

chemical fertiliser was measured for each paddock by weighing before and after fertiliser application.
DM silage yields per cut were measured by weighing each load. DM grazing yields per cut were estimated visually by the farm manager (Van De Vegte, pers. comm.). The visual estimates were calibrated regularly by cutting and weighing strips.
N content of grazed herbage and wilted grass before ensilage was measured at each harvest, by Near Infrared Spectrometry (Williams & Norris, 1987).
The number of growing days between consecutive cuts was calculated. The growing period for a cut starts after the grazing animals have been moved to another paddock or when the wilted grass has been removed. It ends when the grass is grazed or cut again. For split paddocks, growing days were calculated from the average starting date of both parts.
Grassland use covers the complete scheme of grazing and cutting for each paddock, including the type of animals (dairy cows, young stock) and the number of grazing days, as recorded by farm management. Total number of grazing days per cut was calculated. Two to three days after having started grazing dairy cows were transferred to another paddock. Heifers then grazed the remaining herbage. Duration of the grazing period for each cut refers to the sum of grazing days for both dairy cows and heifers. For split paddocks, where both parts are grazed, length of the grazing period refers to the average of both parts.

Calculation of nitrate concentrations in upper groundwater

The model Nitrogen, URine and Pastures (NURP) is used to look for ways to reduce nitrate leaching on 'De Marke' (Vellinga *et al*., 2001). NURP describes the effects of strategic, tactical and some operational management factors such as stocking rate, milk production level, N rate per annum, and grazing system including supplementation per month, on the nitrate concentration in the upper groundwater. NURP is based on the same conceptual model as shown in Figure 4-1. Operational management is carried out according to the recommendations and standards as shown in Table 4-1.

4.4 Results

Tactical management

N rate per annum

Average annual N rate on grassland at 'De Marke' is 250 kg ha^{-1} (Table 4-3), which is exactly the same as the target value. On permanent grassland 230 kg N ha^{-1} is applied, on temporary grassland 260 kg. In some paddocks white clover is present. The contribution of clover to DM production and N uptake is assumed to be small (Baan Hofman, 1994).

For the soil and management conditions of 'De Marke', application of the economically optimal recommendations would lead to N rates of 270-290 kg ha^{-1} without irrigation and 320-340 kg with irrigation (Table 4-3). Actual N application rates at 'De Marke' are 30-90 kg lower.

Realising the MINAS target level of 140 kg N surplus per hectare, yields N rates of 170 and 205 kg N ha^{-1} per annum for non-irrigated and irrigated situations, respectively (Willems *et al.*, 2000) (Table 4-3). These quantities are 80-45 kg N lower than current rates at 'De Marke'.

Grazing system and grazing season

Grazing time per day has gradually been reduced from 8 hours in 1997 and 1998 to 6 hours in 1999, and to 4 hours in 2000, which is in good agreement with the targets. Heifers and calves have been grazing day and night in all years.

In the period 1997-2000, dairy cows started grazing on 30, 8, 15 and 19 April, respectively. Heifers started grazing at about the same time, as they follow the dairy cows. Calves started grazing at the end of May, or in the first week of June.

In the period 1997–2000, dairy cows were housed on 20, 1 and 1 October and on 15 September, respectively. Heifers grazed till 20,14 and 14 November and 15

Table 4-3. N rates (kg ha^{-1}) for a farm economic optimum. Average situation at 'De Marke' and calculated values for grassland farms with a MINAS N surplus of 140 kg ha^{-1} per year.

Situation	Permanent grassland (Soil N supply =140)	Leys (Soil N supply =100)
Economic optimum level		
Irrigated	320	340
Non-irrigated	270	290
Fertilisation 'De Marke'	232	263
Calculated level at MINAS N surplus = 140 kg (100% grassland)		
Irrigated	205	
Non-irrigated	170	

September. Calves grazed till 12, 19 and 11 August in the years 1997, 1998 and 1999 respectively, but remained indoors in 2000.
Compared with the targets, grazing by dairy cows in 1997 and by heifers in the period 1997-1999 lasted too long.

Operational management

N rates per cut for grazing and cutting

Average N rate for grazing cuts was 33–45 kg N ha^{-1} (Table 4-4). Different groups of N rates can be distinguished (Figure 4-2). The first group refers to the first cut (three points at top left in Figure 4-2), which received high N rates. This is in agreement with the fertiliser recommendations based on a total annual application of 250 kg N ha^{-1}. In 1999, N rates for the first cut were the same in all grazing paddocks. In other years, N rates for the first cut were differentiated between paddocks. The second group received high N rates during the growing season, varying from 45 to 75 kg N ha^{-1}. These cuts were planned for silage, but

Table 4-4. Details of grazing cuts for dairy cows (leader-follower system with heifers) at 'De Marke' over the period 1997-2000. Data are averages over all cuts starting before 1 August.

Year	Growing days	Grazing days	DM yield at start of grazing (kg ha^{-1})	N rate (kg ha^{-1})	Herbage N content (g kg^{-1})
1997	19	4.3	1219	38	33.7
1998	23	4.8	1207	34	32.8
1999	21	6.0	1341	45	33.4
2000	23	6.7	1481	33	-

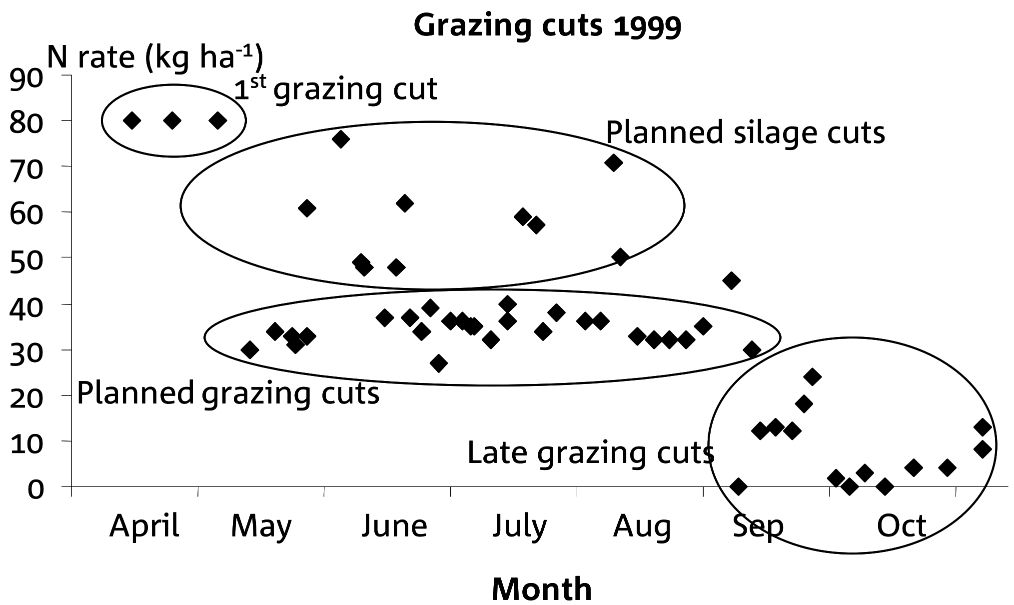

Figure 4-2. Fertiliser N applications for grazing cuts in 1999 at 'De Marke'.

due to shortage of grass, they were used for grazing. As a result the N rates were far too high. The third group consists of cuts with N rates of about 35 kg N ha^{-1}. These cuts were planned and used as grazing cuts. The N rates for planned grazing in the years 1997–2000 were 35, 25, 35 and 30 kg N ha^{-1}, respectively. Recommended N rates for grazing cuts of between 1000 and 1500 kg DM ha^{-1} were on average 27 kg N (Anonymous, 1997b; 1998a). So in 1997 and 1999 the N rates were too high, in 2000 slightly too high, and in 1998 they were in good agreement with the recommendations. Finally, in Figure 4-2 the cuts starting in September and October are shown. These cuts received no chemical fertiliser, but some N from previously applied slurry was still effective.

Table 4-5. Details of silage cuts at 'De Marke' over the period 1997-2000. Data are averages over all cuts starting before 1 August .

Year	Growing days	DM yield (kg ha^{-1})	N rate (kg ha^{-1})	Herbage N content (g kg^{-1})
1997	29	2585	60	28.6
1998	35	2732	64	28.9
1999	32	2640	71	30.4
2000	36	2849	59	-

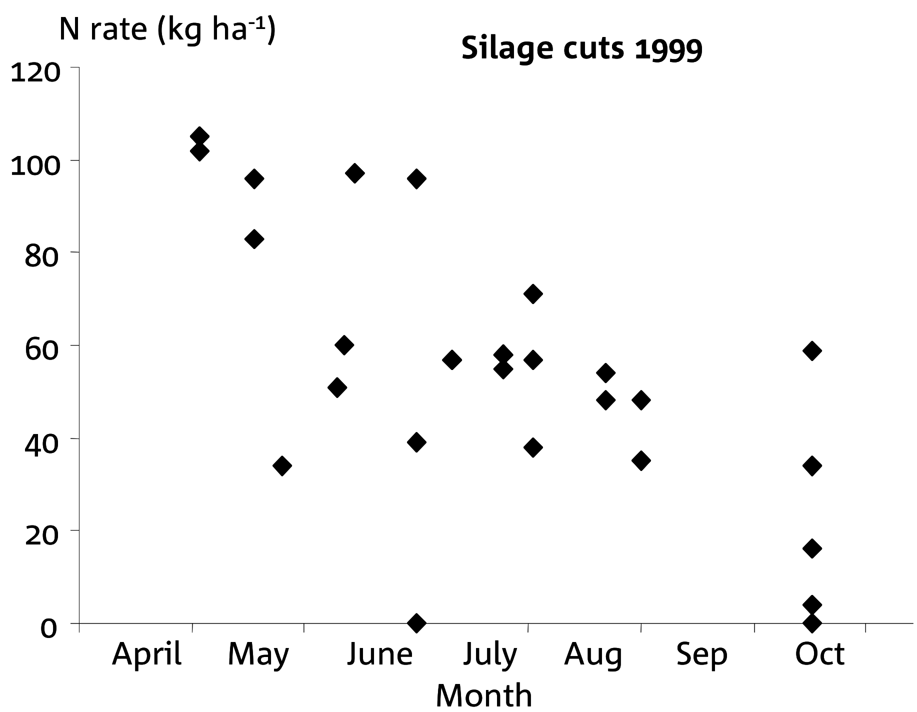

Figure 4-3. Fertiliser N applications for silage cuts in 1999 at 'De Marke'.

Average N rate per silage cut was 59-71 kg N ha^{-1} (Table 4-5), with rates for the first cut of about 100 kg N ha^{-1}, and for later cuts of about 50 kg (Figure 4-3). N rates for silage cuts were in good agreement with the fertiliser recommendations. Chemical fertiliser is applied within 3 days from the start of the growing period.

Slurry application

Slurry application on leys was on average 78 m^3 ha^{-1} and on permanent grassland 52 m^3 (Table 4-6).

The annual amounts on leys were split into 4 portions, the last of which was applied in the first half of August (Table 4-6). Of the total amount of about 2500 m^3 applied on the farm, 200–400 m^3 (more than 10%) were applied after 1 August. The low amount in August 1997 is the result of large applications on 31 July.

N from slurry is effective in four cuts after application (Anonymous, 1998a), which corresponds with a period of 3.5–4 months. Consequently, slurry applications after 1 August lead to fertiliser effects till the end of November. The relatively high grass production in late autumn required late silage cuts to remove the grass. Although these late cuts are important from the point of view of efficient N utilisation, 5 to 10 kg slurry N ha^{-1} is not used for herbage production and remains in the soil-plant-system during winter. Although the slurry applications are in agreement with the recommendations and with Good Agricultural Practice, part of the N is not utilised.

Contractors carry out the application of slurry. To work efficiently they always combine applications to a group of paddocks. Consequently, slurry sometimes was applied more than 10 days after the grass had resumed growth, which actually is too late

Table 4-6. Details of slurry application on permanent grassland and leys at 'De Marke'.

Year	Permanent grassland			Leys		
	Amount (m^3 ha^{-1})	Effective N (kg ha^{-1})	Total after 1 Aug. (m^3)	Amount (m^3 ha^{-1})	Effective N (kg ha^{-1})	Total after 1 Aug.(m^3)
1997	49	88	0	79	145	43
1998	45	74	0	69	116	415
1999	55	95	0	84	148	375
2000	58	99	27	80	137	225

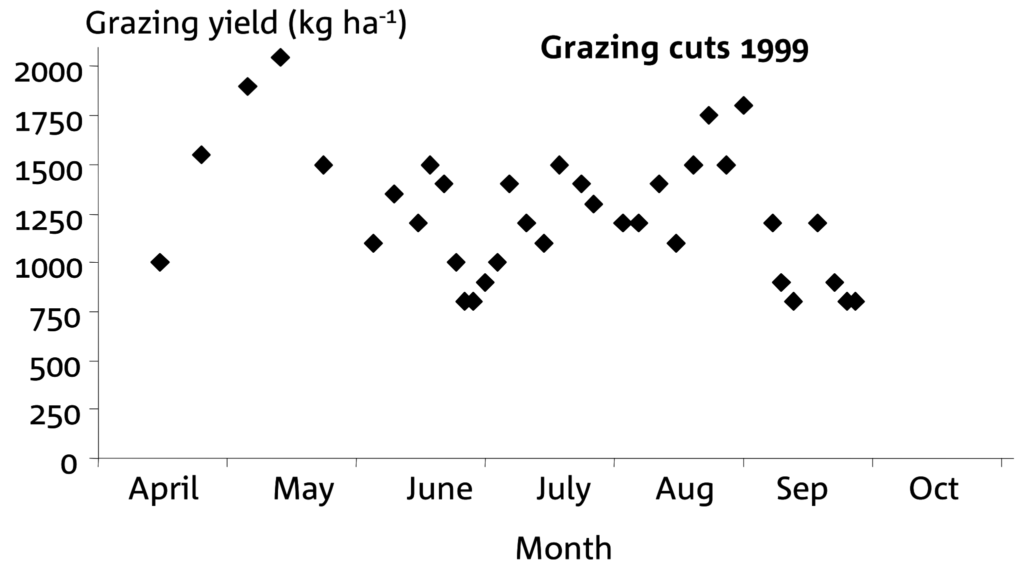

Figure 4-4. DM yields at grazing of dairy cows, heifers and calves in 1999 at 'De Marke'.

DM yield per cut

Table 4-4 presents information on grazing cuts that started before 1 August. The data show that the average yield for grazing was 1200-1400 kg DM ha^{-1}. These yields did not fully meet the targets set by 'De Marke'. The difference is about 100 kg DM ha^{-1}. However, considering the drought-prone conditions of 'De Marke', it is a satisfactory result. Only in 2000, with favourable precipitation conditions, the average target yield for grazing was realised. Although 1300–1500 kg DM ha^{-1} was the target value for the start of grazing during the entire growing season, many grazing cuts yielded less (Figure 4-4). Low DM yields were very common for grazing calves, but also dairy cows started grazing at DM yields of 1000 kg or less. At the end of the season, i.e. for cuts starting after 1 August, DM yields for grazing that exceeded 1000 kg ha^{-1} were not realised anymore in the unfertilised cuts. The situation in 1999 is representative for the entire period 1997–2000. The average DM yield for grazing at 'De Marke' is 300-500 kg below the recommended target yield of 1700 kg ha^{-1}.

The target DM yield for cutting is 2500-3000 kg ha^{-1}, which was realised in all years that were analysed (Table 4-5). Yields were lower for silage cuts at the end of the growing season, mainly as a result of less favourable growing conditions and reduced N applications. In 2000, which was charcterised by a relatively wet summer, DM yields of silage cuts were higher. The recommended DM yield for cutting is 3000 kg ha^{-1}, which is only slightly higher than the targets.

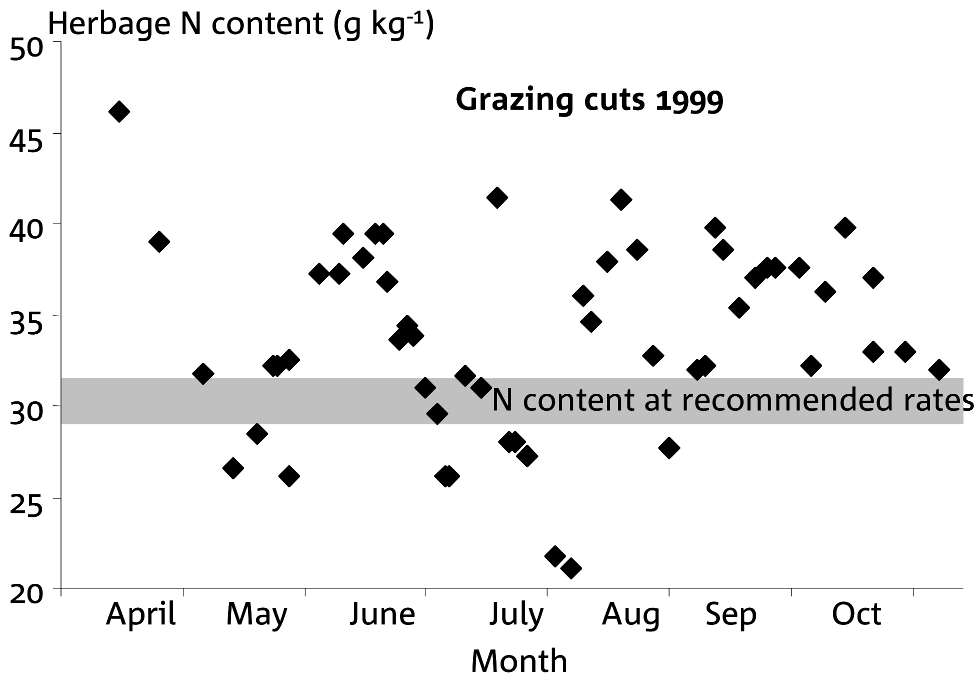

Figure 4-5. Herbage N content of grazing cuts in 1999 at 'De Marke'.

Herbage N content

The average N content of grass for grazing is 33 g per kg DM (Table 4-4). Variation between years is small, but is substantial within years with standard deviations of 3.9-5.8 g kg^{-1} (Figure 4-5). The variations in N rate per grazing cut, in DM yield and probably also in weather conditions are responsible for these large standard deviations. The standard value for N content is about 31-32 g per kg DM (Anonymous, 1998b), so herbage N of 'De Marke' is only slightly higher. However, since 1998, fertiliser recommendations have been changed and the standard value for herbage N content is now about 29-30 g per kg DM (Vellinga, 1998).
N content of silage grass was 29-30 g per kg DM (Table 4-5), which is in good agreement with the standard values (Anonymous, 1998b).

Growing days for grazing and cutting

The average number of growing days for grazing was 19-23 (Table 4-4). In the first half of the growing season the number of growing days was about 20. This later increased to 25-30 (Figure 4-6), while DM yield for grazing remained fairly constant over the season (Figure 4-4). The figures show that the target yield for grazing is met, and that the number of growing days is the result.
The Handbook for Dairy Farming (Anonymous, 1997b) suggests an average of 23-33 growing days for grazing cuts of 1700 kg DM ha^{-1} (Table 4-2), and 20-28

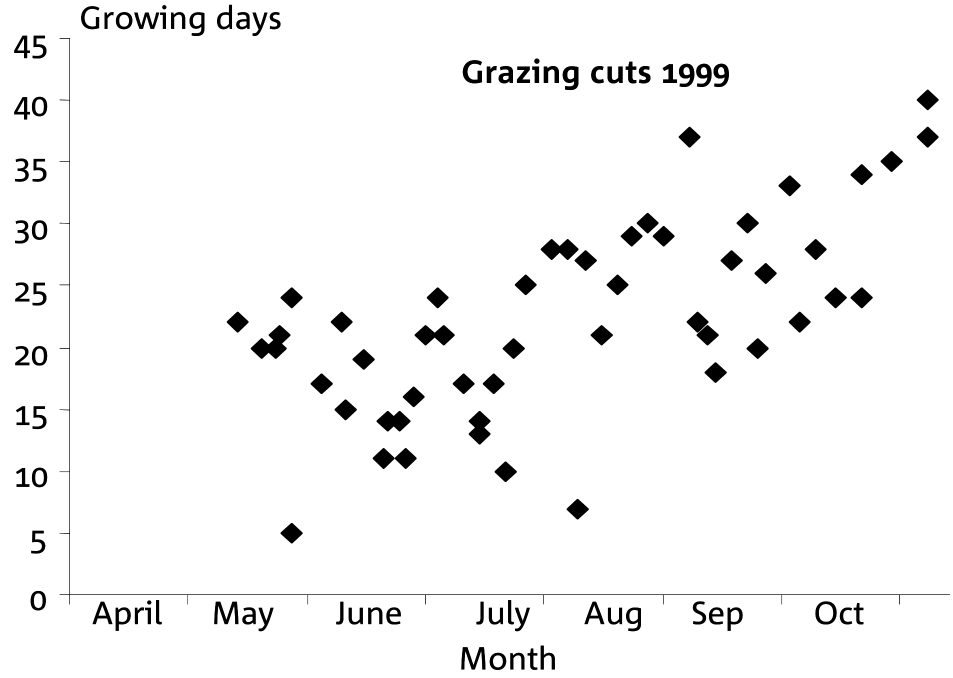

Figure 4-6. Number of growing days for a grazing cut (dairy cows, heifers and calves) in 1999 at 'De Marke'.

days for 'light' grazing cuts (1300 kg DM ha^{-1}). The average number of growing days at 'De Marke' in the period 1997-2000, i.e. 19–23, is in the lower range of average values for light grazing cuts in situations with a relatively high risk of drought stress.
At 'De Marke' a number of 15 growing days or even less also occurs. This occasionally happened with dairy cows, but mostly with grazing calves.
The average number of growing days for silage varied from 29 to36. The increase from almost 30 to slightly over 30 in the course of the growing season was smaller than for grazing cuts. Consequently, a growing period of 4.5-5 weeks was the target for cutting. DM yields were the result of this. For silage cuts of 3000 kg DM ha^{-1} (Table 4-2) on soils with a relatively high moisture holding capacity and fertiliser applications per cut amounting to an annual total of 250 kg N ha^{-1}, the Handbook for Dairy Farming (Anonymous, 1997b) gives values of 30–40 growing days. The number of growing days for silage cuts on 'De Marke' in the period 1997-2000 is in good agreement with these values.

Grazing time and wilting period per paddock
The grazing system at 'De Marke combines grazing of dairy cows and heifers. Paddocks are grazed for 1-4 days by dairy cows, which are then followed by

heifers. Average grazing time per paddock increased from more than 4 days in 1997 to almost 7 in 2000 (Table 4-4). This is the result of the reduction in number of grazing hours per day of the dairy cows, in combination with increased roughage supply during the indoor periods. So the grazing periods per paddock in every year of the study period lasted longer than the target value and the general recommendations.
The wilting period for silage cuts was always very short. Data have not been explicitly recorded, but the standard is 2 days, with cutting and tedding on the first day, and windrowing and ensiling on the second.

Nitrate leaching
Tactical and operational management on 'De Marke' was set up to reduce nitrate concentration to less than 50 mg l^{-1} in the upper groundwater, at the same ensuring the production of enough roughage. During the last years measurements of the nitrate concentration showed average values of 65 mg l^{-1} (Boumans *et al.*, 2001). Calculations with the model NURP ('1999 high' in Figure 4-7) show nitrate concentrations of 65 mg l^{-1} under grassland, which is in good agreement with the measurements. The '1999 high' situation refers to the grazing system and to the N rate of 1999 and the years before, i.e. 8 hours daily grazing for dairy cows, a long grazing period for heifers and an annual N rate of 250 kg ha^{-1}.

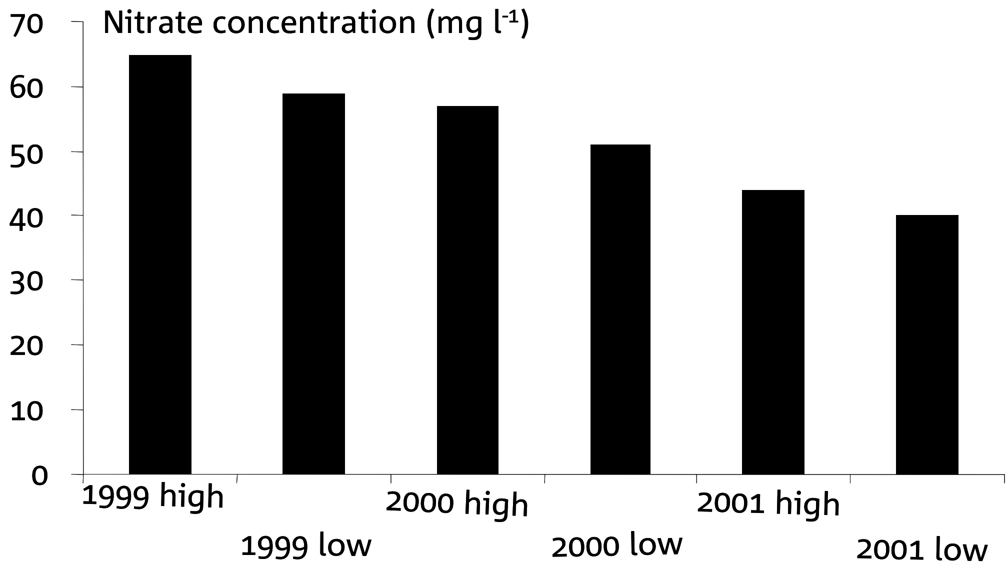

Figure 4-7. Nitrate concentration in the upper groundwater at 'De Marke', calculated with the model NURP (Vellinga *et al.*, 2001), for three grazing systems and two levels of fertiliser N application on grassland (see text for explanation).

A reduction in N rate to 190 kg ha^{-1}, i.e. the average of irrigated and non-irrigated farming systems (Table 4-3), without changing the grazing system ('1999 low' in Figure 4-7), reduces the nitrate concentration, but not sufficiently.
The planned reduction in grazing duration at 'De Marke' (6 hours per day, heifers graze till 1 November ('2000 high' in Figure 4-7)) does not lead to a satisfactory reduction in nitrate concentration.
Restricting grazing duration in combination with a lower N application level of 190 kg ha^{-1} ('2000-low' in Figure 4-7) reduces the nitrate concentration in the upper groundwater to 51 mg l^{-1}.
A more severe restriction of grazing duration, as proposed for 'De Marke' in 2001 (dairy cows grazing 4 hours per day, heifers and calves permanently housed), reduces the nitrate concentration to values well below 50 mg l^{-1}. This is the case in situations with 250 kg N ha^{-1} ('2001-high' in Figure 4-7) and with 190 kg N ha^{-1} ('2001-low' in Figure 4-7). In the '2001-low' situation there is enough room for grazing calves and heifers, which is attractive from the point of view of animal welfare, animal health and a positive image to society. In general, reductions in nitrate leaching are attainable through a combination of restricting grazing and N application levels.
NURP provides no information on the effect of the deviations in operational management. But it can be expected that light grazing cuts and late slurry applications will contribute to nitrate leaching. Long grazing periods per paddock are not expected to have any effect on nitrate leaching.

4.5 Discussion

Improved management is an important issue in the reduction of N losses on dairy farms. It is tried out in experimental farming systems like 'De Marke', but also in monitoring projects (Beldman, 1997b; Rougoor *et al.*, 1999a; Oenema *et al.*, 2001). Comparison of 'De Marke' with monitoring projects will provide information about the 'state of the art' in operational and tactical grassland management in The Netherlands.

Transfer of N surpluses

The average MINAS N surplus on 'De Marke' was 80 kg ha^{-1} (Aarts *et al.*, 1999), which is below the planned levels (Van Den Brandt & Smit, 1998). The low average surplus for the farm as a whole is the result of a low N rate on maize land and a relatively high annual N rate on grassland. The low N rate on maize land leads to surpluses that are much lower than the MINAS levels and will reduce nitrate leaching under maize to acceptable levels (Aarts *et al.*, 1999). The difference

between the MINAS level and the actual level on maize land is partially transferred to grassland, because N uptake by grass can be high. We therefore expect nitrate leaching under grassland to fall below 50 mg l^{-1}. The transfer leads to an annual N rate on grassland that is higher than calculated for pure grassland farms with a MINAS surplus of 140 kg ha^{-1} (Table 4-3). It can be shown from measurements (Boumans *et al.*, 2001) and by the NURP model calculations that a high N surplus on grassland leads to nitrate concentrations above 50 mg l^{-1}. This indicates that transfer of the N surplus from maize land to grassland should be avoided.
A consequence is that annual N rates on grassland could be reduced by 60 kg to about 190 kg ha^{-1}, which in turn will lead to a decreased DM yield. Assuming a DM response to N of 10-15 kg per kg N, DM yield decreases with 600 to 900 kg ha^{-1} per annum. Many dairy farms in The Netherlands have to reduce N rates on grassland (Van Den Brandt & Smit, 1998) and will also be facing reduced DM yields.

The importance of good operational management

Reduction of fertiliser inputs should be combined with optimising the N utilisation on the farm as a whole (Aarts *et al.*, 1992; Beldman, 1997b, Burns, 1997; Laws *et al.*, 2000; Koskamp *et al.*, 2001). This will serve two goals. In addition to reduced inputs, optimising N cycling will reduce N losses even more and can partly compensate the decrease in DM production. The main road to N surplus reduction and improved N utilisation on dairy farms runs on the strategic and tactical level. Measures advised are: (i) increasing milk production per cow, (ii) reducing the number of young stock, (iii) increasing slurry storage, (iv) technically improving slurry application, (v) reducing inputs of fertilisers and concentrates, (vi) replacement of fertilisers by white clover, and (vii) reducing grazing losses by changing the grazing system. In operational management a better timing of slurry application and use of recommendation programmes for fertiliser application are the most used ways to maintain DM production as high as possible. Realising target yields for grazing and grazing periods per paddock are not explicitly mentioned, except for ‘De Marke’. As much attention has already been paid to improvement of strategic and tactical choices on dairy farms, it is important to know whether the operational grassland management on ‘De Marke’ is general practice or not.

Comparison with ‘Management on Sustainable Dairy Farms’

Although no explicit operational goals have been set in the monitoring project ‘Management on Sustainable Dairy Farms’, except for using a fertiliser recommendation computer programme, grassland management has been registered very well. Comparing the results of this project with the model in Figure 4-1 and the recommendations in Table 4-1, the following data can be obtained:

- Actual N rates for grazing and cutting were 5-10 kg higher than recommended (Beldman, 1997c). The main reason was that effective N from slurry was underestimated. Slurry applications after 1 August were about 10 to 15% of the total amount of slurry applied (Beldman, 1997a).
- The realised yield for grazing was not measured, but the average growing period for a grazing cut was 15 days (Holshof, 1997a). So, the grazing yield on the monitoring farms will probably have been lower than at 'De Marke', although drought incidence generally is lower. The average number of growing days for cutting was 28. For grazing and cutting this is 5 days less than at 'De Marke'. Rougoor *et al.* (1999a) found that there is a clear relationship between farmers' behaviour in grazing and in cutting management, which also suggests that low yields for grazing are often 'accompanied' by low yields for cutting.
- The low DM yields for grazing have been supported by rather high herbage N contents of 41 g per kg DM (Holshof, 1997b).
- Average growing time for grazing and silage cuts was 15 and 28 days, respectively, with very little difference between the first and the second half of the growing season.
- The average grazing time per paddock on the monitoring farms was 3.7 days, which is closer to the recommendations than the results of 'De Marke', although large variations are seen between farms and between paddocks per farm (Holshof, 1997a). Also Rougoor *et al.* (1999a) found that on many farms the average grazing period per paddock lasted more than 4 days.

Although the annual N rate is mentioned as an aspect of tactical management, it is a result of N rates per cut and thus is strongly related to operational management. N fertiliser recommendations based on the same target rate per annum can lead to different results in different years, caused by different weather conditions (Beldman, 1997c). Farmers in the monitoring project 'Management on Sustainable Dairy Farms' responded to these differences to a limited extent. The N rate on grassland of 'De Marke' during the last 4 years showed some variation, giving the impression that different weather conditions did affect the grassland management.

We therefore can conclude that operational grassland management of 'De Marke' is a good example of a group of farms that work intensively with nutrient management. This means that conclusions based on data of 'De Marke' can be useful in general.
The central items where operational grassland management can be improved are: (i) low DM yield for grazing, especially in relation to the N rate per cut, (ii) long grazing periods per paddock, and (iii) slurry applications after 1 August.

Combining increased grazing yield and reduced grazing time per paddock
As mentioned before, a DM yield for grazing of 1700 kg ha^{-1} is based more on practical than on scientific evidence. Grass should not have too many stems, and growing periods for grazing cuts should not last longer than four weeks to prevent the presence of dead leaves in the herbage allowance (Lemaire, 1988). The data show that in most cases a yield of 1700 kg is not realised. Low DM yields lead to low N responses and relatively high herbage N contents (Vellinga *et al.*, 1993). As a result, a high utilisation frequency leads to lower annual DM yields as well as lower N rates (Vellinga & André, 1999).
The popularity of low DM yields for grazing is related to the emphasis on milk production, the avoidance of risks and visual advantages. Young grass has a high-energy content, is supposed to be very tasty and should guarantee a high herbage intake, and thus is important for high yielding dairy cows. It is assumed that grazing efficiency is higher and paddocks are left 'clearer'.
However, Meijs (1980) found that grazing efficiency depends on the herbage allowance per cow per day and not on the DM yields per hectare. Long grazing periods per paddock start with very high herbage allowances, which will lead to higher grazing losses. This in turn will result in lower silage yields, because more grassland is needed for grazing (Boxem, 1982). If it is assumed that paddock size will not change, grazing at low DM yields per hectare will lead to shorter grazing periods and thus to lower grazing losses. On many farms the number of dairy cows decreased as a result of a combination of increased milk production and the fixed milk quota system. Consequently, the only way to reduce grazing losses without reducing paddock size was to graze at low DM yields, with a relatively low annual DM production as a side effect. If paddock size does not change, grazing at higher DM yields will lead to longer grazing periods per paddock and to higher grazing losses. In other words, for grazing, the combination of increased DM yields and reduced paddock size is essential for optimising grass production and grass utilisation on dairy farms. This is confirmed by Rougoor *et*

al. (1999a). The relationship between DM yield for grazing and paddock size can be described by the formula:

$$\text{Paddock size (ha)} = \frac{\text{(gross) daily herbage intake (kg day}^{-1}\text{) x target grazing days per paddock (days)}}{\text{DM yield (kg ha}^{-1}\text{)}}$$

To prevent problems with very small paddocks, flexible fences can be used if silage cuts are made. Such fences can be removed easily and provide the possibility of changing paddock size when grazing systems change, as is the planning on 'De Marke'.
Grazing at higher DM yields carries the risk that in periods with favourable growing conditions grass could be too long for grazing. It thus requires careful planning and higher management qualities, but also another attitude towards risks and visual effects.
More careful planning and another attitude towards risks might also prevent the use of planned silage cuts for grazing (Figure 4-2).

Earlier slurry application
Storage capacity for slurry is an important reason for applying slurry in late summer (Van De Vegte, pers. comm.; Beldman, 1997a). At the same time, slurry application in spring will be delayed till after 15 March, to reduce the risk of leaching (Aarts *et al.*, 2001). To prevent late applications, the slurry storage capacity should be increased and slurry should be applied as early as possible. Recent experiments on sandy soils have shown limited leaching risks and high N utilisation of early slurry application after 1 February (Den Boer, 1999; Bussink, 1999). Also the amount of slurry applied might be increased, from 20 m^3 to, for instance, 30 and 25 m^3 for the first and second cut respectively. Slurry application should be discontinued after 1 July to prevent effective N being available in November.

The gain of good grassland management
It is difficult to provide exact figures on the advantage of increased grazing yields, reduced grazing periods per paddock, and earlier slurry applications, but impression can be given using estimates.

- Reducing grazing periods from 6 to 4 days is expected to reduce grazing losses from more than 25 to less than 20%. In case of 8000 kg DM ha^{-1} and 50% grazing, this means 200 kg DM.

- Increased growing periods per cut are expected to lead to increased DM yields of about 200 kg DM ha^{-1}.
- About 200 to 400 m^3 slurry has been applied after 1 August, which on average is about 10 m^3 per hectare of grassland. About 5-10 kg N ha^{-1} is lost. Assuming a DM response of 10 kg per kg N, this loss is comparable with about 50-100 kg DM ha^{-1}, especially if this N is applied earlier in the growing season.

In total an amount of about 450-500 kg DM ha^{-1} can be gained. This figure of course depends on the farm situation and on the farmers' actual grassland management. Although good operational grassland management cannot fully compensate the decrease in DM production, it can contribute to good grassland production.
The reduction in nitrate leaching is difficult to quantify. On the one hand, improved operational management gives room to reduced N inputs, on the other, increased grazing yields will lead to lower herbage N contents and lower N intake by cattle. Earlier slurry applications will reduce the potentially leachable N at the end of the growing season. Therefore, although quantification is difficult, the effects on nitrate leaching are positive.

4.6 Conclusions and recommendations
Analysis of grassland fertilisation and utilisation parameters according to the grassland utilisation scheme as shown in Figure 4-1 shows opportunities for improving operational grassland management by the following measures.

- For grazing and cutting, target yields of 1700 and 3000 kg DM ha^{-1} respectively, should be aimed at to increase annual grass production and improve N utilisation efficiency.
- To increase grazing efficiency, the grazing period per paddock should be reduced to a maximum of 4 days. This can be achieved by adjusting paddock size. There is a strict relationship between daily herbage intake, grazing DM yield, grazing period per paddock, and paddock size.
- Slurry should be applied as early as possible to improve N utilisation efficiency and to restrict late autumn grass production.
- The decrease in grass production by reduced rates of N fertiliser can be partially compensated by a combination of grazing and cutting at higher DM yields per cut, shorter grazing periods per paddock and earlier slurry application.

- Improved operational grassland management can help to reduce nitrate leaching.
- The grassland utilisation scheme proved to be a useful tool in analysing and improving grassland management
- At ‘De Marke’ a combination of restricted grazing and reduced rates of N fertiliser, higher grazing yields, shorter grazing time per paddock, and earlier slurry application provides ample scope for reduced nitrate leaching on dry sandy soils.

Chapter 5

Grassland management and nitrate leaching, a model approach

Vellinga, T.V., A.H.J. Van Der Putten and M. Mooij, 2001. Grassland management and nitrate leaching, a model approach. Netherlands Journal of Agricultural Science, 49 , 229-253.

5 Grassland management and nitrate leaching, a model approach

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

5.1 Introduction
Nitrate concentrations in the upper groundwater in The Netherlands are high (Fraters *et al.*, 1998) and should be reduced to values below 50 mg l^{-1} (Anonymous, 1991a). Intensification of agriculture through increased numbers of cows, increased use of chemical fertilisers and ploughing of old grassland for arable land and leys, leads to an increase in nitrate leaching (Ryden *et al.,* 1984; Aarts *et al.,* 1992; Whitmore *et al.*, 1992). On dairy farms there generally is a certain long-term relationship between fertiliser inputs and stocking rates (Van Burg *et al.*, 1981), but in the short term there is a large independent variation between individual farms in stocking rate, milk production level, grazing system, supplemental feeding, the ratio dairy cows/young stock and susceptibility to drought (Reijneveld, 2000). This between-farms variation received little attention in experiments and modelling on nitrate leaching.
The combined effects of grazing and fertilisation on nitrate leaching have been studied extensively (e.g. Van Der Meer *et al.*, 1987; Benke *et al.*, 1992; Barraclough *et al.*, 1992; Cuttle & Bourn, 1993; Scholefield *et al.*, 1993; Clough *et al.*, 1996; Hack-Ten Broeke *et al.*, 1996, 1999; Vertès *et al.*, 1997). In some experiments the fate of urine nitrogen (N) in relation to time of deposition is studied (Whitehead & Bristow, 1990; Cuttle & Bourn, 1993; Fraser *et al.*, 1994; Clough *et al.*, 1996; Vertès

et al., 1997; Simon *et al.*, 1997; Hack-Ten Broeke & Van Der Putten, 1997). Adaptations in operational grazing management based on these findings show clear decreases in nitrate leaching (Titchen *et al.*, 1993; Lord, 1993; Holshof & Willems, 2001). The mentioned experiments suggest that changes in grassland management could be helpful to reduce nitrate leaching on dairy farms. Especially the combination of several management factors is very effective in reducing N surpluses (Aarts *et al.*, 1992). A model with focus on the large variation in grassland management on dairy farms can be very helpful to find the best changes in management to reduce nitrate leaching that are suitable for the individual farm. To calculate the effect of fertiliser level and grazing on nitrate leaching, models have been developed at catchment scale (Rodda *et al.*, 1995), at farm scale (Van Der Meer & Meeuwissen, 1989; Scholefield *et al.*, 1991; Goossensen & Van Den Ham, 1992), or at plot scale (Decau *et al.*, 1997; Delaby *et al.*, 1997). But a model that focuses on a wide range of grassland management aspects, especially for Dutch farming conditions, is not yet available.
Therefore, a model was developed that would meet the following requirements:

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

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

Table 5-1. Aspects of strategic, tactical and operational grassland management on dairy farms.

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

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

5.2 Model structure

Grassland management can be divided into strategic, tactical and operational management, covering long-, intermediate- and short-term decisions, respectively (Huirne, 1990; Kay & Edwards, 1994). Strategic and tactical management concern the whole farm, they are not paddock-specific (Table 5-1). Operational aspects of grassland management are related to decisions that can vary from paddock to paddock.

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

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

A simple scheme of this part of the model is shown in Table 5-2. The nitrate concentration in the farm's groundwater is calculated from Soil Mineral Nitrogen

Table 5-2. Parameters used for the calculation of Soil Mineral Nitrogen (SMN) components in the NURP model, and of the nitrate concentration at the end of the growing season.

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

(SMN; in kg ha^{-1}), precipitation surplus and a denitrification factor (Table 5-2, the lowest line). SMN is the sum of non-harvested N from fertilisation and N from urine (Table 5-2, the second line from below). The average amount of urine N per ha on the farm is calculated per month and depends on the N intake and utilisation per animal, the number of animals, their daily grazing hours and the total farm area. Urine N is not evenly distributed. The urine spots, with high N loads, are scattered over the grazed area. As most of the grassland is grazed several times during the grazing season, urine spots from consecutive grazings may overlap, which locally may lead to extremely high N loads. The combination of urine N returns and covered area, with growth depression by drought and scorch, defines the monthly contribution to $SMN_{grazing}$. $SMN_{cutting}$ is calculated for the complete growing season.

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

The parameters of the relationship between $SMN_{cutting}$/$SMN_{grazing}$ on the one hand and tactical and strategic management factors on the other are derived from simulation of operational management (part 2 of the model), i.e., grass production and utilisation per paddock and per cut as shown in Figure 5-1. This figure is based on the flow diagram of operational grassland management by Vellinga & Hilhorst (2001).

Slurry and chemical fertilisers are applied per cut. Non-harvested N is an accumulation from several cuts. Grass is used per cut and the herbage N content is the result of N rates and grazing yields per cut. The area covered by urine N and the overlap of urine spots are the result of the grazing time per cut and the number of grazings per paddock. The rules for good operational grassland

management as described by Vellinga & Hilhorst (2001) are used as standard in the calculations.
The steps of N uptake per cut, N intake and utilisation by animals and the area covered by urine are discussed in more detail.

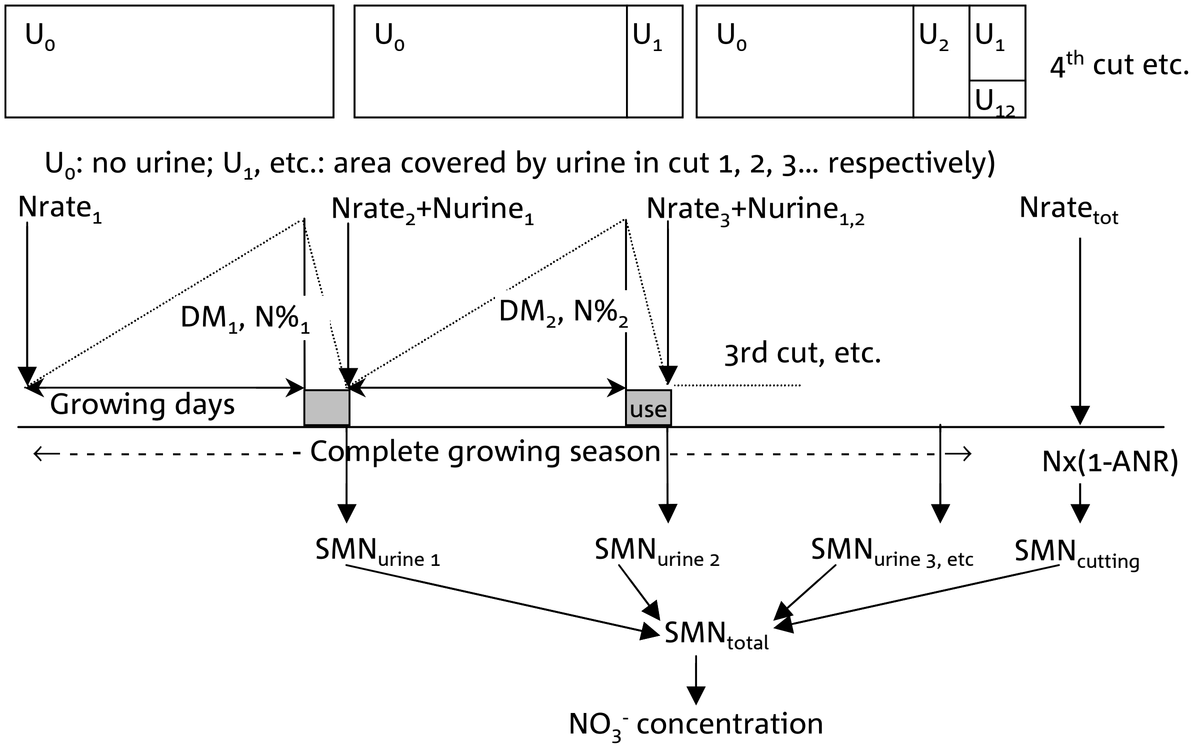

Figure 5-1. Scheme of grassland utilisation with a rotational grazing system, and the way the accumulation of SMN is calculated. N rates per cut consist of effective N from slurry and N from chemical fertiliser. After the first grazing, grass production is also affected by N from urine. Dry matter yields per cut and related herbage N content are realised after a number of growing days and are used for grazing or cutting. Total N rates per year (N_{tot}) are the sum of the N rates per cut. After grazing, part of the area is covered with urine (schematised); after repetitive grazing overlap of urine spots occurs. SMN from urine is calculated per cut; SMN from fertiliser is calculated over all cuts at the end of the growing season. Total SMN is the sum of $SMN_{grazing}$ and $SMN_{cutting}$ and is subject to leaching.

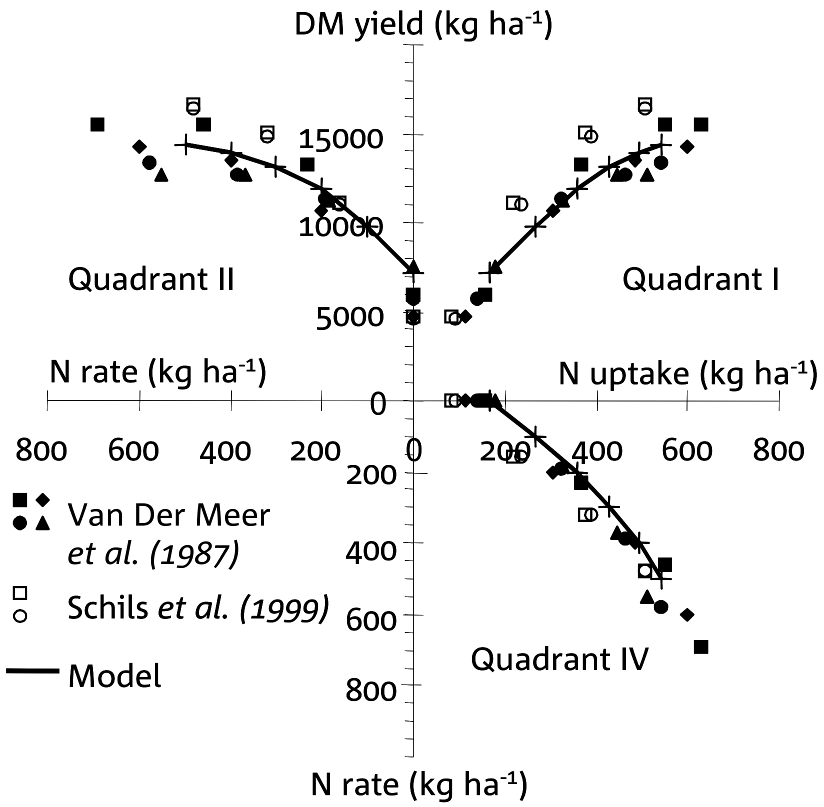

Figure 5-2. Effects of N fertiliser application on N uptake (quadrant IV), DM yield (quadrant II), and nitrogen use efficiency (NUE) (quadrant I) for the grass production model (lines) and for the experiments of Van Der Meer *et al*. (1987) (closed symbols) and Schils *et al*. (1999) (open symbols).

Dry matter yield and N uptake at cutting

N is applied per cut. The N rate per cut is a combination of effective N from slurry and N from chemical fertiliser. The relationships between N rates and N uptake and dry matter yield and herbage digestibility for every cut in the grazing season have been derived from growth experiments of Prins *et al*. (1980), Wieling & De Wit (1987), De Wit (1987a; 1987b) and Vellinga (1989). Reduced N uptake by drought is incorporated according to Anonymous (1997b). Simulation of the grass production per cut, resulting in N rates and dry matter yields per ha per year and N recoveries per year are in good agreement with experimental data of the slurry experiments described by Van Der Meer *et al*. (1987) and Schils *et al*. (1999) (Figure 5-2).

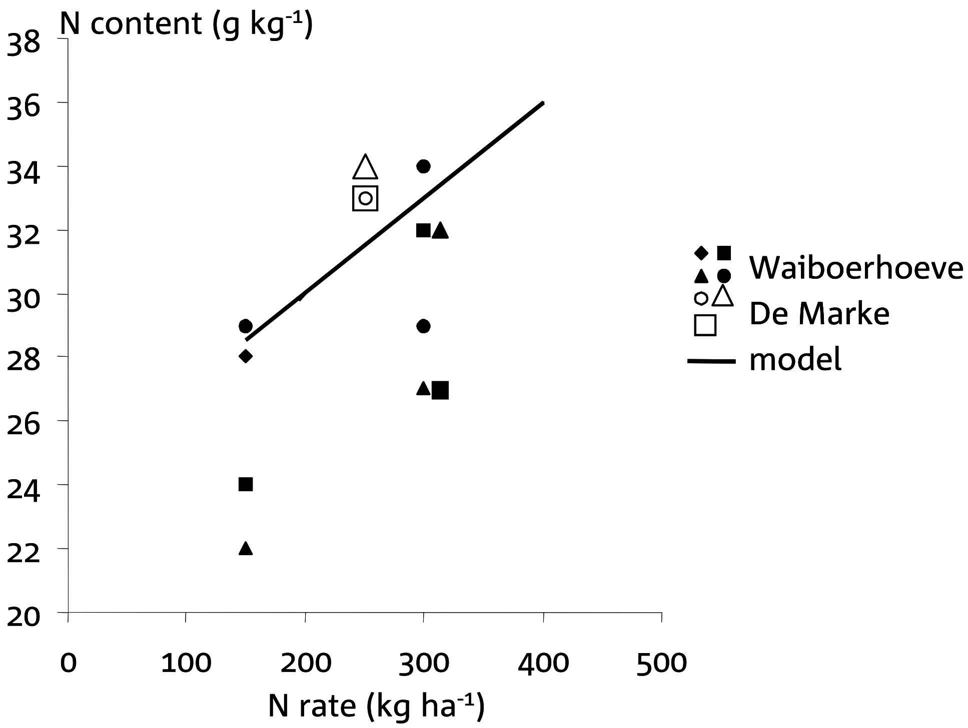

Figure 5-3. N content of the grass used for grazing as affected by the N application rate. Data as calculated by the model, and data from grazing experiments at the Waiboerhoeve (young marine clay) and at 'De Marke' (3 open circles) at 250 kg ha-1 per year.

Comparison of the calculated herbage N content for grazing with data from grazing experiments on clay (Waiboerhoeve, unpublished data) and at 'De Marke' from 1997-1999 (Vellinga & Hilhorst, 2001) (Figure 5-3), shows a strong year-to-year effect, especially on clay soils. Despite this variation, N content of the herbage is estimated satisfactorily.

N uptake and dry matter yield from urine spots

N uptake and grass production are strongly stimulated in urine spots. The N taken up from these spots is calculated in addition to the N uptake from fertilisers. Urine depositions early in the growing season lead to a higher additional N uptake than depositions late in the season (Figure 5-4, Van Der Putten, unpublished data; Hack-Ten Broeke & Van Der Putten, 1997). The higher uptake is caused by the good growing conditions in the first half of the growing season and the long period of N uptake by grass. Apparent N recovery (calculated fraction of deposited N taken up by the grass) is 70% at the most in the case of early urine depositions. It decreases to 0 for urine depositions at the end of the growing season. This indicates average apparent N recoveries of 30-35%. Additional N uptake and dry matter (DM) yield are suppressed by increasing N fertilisation on the paddock (cf. Cuttle & Scholefield, 1995; Deenen & Middelkoop, 1992). If herbage production is reduced by drought, N uptake from urine spots is reduced proportionally. In the case of overlapping urine spots, additional N uptake is based on the last urine deposition.

Decau *et al*. (1997), reviewing published evidence, calculated an average N recovery of 29%. Fraser *et al*. (1994) reported a 43% real N recovery in one year, Whitehead & Bristow (1990) 21% of urine N over the period August-October, and Clough *et al*. (1996) 11-35% from urine spots. These data were derived from experiments using ^{15}N. Experiments with labelled N suggest that Apparent N Recovery (ANR) is often higher than real N recovery, partly as a result of pool substitution of N (Rao *et al*., 1992). The data obtained by Van Der Putten are in good agreement with the data from the literature.

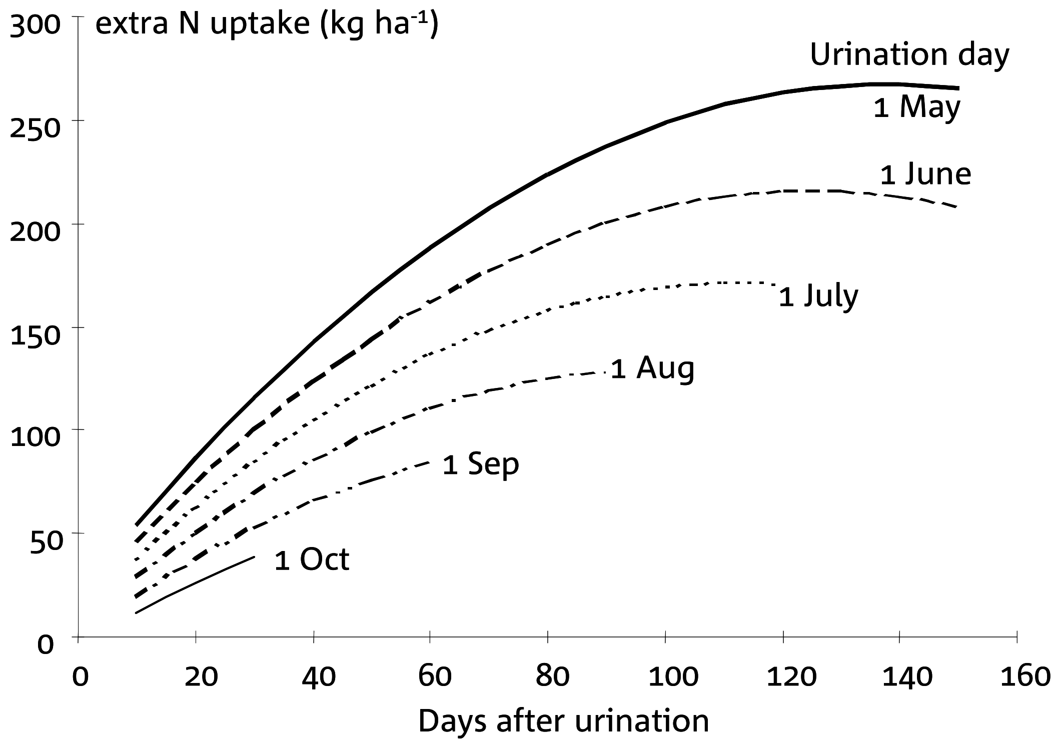

Figure 5-4. Cumulative additional N uptake from urine spots from different deposition days. Fertilisation level 200 kg ha^{-1} $year^{-1}$. N load in the urine spots is equivalent to 400 kg ha^{-1}.

N from dung hardly contributes to nitrate leaching (Lantinga *et al.*, 1987, Deenen & Middelkoop, 1992).
At high fertilisation levels the grass is more susceptible to urine scorch (Lantinga *et al.*, 1987; Deenen & Middelkoop, 1992). Therefore, urine scorch is incorporated optionally in the model. In urine-scorched grass, N uptake from urine and from fertiliser is reduced to zero, which in turn strongly reduces average N recovery from urine. There is no clear relationship between N rate and urine scorch. Moreover, weather conditions play an important role (Lantinga *et al.*, 1987). Hence, a very simple formula was developed in which urine scorch increases from 0% at N rates of 150 to 200 kg N ha^{-1} per year (half the recommended rates) to 50% in June, July and August at recommended N rates of 350 to 400 kg N ha^{-1} per year. This is similar to 25% urine scorch per 100 kg of N.

N utilisation by cows and young stock
N excreted via urine is calculated according to the following Equation.

$N_{urine} = N_{intake} - N_{milk,meat} - N_{dung}$ (Valk *et al.*, 1990) **(1)**
(all quantities in g kg^{-1} day^{-1})

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

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

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

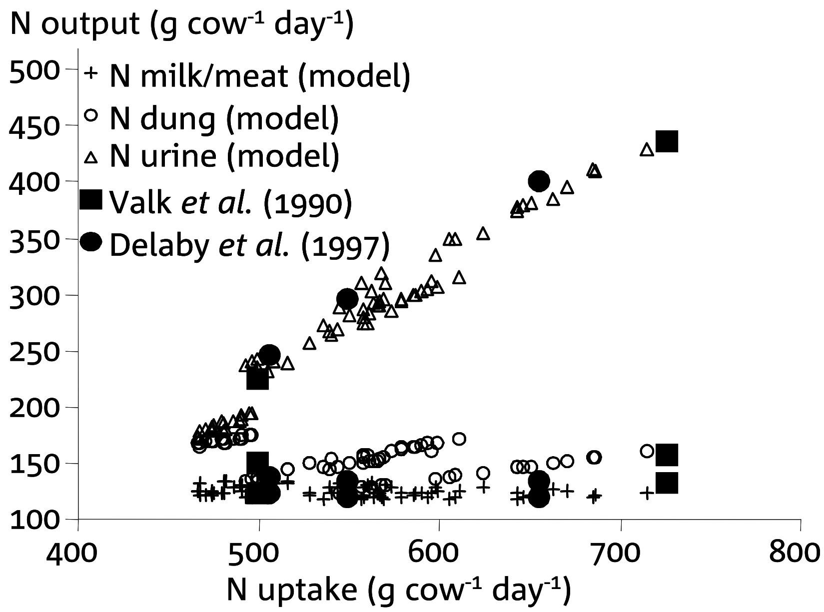

Figure 5-5. Calculated N production in milk/meat, dung and urine of dairy cows producing 7500 kg milk per cow per year as affected by N intake via herbage, maize and concentrates. Results compared with data from Valk *et al*. (1990) and Delaby *et al*. (1997).

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

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

where
U_{day} = daily urine production (litres cow^{-1}), and
N_{urine} = urine N excretion (g cow^{-1}).

Average urine N content varies between 7 and 8 g kg^{-1}. It increases only slightly with increased N excretion, which in turn increases with the amount of urine (Table 5-3). The average urine N content is in good agreement with average data of Vertès *et al*. (1997), although they found considerable variation.

Table 5-3. Characteristics of urine depositions in grassland as affected by the N fertilisation level.

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

Table 5-4. Areas (m^2 ha^{-1}) affected by 0-7 overlapping urine depositions after 7 consecutive grazing periods. Areas calculated by repetitive use (7x) of the non-overlap function and by the Poisson-distribution according to Richards & Wolton (1976).

	Number of urinations							
Urine covered area (m^2 ha^{-1}) by distribution:	0	1	2	3	4	5	6	7
Non-overlap 7x	5863	3253	772	102	8	0	0	0
Poisson	5981	3074	790	135	17	2	0	0

Area covered by urine spots

For dairy cows the area affected by one urination is assumed to be 0.68 m^2 (Lantinga *et al*., 1987). For heifers and calves an area of 0.50 m^2 per urination was assumed. Amounts of 3.5 and 2.5 kg urine per urination were assumed for dairy cows and young stock, respectively. The calculated N 'load' in urine spots is 340-410 kg N ha^{-1}, which is in good agreement with data of Vertès *et al*. (1997). We assumed no preferential behaviour for grazing and urinating nor overlap within one grazing in paddocks with intensive rotational grazing. But urine spots in one grazing can overlap with urine spots from a previous grazing. The chance of being 'hit' by a urine spot in a second grazing is proportional to the affected and non-affected area in the first grazing. In the case of three grazings, single, double and triple spots are taken into account, and so on. Results of a calculation for seven consecutive grazing events are very similar to those derived from the Poisson distribution developed by Richards & Wolton (1976) (Table 5-4).

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

$$U_t = 0.68 * U_{day}/U_{amount} * n_{animals} * days * \%U \quad \textbf{(3)}$$

where

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

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

Calculation of soil mineral N

N rates and urine N are not completely recovered in the herbage (e.g. Decau *et al.*, 1997; Vellinga & André, 1999) but remain in the soil-plant system. This non-harvested N is in part found back as soil mineral N (SMN) at the end of the growing season (Prins, 1983; Wouters *et al.*, 1995; Tyson *et al.*, 1997; Hack-Ten Broeke *et al.*, 1999). A relationship between non-harvested N and SMN accumulated in the layer 0–100 cm at the end of the growing season has been developed for sandy soils (Figure 5-6) using the equation:

$$SMN_a = -54.5 + 88.3 * \exp(-0.0116678*(SMN_s + N_n)) + 0.774 * (SMN_s + N_n) \quad \textbf{(4)}$$

(R^2 = 0.85; residual mean square = 47.2)

where

- $SMN_{a/s}$ = soil mineral N in the layer 0–100 cm in autumn (a) and spring (s), respectively;
- N_n = N not harvested in the crop: [$N_{applied}$ * (1 - ANR)].

Comparison of model results with data from the experiment System of Adjusted Nitrogen Supply (SANS, Hofstede, 1995a, 1995b; Hofstede *et al.*, 1995) showed good agreement. Only for extreme high amounts of precipitation during

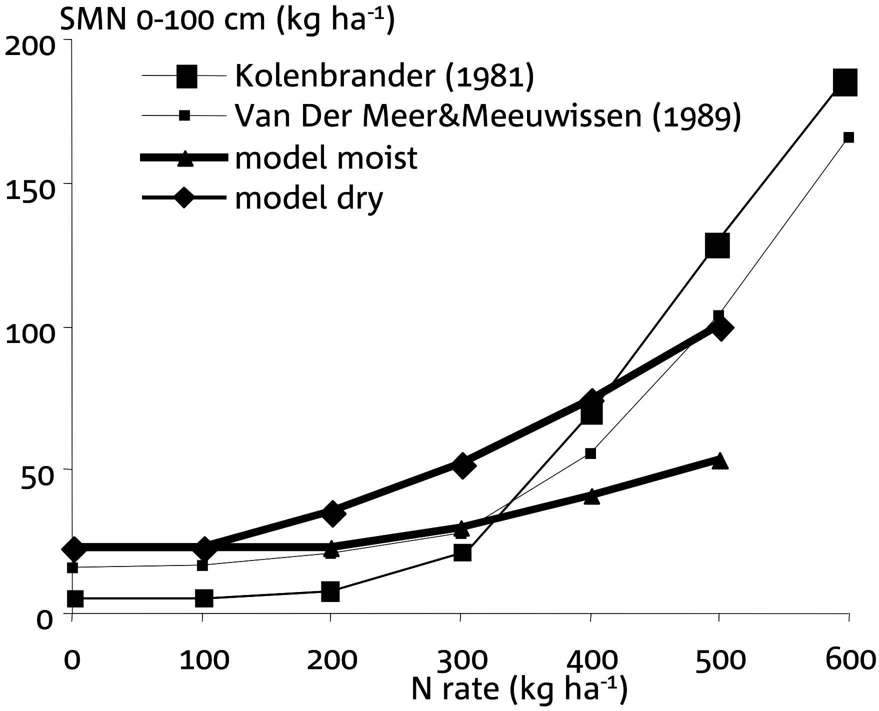

Figure 5-6. Calculated Soil Mineral Nitrogen (SMN) in autumn in the soil layer 0-100 cm of a moist and a dry sandy soil in relaton to N fertliser rate. Results are compared with data from Kolenbrander (1981) and Van Der Meer & Meeuwissen (1989).

the growing season (e.g. 1994) the model overestimates SMN in autumn. The minimum value in the equation is 32 kg N. This value has been adapted for low fertiliser levels to 23 kg N ha^{-1} with data from Wouters & Everts (1996, 1997, 1998, 1999), who observed values below 30 kg N in the 0-100 cm soil layer.
Non-harvested N from the simulation of grass production is used as input in equation (4). The dry sandy soil shows a faster increase in SMN, caused by reduced N uptake under drought (Figure 5-6). Comparison of the calculated SMN for moist, moderately dry and very dry sandy soils with data on nitrate leaching from Kolenbrander (1981) and Van Der Meer & Meeuwissen (1989) shows that the calculated SMN is higher at low N application rates, but that it increases more gradually with increasing N rate than is suggested by the Kolenbrander (1981) and Van Der Meer & Meeuwissen (1989) relations (Figure 5-6). The strong increases in SMN reported by Kolenbrander (1981) and Van Der Meer & Meeuwissen (1989) suggest a strong increase in non-harvested N, indicating a sharp decrease in ANR. This sharp decrease is probably caused by the use of older experiments where ANR was low (Vellinga & André, 1999), or by drought sensitivity. It was concluded

that in the range of N rates of 0-50 kg N ha^{-1} calculated SMN values agree satisfactorily with data from literature.
SMN from urine N is higher in late depositions (Van Der Putten, unpublished data), as shown by the following equation:

SMN_a = SMN_{start} x (-0.296+ 1.2979/ (1 + 0.01841 x days between urination and 1 November; **(5)**

where

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

SMN decreases very fast immediately following deposition. Although Cuttle & Bourn (1993) also reported high initial losses of N, they assume that denitrification, ammonia volatilisation and very fast leaching could not fully explain the observed losses. Whitehead & Bristow (1990) assume rapid loss via soil micropores and measured about 18% ammonia volatilisation in about two weeks. Fraser *et al*. (1994) and Clough *et al*. (1996) did not measure these losses, but calculated them via ammonia volatilisation (16-56%) and denitrification (28%), to complete the N balance.
Under dry conditions and in case of urine scorch the uptake of N from fertiliser and urine is reduced and the N not taken up is fully added to the SMN.

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

NO_3^- concentration = 62/14 x SMN x DNF / Precip. x 10^4 **(6)**

where

SMN = Soil Mineral Nitrogen in the soil layer 0-100 cm (kg ha^{-1});

DNF = denitrification factor, according to Boumans *et al*. (1989);

Precip. = precipitation (mm) during the winter period, according to Van Drecht & Scheper (1998).

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

On lighter sandy soils, Goossensen & Meeuwisen (1990), Barraclough *et al*. (1992) and Cuttle & Bourn (1993) have found good relationships between SMN and nitrate leaching. On sandy soils, SMN in autumn is completely leached during the winter period (Rück & Stahr, 1996; Holshof & Willems, 2001). On the other hand Lord *et al*. (1995) and Rück & Stahr (1996) hardly found any relationship, SMN and leaching are examined over a range of soil types and crops.
The denitrification factor only corrects for denitrification losses during the winter period. On dry sandy soils little denitrification occurs during that season (Boumans *et al.*, 1989; Corré, 2000) but on moist soils denitrification can be strong (Boumans *et al.*, 1989).

Validation and uncertainty analysis
So far the different steps of the model have been validated. Despite satisfactory agreement between the model formulae and the data from literature, a large variation was sometimes found. Validation of the complete model is still necessary.
The number of data sets for validation is limited. However, the monitoring programme carried out by RIVM (Fraters *et al.*, 1998) is based on measurements on about 80 farms during 4 years. Data from 'De Marke' are based on a 6-year period (Boumans *et al.*, 2001). Data are also available for two commercial farms on dry sandy soils.

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

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

Table 5-5. Parameter ranges for the calculation of the uncertainty analysis of NURP.

Formulae/parameters	Range
N uptake by grass from fertiliser and slurry	+/- 25 kg N ha^{-1} (Schils *et al.*, 1999)
N uptake by grass from urine spots	+/- 25%
N surplus in the animals ration	+/- 25%
Size urine spot	+/- 25%
Urine scorch	+/- 100%
$SMN_{cutting}$	+/- 25%
$SMN_{grazing}$	+/- 25%
Precipitation surplus in the leaching period	+/- 25%
Denitrification correction	+/- 50%

Table 5-6. Input data for the NURP model to calculate the nitrate concentration in the upper groundwater at 'De Marke' and on dairy farms on dry sandy soils, according to Fraters *et al*. (1998).

	'De Marke'			Fraters *et al*. (1998)		
Area (ha)	31			20		
Fertiliser level (kg ha^{-1})	250			80-450		
Groundwater table depth (m)	1.20-2.00	(min -max)		-		
Yield reduction by drought (%)	15			21		
Animals:	Dairy cows	Heifers	Calves	Dairy cows	Heifers	Calves
Number	65	21	22	40	19	20
Milk production (kg cow^{-1} $year^{-1}$)	8500			6500		
Grazing regime						
April	H[1]	H	H	H	H	H
May	D+6[2]	DN	H	DN/D+4[3]	H	H
June	D+6	DN	DN	DN/D+4	DN	DN
July	D+6	DN	DN	DN/D+4	DN	DN
August	D+6	DN	DN	DN/D+4	DN	DN
September	D+6	DN	H	DN/D+4	DN	H
October	H	DN	H	DN/D+4	DN	H
November	H	DN	H	H	H	H
Calculated NO_3^- conc. (mg l^{-1})	65			See Figure 5-7		
Measured NO_3^- conc. (mg l^{-1})	63			See Figure 5-7		

[1] Housed.
[2] Day grazing with 6 kg DM of maize silage as supplement.
[3] Day-and-night or day grazing, with 4 kg DM of maize silage as supplement.

5.3 Results and discussion

Model validation

Comparison of the farm model with results of extensive measurements by the National Institute of Public Health and the Environment (RIVM; Fraters *et al.*, 1998) is shown in Table 5-6 and Figure 5-7. The method of Fraters *et al*. (1998) is based on N surpluses, so the fertiliser levels from NURP were translated into N surpluses. It was assumed that up to a fertiliser level of 340 kg N ha^{-1} $year^{-1}$, 1 kg

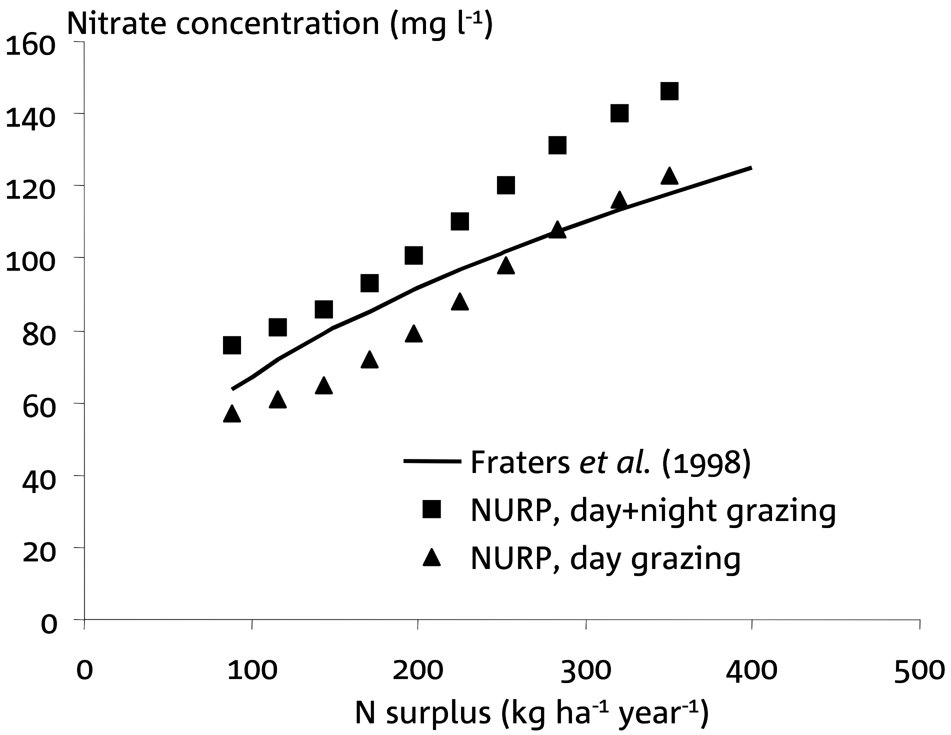

Figure 5-7. Nitrate concentrations in the upper groundwater as affected by the N surplus at farm level. Measurements by Fraters *et al.* (1998) compared with data calculated by the NURPmodel for two grazing systems on dry sandy soils.

increase in N-fertiliser leads to an increase of 0.7 kg N surplus. This is in agreement with the data from Willems *et al.* (2000). For fertiliser levels above 340 kg $ha^{-1}.year^{-1}$ it was assumed that each kg fertiliser N increases the surplus by 1 kg, because at such levels of N fertiliser application additional dry matter yield production on dry sandy soils is very low. In their regression model Fraters *et al.* (1998) neither defined a grazing system nor a stocking rate. We calculated the effect of day-and-night grazing and of day grazing, with a fixed stocking rate of 2 cows per ha, with associated young stock (ratio dairy cows/young stock = 1:1).
For day-and-night grazing, the model calculates equal or higher nitrate concentrations than found by Fraters *et al.* (1998) for the complete range of fertiliser levels, while for day grazing equal or lower values are calculated (Figure 5-7).
The regression model of Fraters *et al.* (1998) shows that the relationship between fertiliser level and nitrate concentration levels off. This might be associated with a change in grazing system. Extensive farms – with low surpluses – probably prefer day-and-night grazing, whereas intensive farms, - with high surpluses – prefer day

grazing. Another reason could be that in the lower surplus range increasing surpluses are related to increasing stocking rates, while this is not the case in the higher surplus range.
It can be concluded that the steeper slope of our model is not in contradiction with the results of the RIVM measurements.
Using characteristics of the 'De Marke' dairy farm (Table 5-6), the NURP-calculated nitrate concentration on grassland is on average 65 mg l^{-1}. The measurements described by Boumans *et al*. (2001), and corrected for weather conditions, show an average nitrate concentration of 63 mg l^{-1}. Reported average values for the different years at 'De Marke' are affected by changes in the paddocks used (Boumans *et al*., 2001; Aarts *et al*., 2001). This may lead to somewhat lower nitrate concentrations. The results of our model thus appear in good agreement with measured data. Model calculations by Hack-Ten Broeke *et al*. (1999) show similar results, with an average nitrate concentration for grassland of 67 mg l^{-1}.

Table 5-7. Input data for the NURP model to calculate SMN at the end of the growing season for two dairy farms in Mander.

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

[1] Housed.
[2] Day-and-night grazing, with 3 kg DM of maize silage as supplement.
[3] Day grazing with 5 kg DM of maize silage as supplement.

In the autumn of 1999, SMN was measured on two dairy farms on slightly to moderately dry sandy soils near Mander, in the vicinity of the Dutch-German border. The necessary farm characteristics used as input for the NURP model, and the calculated and measured SMN are shown in Table 5-7. Calculated and measured SMN on grassland are virtually identical for both farms, although there is variation between paddocks.

Uncertainty analysis

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

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

Effect of changes in grassland management

When analysing experiments, the effects of fertilisation level and stocking rate are often confounded (Barraclough *et al.*, 1992; Simon *et al.*, 1997). With NURP these effects can be separated (Figure 5-8a). Calculations were performed for a situation on dry sandy soils comparable with 'De Marke', with dairy cows with an average annual milk production of 7500 kg, grazing only by day, and with 4 kg DM of maize silage as supplementary feed. The ratio dairy cows/young stock was 1:1. Doubling the stocking rate from 1.0 dairy cow (+ young stock) to 2.0 dairy cows per ha, at N fertiliser levels of 150 and 350 kg N ha^{-1}, results in an increase of calculated nitrate concentrations of 16 and 27 mg l^{-1}, respectively. Increasing N fertiliser level at constant stocking rate leads to doubling of the nitrate concentration, from 39 and 56 to 78 and 105 mg l^{-1} for the low and high stocking rate, respectively. A marked increase in nitrate leaching from 40 to 88 mg l^{-1} as a combined effect of increasing stocking rate (from 1.0 to 1.5 cows per ha) and - to meet fodder demand - increasing fertiliser application (from 150 to 350 kg N ha^{-1}), is also found in literature (Vertès *et al.*, 1997). This suggests that extensification is an effective way to reduce nitrate leaching.

The importance of grazing is also shown in Figure 5-8b. Increasing grazing time from 8 to 20 hours per day and reducing protein-poor supplements, leads to a strong increase of urine N and consequently to a strong increase in nitrate concentration in the upper groundwater. Reduction of grazing time has been mentioned as an effective way of reducing nitrate concentration (Aarts *et al.*, 1992). Increasing low-protein supplementation to 10 kg dry matter per cow per day only leads to a very small reduction in nitrate concentrations.

Increased milk production at the same stocking rate slightly increases nitrate concentrations (Figure 5-8c) and seems an ineffective way to reduce nitrate concentrations. But with the fixed milk quota per ha, increased milk production will lead to lower stocking rates and thus to lower nitrate concentrations. Keeping less young stock is another way to reduce grazing and also is an effective way to reduce nitrate leaching (Figure 5-8d). On many dairy farms in The Netherlands the ratio dairy cows/young stock is high, i.e. between 1:0.8 and 1:1. On these farms reducing young stock is effective. On farms with low replacement ratios, like organic farms, further reduction is not possible.

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

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

In the foregoing the importance of reduced grazing was demonstrated. Following the introduction of automatic milking, many farmers tend to house the dairy cows permanently. As a reaction the ministry of Agriculture, Nature Management and Food Quality and the farmers organisations want to stimulate grazing. From this point of view it is interesting to know whether reduced grazing at the end of the growing season will be more effective in reducing nitrate concentrations than reduced or no grazing during the whole season. On most dairy farms in The Netherlands grazing is continued until 1 November. Grazing of dairy cows at 'De Marke' already stops on 1 October, and from the year 2000 onwards the dairy

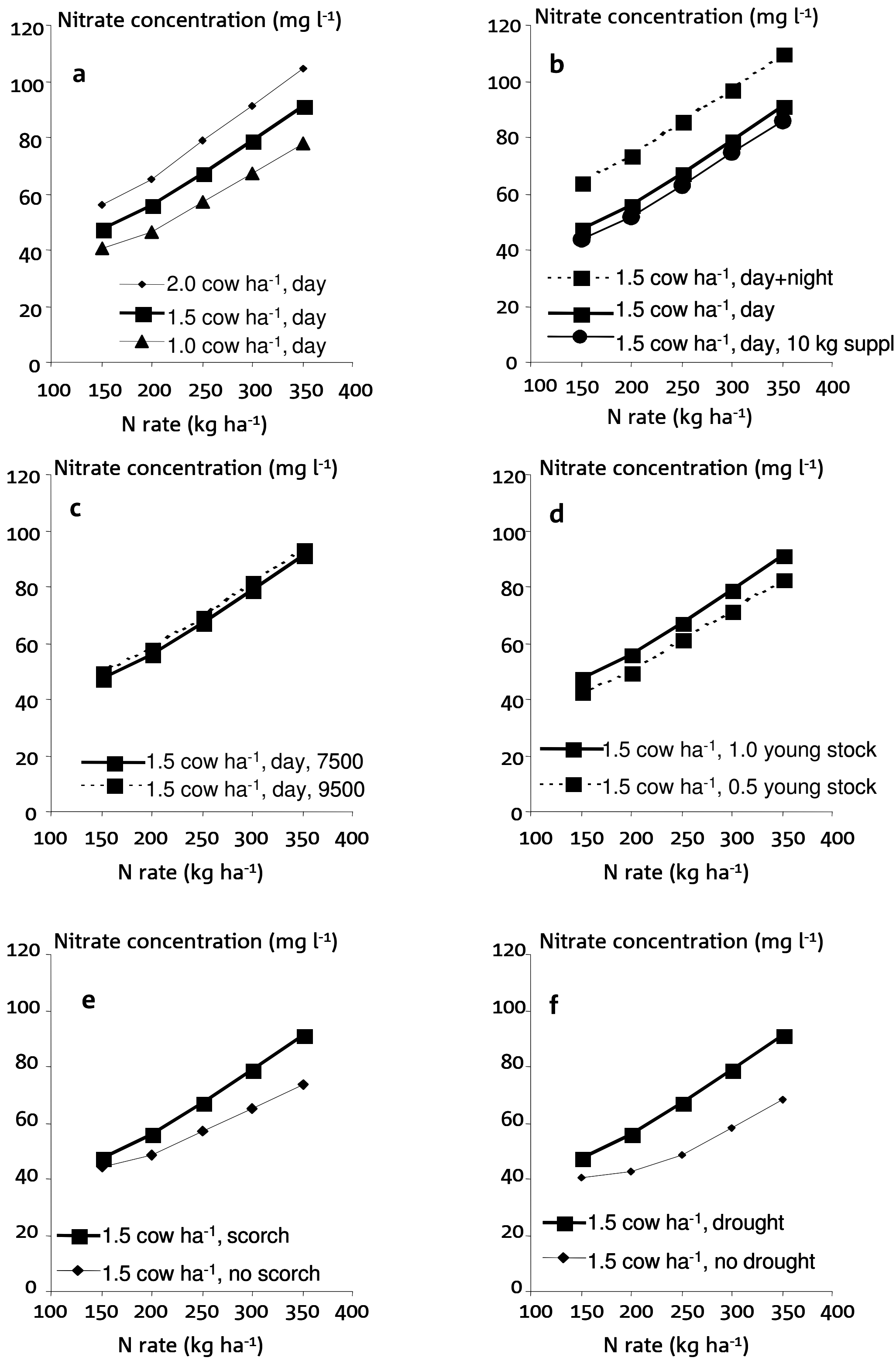
Nitrate concentration (mg l-1)
a
2.0 cow ha-1, day
1.5 cow ha-1, day
1.0 cow ha-1, day
N rate (kg ha-1)
Nitrate concentration (mg l-1)
b
1.5 cow ha-1, day+night
1.5 cow ha-1, day
1.5 cow ha-1, day, 10 kg suppl
N rate (kg ha-1)
Nitrate concentration (mg l-1)
c
1.5 cow ha-1, day, 7500
1.5 cow ha-1, day, 9500
N rate (kg ha-1)
Nitrate concentration (mg l-1)
d
1.5 cow ha-1, 1.0 young stock
1.5 cow ha-1, 0.5 young stock
N rate (kg ha-1)
Nitrate concentration (mg l-1)
e
1.5 cow ha-1, scorch
1.5 cow ha-1, no scorch
N rate (kg ha-1)
Nitrate concentration (mg l-1)
f
1.5 cow ha-1, drought
1.5 cow ha-1, no drought
N rate (kg ha-1)

Figure 5-8. Nitrate concentration in the upper groundwater on a farm with dry sandy soils as affected by N fertiliser levels. The thick line in all figures represents day grazing dairy cows with 4 kg DM silage maize as supplementary feed, a milk production level of 7500 kg per cow per year, a stocking rate of 1.5 cows per ha, and a dairy cows/young stock ratio of 1:1. The figures a-f represent combinations of the basic situation with:

a. Stocking rates of 1.0 and 2.0 cows per ha.
b. Day-and-night grazing dairy cows without supplemental feeding and day grazing with a supplement of 10 kg DM from silage.
c. A milk production level of 9500 kg per cow per year.
d. A dairy cows/young stock ratio of 1:0.5.
e. A situation without urine scorch.
f. A situation without drought.

cows are kept indoors after 1 September. Simulation results with NURP (Figure 5-9) show that if dairy cows are housed one month earlier and heifers are also housed on 1 September instead of 1 December - under otherwise similar conditions - nitrate concentration will decrease from 65 to 54 mg l^{-1}. Titchen *et al.* (1993), Lord (1993) and Holshof & Willems (2001) have reported similar effects of earlier housing of animals.

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

Effect of scorch and drought on nitrate leaching

The contribution of urine scorch to the fertiliser effect on nitrate concentrations is substantial. If the fertiliser level is increased from 150 to 350 kg N ha^{-1}, nitrate concentration increases from 48 to 91 mg l^{-1} (Figure 5-8e). If no urine scorch would occur, nitrate concentration would increase from 45 to 74 mg l^{-1}, i.e. about one third of the concentration increase is associated with urine scorch.

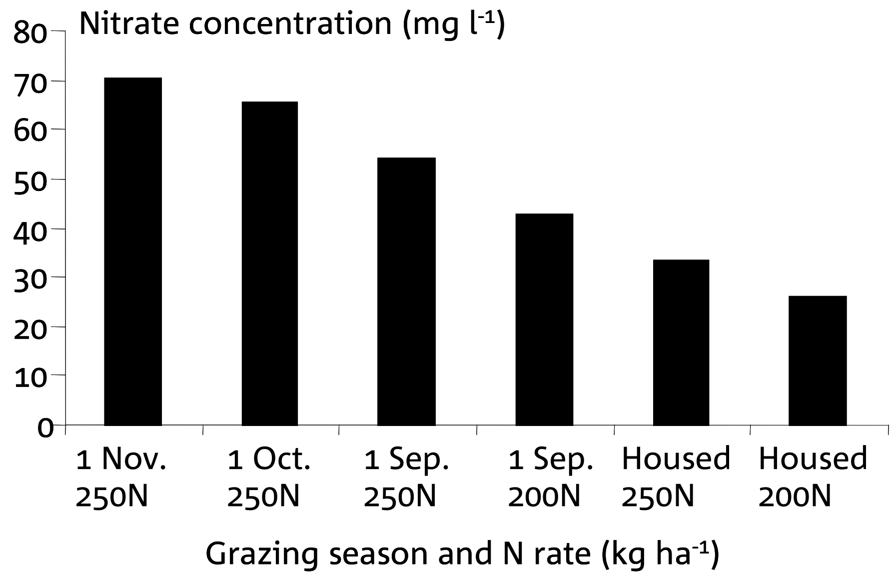

Figure 5-9. Nitrate concentration in the upper groundwater on dry sandy soils, when the cows and heifers are housed earlier in the grazing season, or N fertilisation is reduced, or both grazing and fertilisation are reduced.

Both urine scorch and drought affect N uptake from urine spots. In the standard situation of 1.5 cow per ha at N rates from 150 to 350 kg ha^{-1}, the nitrate concentration increases from 48 to 91 mg l^{-1} when drought reduces growth, and from 40 to 68 mg l^{-1} when grass production is not reduced (Figure 5-8f). Without drought, nitrate concentration increase is only two thirds of the increase in case of drought.

Aspects of other models versus NURP

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

Some authors developed relationships between N fertiliser rates and nitrate leaching (Kolenbrander, 1981; Van Der Meer & Meeuwissen, 1989). But e.g. Prins (1983) and Tyson *et al*. (1997) showed that it is better to work with non-harvested N from fertilisers and urine N. The use of non-harvested N as input for SMN also made it possible to pay attention to N uptake reduced by drought and urine scorch. As was shown, the effects of drought and urine scorch on nitrate leaching are substantial and cannot be neglected.
Other models (Scholefield *et al*., 1991; Delaby *et al*., 1997; Decau *et al*., 1997) have incorporated the effect of white clover on the N contribution to the sward and on nitrate leaching. Cuttle (1992) and Cuttle *et al.* (1992) found little difference in nitrate leaching between clover- and fertiliser-based swards of similar stock carrying capacity. According to Cuttle & Scholefield (1995), the advantage of clover-based swards is more associated with less intensive grassland systems than with a lower nitrate leaching at comparable levels of N flow in clover- and fertiliser-based swards. Although it is a simplification, the contribution of white clover, i.e., N fixation, to nitrate leaching in the NURP model can be estimated on the basis of its contribution to total N input. However, Cuttle & Jarvis (1995) modify this statement by assuming a feed-back system, which reduces N fixation in urine spots, thus preventing a 'double load' of N, and leading to lower values of nitrate leaching than would be the case with fertilisers.
Grassland renovation may result in small losses due to enhanced mineralisation through ploughing, which in turn can lead to a small increase in nitrate leaching. Ernst & Berendonk (1990) measured nitrate-leaching values of 5-15 kg N ha^{-1} following grassland renovation in spring, increasing nitrate concentration from 18 to 21-29 mg l^{-1}. Nitrate leaching following grassland renovation in autumn was more than three times higher (exceeding 50 kg N, nitrate concentrations of 53-60 mg l^{-1}). Possibly, the small losses are the result of a combination of increased leaching during the renovation phase, increased N uptake by the new grass sward and increased immobilisation. If 10% of the grassland area is renovated every year, nitrate concentration will increase by about 1 to 4 mg l^{-1}, following renovation in spring and autumn, respectively. Although the effect of grassland renovation is not as strong as that of grazing and fertiliser level, it should not be neglected.
Ploughing grassland for arable crops can lead to substantial increases in nitrate leaching (Whitmore *et al*., 1992; Hoffmann, 1999). N losses are higher under older grassland than under young grassland (Whitehead *et al*., 1990). Under young grassland and under ley-arable crop rotations, immobilisation levels are higher and consequently nitrate leaching lower (Scholefield *et al.,* 1993). N losses

associated with grassland renovation and ley-arable rotations are not incorporated in NURP. Especially if grassland is renovated in autumn, and older grassland is ploughed up to grow silage maize, the effects on nitrate concentrations can be substantial, and thus have to be incorporated in the model. Summarising, the model NURP is a useful tool in research and extension work to reduce nitrate leaching. A wide range of management factors can be varied independently and attention is paid to interactions between the various factors. The conclusion that fertiliser input and grazing are important factors is not new, nor surprising. However, the largest advantage of the model is its possibility to develop effective combinations of management measures to realise the reduction in nitrate leaching. The model validation showed satisfying results. The uncertainty analysis made clear that, although promising management strategies to reduce nitrate leaching can be developed, there is no guarantee that this will always happen in practice.

Acknowledgements
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Chapter 6

Sixty years of Dutch nitrogen fertiliser experiments, an overview of the effects of soil type, fertiliser input, management and of developments in time

Vellinga, T.V. & G. André, 1999. Sixty years of Dutch nitrogen fertiliser experiments, an overview of the effects of soil type, fertiliser input, management and developments in time. Netherlands Journal of Agricultural Science 47: 215-241.

6 Sixty years of Dutch nitrogen fertiliser experiments, an overview of the effects of soil type, fertiliser input, management and of developments in time

Abstract

Data of Nitrogen fertilisation experiments of 1934-1994 have been analysed, using models for N uptake and DM yield. Both models were affected by fertiliser level, soil type, soil organic matter content, grassland use, cutting frequency, grassland renovation, white clover content and the N content analysis (Crude Protein or total-N). Effects on Soil Nitrogen Supply (SNS), Apparent Nitrogen Recovery (ANR) and Nitrogen Use Efficiency (NUE) are discussed.

Differences in SNS, ANR and NUE between sand and clay were small, SNS on poorly drained peat soil was 60 and 80 kg N per ha higher than on clay and sand, respectively, ANR on poorly drained peat soil was 7 and 10% lower. The NUE was similar on sand, clay and poorly drained peat.

ANR was low at low N application levels, due to immobilisation. ANR increased from 35% to 65% at application levels of 50 and 250 kg N per ha, respectively. At application levels of more than 250 kg N per ha, ANR decreased. NUE decreased from 45 to 29 kg DM per kg N with increasing N application levels of 0 and 550 kg per ha. It is suggested that for a good N utilisation a minimum N application of 100 kg N per ha should be used.

SNS increased by a mixed use of grazing and cutting with 27 and 40 kg N per ha for sand/clay and poorly drained peat respectively. ANR on sand decreased from 5 to 10% at applications of 200 and 500 kg N per ha and NUE decreased with 1-2 kg DM per kg N. The effect of grazing was stronger under pure grazing than with a mixed use of grazing and cutting.

Increasing the cutting frequency from 3 to 8 cuts per year had no effect on SNS, increased ANR with 0-20% and decreased NUE with 4-7 kg DM per kg N. The positive effect of the higher ANR compensated the lower NUE at application levels of 400 kg N per ha.

Changes in ANR over the last sixty years can be explained by changes in experimental conditions, experimental treatments and chemical analysis. Changes in NUE can be explained by a higher proportion of perennial ryegrass and genetic improvement.

6.1 Introduction

A large number of experiments on nitrogen (N) fertilisation of grassland have been carried out in The Netherlands in the last sixty years. From about 1935 until about 1970 the main objective was to increase herbage production. After 1970, there was an increasing concern about losses of N to the environment by nitrate leaching, ammonia volatilisation and denitrification, leading to a shift in research topics. Quantifying losses (e.g. Ryden, 1984; Bussink, 1994; Velthof, 1997) and developing management rules to reduce N losses (Korevaar & Den Boer, 1989; Wouters & Hassink, 1995; Cuttle & Scholefield, 1995; Peel *et al.*, 1997) became the main objectives of the N research. Further research on N will emphasise the complexity of soil processes and the scaling of effects to reduce N-losses (Jarvis, 1996).

From the farmers point of view, improved N utilisation creates possibilities to reduce N inputs and losses without severe reductions in technical and financial results. Therefore a good knowledge about the effects of N fertilisation in relation to farm management is important.

In many fertilisation experiments the effect of single management factors (e.g. cutting frequency, grazing vs. cutting) on DM yield and N uptake have been analysed by using the three quadrant diagram (Frankena & De Wit, 1958; De Wit, 1953). For a good understanding of the differences in the response of herbage yield to fertiliser N the following aspects should be analysed in the three quadrant diagram (Van Der Meer & Van Uum-Van Lohuyzen, 1986):

- N supply from other sources than fertiliser, mostly measured on unfertilised plots. The most important source is the net mineralisation (Hassink, 1995b), but N from precipitation and dry deposition and N supply by white clover and other N fixing organisms can contribute a substantial amount. This (combined) source is often called the Soil Nitrogen Supply (SNS);
- the extra N uptake in the harvested DM in relation to the amount of applied fertiliser N. This is calculated as *(N uptake - SNS) / N applied* and called the Apparent Nitrogen Recovery (ANR). The complement of the nitrogen recovery gives information about the nitrogen that might remain in the soil (organic and inorganic N) and in roots and stubble of the plants. Therefore knowledge about the nitrogen recovery is an important factor to detect and develop efficient grassland fertilisation and management systems;
- the DM production per kg of N uptake in the harvested DM, the Nitrogen Use Efficiency (NUE). This relationship defines the total DM yield and the N content of the herbage. Consequently, this partly defines the N losses by utilisation of the herbage by animals (Van Vuuren, 1993).

Brockman (1969), Brockman *et al.* (1971) and Richards & Hobson (1977) analysed relationships between soil N, fertiliser N and N-uptake in UK-experiments. Van Der Meer & Van Uum-Van Lohuyzen (1986) analysed the change in ANR over the last fifty years in Dutch fertilisation experiments. They concluded that ANR had increased strongly after 1970. Ruitenberg *et al.* (1991) developed a relationship between optimum N-application rates, SNS and ANR. These overviews give a useful characterisation of relationships between fertiliser input and N uptake.
For a complete understanding of the proces of fertilisation, N uptake and DM production, also the relationship between SNS, ANR and NUE must be analysed. Until now, such a combined analysis of SNS, ANR and NUE has not been made in a group of experiments.
During the last sixty years many fertilisation experiments have been carried out. In this paper the available data from these experiments have been analysed to characterise changes in SNS, ANR and NUE in relation to a number of management factors and to trace changes in time. Special attention has been paid to the effects of soil type, the application level of N, grazing versus cutting and the cutting frequency.

6.2 Materials and methods

The collected experiments

We collected data from N fertilisation experiments using calcium ammonium nitrate (CAN), carried out in The Netherlands in the period 1934-1994. Experiments and treatments without adequate application of P and K were excluded.
For all experiments several characteristics, if available, have been recorded:

- soil type: sand, clay, poorly drained and well drained peat;
- organic matter content or organic nitrogen content of the soil;
- white clover content on the unfertilised plot and on the fertilised plot;
- N content: Crude Protein (CP) or the total N (N_t);
- number of cuts per year;
- utilisation, a mix of grazing and cutting or pure cutting;
- other management factors: grassland renovation, cutting effect of slurry injection equipment.

The number of experiments for one and two years is limited, there is a large group of long-term experiments, with a maximum time of 22 years. Permanent

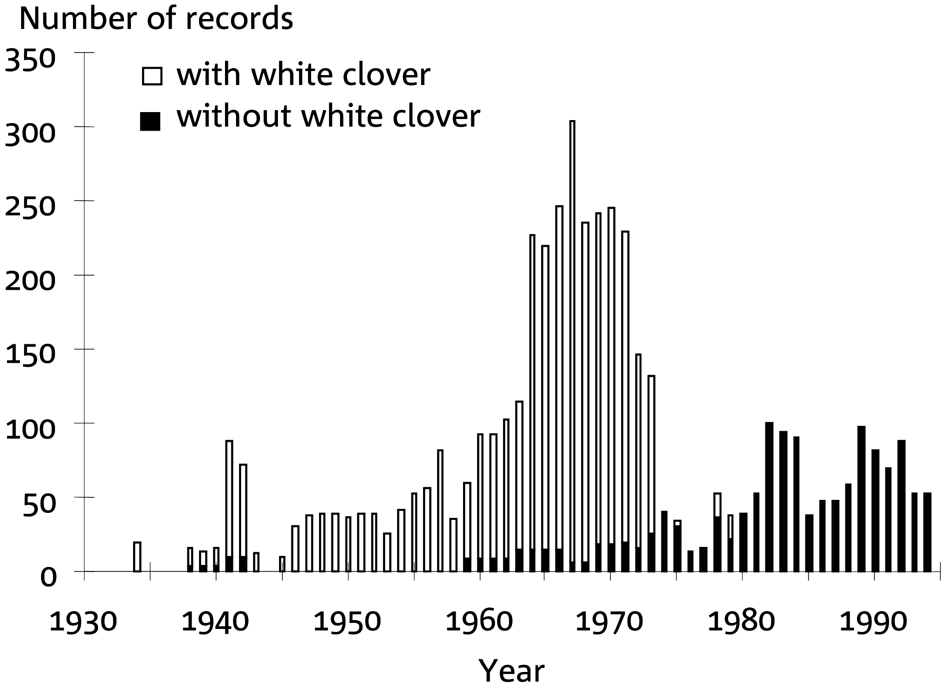

Figure 6-1. Frequency distribution of experimental records in the "sixty-year" dataset of nitrogen fertiliser experiments over the periode 1934-1994. White parts are records with white clover, black parts are records without white clover.

grassland was the basis for almost all the experiments. The exact history of all the experimental sites is unknown, but in general the experiments before 1970 were carried out on (very) old grassland (>10 years old). After 1970 relatively more experiments were carried out on renovated, but still permanent grassland. In the experiments of the research station for cattle husbandry, renovated grassland had to be older than 3 years to be used in fertiliser experiments. Grassland renovation as experimental treatment has been marked in the dataset.
In total a unique dataset of 4700 records has been made (see Annex) The data are spread over the whole period, with a peak in the period 1960-1975 (Figure 6-1). A total of 4400 records was available for N application rates in the range of 0-400 kg N per ha per year. About 300 records were present for application rates between 400 and 500 kg N per ha per year. Only 70 records with very high application rates (> 800 kg N per ha per year) were present (Figure 6-2). Most of the records included white clover, also most of the records came from cutting experiments (Table 6-1). The average number of cuts was 5.3 with a variation between 2 and 10 cuts per year.

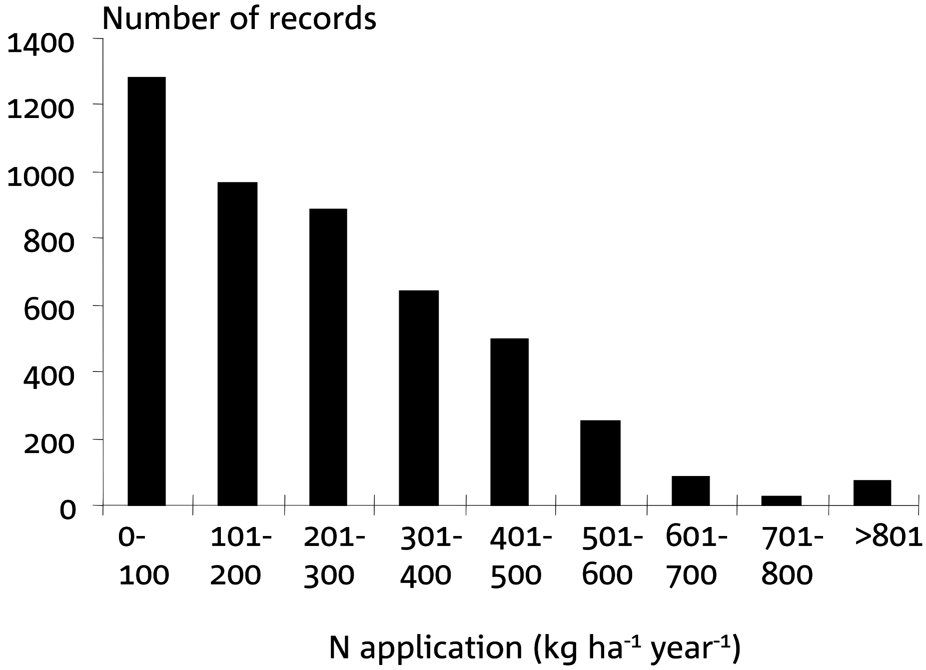

Figure 6-2. Number of records as a function of the level of fertiliser N application in the "sixty-year" dataset of nitrogen fertiliser experiments.

Table 6-1. Records of the "sixty-year" dataset of nitrogen fertiliser experiments sorted after soil type, the presence of white clover (wc), grassland use (grazing/cutting) and the average, minimum and maximum number of cuts.

Parameter	Soil type				Total
	Clay	Peat, well drained	Peat, poorly drained	Sand	
Without wc	417	164	237	587	1403
With wc	1436	5	752	1091	3284
Cutting	1679	90	889	1370	4028
Grazing	174	79	100	308	661
Cuts average	5.3	6.3	5.2	5.2	5.3
Minimum	3	5	2	3	2
Maximum	9	7	7	10	10
Total	1853	169	989	1678	4689

Well drained peat was excluded from the statistical analysis because half of the data came from a site where peat was recently covered with 6-18 cm of sand to improve bearing capacity. The other half of the data came from one site (Zegveld) and will be included in the results.

Statistical analysis

Models have been defined for both N uptake and DM yield. They consist of a fixed non linear submodel for the expected value and a random linear submodel for the deviation. First the fixed submodel was fit, using the maximum likelihood method of Genstat with FITNONLINEAR. Only significant parameters were incorporated in the model (P<0.05). Secondly the submodel was fit for the deviations with the residual maximum likelihood method of Genstat using REML. We used Genstat 5, Release 4.1 (Anonymous, 1997a).

The N uptake model, the fixed non linear submodel

For the expected value N_m we used a double Mitscherlich function (Equations 1 and 2):

$$N_m = \alpha_0 + (\alpha_1 - \alpha_0) \, . \, [1 - \exp\{N_b / (\alpha_1 - \alpha_0)\}] \qquad \textbf{(1)}$$

Morrison *et al.* (1980) found a lower ANR at an application level of 150 kg N per ha, compared to 300 kg N per ha. Dowdell *et al.* (1980) and Dilz (1966, 1987) suggested the possibility of immobilisation of applied N in stubble, roots and microbial biomass, competing for N with harvestable herbage at low N soils. To test whether this would be the case in our dataset, we corrected the applied N for this possible immobilisation using a second Mitscherlich function:

$$N_b = N_g - \alpha_2 \, . \, [1 - \exp(N_g / \alpha_2) \,] \qquad \textbf{(2)}$$

N_m	=	expected value of N uptake (kg ha^{-1})
α_0	=	N uptake when no N is applied, the SNS (kg ha^{-1})
α_1	=	maximum N uptake, realised at high levels of applied N (kg ha^{-1})
α_2	=	maximum immobilisation of applied N into stubble, root and microbial biomass. This immobilisation can be be temporarily or more permanent (kg ha^{-1})
N_b	=	applied N_g minus immobilisation, which is maximally α_2 (kg ha^{-1})
N_g	=	N application rate (kg ha^{-1})

The parameters α_0, α_1 and α_2 were related to soil type, the number of cuts, utilisation (grazing or cutting), soil organic matter, grassland renovation and white clover content (Equations 3 and 3a). We used an exponential function which can account for interactions between soil type, utilisation etc., It also has the advantage that all parameter estimates remain positive. Because we assumed that without soil organic matter the SNS (=α_0) would be nil, the α_0-function was slightly different from the others.

$$\alpha_0 = a_0.[1 - \exp((om_0 + om_{0S})OM)].\exp[c_0C+s_0S+(g_0+g_{0S})G+(wc_0+wc_{0S})WC+r_0R] \quad \textbf{(3)}$$

$$\alpha_i = a_i.\ \exp[(om_i + om_{iS})OM + c_iC+s_iS +(g_i+g_{iS})G+(wc_i+wc_{iS})WC+r_iR] \quad \textbf{(3a)}$$

i	=	1, 2 for the parameters α_1 and α_2
om_0, om_i	=	the coefficient for soil organic matter content
om_{0S}, om_{iS}	=	extra coefficient on soil type S for soil organic matter content
OM	=	organic matter content of the soil (%)
s_0 , s_i	=	coefficient for the effect of soil type, not related to the other factors
S	=	soil type, sand, clay or poorly drained peat
c_0, c_i	=	coefficient for the number of cuts
C	=	number of cuts minus 5; 5 cuts is chosen as the reference value
g_0, g_i,	=	coefficients for grazing/cutting
g_{0S}, g_{iS}	=	extra coefficients for grazing/cutting on soil type S
G	=	grazing/cutting, in case of cutting G = 0; in case of grazing G = 1
wc_0, wc_{0S}, wc_i, wc_{iS}	=	coefficients for white clover
WC	=	white clover as percentage dry weight on the unfertilised plot
r_0, r_i	=	coefficient for grassland renovation
R	=	grassland renovation with ploughing: no renovation = 0, renovation = 1.

About three quarter of the data of N uptake were based on a crude protein analysis, using the Kjeldahl method. The remainder was based on a total N analysis. A correction for these different techniques was added (Equation 4):

$$N_c = N_m\ .\ \exp(-\lambda_1 N_m) \quad \textbf{(4)}$$

N_c	=	the corrected N uptake
N_m	=	the N uptake in the dataset
λ_1	=	correction for the N uptake when the Kjeldahl method was used.

The N uptake model, the random linear submodel

The submodel for the deviations is shown in (Equation 5) and consists of stochastic, normal distributed terms for year and plot/site, their interactions and random effects.

$$Y_N = N_c + \varepsilon_Y + \varepsilon_P + \varepsilon_{YP} + \varepsilon_R \quad \textbf{(5)}$$

In which:

Y_N	=	the measured N uptake in the experiments (kg ha^{-1})
N_c	=	the corrected N uptake (kg ha^{-1})
ε_Y	=	deviation caused by year effects
ε_P	=	deviation caused by plot/site effects
ε_{YP}	=	deviation caused by interactions between year and plot/site effects
ε_R	=	deviation caused by random effects

The DM yield model, the fixed non linear submodel

The DM yield is expressed as a function of N uptake and is based on the assumption that initially the N content increases slowly as N application increases (Reid, 1970, 1972). At high N applications a linear relationship between N application and N content was assumed. Hence, (Equation 6):

$$N / DM = \beta_o + \beta_1^{-1}[1-\exp(-\rho N)]N \quad \textbf{(6)}$$

Transformation resulted in the following function(Equation 7):

$$DM = [\beta_o/N + \beta_1^{-1}(1-\exp(-\rho N))]^{-1} \quad \textbf{(7)}$$

DM	=	the expected value of DM yield (kg ha^{-1})
β_o	=	minimum N content (kg kg^{-1})
β_1	=	maximum DM yield that can be realised at very high levels of N uptake (kg ha^{-1})
ρ	=	defines the change over of the grass to luxury consumption (-)
N	=	the N uptake (kg ha^{-1}).

The parameters β_o, β_1 and ρ are related to soil type, number of cuts, utilisation (grazing or cutting), soil organic matter, grassland renovation and white clover content (see Equations 8 and 9):

$$\beta_i = b_i.\ \exp\mathbf{[}(om_i + om_{iS})OM + c_iC+s_iS +(g_i+g_{iS})G+(wc_i+wc_{iS})WC+r_iR\mathbf{]} \quad \textbf{(8)}$$

$\rho = r.\ \exp[(om_r + om_{rS})OM + c_rC + s_rS + (g_r + g_{rS})G + (wc_r + wc_{rS})WC + r_rR]$ **(9)**

i = 1, 2 for the parameters β_1 and β_2

r = for the parameters belonging to ρ

with S, C, G, OM, R, WC being the same as above.

To test whether the CP or N_t analysis affected the relationship between DM yield and N uptake we used the same equation as is used in the N uptake model. Only the parameter λ_1 has been replaced by λ_2 (Equation 10):

$N_c = N_m\ .\ \exp(-\lambda_2\ N_m)$ **(10)**

N_c = the corrected N uptake

N_m = the N uptake in the dataset

λ_2 = correction for the N uptake when the Kjeldahl method was used.

The DM yield model, the random linear submodel

The model for the deviations is shown in Equation 11 and consists of stochastic, normal distributed terms for year and site:

$Y_{DM} = DM + \varepsilon_Y + \varepsilon_P + \varepsilon_{YP} + \varepsilon_R$ **(11)**

In which:

Y_{DM} = the measured DM yield in the experiments (kg ha^{-1})

DM = the calculated DM yield (kg ha^{-1})

Deviation terms are the same as in Equation 5.

6.3 Results

Firstly, the results of the statistical analysis will be discussed. Secondly, the relationship between N fertiliser application, DM yield, N uptake and ANR will be presented. Therefore the three quadrant diagram as developed by De Wit (1953) will be extended to a four-quadrant-diagram. Additional to the three quadrants with N application, N uptake and DM yield, the ANR has been calculated from the lines in the fourth quadrant (N uptake and N application) and shown separately in the quadrant III (below-left). To show the NUE in the diagram, dotted lines are placed in the first quadrant (above-right), (e.g. Figure 6-3).

N uptake model

The fixed model for N uptake accounted for 72.1% of the total variance (Table 6-2), for 36.4% of the total “between-year” variation, for 64.9% of the “between-site” variation and for 89.9% of the random and experimental (fertiliser level,

Table 6-2. Estimates of variance for the contribution of year, site, year by site interaction and random terms, the relative importance of the residual variance of the four components and the percentage of the total variance that is accounted for by the N uptake model.

N uptake model			
Component	Estimate of variance ($kg\ ha^{-1}$)	Relative importance of total variance (%)	Percentage of total variance accounted by the model (%)
σ^2_{year}	795	18.3	36.4
σ^2_{site}	801	18.5	64.9
$\sigma^2_{year\ by\ site}$	1571	36.2	-
σ^2_{random}	1173	27.0	89.9
σ^2_{total}	4340	100.0	72.1

Table 6-3. Parameter values of the model for N uptake based on the analysis of the "sixty-year" dataset of nitrogen fertiliser experiments.

N uptake model	Estimate	s.e.
Soil Nitrogen Supply (α_0, $kg\ ha^{-1}$)		
a_0	192.45	2.87
$s_{0,peat}$	0.2691	0.0163
om_0	0.984	0.224
$om_{0,sand}$	-0.735	0.224
g_0	0.1335	0.0228
$wc_{0,sand}$	0.00364	0.00121
Maximum N uptake(α_1, $kg\ ha^{-1}$)		
a_1	696.2	17.6
om_1	-0.004944	0.000934
g_1	-0.4217	0.0569
$g_{1,peat}$	0.2324	0.0774
r_1	0.2017	0.0886
c_1	0.1407	0.0103
Immobilisation(α_2, $kg\ ha^{-1}$)		
a_2	51.42	5.49
wc_2	0.04050	0.00473
R_2	0.661	0.105
Chemical analysis (λ_1, -)		
λ_1	0.0000445	0.0000195

grazing/cutting, cutting frequency, white clover) variation. The standard error of the observations was estimated to be 65.9 kg N per ha. Results of the random model for N uptake (Equation 5, Table 6-2) show that 18% of the total variation was caused by year and site effects, and 36% by year-site interactions. Random variation was still 27% of the total variation.

The values of the parameters are shown in Table 6-3. Values of a_0, a_1 and a_2 are in kg per ha. The other parameters are without dimension, positive values of these parameters indicate an increase of a_i, negative values a decrease.
The Soil Nitrogen Supply (α_0) was significantly affected by the soil organic matter, soil type, grassland use and, on sand, by the white clover content. The effect of soil organic matter on sand was significantly different from that on clay.
The maximum uptake level (α_1) was increased by grassland renovation and a higher cutting frequency. The maximum uptake level was sharply decreased by grazing instead of cutting, although the effect was less strong on peat. Increasing organic matter contents also reduced the maximum uptake level.
The immobilisation of applied N (α_2) was significantly affected by grassland renovation and the white clover content.
Measuring N uptake by CP analysis gave a significantly lower uptake than measuring by the N_t analysis.

DM yield model

The fixed model for DM yield accounted for 87.0% of the total variation, with a standard error of 999 kg. Of the total between year variation, almost 70% was accounted for by the fixed part of the model, for the between site variation this was 83% and for the variation not related to year or site (fertiliser level, grazing/cutting, cutting frequency, white clover) this was 92% (Table 6-4). Results of the random model (Equation 10, Table 6-4) show that only 20-22% of the total variation was caused by year and site effects, the variation caused by year-site interactions was only 13.4%. Variation not related to year or site was 44.3% of the total variation.
The values of the parameters are shown in Table 6-5 The minimum N content (β_0) was significantly different for the three soil types. The minimum N content was significantly increased by a higher cutting frequency, grassland renovation and grazing, the effect of grazing was stronger than from the other two factors.
The maximum DM yield at very high levels of N uptake (β_1) was on clay significantly higher than on sand and peat, indicating lower N contents on clay. The value also was increased by grazing, grassland renovation and cutting frequency. The effect of cutting frequency was also sigificant, but smaller in comparison to the other factors. The white clover content had no effect on the parameter.
The change over to luxury consumption (ρ) was on clay significantly lower than on peat and sand. The ρ was significantly increased by a higher cutting frequency and white clover. The effect of white clover was much smaller than the effect of

Table 6-4. Estimates of variance for the contribution of year, site, year by site interaction and random terms, the relative importance of the residual variance of the four components and the percentage of the total variance that is accounted for by the DM yield model.

DM yield model			
Component	Estimate of variance (kg ha^{-1})	Relative importance of total variance (%)	Percentage of total variance accounted by the model (%)
σ^2_{year}	204113	20.5	69.6
σ^2_{site}	217447	21.8	83.1
$\sigma^2_{year\ by\ site}$	134028	13.4	37.1
σ^2_{random}	441704	44.3	92.0
σ^2_{total}	997292	100.0	87.0

Table 6-5. Parameter values of the model for DM yield based on the analysis of the "sixty-year" dataset of nitrogen fertiliser experiments

DM yield model	Estimate	s.e.
minimum N content (β_0, kg kg^{-1})		
b_o	0.018750	0.000233
c_0	0.04143	0.00735
r_0	0.0977	0.0163
g_0	0.1875	0.0211
$s_{0,peat}$	-0.0926	0.0202
$s_{0,sand}$	-0.2108	0.0166
maximum DM yield(β_1, kg ha^{-1})		
b_1	31418	583
c_1	0.0342	0.0106
r_1	0.2803	0.0324
g_1	0.2295	0.0485
$s_{1,peat}$	-0.0860	0.0288
$s_{1,sand}$	-0.2141	0.0230
Speed of luxury consumption(ρ,-)		
R	0.006400	0.000481
c_r	1.218	0.107
wc_r	0.0871	0.0111
$s_{r,peat}$	3.794	0.470
$s_{r,sand}$	2.862	0.426
Chemical analysis (λ_2, -)		
λ_2	-0.0001496	0.0000168

cutting frequency. There was almost a linear increase of the N content at increasing uptake levels. Only at very low uptake levels on clay soil a slower increase in N content was found.

There was a sigificant effect of the way the N uptake was analysed. The value of λ_2 was negative, but in combination with the minus sign, the result was positive. This means that the NUE was lower in case of a CP analysis, compared to an N_t analysis.

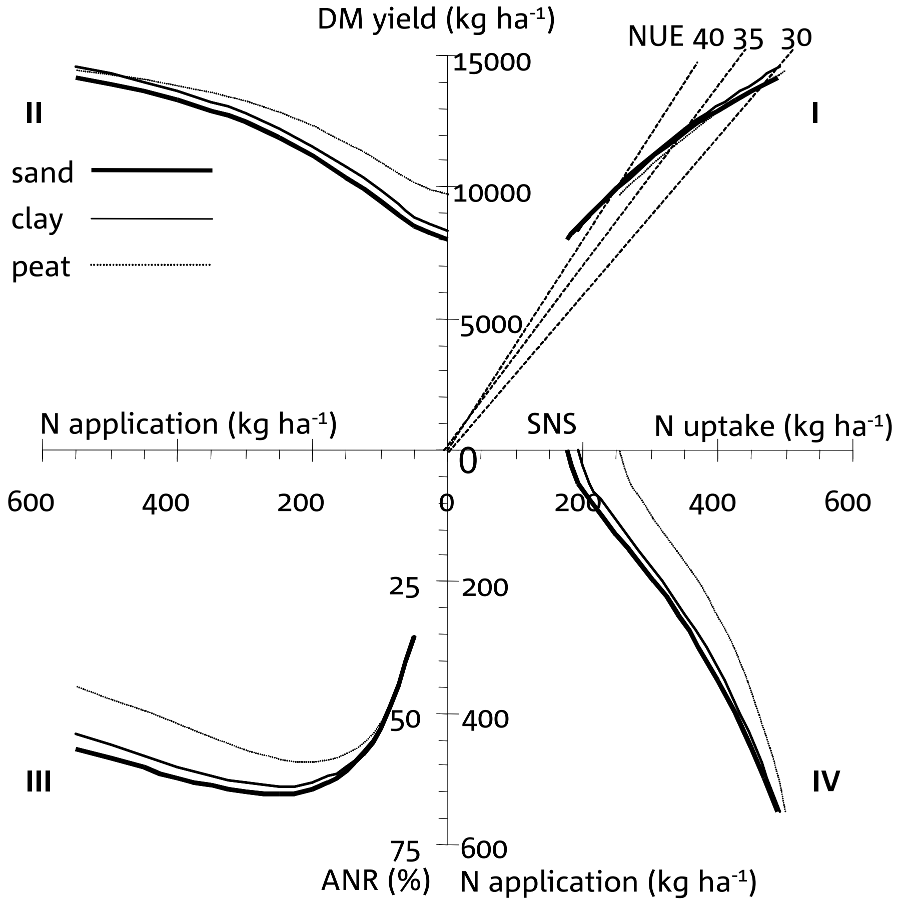

Figure 6-3. Mean effects of N fertiliser application on N uptake (quadrant IV), DM yield (quadrant II), ANR (quadrant III) and NUE (quadrant I) as a function of soil type (sand, clay and peat). Mean relationships are based on the whole "sixty-year" dataset of nitrogen fertiliser experiments.

Effect of soil type

The mean SNS on poorly drained peat soils was 252 kg N per ha. On sand and clay, SNS was 176 and 192 kg N per ha, respectively (Figure 6-3). In the dataset the average OM content in the top soil (0-5 cm) on peat soils was 45%, on sand and clay this was 10 and 20%, respectively. The SNS on sand decreased in the years after 1970, due to a decrease in soil organic matter (Figure 6-4). This decrease in SNS was not seen on clay, despite the decrease in soil organic matter (Figure 6-4). Drainage of peat soils led in the first years to a strong increase in SNS (Boxem & Leusink, 1981). However, experiments twenty years later on the same site did not show a higher SNS on the drained peat soil (Hofstede *et al.*, 1995; Hofstede, 1995a, 1995b)

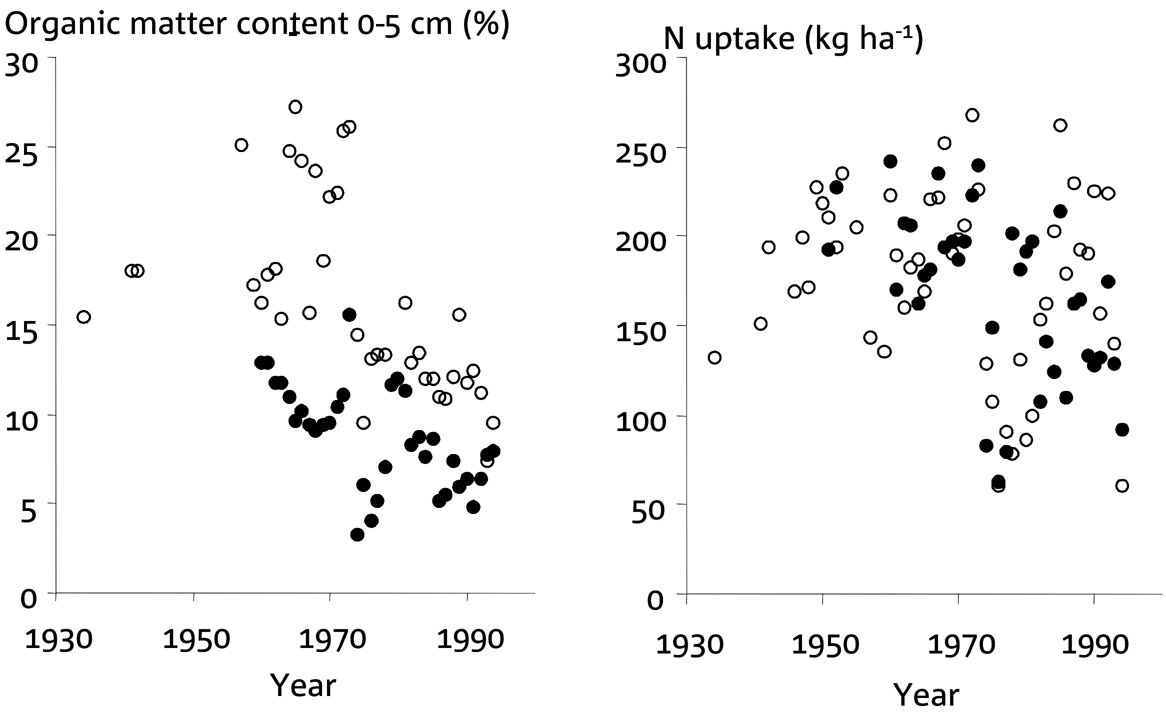

Figure 6-4. The soil organic matter content in the layer 0 to 5 cm and the N uptake on the unfertilised plots on the experimental sites in the "sixty-year" dataset of nitrogen fertiliser experiments. (Open dots = clay, closed dots = sand).

The mean ANR on poorly drained peat soils was 7 to 10% lower than on sand and clay at N application levels higher than 200 kg N per ha (Figure 6-3). On well drained peat soils the ANR was much lower than on poorly drained peat, caused by a very high SNS. In the later experiments, with the same SNS on well and poorly drained peat soil, also no difference in ANR was found. Differences in mean ANR between sandy soils and clay soils were small.
At low levels of N uptake the mean NUE on sand was 0.7 kg DM per kg N uptake higher than on clay and poorly drained peat (not to be seen in Figure 6-3). At high uptake levels (400-500 kg N) the mean NUE on clay was 0.5 to 1.0 kg DM per kg N higher than on sand.

Effect of fertiliser level

At low N application levels, the N uptake increased slowly and the mean ANR was low (Figure 6-3, quadrant III), e.g., with 50 kg N per ha the ANR on sand was 35%. Increasing N application to 200 kg per ha led to a stronger increase in N uptake (quadrant IV) and mean ANR increased to a maximum level of 65-70% (quadrant

III). Higher N applications led to a slower increase in N uptake and a decreasing ANR. At 550 kg N per ha the mean ANR was 55-60%.
The maximum N uptake level was not presented in Figure 6-3, but was 660, 630 and 560 kg N per ha for sand, clay and peat, respectively. These asymptotic values are realised at N applications of more than 1000 kg N per ha.
Mean NUE decreased at increasing levels of N uptake. At an N uptake of 200 kg per ha, the mean NUE was 43 kg DM per kg N, whereas at about 490 kg N per ha (the maximum N uptake in Figure 6-3), the mean NUE was 29 kg DM per kg N. At the maximum N uptake level of the uptake model the mean NUE was 24.2, 26.0 and 27.4 kg DM per kg N for sand, clay and peat respectively, with five cuts per year.

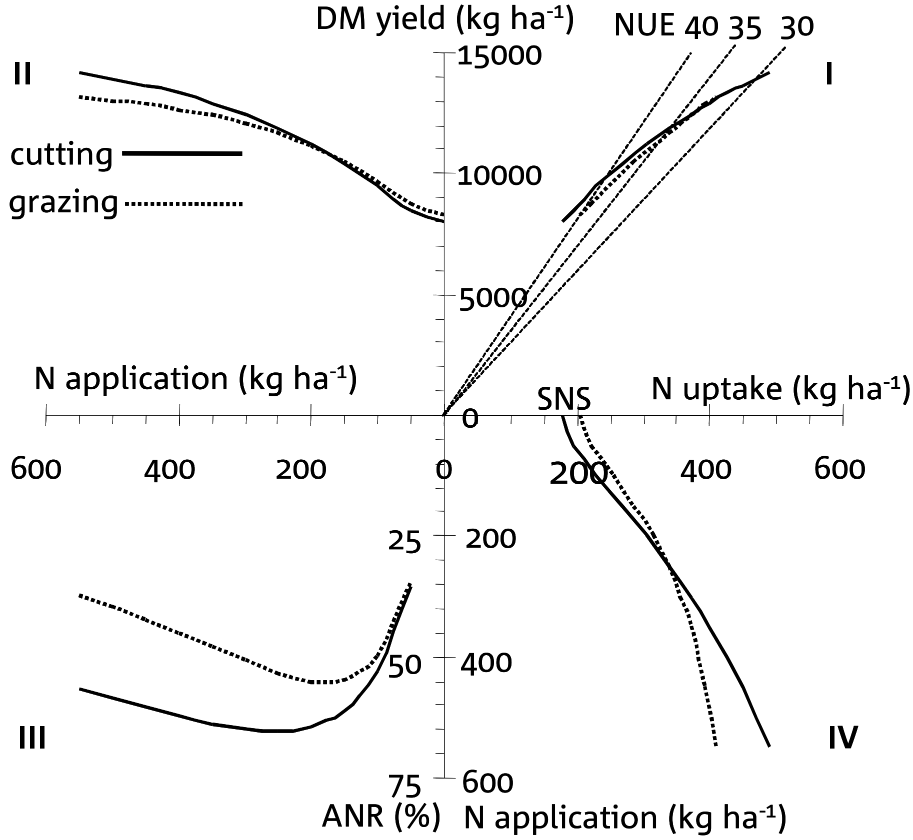

Figure 6-5. Mean effects of N fertiliser application on N uptake (quadrant IV), DM yield (quadrant II), ANR (quadrant III) and NUE (quadrant I) under pure cutting and mixed grazing/cutting conditions on sand. Mean relationships are based on the whole “sixty-year” dataset of nitrogen fertiliser experiments.

Comparison between grazing and cutting

SNS was increased by a mixed use of grazing and cutting with 27 kg N per ha on sand and clay compared with only cutting. On peat the SNS increased with 40 kg N per ha. The maximum N uptake was decreased with about 200 kg N per ha on sand and clay and with about 100 kg N per ha on peat.

The increase in SNS and the decrease in maximum N uptake led to a lower ANR with grazing (Figure 6-5). This effect became stronger with increasing N levels. At 200 kg N per ha, the difference in ANR was 5%, at 500 kg N per ha the difference increased to 10%.

Grazing resulted in a decrease in NUE of 2 kg DM per kg N uptake at levels of 200-300 kg N uptake (Figure 6-5). These differences decreased at increasing N levels.

Effect of cutting frequency

The mean SNS was not affected by cutting frequency. The maximum N uptake level was higher with an increased cutting frequency. N uptake levels on sand with 3, 5 and 8 cuts per year with an N application of 550 kg per ha, were 430, 490 and 550 kg N per ha, respectively. The higher maximum N uptake level led to a higher ANR by frequent cutting. This increase in ANR was stronger at higher application levels (Figure 6-6). An increased cutting frequency from 3 to 8 cuts at application levels of 200 and 400 kg N per ha per year led to an increase in ANR of 8 and 18 units respectively. The mean NUE was decreased by frequent cutting. Increasing the cutting frequency from 3 to 8 cuts per year led to a decrease in NUE of 3 to 4 units. The DM yield is a result of the ANR and the NUE, according to Equation 12:

$$DM = NUE_{Nuptake} \times (SNS + ANR_{Napplied} \times N_{applied}) \qquad \textbf{(12)}$$

In this equation the strong increase in ANR at an application level of 400 kg N per ha was enough to compensate the decrease in NUE and the DM yield was higher with 8 cuts, compared to 3 cuts per year.

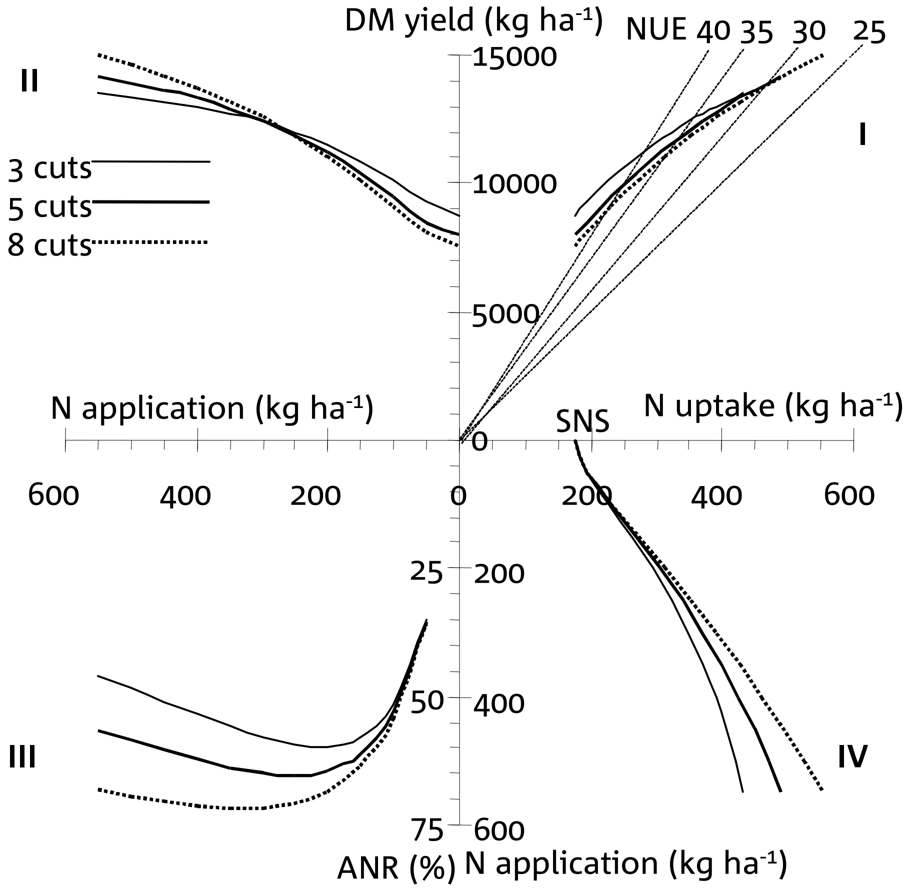

Figure 6-6. Mean effects of N fertiliser application on N uptake (quadrant IV), DM yield (quadrant II), ANR (quadrant III) and NUE (quadrant I) at 3, 5 and 8 cuts per year on sand. Mean relationships are based on the whole “sixty-year” dataset of nitrogen fertiliser experiments.

Effect of CP/N_t analysis

At N application levels of 200 and 400 kg N per ha, the N uptake was 319 and 433 kg per ha, respectively. At those uptake levels, the difference in calculated N uptake between the CP and the N_t analysis was 4.5 and 8 kg per ha, respectively. Related to this, the ANR was underestimated by 1.5 to 2% by using the CP analysis instead of the N_t analysis (Table 6-6).

When N uptake was measured as CP, the DM yield, and with it, the NUE was lower than with the same N uptake based on the N_t analysis. The difference between both methods was about 0.90 kg DM per kg N uptake (Table 6-6).

Table 6-6. The ANR at three levels of N application and the NUE at three levels of N uptake, with the N uptake based on the CP analysis and the N_t analysis. Analysis based on the “sixty-year” dataset of fertiliser experiments.

N application (kg N ha^{-1})	ANR (%) CP-analysis	N_t analysis	N uptake (kg N ha^{-1})	NUE (kg kg^{-1}) CP-analysis	N_t analysis
200	63.0	64.5	200	42.5	43.3
400	60.5	62.3	400	31.4	32.3
600	53.2	54.8	600	24.8	25.7

6.4 Discussion

Soil type

On peat soils SNS was much higher than on clay and sand. The strong increase in SNS short after the improved drainage (Boxem & Leusink, 1981) could not be repeated in later experiments in 1992-1994 (Hofstede *et al.*, 1995; Hofstede 1995a, 1995b). The reason for this is not clear, the physical changes in peat soil by drainage might play a role (Schothorst, 1982).

The SNS on clay was about 15 kg N per ha higher than on sand. This difference was related to a higher organic matter content on clay than on sand. The N uptake model showed a faster increase in mean SNS related to soil OM on clay than on sand. Due to the lack of experiments with low organic matter contents on clay in our dataset it is likely that no good relationship on this soil type could be established. The results from other datasets are confusing. Hassink (1995b) found at similar levels of soil organic matter a lower SNS on clay soils than on sandy soils. In contrast, Herlihy & McAleese (1978) found a higher SNS on loam, compared to sandy loam. On the other hand, Whitehead (1984) did not find any relationship between the proportion of availabe soil N and the content of organic matter.

The mean ANR on sandy soils in our dataset was slightly higher than on clay soils. This is in agreement with the findings of Herlihy & McAleese (1978). They found ANR values of 59, 57 and 54% for sandy loam, coarse sandy loam and loam, respectively. In contrast, Whitehead (1984) could not find any relationship between apparent recovery and soil characteristics like contents of sand, clay, silt and organic matter.

Fertiliser level

In agreement with our results, low levels of ANR at low application levels have also been found by Herlihy *et al.* (1978) and Morrison *et al.* (1980). Dilz (1966,

1987) stated that there is a substantial N buffering in stubble and roots, which might cause low ANR's at low fertiliser levels. Although Dilz (1966, 1987) and Dowdell *et al.* (1980) stated that this immobilisation might occur at low N swards, we found this as an overall effect on swards with low to high levels of SNS. Also Reid (1970, 1972) found the same course of ANR as in our model, by using a four parameter function for N uptake.

Fertilisation might affect the SNS by a priming effect (Dowdell *et al.*, 1980; Dawson & Ryden, 1985), pool substitution (Rao *et al.*, 1992) or by increased root growth (Whitehead, 1984). A priming effect by fertilisation would increase the calculated ANR, already at low application levels, which is in contrast with the results of our model.

ANR decreased with increasing applications over 200-250 kg N per ha. This has also been reported by Bartholomew & Chestnutt (1977) and Morrison *et al.* (1980). Richards & Hobson (1977) fitted a quadratic curve which implies a decreasing ANR over the whole range of fertiliser levels.

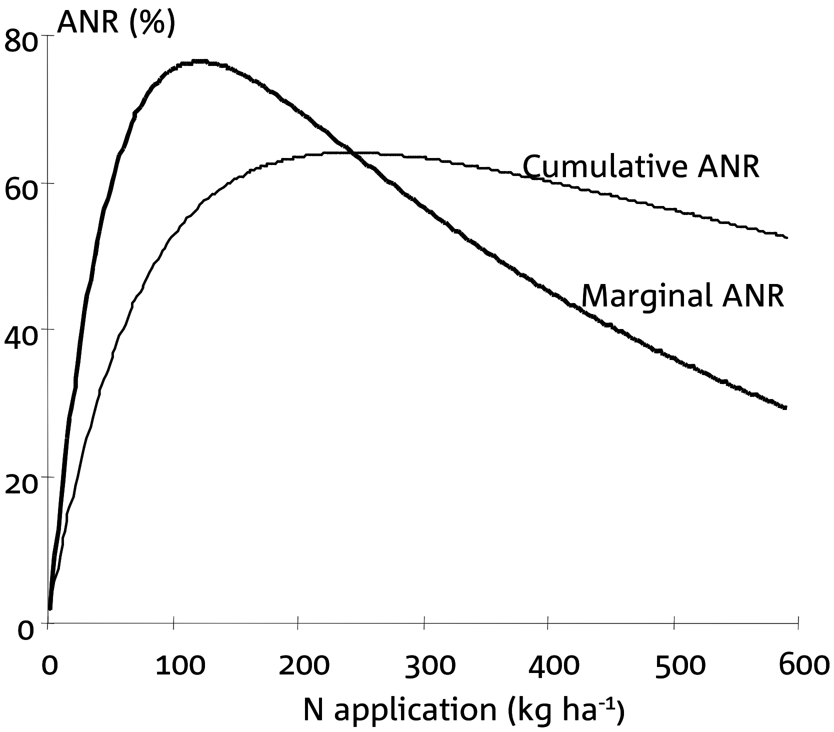

Figure 6-7. The course of the cumulative (related to the unfertilised plot) and the marginal ANR (related to the last kg of applied N) in relation to N application on sand. Data based on the "sixty-year" dataset of fertiliser experiments.

When instead of the cumulative ANR, based on the unfertilised plot: ($Nuptake_A$ - $Nuptake_0$)/(N_A - N_0)), the marginal ANR (($Nuptake_A$ - $Nuptake_{A-1}$) / (N_A - N_{A-1})) is calculated, the increase and subsequent decrease of ANR with increasing application levels are much stronger (Figure 6-7). The maximum marginal ANR of 78% was reached at about 100 kg N per ha. At that application level, the immobilisation of N (the A_2 in the model) was almost maximal. This suggests that the competition for N between microbial biomass, roots and stubble ends when more than 100 kg N per ha is applied.

In agreement with our results, a decreasing NUE (or an increasing N content) at increasing levels of N uptake has been seen many times (e.g. Reid, 1970, 1972; Morrison *et al.*, 1980; Harkess & Frame, 1986; Hopkins *et al.*, 1990). However at low application levels (between 0 and 100 kg N per ha) and low levels of SNS a constant or even increasing NUE has been found (Reid, 1970, 1972). We also found this effect in our model on clay soils at low N uptake levels(<100 kg N per ha).

The increase in ANR at low application levels and the relatively slow decrease in NUE indicate that a minimum application level of at least 100 kg N per ha is required to realise a good N utilisation. This means that on a farm with low N input levels, it might be more efficient to fertilise only half of the paddocks with 100 kg N per ha instead of applying 50 kg N per ha on all the paddocks.

Comparison of grazing and cutting

SNS was increased by a mixed use of grazing and cutting. This was confirmed by Prins & Brak (1984) and Thomas *et al.* (1990). Beside the the return of excreta, increased tiller numbers on grazed plots might increase exploitation of soil N, leading to a higher SNS (Thomas *et al.*, 1990).

In agreement to our results, a decreased ANR has been found by Jackson & Williams (1979), Prins & Brak (1984) and Deenen & Lantinga (1993). However, there are differences in the decline of the ANR by grazing between the different authors.

Prins & Brak (1984) found a stronger reduction in ANR in individual cuts on only grazed plots compared to plots with a mixed use of grazing and cutting. Differences between pure cutting plots and mixed use plots were relatively small. The grazing trials in our dataset had a mixed use with one or two cuts for silage, to realise a common use in The Netherlands. The strong decrease in ANR, as found by Jackson & Williams (1979) and Deenen & Lantinga (1993) might be related to the strong negative effects of pure grazing on sward quality, caused also by winter damage, poaching and urine scorch. The negative effect of urine scorch has also been mentioned by Prins & Brak (1984). Model calculations showed that urine scorch was the most important factor in decreasing herbage response to fertiliser N (Mooij & Vellinga, 1993). Also the very high ANR on the cutting plots in the experiments of Deenen & Lantinga (1993) might enhance the difference between grazing and cutting.

Grazing also led to an decrease in NUE (Figure 6-5), at low N application levels. This was confirmed by Prins & Brak (1984), who found similar effects for pure grazing and mixed use. Data from Deenen & Lantinga (1993) showed that the poor sward quality (i.e. an open sward) also resulted in a stronger reduction in NUE than was found in our model and by Prins & Brak (1984). This effect of a low NUE at open swards was also found in pot experiments by Van Loo (1993).

Fertiliser recommendations for grazing and cutting have been discussed intensively. No difference in recommendations was made for grazing and cutting, except for the target yield (Mooij & Vellinga, 1993). However, the calculated optimal N application level was about 40 kg N lower for grazing, based on data in the United Kingdom and The Netherlands (Unwin & Vellinga, 1994). Deenen & lantinga (1993) stated that the optimal application level for grazing was lower than 250 kg N per ha, a difference of about 150 kg N with the optimal application level for cutting. The optimal N application levels for cutting and grazing at the same cutting frequency in our analysis were 410 and 320 kg N, respectively. This difference between grazing and cutting is thus stronger than was stated by Mooij & Vellinga (1993) and Unwin & Vellinga (1994), but fits well with the new fertiliser recommendations (Vellinga, 1998).

It is concluded from our model and the literature that the negative effects of grazing are much stronger under pure grazing than with a mixed use of grazing and cutting. This implies that a mixed use of grazing and cutting should be recommended in practice.

Cutting frequency

In our dataset cutting frequency had no effect on SNS (Figure 6-6). This was also found by Holliday & Wilman (1965), Frame (1973), Reid (1978) and Kirkham & Wilkins (1994). In contrast, Bartholomew & Chestnutt (1977) found an increasing SNS (from 104 to 151 kg N per ha) with decreasing cutting frequency (from 10 to 3 cuts per season). However, a decreased cutting frequency by a delay of the first cut from half May to the half of June resulted in a decrease in SNS of about 20 kg N on average (Korevaar, 1986). When there were only two cuts per year, the SNS decreased even more (Holliday & Wilman, 1965; Bartholomew & Chestnutt, 1977).

ANR increased strongly with more frequent cutting. This was also found by Bartholomew & Chestnutt (1977), Reid (1978) and Kirkham & Wilkins (1994). In contrast, Holliday & Wilman (1965) and Frame (1973) did not find an effect of changes in the cutting frequency on ANR. This was possibly related to their lower maximum N levels and the presence of white clover.
More frequent cutting always led to a decrease in NUE (Figure 6-6). This was confirmed by Holliday & Wilman (1965), Frame (1973), Bartholomew & Chestnutt (1977), Reid (1978) and Kirkham & Wilkins (1994).
In addition to this, a large delay of the first cut, at the same number of cuts during the whole season, led to an increased NUE (Kreil & Kaltofen, 1966; Kirkham & Wilkins, 1994). The increase in NUE over the whole year was less than for the first cut, since the later cuts were cut at a younger stage and tended to have a higher N content.

Cumulative effects
The analysis of the data on an annual basis shows the importance of good grassland management in terms of a combination of grazing and cutting and the cutting frequency. Also practical conclusions may be drawn from this analysis. But analysing N uptake and DM yield per year,was still an analysis of cumulative effects. The N uptake and DM yield per year are the result of applying N per cut and harvesting per cut. To improve our understanding of the effects and interactions of application level, grassland use and cutting frequency better, results should be analysed per cut. For a single cut the relationships between growth period, SNS, ANR and NUE are more clear than for a complete growing season. Residual effects of individual cuts can be large, heavy cuts leading to regrowth retardation (Wieling & DeWit, 1987), heavy applications to considerable residual N effects (Prins, 1983). Fertiliser experiments with succesive harvests in individual cuts and special attention to the pretreatment (N application, yield of the previous cut) provide the right data for such an analysis (Prins *et al.*, 1980; Wieling & De Wit, 1987).

Development over time
A dataset of such a long period invites to analyse changes over time. Such an analysis must be done very carefully. There is a large variation in weather conditions and the dataset is not balanced. The records are not even spread over the whole period. Cutting and drying techniques have changed. In some of the oldest experiments yields were expressed in kg hay, which was assumed as having a dry matter content of 88%. Cutting height was always kept constant in an

experiment with one or more sites. But between experiments there might have been some differences in cutting height. The effect of a variation in cutting height was expected to be small (Del Pozo Ibanez, 1963).
Grassland renovation, drainage, soil fertility, grassland management and other factors are confounded with time. Since about 1970 remarkable changes in experimental conditions took place. After 1970 the average number of cuts increased from five to about six cuts per year (Figure 6-8). Despite the increased cutting frequency, in most of the treatments cutting was still carried out according to date. Before 1970, white clover was present in most of the experiments (Figure 6-1). Furthermore, relatively many fertilisation experiments took place with grazing. Since 1973 SNS of experimental sites on sand was lower than before, due to the lower content of soil organic matter (as a result of ploughing) and the larger share of young grassland (Figure 6-4). Since 1970 also the technique to measure N uptake has changed from the CP analysis to the N_t analysis (Table 6-6).
Van Der Meer & Van Uum-Van Lohuyzen (1986) reported an increase in ANR after 1970, possibly caused by improved drainage and improved grassland management and the absence of clover in unfertilised plots. The dataset of Van Der Meer & Van Uum Van Lohuyzen (1986) contained many data from peat soils before 1970, but only a few after 1970. After corrections are made for soil type and the change in experimental conditions since 1970 (grazing/cutting, cutting frequency, white clover (Frame, 1973), grassland renovation and chemical analysis of N uptake), an increase in ANR in time has not been found.

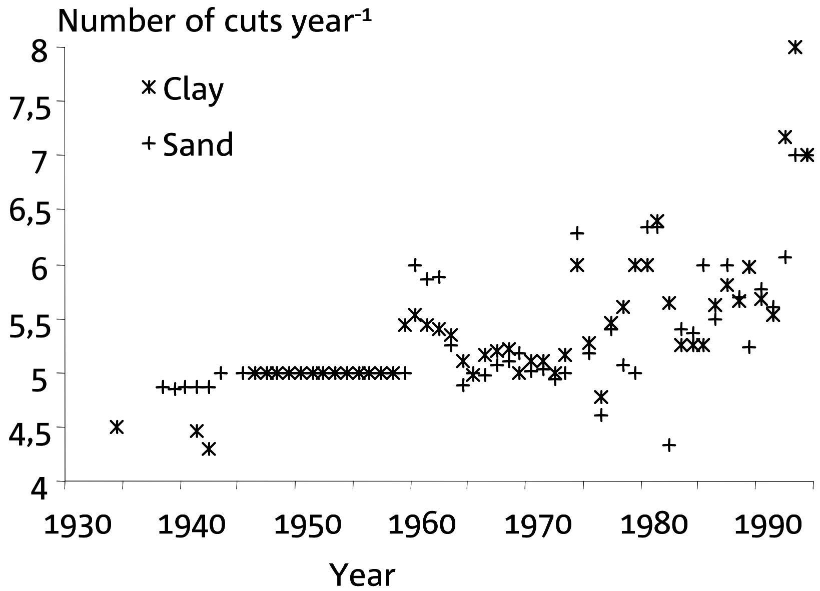

Figure 6-8. The number of cuts per year in the fertilisation experiments in The Netherlands. (+ = sand, * = clay).

The change from the CP analysis to the N_t analysis around 1970 also affected NUE (Table 6-6). The N_t measurement had a higher NUE of about 1 kg DM per kg N, compared to the CP measurement. This sounds surprising, because the opposite effect would be expected. In an N_t analysis, also nitrate was included, but nitrate has not contributed to the formation of dry matter, so its NUE is nil. Grassland renovation led to a larger share of perennial ryegrass and the the latest varieties were sown. Harkess & Frame (1986), Sheldrick *et al.* (1986) and Frame (1991) clearly showed the superior NUE of perennial ryegrass in relation to other species. Van Loo *et al.* (1992), Vellinga & Van Loo (1994) and Baan Hofman (1988) showed that genetic improvement towards persistency and higher growth rates lead to a higher NUE. Data from Hopkins *et al.* (1990, 1995) also show a higher NUE on reseeded grasland, compared to old swards.
This increase in NUE might be small, only 1 kg DM per kg N. But the NUE plays a very important role in the DM production, as shown by Equation 12.
In our dataset the mean SNS on mineral soils was about 180 kg N, the mean ANR at a fertilisation level of 200 kg N per ha was 65% and the total N uptake was 310 kg per ha. At that level of N uptake the mean NUE was 34 kg DM per kg N. Changes in SNS, ANR and NUE of 1 kg N, 1% and 1 kg DM per kg N uptake result in changes in DM yield of 34, 68 and 310 kg per ha, respectively.
In conclusion, changes in ANR over time could be explained by soil type, sward age (and soil organic matter content), grassland use, cutting frequency, white clover and chemical analysis of N uptake. Changes in NUE over time are due to the increase and genetic improvement of perennial ryegrass.

6.5 Conclusions

Analysis of a dataset of many years of fertilisation experiments led to a confirmation of well known results, but also to some new results:

- The increasing ANR and the slowly decreasing NUE at low N application levels indicate the necessity of a minimum application of at least 100 kg N per ha to realise a good N utilisation.
- Grazing leads to a higher SNS, a lower ANR and NUE, compared to cutting. These effects are stronger with pure grazing than with a mixed use of grazing and cutting.
- Changes in SNS on clay soil over time have not been found, a decrease in SNS on sand in the years after 1970 could be explained by a decrease in soil organic matter content.
- Changes in the ANR in fertiliser experiments over the last sixty years can be fully explained by changes in experimental conditions (soil type, sward age,

organic matter content, white clover), experimental treatments (grazing/cutting, cutting frequency) and chemical analysis (N_t instead of CP).

- Changes in the NUE in fertiliser experiments over the last sixty years can be explained by the genetic improvement and the higher proportion of perennial ryegrass.

Acknowledgements

We would like to thank Hugo Van Der Meer from Plant Research International for his permission to use the complete data of the experiments CI 203 and PAW 970 and for his overview of collected experiments (Van Der meer & Van Uum-Van Lohuyzen, 1986).

Thanks are also due to Oene Oenema, René Schils and Agnes Van Den Pol-Van Dasselaar for critical comments on the first draft.

Annex

Overview of used fertiliser experiments for the analysis of SNS, ANR and NUE.

Experiment	Source	Soil type	Years	Records
Pr149	Frankena (1939)	Poorly drained peat	1934	10
Pr154	Frankena (1939)	Clay	1934	10
Pr458	Frankena (1945)	Sand	1938-1942	20
CI15	Bosch *et al.* (1963)	Sand	1938-1960	221
CI16	Frankena (1945)	Poorly drained peat	1941-1942	8
CI18	Frankena (1945)	Clay	1941-1942	4
Pr640	Mulder (1949)	Poorly drained peat	1941-1942	58
Pr641	Mulder (1949)	Clay	1941-1942	58
CI203	Van Der Meer (pers. comm)	Clay	1946-1963	228
CI203	Van Der Meer (pers. comm)	Poorly drained peat	1946-1963	178
CI203	Van Der Meer (pers. comm)	Sand	1946-1963	68
CI1300b	Minderhoud (1960)	Poorly drained peat	1954-1957	15
CI1300	Minderhoud (1960)	Clay	1956-1957	65
CI1812	Hoogerkamp (1973)	Clay	1956-1962	48
PAW169	Hoogerkamp (1973)	Clay	1959-1964,1967	112
PAW246	Krist (1965), unpublished data	Well drained peat	1959-1966	72
PAW479	Mooij & Vellinga (1993)	Clay	1960-1971	84
PAW480	Mooij & Vellinga (1993)	Sand	1960-1971	84
PAW481	Mooij & Vellinga (1993)	Poorly drained peat	1960-1971	84
PAW642	Mooij & Vellinga (1993)	Clay	1962-1971	70
PAW643	Mooij & Vellinga (1993)	Sand	1962-1971	70
PAW644	Mooij & Vellinga (1993)	Poorly drained peat	1962-1971	70
PAW667	Woldring (1975a)	Clay	1963-1972	160
PAW803	Krist (1972)/Woldring (1975c)	Sand	1963-1973	66
PAW970	Van Der Meer (pers. comm)	Clay	1964-1973	504
PAW970	Van Der Meer (pers. comm)	Poorly drained peat	1964-1973	342
PAW970	Van Der Meer (pers. comm)	Sand	1964-1973	486
PAW764	Hoogerkamp (1973)	Sand	1965-1967	24
PAW1120	Woldring (1974)	Sand	1966-1970	90
ALG97	Hoogerkamp (1973)	Clay	1966-1971	54
ALG119	Hoogerkamp (1973)	Clay	1967	45
IBS1162	Ennik (1972)	Clay	1969	12
PAW1682	Woldring (1975b)	Sand	1970-1973	12
Pr11	Boxem & Leusink (1978)	Well drained peat	1970-1975	36
Pr11	Boxem & Leusink (1978)	Poorly drained peat	1970-1975	36
IB2032	Prins & Van Burg 1979)	Clay	1973	8
IB2145	Prins *et al.* (1981)	Clay	1974	21
IB2146	Prins (1983)	Sand	1974-1978	30
PR416	Woldring (1977)	Sand	1975	4
IB2244	Prins (1983)	Clay	1975-1978	19
IB2259	Prins (1983)	Clay	1975-1978	22
PR577	Unpublished data	Sand	1978	12
PR700	Snijders *et al.*(1987)	Sand	1978-1981	32
PR652	Unpublished data	Sand	1979	16
PR653	Unpublished data	Sand	1979	16
CABO314	Van Der Meer (pers. comm.)	Clay	1979-1982	24
PR804	Snijders *et al.*(1987)	Sand	1979-1983	40
PR844	Snijders *et al.*(1987)	Sand	1980-1984	40

PR891	Korevaar (1986)/unpublished data	Poorly drained peat	1980-1988	81
PR965	Snijders *et al.*(1987)	Clay	1981-1983	12
ZV30	Korevaar (1986)/unpublished data	Poorly drained peat	1981-1988	72
CABO	BaanHofman (1988)	Sand	1982-1984	96
PR49	Wouters *et al.* (1995)	Sand	1982-1984	36
BZ25	Korevaar (1986)/unpublished data	Clay	1982-1991	144
PR228	Schils (1992)	Sand	1984-1985	8
PR229	Schils (1992)	Clay	1984-1985	8
IB3079	NMI, unpublished data	Clay	1986	5
PR386	Schils (1992)	Sand	1986-1988	12
PR387	Schils (1992)	Clay	1986-1988	12
PR388	Schils (1992)	Sand	1986-1988	12
IB3133	NMI, unpublished data	Clay	1987	5
IB3182	NMI, unpublished data	Sand	1988	5
IB3184	NMI, unpublished data	Clay	1988	5
IB3230	NMI, unpublished data	Sand	1989-1990	16
PR1536	Schreuder *et al.* (1995)	Sand	1989-1991	28
PR2531	Schreuder *et al.* (1995)	Clay	1989-1991	28
PRCd	Snijders *et al.* (1994)	Sand	1989-1992	48
PR1535	Schreuder *et al.* (1995)	Sand	1989-1991	16
PR4533	Schreuder *et al.* (1995)	Clay	1989-1991	16
PR5533	Schreuder *et al.* (1995)	Well drained peat	1989-1991	16
PRBZ	Schils *et al.* (1998)	Sand	1990-1992	30
PRWbh	Schils *et al.* (1998)	Clay	1990-1992	30
PR1578	Hofstede *et al.* (1995) Hofstede (1995a,b)	Sand	1992-1994	40
PR3044	Hofstede *et al.* (1995) Hofstede (1995a,b)	Clay	1992-1994	40
PR5562	Hofstede *et al.* (1995) Hofstede (1995a,b)	Poorly drained peat	1992-1994	40
PR5563	Hofstede *et al.* (1995) Hofstede (1995a,b)	Well drained peat	1992-1994	40
Total				4689

Chapter 7

The impact of grassland ploughing on CO_2 and N_2O emissions in The Netherlands

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7 The impact of grassland ploughing on CO_2 and N_2O emissions in The Netherlands

Abstract

The contribution of ploughing permanent grassland and leys to emissions of N_2O and CO_2 is not yet well known. In this paper, the contribution of ploughing permanent grassland and leys, including grassland renovation, to CO_2 and N_2O emissions and mitigation options are explored.

Land use changes in The Netherlands during 1970-2020 are used as a case study. Three grassland management operations are defined: i) conversion of permanent grassland to arable land and leys; ii) rotations of leys with arable crops or bulbs and iii) grassland renovation. The Introductory Carbon Balance Model (ICBM) is modified to calculate C and N accumulation and release. Model calibration is based on ICBM parameters, soil organic N data and C to N ratios. IPCC emissions factors are used to estimate N_2O-emissions. The model is validated with data from the Rothamsted Park Grass experiments.

Conversion of permanent grassland to arable land, a ley arable rotation of 3 years ley and 3 years arable crops, and a ley bulb rotation of 6 years ley and one year bulbs, result in calculated N_2O and CO_2 emissions totalling 250, 150 and 30 ton CO_2-equivalents ha^{-1}, respectively. Most of this comes from CO_2. Emissions are very high directly after ploughing and decrease slowly over a period of more than 50 years.

N_2O emissions in 3/3 ley arable rotation and 6/1 ley bulb rotation are 2.1 and 11.0 ton CO_2-equivalents ha^{-1} $year^{-1}$, respectively. From each grassland renovation, N_2O emissions amount to 1.8 to 5.5 ton CO_2-equivalents ha^{-1}. The calculated total annual emissions caused by ploughing in The Netherlands range from 0.5 to 0.65 Mton CO_2-equivalents ha^{-1} $year^{-1}$.

Grassland renovation in spring offers realistic opportunities to lower the N_2O emissions. Developing appropriate combinations of ley, arable crops and bulbs, will reduce the need for conversion of permanent pasture. It will also decrease the rotational losses, due to a decreased proportion of leys in rotations. Also spatial policies are effective in reducing emissions of CO_2 and N_2O.

Grassland ploughing contributes significantly to N_2O and CO_2 emissions. The conclusion can be drawn that total N_2O emissions are underestimated, because emissions from grassland ploughing are not taken into account. Specific emission factors and the development of mitigation options are required to account for the emissions and to realise a reduction of emissions due to the changes in grassland ploughing.

7.1 Introduction

The increasing concentration of greenhouse gases in the atmosphere is an international environmental concern. In Kyoto in 1997, many governments agreed to reduce the emissions of the greenhouse gases CO_2 and others, such as nitrous oxide (N_2O) and methane (CH_4). The main sources for CH_4 are enteric fermentation and animal manure (Van Den Pol-Van Dasselaar *et al.*, 1999). For N_2O the focus is on the effects of application of manure and fertilisers (Freibauer & Kaltschnitt, 2003; Olivier *et al.*, 2003).

Agricultural activities are responsible for up to 40% of the estimated global emission of 14 Mton of N_2O into the atmosphere (Prather *et al.*, 1995). A similar contribution of agriculture to national N_2O-emissions is found in The Netherlands (Anonymous, 1997c). To ensure compliance with the Kyoto agreement it is essential to identify major sources and practices that lead to production and emission of greenhouse gases.

Agricultural activities affect the emission of CO_2 through oxidation of soil organic matter (Smith *et al.,* 2001) and by sequestration of CO_2 in soil organic matter (Conant *et al.*, 2001). Land use changes by ploughing permanent grassland for arable cropping or establishing ley-arable rotations have only recently been identified as an important regulating management factor in CO_2 emissions (Sauerbeck, 2001; Guo & Gifford, 2002; Del Galdo *et al.*, 2003). Also, large losses of soil organic N, caused by land use changes have been reported (Whitehead *et al.*, 1990; Whitmore *et al.*, 1992; Hoffmann, 1999; Bhogal *et al.*, 2000) Corresponding large emissions of N_2O seem likely. The effect of land use changes on CH_4 emissions will be marginal (Van Den Pol-Van Dasselaar *et al.*, 1999). Few countries consistently report their emissions (UNFCCC, 2000). The contribution of grassland ploughing to overall N_2O emissions is not quantified yet.

This paper reports quantification of the contribution of grassland ploughing including grassland renovation to CO_2 and N_2O emissions. Options to reduce such emissions will be explored. The Netherlands will be used as a case study, because significant land use changes have occurred since 1970 and are expected during the next 15 to 20 years. A simple simulation model (ICBM; Andrén & Kätterer, 2001) will be used to estimate the C and N release and associated CO_2 and N_2O emissions from ploughed grassland on a field scale in combination with IPCC emission factors.

Table 7-1. Strategic grassland management operations that include ploughing in The Netherlands.

Conversion of permanent grassland	Ploughing permanent grassland to arable land for continuous cropping of silage maize or to rotations of ley with arable crops, leguminous crops and bulbs.
Rotation with leys	Land use with temporary grassland (Anonymous, 1999b) in combination with arable crops or bulbs. Most common cropping systems: i) Arable crops/fodder crops, a rotation of 3 years ley and 3 years arable crops (Aarts *et al*., 2000a, 2000b) ii) Bulb crops, like tulip, lily and gladiolus, a rotation of 6 years ley with 1 year bulbs.
Renovation of permanent grassland	Ploughing in spring or autumn, immediately followed by reseeding in order to improve sward quality or introduce new (higher yielding or more resistant) varieties of mainly perennial ryegrass.

7.2 Material and methods

Grassland management operations

There was 1 Mha of intensively managed grassland in The Netherlands in 2001. Most grassland here is used for grazing and cutting, with 5-7 cuts per annum, and an annual application of 250-450 kg ha^{-1} of N in animal manure and mineral fertilisers. *Lolium perenne* L. is the dominant species, with a ground cover of 60 to 95% in most grasslands. Production varies between 10 and 16 tons of dry matter $year^{-1}$ (CBS, 2000). Each year 5-10% of the total grassland area is ploughed (Anonymous, 2000a). Although there is some variation in practice, three “strategic grassland management operations” can be distinguished: i) conversion of permanent grassland to arable cropping systems, ii) rotation of ley with other crops and iii) renovation of permanent grassland. These operations are described in Table 7-1.

Changes in land use between 1970 and 2020

Developments between 1970 and 2020 are shown in Table 7-2. During a period of 50 years, three major developments can be identified:

- The acreage of grassland decreased over the whole period 1970-2000 and will decrease further from 2000 to 2020, due to urbanisation, expansion of infrastructure, natural habitat recreation, recreational use and an increase in fodder maize production (CBS, 2000; MHSPE, 2001). In the period 2000-2020, the area of permanent grassland is expected to decrease faster than the total grassland area;

Table 7-2. Acreage developments concerning permanent grassland, ley, bulbs and fodder maize between 1970 and 2020 in The Netherlands. Bold numbers are based on surveys and statistics (CBS, 2000). All data in thousands of hectares.

Land use ↓ Year →	1970	1980	1990	1995	2000	2020
Total grassland	**1345**	**1198**	**1095**	**1050**	**1010**	850
Permanent grassland	**1310**	**1160**	**1060**	**1010**	**920**	640
Ley	**35**	**38**	**35**	**40**	**90**	210
Ley-arable 3/3: ley	10	10	10	15	30	90
Ley-arable 3/3: arable	10	10	10	15	30	90
Total bulb area	**12**	**14.5**	**17**	**17.5**	**22.5**	30
Ley-bulbs 6/1: ley	25	25	25	30	60	120
Ley-bulbs 6/1: bulbs	**4**	**4**	**4**	**5**	**10**	20
Total maize area	**5**	**140**	**200**	**235**	**250**	250
Land use change:						
Conversion of permanent grassland for maize	0	100	60	20	0	0
Conversion of permanent grassland for leys	0	0	0	5	50	120
Annual ley area ploughed up in rotations	7	7	7	10	20	60
Annual grass area for grassland renovation*	**20**	**40**	**50**	**50**	**50**	30

* Grassland renovation is exclusively in autumn until 2000. Trend analysis and implementation of manure policy will change grassland renovation gradually to spring (25 000 ha in 2020) and less in autumn (5000 ha).

- There has been a large increase in the maize growing area (CBS, 2000) and in grassland renovation (Anonymous, 2000a) until about 2000. The total maize area from 2000 and onwards is expected to remain constant. Grassland renovation will decrease proportionally with the decrease in the area of permanent grassland;
- There will be an increase in the total area receiving ley management, as a result of an expected increase in ley-arable rotations due to a stimulation of organic farming (MANMF, 2001), ley-maize rotations (Aarts *et al.*, 2000a, 2000b) and an increase in ley bulb rotations. The latter wil be caused partly by a switch from continuous cropping to ley-bulb rotations and an increase in the total area (MHSPE, 2001) after 2000.

Modelling C and N losses

Model concept

The effects of the three management operations and their growth and decline in land of area on the emission of CO_2 and N_2O is calculated with a simple model for net accumulation and release of soil organic C and N. The principles of this model are shown in Figure 7-1 and are based on Jenkinson *et al.* (1987) and Jenkinson (1988). Soil organic C and N accumulate relatively quickly under young

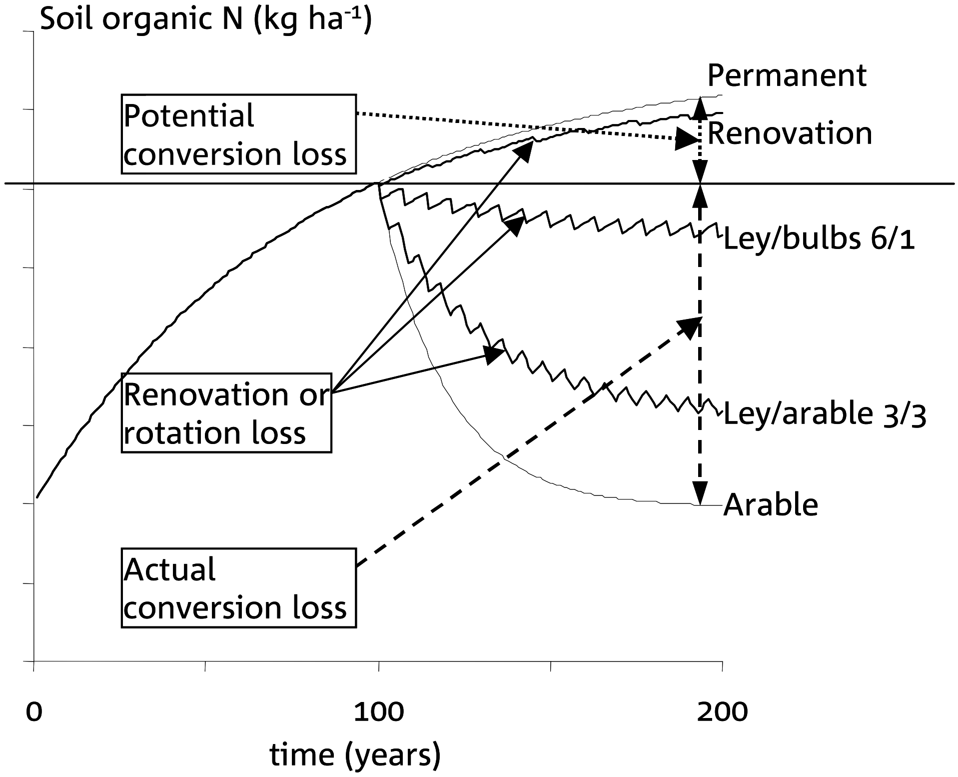

Figure 7-1. Patterns of soil organic N accumulation and losses on permanent grassland over time for situations with and without regular renovation by ploughing and patterns of soil organic N decrease when 100 year old grassland is ploughed and converted to arable or ley arable systems with different rotational length. "Actual" losses from conversion, rotation and renovation and a so-called "potential" loss are distinguished. The latter represents the continued N accumulation until equilibrium conditions are reached.

pastures (Whitehead *et al.*, 1990; Hassink & Neeteson, 1991) and continue to accumulate at a lower rate in older pastures as well (Jenkinson *et al.*, 1987*)*. Grassland ploughing enhances the release of C and N following decomposition of soil organic matter (e.g. Strebel *et al.*, 1988; Whitehead *et al.*, 1990; Whitmore *et al.*, 1992; Campbell *et al.*, 2001). This may continue for a relatively long time before equilibrium conditions are reached (Kortleven, 1963; Allison, 1973; Richter *et al.*, 1989; Schlesinger, 1991).
In ley-arable rotations the proces of accumulation and release of soil organic C and N occur subsequently and repeatedly. This annual accumulation and release affects the actual equilibrium level of organic matter that is reached after several decades. As a consequence, the new equilibrium range of soil organic C and N,

when permanent grassland is converted to a ley-arable or a ley-bulb rotation, depends on the number of grassland years in the rotation. Thus, in the ley-bulb rotation with 6 ley years out of 7, C and N still accumulate and this leads to higher soil organic C and N contents than ley-arable rotations with 3 ley years out of 6.
The loss of soil organic C and N in rotations, until equilibrium is reached, consists of two processes: i) the release caused by the conversion of permanent grassland to arable land or ley: an "actual" loss is distinguished from a "potential" loss. The "actual" loss is real and takes place following decrease of soil organic N and C. The "potential" loss is a potential N and C sequestration which would have taken place when the conversion of grassland not had been executed. ii) The release caused by the specific configurations of the ley-arable or ley-bulb rotations (Loiseau *et al.*, 1994): the rotational releases for N can best be calculated from the equilibrium condition. In rotation, there is no net change in C assumed, since C is released during the arable years but immobilised during the grassland period. Any loss of N however would have to be compensated for by new input and immobilisation of N and would result in N_2O emissions that depend on the specific source of N and emissions along the production chain of N sources, i.e. fertiliser or manure (Velthof *et al.*, 1997).
During the brief fallow period associated with grassland renovation, soil organic C and N decrease sharply. When the grass sward is re-established, accumulation continues. Here the equilibrium condition eventually equals the C and N content in undisturbed pasture although it may take more time before it is reached. In the case of grassland renovation, there is no net change in C assumed, comparable to ley-arable rotations.
To quantify the effect of ploughing on accumulation and release of soil organic C and N the factors sward age, soil type, ley-arable rotation and renovation are taken into account. The effects due to specific arable crops (cereals, root crops etc.), the choice and application rate of manure and other fertilisers and site conditions (climate, soil conditions, pH, drainage) are neglected, although it is known that they also affect C and N accumulation and release as well (Jenkinson *et al*. 1987; Whitehead *et al*., 1990; Whitmore *et al*., 1992; Loiseau *et al*., 1994).

The model

The Introductory Carbon Balance Model (ICBM; Kätterer & Andrén, 1999) is used to quantify the amounts of C and N which are accumulated or released under grassland and arable land, by simulating soil organic N turnover and

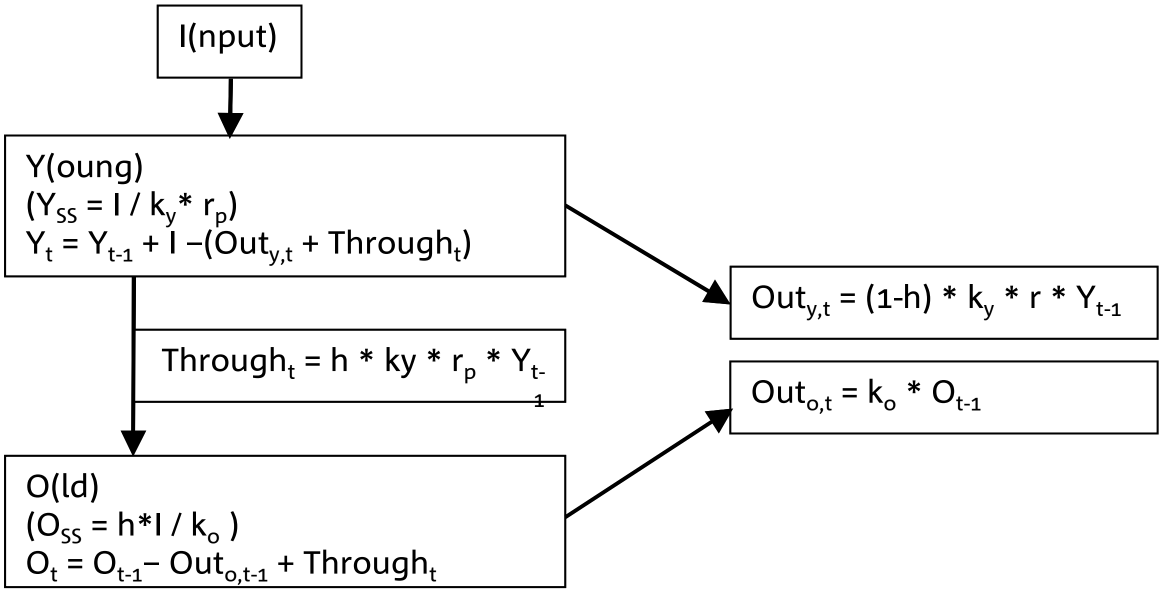

Figure 7-2. Structure of the Introductory Carbon Balance Model (ICBM) by Andrèn & Kätterer (2001). State variables are Y_t and O_t, representing a young, unstable and an old, stable organic N pool respectively (kg ha^{-1}) and their steady state condition (Y_{ss} and O_{ss}, respectively, kg ha^{-1}), k_y and k_o are decomposition rates for the young and old pool respectively (kg ha^{-1} $year^{-1}$), h is the humification factor (-), r_p is the "ploughing" coefficient (-). $Through_t$, on the left, is an internal flux, the throughput of N from the young to the old pool (kg ha^{-1} $year^{-1}$). External fluxes are $Out_{y,t}$, $Out_{o,t}$, the N release by the young and old N pools respectively (kg ha^{-1} $year^{-1}$). t represents time (year).

assuming a constant C to N ratio in soil organic matter. Kätterer & Andrén (1999) defined two organic C pools: young and old, with a high and low rate parameter, respectively, for C mineralisation and a humification parameter for throughput of mineralised C from the young to the old pool. The pools have been redefined for the ICBM as follows: a relatively unstable organic N-pool (young) and a stable organic N-pool (old), with their own decomposition rates and humification factor were defined as in Figure 7-2.

State variables

$\boldsymbol{Y_{SS}, O_{SS}}$	=	the amounts of "Young" and "Old" soil organic N under the steady state condition respectively (kg ha^{-1})
$\boldsymbol{Y_t, O_t}$	=	the amounts of "Young" and "Old" soil organic N at time = t, respectively (kg ha^{-1})

Fluxes

$Out_{y,t}$, $Out_{o,t}$ = the N release by “Young” and “Old” organic N pools (kg ha^{-1} $year^{-1}$).

$Through_t$ = the N throughput from the “Young” to the “Old” organic N pool (kg ha^{-1} $year^{-1}$).

Model parameters

K_Y, K_O = decomposition rate constants for the “Young” and “Old” soil organic N ($year^{-1}$).

I = the annual input of N (kg ha^{-1} $year^{-1}$)

H = the humification factor, the amount of “Young” organic N that is transferred into “Old” organic N (-).

r_p = ploughing coefficient, defined by Andrén & Kätterer (2001) as the “external influence coefficient”. (-)

Model calibration

Soil organic N (and C) content depends on the assigned decomposition rates (k_y and k_o) and the N input level (I). The stable organic N-pool is assumed to be comparable to the old organic matter pool from Kätterer & Andrén (1999), k_o = 0.006 is used and the humification factor is set at 0.1.

Hassink (1994) reported 0.1% and 0.15% N as minimum soil organic N values on young grassland after a long period of arable cropping in the layer 0-20 cm for sand and clay, respectively. Related to these contents, soil organic N is set at 3000 and 4000 kg N per ha, for sand and clay respectively. The theoretical maximum of SON in Figure 7-1 is realised on old permanent grassland, with amounts of SON of 0.21% and 0.42% for sand and clay respectively in the layer 0-10 cms (Hassink, 1994). Assuming these organic N contents over the top layer of 0-20 cms, the total amount of soil organic N is set at 6000 and 12000 kg N per ha for sand and clay respectively.

Soil Nitrogen Supply on permanent grassland under grazing conditions is about 200kg N ha^{-1} $year^{-1}$ on sand and clay soils (Vellinga & André, 1999). This agrees well with data from immobilisation ranges as found by Whitehead *et al.* (1990), Hassink & Neeteson (1991) and Hassink (1995c). Annual net input of N on grassland is set at 200 kg ha^{-1}. Annual net N input on arable land is set at 100 kg ha^{-1}.

Table 7-3. Data on soil organic N, C to N ratio, humification factor, N inputs and rate parameters to be used the ICBM model (Andrèn & Kätterer, 2001) for simulating C and N release of conversion of permanent grassland to arable land and leys.

Parameter	Sand	Clay	
Soil organic N, minimum	3000	4000	(Hassink, 1994)
Soil organic N, maximum	6000	12000	(Hassink, 1994)
Input grassland	200	200	(Hassink, 1995c; Vellinga & André, 1999)
H	0.1	0.1	(Andrèn & Kätterer, 2001)
C:N-ratio	15	10	(Hassink, 1994)
Ratio k_{sand}:k_{clay}	2	1	(Verberne *et al.*, 1990; Hassink, 1994; Vellinga & André, 1999)
R_p	3	3	(Koornneef, 1945; Allison, 1973; Whitmore *et al.*, 1992;)
k_o	.006	.003	(Andrèn & Kätterer, 2001)
$Y_{t=0}$	600	1000	*Calculated with model simulation*
$O_{t=0}$	2000	4000	*Calculated with model simulation*
Y_{ss}	3333	6667	*Calculated with model simulation*
O_{ss}	2040	4125	*Calculated with model simulation*
k_y	.06	.03	*Calculated with model simulation*
Input arable	100	100	*Calculated with model simulation*

Verberne *et al.* (1990) and Hassink (1994) reported lower decomposition rates on clay soils than on sandy soils as a result of physical protection. The overall decomposition rates of $(Out_{y,t}+Out_{o,t})/(Y_{ss}+O_{ss})$, 200/6000 and 200/12000 for sand and clay respectively, indicate a 2:1 ratio. So, k_o for clay is adjusted to 0.003, k_o for sand is kept at 0.006.

Grassland ploughing enhances release of soil organic N. Results from long term experiments of grassland conversion to arable land show decomposition rates between 5 and 12% (Koornneef, 1945; Allison, 1973; Whitmore *et al.*, 1992) Thus the net decomposition rate of soil organic matter is about three times faster under arable than under grassland conditions, the value of r_p is set at 3.

Simulation runs to find the decomposition rate k_y and the partitioning between Y and O were carried out for a 300 year period with 100 year grassland on previous arable land, followed by 200 year of arable management. Parameter values were chosen in order to realise a stable model, i.e. the values of Y and O should be about the same at t=0 and t=300 years. The results are shown in Table 7-3.

Table 7-4. Data of N losses in stubble and root, extra N uptake and reduced inputs of fertiliser N in rotations of leys with arable crops and bulbs.

Parameter	Value	Rationale	Reference
$N_{stubble,root}$	300 kg ha^{-1},	for permanent grassland and 6 year old ley,	Whitehead *et al.* (1990)
	200 kg ha^{-1}	for 3 year old ley	
$N_{uptake,extra}$	25 kg ha^{-1}	1 year bulbs	-
	100 kg ha^{-1}	3 years arable: 1x50 + 2x25	
	700 kg ha^{-1}	permanent arable in 25 years: (3x50) + (22x25)	
Reduced	25 kg ha^{-1}	In bulbs, every rotation	Van Dam (pers.comm)
N_{input}	100 kg ha^{-1}	50 + 2x25 in 3 arable years	Van Dijk (1997)
	150 kg ha^{-1}	100 + 2x25 = 150 in years 1-3 after ploughing	

Nitrogen from stubble and roots, additional N uptake and reduced fertiliser inputs are summarised in Table 7-4. Vergeer & Bussink (1999) predicted an additional N demand of about 300 kg N ha^{-1} for grassland renovated in autumn, caused by N losses during the brief fallow period. Ernst & Berendonk (1990) and Adams & Jan (1999) reported greater N losses for late autumn renovation compared with early autumn renovation. A 3:1 ratio is used for N loss by autumn and spring renovation respectively.

N_2O and CO_2 losses

Nitrogen loss is partly emitted as N_2O. A grass residue emission factor (stubble and roots) of 1.25% is used (IPCC, 1997). For released N after ploughing up grassland or grassland in rotations, no specific emission factor has been defined. A combination of emission factors defined for direct and indirect N losses is used: 1.25% for direct emission (equivalent to the emission factor for mineral fertiliser) and 2.5% for indirect N losses by nitrate leaching (IPCC, 1997). N_2O is converted to CO_2-equivalents by using the Intergovernmental Panel on Climate Change's GWP of 310 for a time horizon of 100 years. Emissions are calculated as follows:

CO_2-emission = C loss * 44/12 (kg)

N_2O-emission = N loss * (0.0125 + 0.025) * 44/28 * 310 (kg CO_2-equivalents) N_2O emissions of 3% from field measurements with slurry and fertiliser applications were reported by Scanlon and Kiely (2003). Freibauer and Kaltschnitt (2003) developed a fertiliser-based model with the same order of magnitude of N_2O emissions.

Model validation

Data for C and N contents obtained in the long term Rothamsted experiments (Jenkinson, 1988) are used to validate the used ICBM-model. The N contents are converted to C and vice-versa using C to N ratios of 10 and 15 for sand and clay, respectively. Comparison of simulation results with experimental data results in a correlation (R^2) of 0.72 and 0.60 for N and C, respectively (Figure 7-3).
Large C losses of 55 to 65% of the total C under pasture are reported in a meta-analysis by Guo & Gifford (2002). Simulation runs with the ICBM model show C losses of 50-60% when old permanent grassland is converted to arable land.

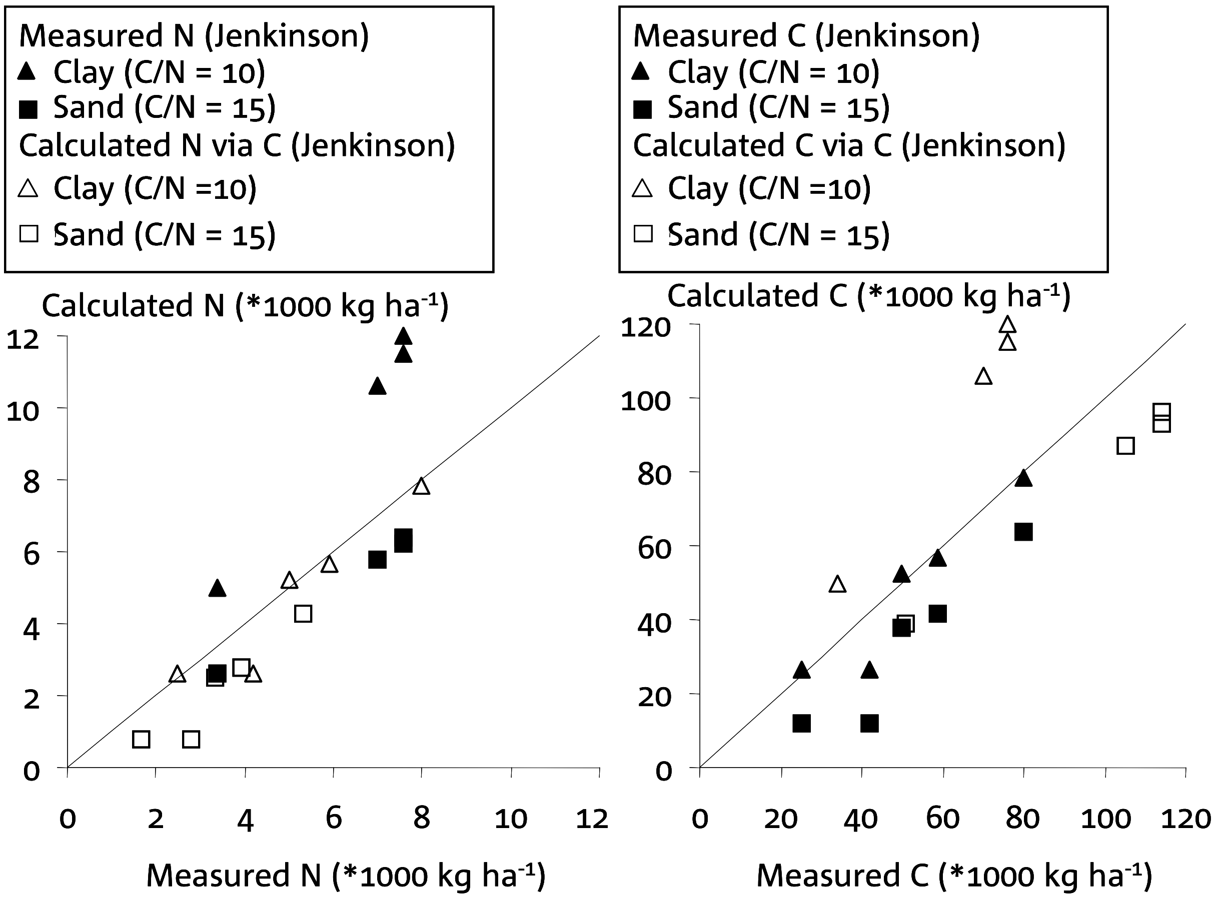

Figure 7-3. Measured and calculated N (left graph) and C amounts (right graph) from Rothamsted experiments (Jenkinson, 1988) and simulations with the ICBM-model (Andrén & Kätterer, 2001). Closed dots are measured N and C data from the Rothamsted experiments compared with model results. Open dots are calculated N and C from measured C and N data by using C/N ratios of 10 and 15 for sand and clay respectively compared with model results.

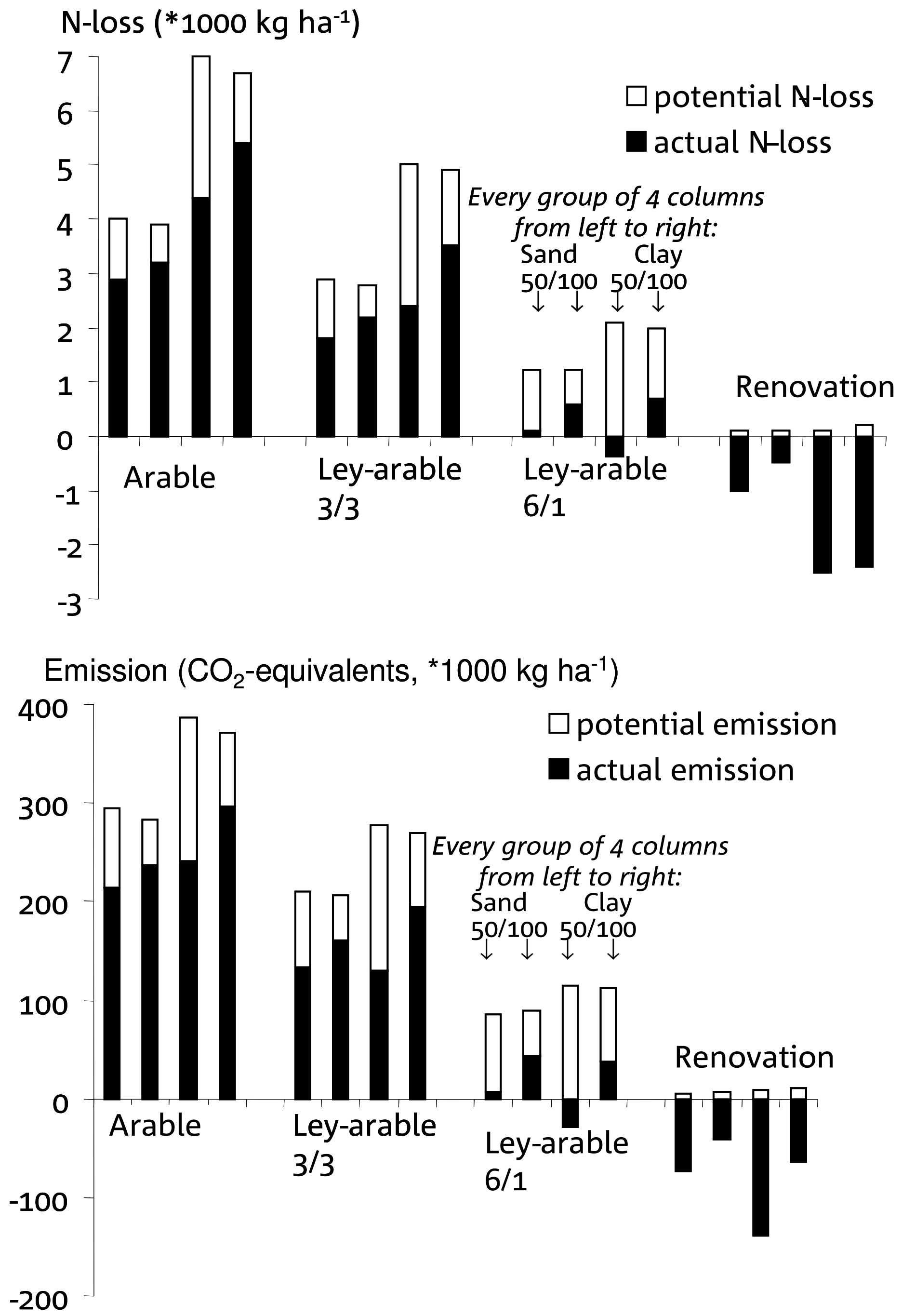

Figure 7-4. Actual and potential conversion N-losses and emissions in CO_2-equivalents (both in 1000 kg ha^{-1}) when grassland on sand and clay of 50 and 100 years old is ploughed and used as permanent arable land, 3/3 ley-arable rotations, 6/1 ley-bulb rotations and grassland renovation. Per group of 4 columns from left to right: sand of 50 and 100 year old respectively and clay of 50 and 100 years old respectively. Numbers are presented as total losses and emissions.

7.3 Results

Losses of C and N from conversion

The net C and N losses that occur when converting permanent grassland to arable land or ley-arable rotations are calculated for 50 and 100 year old grassland on sand and clay, respectively representing accumulated emissions from the moment of ploughing until a new equilibrium is established. The calculated “actual” and “potential” N losses are 50 –70% higher with clay soils compared with sand (Figure 7-4). However, with the higher C to N ratio on sand, C losses are similar for sand and clay (Figure 7-4). Greenhouse gas emissions in terms of CO_2-equivalents from clay soils are still 25% higher on clay than on sand. The total contribution of N to the total CO_2-equivalents emission is 25 and 33% on sand and clay, respectively.

The effect of sward age at ploughing on the sum of actual and potential loss is small. However, ploughing older swards leads to larger actual losses and smaller potential losses, compared to ploughing younger swards (Figure 7-4).

Actual and potential losses of C and N are less where there is a smaller proportion of arable periods in the rotation and are lowest with grassland renovation, when the arable period is minimal. In the case of a 1 to 6 rotation with bulbs and with renovation, accumulation still continues on relatively young swards (Figure 7-4).

Table 7-5. Simulated annual rotational N losses (1000 kg ha^{-1} $year^{-1}$) and N_2O emissions (expressed as CO_2-equivalents; 1000 kg ha^{-1} $year^{-1}$) of rotations of ley-arable crops (3 years ley, 3 years arable) and ley-bulbs (6 years ley, 1 year bulbs) and by renovation in autumn and spring (once in 15 years).

	Ley-arable 3/3	Ley-arable 6/1	Renovation
	Rotational N loss (1000 kg ha^{-1})		
Sand and clay	0.12	0.60	
Spring renovation			0.1
Autumn renovation			0.3
	Rotational emission (CO_2-equivalents, 1000 kg ha^{-1})		
Sand and clay	2.1	11.0	
Spring renovation			1.8
Autumn renovation			5.5

Losses of N in rotation and renovation

For 3/3 ley-arable rotations, average N losses are estimated at 120 kg N ha^{-1} $year^{-1}$ and emissions in CO_2-equivalents are estimated at 2.1 tons ha^{-1} $year^{-1}$ (Table 7-5). Losses and greenhouse gas emissions in the case of bulbs are 5 times higher due to a longer ley period and a decreased opportunity to utilise the released N, and are 600 kg N ha^{-1} and 11 tons of CO_2-equivalents ha^{-1} $year^{-1}$, respectively. Losses caused by grassland renovation are 100 and 300 kg N ha^{-1} for spring and autumn renovation, respectively. The total greenhouse gas emission in CO_2-equivalents caused by grassland renovation ranges between 1.8 and 5.5 tons ha^{-1} (Table 7-5).

Emissions of CO_2 and N_2O from land use changes between 1970 and 2020

Carbon dioxide and N_2O-emissions due to land use changes (Table 7-2) were calculated on a per hectare basis and presented as annual amounts emitted over the period between ploughing and a newly established equilibrium condition for soil C and N (Table 7-5 and Figure 7-4). The potential C- and N-losses are shown separately. Land use changes before 1970 are not included. To include long term effects, calculations on C and N dynamics are presented up to 2100 (Figure 7-5).
Total annual emissions of CO_2 and N_2O increased sharply between 1970 and 1980 from about 0.5 Mton to 1.7 Mton CO_2-equivalents and are predicted to decrease to 1.0 Mton in 2005. Total greenhouse gas emissions remain fairly constant until 2020 and will gradually decrease to about 0.5 Mton in 2090.
Following the initial increment from 0.25 to 0.65 Mton between 1970 and 1980, N_2O-emissions remain fairly constant at 0.5-0.6 Mton CO_2-equivalents. Before the year 2000 N_2O emissions can be mainly attributed to grassland renovation and conversion of grassland to maize. From 2000 and on, rotations of ley with arable crops and bulbs gradually become the major emitters. From 1995 until roughly 2050, the anticipated conversion of grassland into ley systems is a major contributor to N_2O-emissions from grassland ploughing.
The CO_2-emissions caused by grassland conversion to arable land and ley management increased sharply from 0.25 Mton in 1970 to 1.1 Mton in 1980. Between 1980 and 2005, annual CO_2-emissions decrease to 0.4 Mton and then remain constant until 2020. From 2020 and onwards CO_2-emissions slowly decline to about nil, because no further land use changes after 2020 are used in the calculations.
Potential losses range from 0.4 Mton during the period 1980-2000, to 0.2 Mton during the period after 2020 and represent the potential sink strength of the grassland without the conversion to arable and ley management.

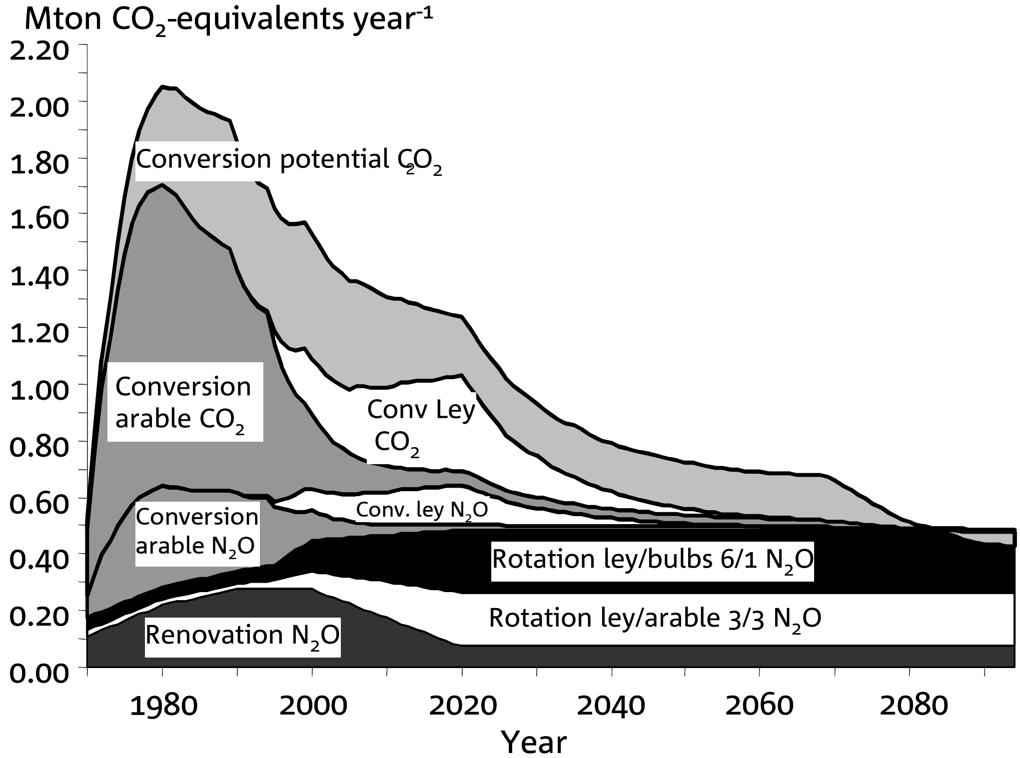

Figure 7-5. Emission of N_2O by ploughing permanent grassland for renovation and by ploughing ley in rotations, and emission of N_2O and CO_2 caused by conversion of permanent grassland to arable cropping (maize) and ley systems. The actual conversion emission is split up for C and N and in ploughing between 1970 and 2000 for maize and between 1995 and 2020 for ley systems. The potential CO_2 emission is combined for all conversions in the whole period 1970-2020. All emissions are expressed as CO_2-equivalents in Megatons ha^{-1} $year^{-1}$. Results based on Figure 7-3, Table 7-5 and acreage developments of Table 7-2.

Table 7-6. Relative changes in CO_2 and N_2O emissions of conversion of permanent grassland, rotations of ley with arable crops and bulbs and grassland renovation, when parameters concerning organic matter dynamics, emission factors and areal developments are 50 and 150% of the standard value, respectively.

Parameter	Standard	Alternative (standard = 100%)	Change in emission (standard = 100%)			
			Con-version	Rotation ley arable	Rotation ley bulb	Reno-vation
Organic matter dynamics						
Rate k_y, k_o	0.06/0.006	50-150	190-67	99-102	97-105	98-103
r_p constant	3	50-150	80-107	81-109	60-130	55-142
C/N ratio-constant over time	15; 10	50-150	65-135	100	100	100
C/N ratio-changing over time	15; 10	50-150	128-72	100	100	100
Emission factors						
N ➔ N_2O	3.75%	50 –150	86-115	50-150	50-150	50-150
Areal developments						
Sand share in ley rotations	50	50-150	106-94	100	100	100

Uncertainty analysis

To analyse the effects of variation and uncertainty in model parameters on the calculated emissions, an uncertainty analysis was conducted (Table 7-6).
Conversion losses are more than proportionally affected by a reduction of k_y and k_o, as a result of a large change in equilibrium levels of soil organic N. Losses due to conversion are less than proportionally affected by an increase of k_y and k_o, changes in r_p or in C to N ratios, the N_2O-emission factor and in the distribution of land use changes over sandy and clayey soils.
Changes in k_y/k_o and C to N ratios have hardly any effect on rotation and renovation losses. They are more strongly affected by changes in r_p. If one assumes that the rate parameter k_y* r_p, is decreasing over time (Yang, 1996), then very high emissions in the first year after ploughing are followed by a sharp decline in emissions in later years. Losses due to total conversion are not affected by a variable rate k_y*r_p , but emissions are much greater in the year immediately after ploughing and decline sharply in later years, than with a constant rate parameter. With bulbs and grassland renovation, a variable k_y*r_p will lead to greater losses. Effects are comparable to those using an increased r_p, that is constant over time. In the case of a 3/3 ley-arable rotation, the very high losses in

the first year may be compensated by lower losses in the second and third year, indicating that total losses may remain unchanged.

7.4 Discussion

Grassland renovation and land use change converting permanent grassland to arable land and leys have led and still lead to significant emissions of greenhouse gases compared to other sources of greenhouse gases from agriculture in The Netherlands. It is estimated that in 2000 approximately 1.7 Mton CO_2-equivalents of which 0.65 Mton from N_2O have been emitted as a result of ploughing grassland. However, these emissions are reported as only N_2O emissions from manure, fertilisers, ground and surface waters are included in the national inventory (Spakman *et al*., 1997). This is a clear underestimation of the reported agricultural N_2O emissions, estimated at 7.0 Mton CO_2-equivalents in 2003 (Olivier *et al*., 2003).

As no specific emission factors for grass sward residues or soil organic matter decomposition as a result of ploughing are available in the IPCC approach, the default emission factor of 1.25% for N in crop residues (IPCC, 1997) is used. This leads to substantial N_2O emissions (Figure 7-5). Considerable short term N_2O losses have been reported by Davies *et al.* (2001) and Estavillo *et al.* (2002). More accurate calculations will be possible in the future, as data from experiments and field trials will be available (Dolfing *et al.,* 2004).

Analysis of historical data shows that land use changes as considered in this paper are not unique. Significant land use changes for the 19^{th} century are reported by Priester (1991) and Hoffmann (1999) in The Netherlands and Sweden, respectively. Trienekens (1985) and Whitmore *et al*. (1992) reported a large shift from grassland to arable land in the period 1940-1945. And today conversion of permanent grassland is continuing (Anonymous, 2000a; Guo & Gifford, 2002). Thus the presented case is not unique.

Although the datasets, calculations and forecasts in this paper do hold uncertainty and are analysed for Dutch conditions only, it can be concluded that the emissions as a result of land use changes and rotations with leys have been and still are substantial in other countries as well.

To account for such emissions of greenhouse gases as a result of the large scale application of grassland ploughing, it would help to develop either specific emission factors or response functions to be included in simple simulation models such as used in this paper.

Grassland management options to reduce emissions
The 1997 Kyoto agreement calls for lowering greenhouse gas emissions. In light of the significant contribution to CO_2 and N_2O emissions of land use changes and ploughing leys, identification of relevant mitigation options is an important issue. This is even more so because these emissions are not yet accounted for in many national inventories of greenhouse gas emissions,
Of the identified options, effects of less frequent grassland renovation and changing from autumn to spring renovation are already incorporated in the calculations. The introduction of minimum tillage by spike seeding (Roberts *et al.*, 1989), reduced herbicide application (Tenuta & Beauchamp, 1996), reduced fertiliser application and reduced grazing (Davies *et al.*, 2001), may reduce greenhouse gas emissions even further. Yet, in the case of persistent weeds and unwanted grasses or a very deteriorated sward, spike seeding and omitting herbicides is not always an effective way to improve sward quality.
Another option is to develop appropriate combinations of ley, arable land and bulbs which will reduce the proportion of ley in the rotation and to include more arable crops and bulbs and maintain soil fertility and soil organic matter contents. Such innovations will reduce the need for additional land use changes and as such reduce conversion losses, although the losses per hectare might increase, due to a lower equilibrium soil C status. Losses due to rotations will be reduced due to smaller accumulation during the ley period and a better utilisation of the slower N release during the arable period. To achieve this, dairy farmers, arable farmers and bulb growers will be required to cooperate intensively. Since there are many ways to combine crops in rotations, more precise quantitative effects are difficult to predict.
Spatial planning by governmental actions and policies also provides opportunities for emission reduction, e.g. by concentrating land use changes on sand instead of clay. Relevant is the so called “outplacement” of dairy farms to the traditional arable regions, as a part of the Dutch policy to extensify dairy farming in heavily stocked and sensitive areas (Anonymous, 2000b, 2000c) These outplaced dairy farms require (additional) grassland. Combining this with ley-arable and ley-bulb rotations would decrease the need to plough up permanent grassland, as leys are established on former arable land.

7.5 Conclusions
Ploughing grassland for conversion to ley and arable land, ley rotations and for grassland renovation is responsible for considerable N_2O and CO_2 emissions in The Netherlands. In the case of land use change converting permanent grassland to

arable land or ley the emission of CO_2 is greater than that of N_2O (expressed as CO_2-equivalents). Emissions of N_2O and CO_2 are affected by land use changes for a period of more than fifty consecutive years.
The total current N_2O emissions from Dutch agriculture are underestimated with 0.65 Mton year^{-1} because the effects of grassland ploughing are ignored. The widespread use of ley arable systems and the fact that the historical and anticipated land use changes in The Netherlands are not unique emphasise the need for the development of emission factors or response functions that facilitate the transparent reporting of emissions associated with land use changes and the development of mitigation options.

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Chapter 8

General discussion

8 General Discussion

8.1 Introduction

The availability of cheap nitrogen (N) fertilisers from the second half of the 20th century has played a dominant role in the intensification of agricultural production. In Western European countries, the application of N fertiliser to grassland has boosted herbage production and has significantly contributed to the intensification of dairy farming. Intensively managed grassland in Western Europe, and especially in The Netherlands are among the agricultural systems that received the highest amounts of N fertiliser (Van Burg *et al.*, 1981; De Clercq *et al.*, 2001), apart from vegetable growing and greenhouse horticultural systems. These intensively managed grassland systems have also been blamed for low N use efficiency and high N losses to the environment, in part because of the poor utilisation of nutrients from animal manure and the inappropriate adjustment of N fertiliser supply to the N demand of the herbage (Van Der Meer *et al.*, 1987; Aarts *et al.*, 1992; Whitehead, 1995).
From the second half of the 1980's onwards, the intensification of dairy farming in The Netherlands and elsewhere in the EU is regulated via milk quota and the implementation of an increasing number of environmental policies (Henkens & Van Keulen, 2001; Oenema & Berentsen, 2004). The environmental policies force farmers to use N more efficiently and to decrease N losses to the environment. Currently, the most important environmental policy in EU affecting N fertiliser application is the Nitrates Directive (Anonymous, 1991a). With the implementation of the EU Water Framework Directive (Anonymous, 2000e), farmers will have to further increase the utilisation of N and P and to further decrease N and P losses especially to surface waters. Because of all these governmental policies, nutrient management has become and will remain extremely important in dairy farming.
In response to the implementation of environmental governmental policies, farmers often take a whole range of different activities and measures, depending on the specific policy, farming system and personal motives. When forced to improve nutrient use efficiency, it seems logical 'to pick the low-hanging fruit first', and the implementation of a series of relatively simple best management practices is usually very effective for increasing the nutrient use efficiency. Many of these best management practices are defined at the operational day-to-day management level and/or at the tactical management level. Evidently, defining the optimal amount and the optimal time of N fertiliser and animal manure applications is of utmost importance, especially in grassland management (e.g.

Hemingway, 1999; Rougoor *et al.*, 1999a; Oenema & Van Den Pol-Van Dasselaar, 1999; Laws *et al.*, 2000).

On grass-based dairy farms, grass is an intermediate product, used for dairy and beef production. The grass is harvested several times per year by grazing and cutting, but usually there is still surprisingly little information available about the yield, quality and protein content of the harvested herbage in practice. While milk production and animal performance are registrated twice daily and intake of concentrates recorded and its feed quality certified, farmers usually don't know how much herbage is harvested. The relationships between N application and growth time and yield and quality of herbage are still poorly understood. In short, the operational management of grassland still has open questions.

In management theory the decisions at strategic level set constraints to the tactical and operational management levels, and the decisions at tactical level define the room for manœuvre at operational level (e.g. Kay & Edwards, 1994). In exploring possibilities for improving operational grassland management, it may be worthwile also to examine the relationship in the opposite direction: do the management possibilities at operational management level pose constraints on the tactical management level?

The current study focussed especially on the role of N application in operational grassland management. In my study, N application, both via N fertiliser and animal manure, is seen as a management tool for optimising grassland utilisation, in accordance with Hemingway (1999).

My thesis research focussed on three specific objectives:

1. to increase the understanding of the relationships between N application rates and herbage yield and quality in single cuts at operational level, and to increase the understanding of the consequences of decisions at operational level, for the farm and tactical management levels;
2. to identify possible tools for improving operational grassland management, and;
3. to increase the understanding of the interactions between operational, tactical and stragic management.

To be able to achieve these objectives, I analysed and reviewed data from existing multi-site and many-years' field experiments using various statistical models, analysed the operational and tactical grassland management of experimental dairy farm "De Marke" using a descriptive technique, and developed and tested two simple simulation models for the analysis of the effects of grassland management on nitrate leaching and nitrous oxide (N_2O) emissions and soil carbon sequestration. The multi-site and many-years field experiments allowed analysing the effects of weather and soil conditions. The combination of large amounts of empirical data, detailed statistical analyses and simulation models provided detailed insights in the complexities of operational grassland management and of the important role of N in general. This study focuses on N fertiliser as tool in grassland management, but the N from applied fertiliser and N from applied animal manure can be exchanged to some extent in practice. In fact, a large part of the N applied to current grassland systems is from animal manure. For convenience's sake, I focused in my study on N fertiliser.

This chapter summarises and discusses the major research findings. The pros and cons of the research approaches chosen are also briefly discussed. Finally, suggestions for further studies are discussed.

8.2 Major findings of the thesis

This paragraph summarises the major research findings of my PhD thesis research. Some of the findings provide new insights, while other findings may be seen as a confirmation of what others have found before. Some of the research findings are important for farmers as well.

Role of N in operational grassland management:

- The combined effects of applied N and growth time on dry matter yield, herbage N content and unrecovered N have been quantified. Herbage N content and unrecovered N have been identified as criteria for optimising fertiliser N application. The developed relationships and criteria provide information for optimising N application rate and the optimal timing of grazing/cutting to produce the herbage that is needed for optimal N utilisation by dairy cows (Chapters 2 and 3).
- Measurement of soil mineral N to adjust N application rates is of limited value on mineral soils and of no value on peat soils. A simple bookkeeping system, accounting for the previously applied N is much easier to apply and has similar accuracy compared to repeated measurements of soil mineral N (Chapter 3).
- The grassland calendar provides the information for the bookkeeping system. It is also a useful tool to analyse operational grassland management. For the experimental dairy farm "De Marke" and for practical dairy farms, my analysis has shown that the operational grassland management can be

improved by increasing the growth time per cut for grazing and cutting (Chapter 4).

- Applied N requires time to become fully effective. As a consequence, there are significant residual effects of previously applied N when grass is harvested after a short growth time, which contribute to a low apparent N recovery of a subsequent 'fresh' N application (Chapters 2 and 3). Hence, utilising the grassland for grazing while fertilising it for silage bears the risk of poor N utilisation.

Role of N in tactical and strategic grassland management:

- The N application rate and the stocking rate are important determinants for nitrate leaching from grazed grassland. Estimating the contribution of each of these is complicated as these factors are often confounded (e.g. Barraclough *et al*., 1992; Cuttle & Scholefield, 1995; Simon *et al*., 1997). For a good analysis of the management options to reduce nitrate leaching, the effects of N application rate and stocking rate must be analysed as independent factors (Chapter 5).
- A detailed analysis of fertiliser N experiments in The Netherlands between 1934 and 1994 shows that the increase in the Apparent N Recovery (ANR) is related to changes in grassland management at both strategic (e.g. sward age, organic matter content, the use of white clover, genetic improvement, a higher proportion of perennial ryegrass), tactical (e.g. grazing/cutting, number of split applications) and operational management levels (e.g. cutting frequency) (Chapter 6).
- Ploughing out grassland and changing permanent grassland to ley-arable rotations reduces the amount of soil organic carbon and nitrogen through increased mineralisation (Chapter 7). The release of mineralised N after ploughing ley is often too high to be utilised completely by silage maize. So, optimising the N efficiency on dairy farms by using maize in the diet of the animals should be based on nutritional criteria and on the optimal N utilisation of the combination of permanent grassland, ley and fodder maize.
- The strategic choice of changing permanent grassland to a ley-arable rotation increases the emissions of N_2O and CO_2 on farm level. The national N_2O-emission total in The Netherlands is underestimated when grassland ploughing is ignored as source of greenhouse gases. The contribution of CO_2 emissions is larger than that of N_2O emissions, when expressend in CO_2-equivalents (Chapter 7).

8.3 Discussion

Managing herbage N content and DM yield per cut

The effects of growth time on DMY, herbage N content, the amount of unrecovered N and the marginal N response are shown in Figure 8-1 for the second, fourth and sixth cut with an N application rate of 40 kg ha^{-1}. This is about the recommended N application rate for grazing cuts (Vellinga, 1998; Stienezen, 2002). The combination of N application rate and growth time provides a wide range of values for the criteria marginal N response, herbage N content and unrecovered N. The marginal N response is based on the difference in calculated DM yields between application rates of 39 and 40 kg N ha^{-1}. In all cuts, the marginal N response of applied N increases with growth time, while the herbage N content and the unrecovered N decrease. For example, increasing the growth time from 15 to 35 days for the second cut, increases the marginal N response from 4 to 17 kg DM kg^{-1} N, and decreases the herbage N content from 38 to 24 g kg^{-1} DM and the unrecovered N from 28 to 13 kg N ha^{-1}.

The data shown in Figure 8-1 are average results based on multi-site experiments over a six year period on sand and clay soils, as described in Chapters 2 and 3. The experimental conditions were comparable to those of the field experiments described in Chapter 6. The experiments in Chapters 2 and 3 have also been the basis for the models GRAMIN (from Gramineae) and NURP (Nitrogen, URine and Pastures) that have been used for the derivation of the current N application recommendations for grassland (Vellinga, 1998; Stienezen, 2002). Currently, GRAMIN and NURP are also being used by extension services. Comparisons of results of field experiments with simulations with GRAMIN and NURP have shown satisfactory results (Chapter 4). Simulated data about herbage quality (energy and protein contents) also fit well with data derived from service laboratories (mentioned in Tamminga *et al.*, 2004) and are accepted in practice.

Derived information about herbage energy and protein content in relation to time of the growing season and N application has been compiled in handbooks (Anonymous, 1997b, 1998b).

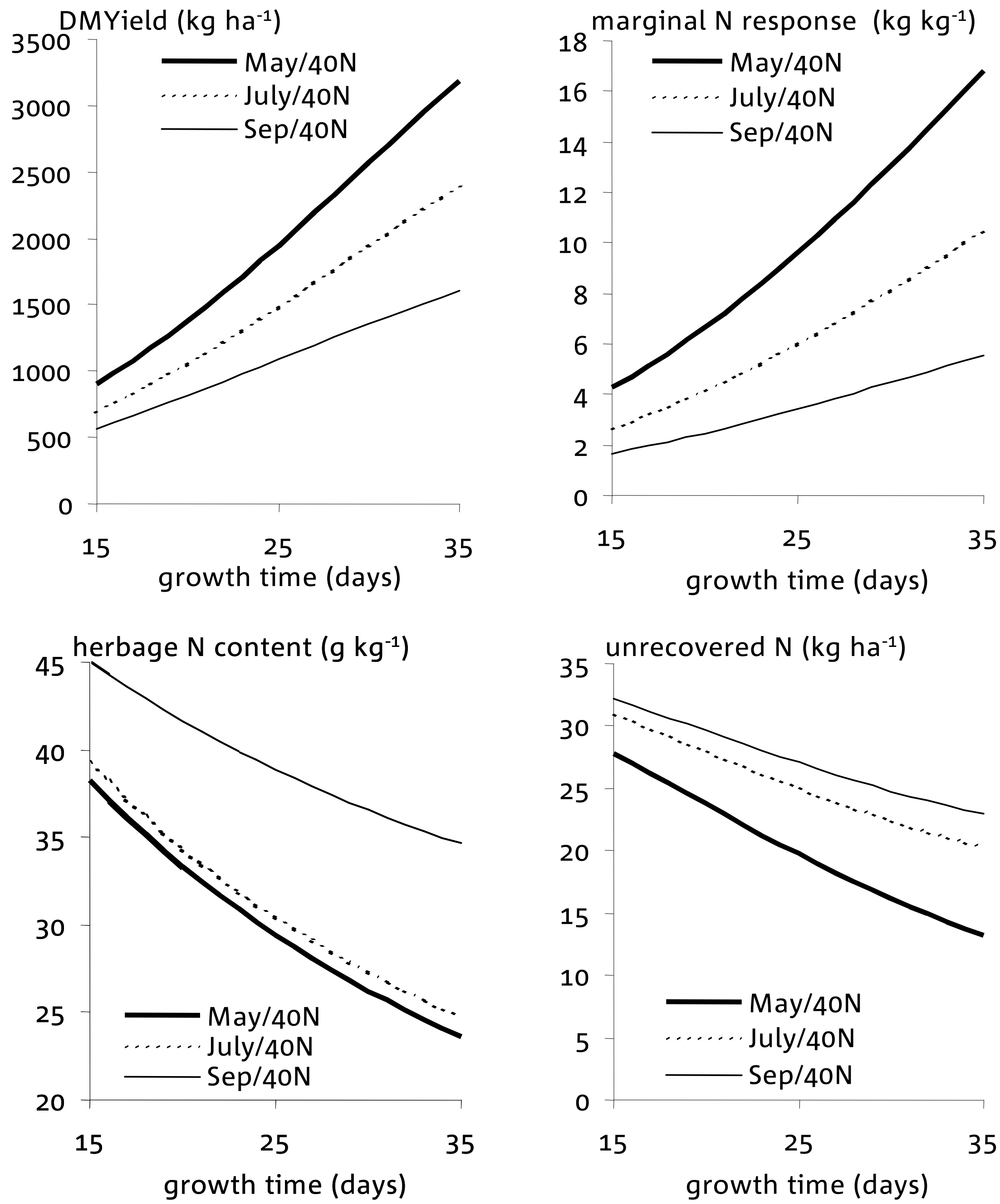

Figure 8-1. Relationships between growth time (X-axis) and mean dry matter yield (kg ha^{-1}) (upper left), the mean marginal N response (kg DM kg^{-1}N) (upper right), the mean herbage N content (g N kg^{-1} DM) (lower left) and the mean amount of unrecovered N (kg ha^{-1}) (lower right) in the second, fourth and sixth cut, starting at 1 May, 1 July and 1 September, with a nitrogen application rate of 40 kg ha^{-1} (and preceding applications of 80 kg N ha^{-1}). The marginal N response in the upper right panel literally depicts the increase in DM following an increase in N application from 39 to 40 kg ha^{-1}. Data based on calculations using the model derived in chapter 2.

Some explorative calculations
How can the results discussed above be used to define appropriate combinations of N application rates and growth times in order to i) produce good quality herbage with a good N content; ii) maximise the annual DM yield and iii) stay within the environmental limits and/or an allowed maximum annual N application rate?

To answer these questions it is necessary to know the protein requirement of the animal, which is related to the level of herbage and energy intake and the level of milk production. In the discussion below, I used data of Valk (2003) of a spring calving dairy cow, with an annual milk production of 10 000 kg. Based on a minimum crude protein (CP) content of the diet of 140 g kg^{-1} (Peyraud & Astigarraga, 1998), and a basal diet consisting of grass/maize silage that ranges from 50/50 to 100/0% , supplemented with 7 kg of concentrates, the herbage N content should be between 10 and 30 g kg^{-1} DM, depending on the CP content of the concentrates (Figure 8-2). Valk (2003) mentioned a critical CP level in the diet

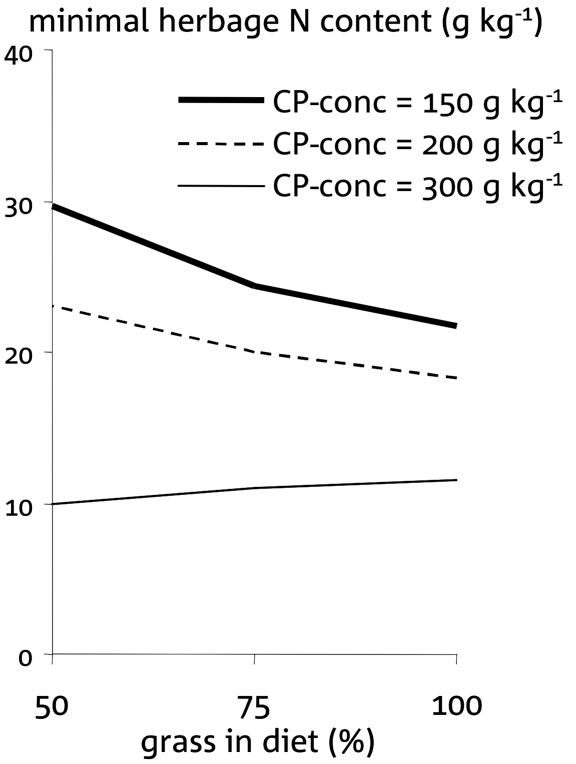

Figure 8-2. The minimal herbage N content necessary to meet the protein demand for high productive dairy cows with a DM intake of 16.5 kg from roughage and 7 kg from concentrates in relation to three levels of concentrate crude protein content (150, 200 and 300 g kg^{-1}). Data based on Valk (2003).

of 130 g kg^{-1} DM (= 20.8 g N kg^{-1} DM) for high yielding dairy cows. With a basal diet of 50/50 grass/maize silage, supplemented with 7 kg of concentrates with a CP content of 150 g kg^{-1}, the herbage N content should be about 25 g kg^{-1} DM. Meijs (1980) observed that total N intake in herbage by grazing cows is about 12% higher than is calculated on the basis of the mean measured N content in the herbage on offer. This relative increase is caused by selection during grazing. This suggest that the measured mean herbage N content may be even lower than the above mentioned value of 25 g kg^{-1} DM. Evidently, the required CP content in the herbage depends on the amounts of silage maize and concentrates in the ration. From a nutritional point of view, high herbage N contents are not necessary, even with a high level of maize supplementation.

Herbage N contents of 25 g kg^{-1} are realised after a growth time of more than 30 days in spring and early summer according Figure 8-2. In late summer, the herbage N content stays relatively high. Hence, there is sufficient protein in grass, from animal nutrition point of view, when growth time is in the range of 25-35 days for obtaining a marginal N response of no less than 7.5 kg DM kg^{-1} N, even with relatively low N fertiliser application rates. Also Whitehead (1995), Valk (2003) and Duru & Delaby (2003) suggested increased growth times to optimise N utilisation and increase annual DM yields. The consequences of increased growth time for herbage digestibility will be discussed in the next paragraph.
Low-yielding dairy cows receive little or no concentrates with a grass/maize diet ratio of 50/50. In this case, the herbage N content must be 30 g kg^{-1}, to be able to realise an average protein content of the diet of 140 g kg^{-1}. With an N application of 40 kg ha^{-1}, a growth time of 24 days in May and 26 days in July (Figure 8-1) are needed to realise a herbage N content of 30 g kg^{-1}. Because a dairy farm is an economic enterprise, the marginal N response should not be less than about 7.5 kg DM kg^{-1} N. In May, with 24 days of growth, the marginal N response is about 10 kg kg^{-1} and residual N is about 20 kg ha^{-1}. In July, with 26 days of growth, the marginal N response is only about 6 kg kg^{-1} and the amount of residual nitrogen is 25 kg ha^{-1}. Hence, in July, the utilisation of the N applied is poor from economic and environmental points of view when meeting the “nutritional” criterium of 30 g N kg^{-1} DM. Increasing the growth time in July with 5 to 10 days decreases herbage N content to 27 and 25 g kg^{-1} and increases the marginal N response to 10 and 8.5 kg kg^{-1}, respectively. When doing so, the animals’ diet should be adjusted to a higher grass content to be able to meet the protein requirement of the animal. These examples show that the possibilities of supplementing maize to

dairy cows are constrained by the herbage that can be produced, when animal nutrition, economical and environmental aspects are taken into account.

The consequences of grazing at a later stage

In general, herbage digestibility decreases with about 1.5-2.5% per week (Korevaar, 1986; Han *et al*., 2003; Stakelum & Dillon, 2004). This suggests that grazing at later growth stages leads to a decrased energy intake from herbage. However, Tharmaraj *et al*. (2003) and Stakelum & Dillon (2004) found positive effects of standing herbage mass and sward surface height on herbage intake. This anomaly suggests that there are other possible factors that have a compensating effect.

Grazing at a later stage with higher DM yields lead to a higher herbage allowance and to longer grazing periods per paddock. Daily herbage allowance (in kg DM cow^{-1} day^{-1}) is an important management factor in herbage intake and in grazing efficiency (Meijs & Hoekstra, 1984; Hijink & Remmelink, 1987; Maher *et al*., 2003; Stakelum & Dillon, 2004). Herbage allowance can be managed by adjusting paddock size. Short grazing periods per paddock per cut lead to more steady herbage intake and to lower grazing losses than long grazing periods (Boxem, 1982; Meijs & Hoekstra, 1984; Kuusela & Khalili, 2002). A steady herbage intake leads to a steady and on average higher milk production level (Boxem, 1982; Kuusela & Khalili, 2002). Also “leader-follower” grazing systems with production groups or with young stock as followers have been developed and have shown to be succesful in maintaining high milk production levels (Mayne *et al*, 1988; Kyne *et al*., 2001). This suggests that grazing at a later stage is possible without negative effects on herbage intake, milk production and grazing efficiency.

Increasing the growth time by 10 days decreases the herbage N content by 8 g kg^{-1} and decreases animal N intake by 60-120 g $cow^{-1}day^{-1}$ on a daily total of 480-600 g day^{-1}. It will decrease N excretion via urine by about 50-100 g cow^{-1} day^{-1} and it will increase herbage N utilisation via milk from about 20 to 25% , based on a 100% grass diet (Chapter 5). This suggests that, with a stocking rate of 2 cows per ha, nitrate leaching can be reduced by 7-14 mg l^{-1} (Chapters 4 and 5). Calculations with the model from Chapter 6 indicate that an increase of 300-600 kg DM ha^{-1} $year^{-1}$ is possible, when the number of growing days per cut is increased by 10.

Summarising, herbage production and N utilisation can be improved and nitrate leaching can be decreased by using both herbage N content and marginal N response as criteria for defining optimal N application rates. The disadvantages of using higher DM yields for grazing are limited and appear to be compensated by associated positive aspects through a higher sward surface height and by managing the herbage allowance and grazing period per paddock by adjusting the paddock size. The advantages are the reduction of N intake by grazing dairy cows and the subsequent reduction of nitrate leaching.

Barrieres for improving grassland management in practice

The relatively short growth times per cut and the relatively high herbage N contents on for example "De Marke" (Chapter 4) and on dairy farms in practice (Holshof 1997a, 1997b) are in contrast with the findings presented here about an 'optimal' growth time of 25-35 days, to be able to produce herbage with a proper N content and a satisfactory marginal N response. In practice, grazing young herbage is still common, even though fertiliser N application rates have decreased significantly over the last decade (LEI/CBS, 2004). Tamminga *et al.* (2004) reported for the year 2003 an average herbage N content for grazing of 35.8 g kg^{-1}. A questionnaire by Stienezen *et al*. (2005) showed that 41% of the farmers grazed at DM yield of less than 1700 kg ha^{-1} and 16% at a DM yield of more than 1700 kg ha^{-1}.The other respondents used criteria as "two fists high".

Why do farmers prefer herbage in a young growth stage and with a low DM yield for grazing animals? It seems that they prefer herbage at a relatively young stage because of the presumed tasty herbage with high energy content (Ondersteijn *et al.*, 2003). The drive to grazing at a young growth stage is enhanced by the perceived decrease in herbage digestibility with a decrease in fertiliser N input. Results of an inquiry among farmers by Stienezen *et al*. (2005) provide additional information. Farmers prefer short grazing periods for regular intake and low grazing losses. Farmers fear the risk of decreases in milk production because of the perceived lower herbage energy content, lower palatibility, increased number of stems and irregular herbage intake when switching to grazing (and cutting) of herbage of older growth stage. Farmers do not want to run the risk of decreases in milk production, because these are in part irreversible (Boxem, 1982; Subnel *et al*., 1994). Risk averse attitude towards milk yield is also reflected in part in feeding higher amounts of concentrates than is recommended (Van Dongen, 2003). Risk averse behaviour is rather common in agriculture; it has also been shown in arable cropping that risk averse farmers tend to use more fertiliser N than risk neutral farmers (Choi & Feinermann, 1995; Mosier *et al.*, 2004).

Risk adverse behaviour is related in part to the availability of convincing information (e.g. Babcock & Hennessy, 1996; Bärenklau, 2005), and to the intermediate position of herbage in the "production chain" on a dairy farm. There is indeed a large body of literature that clearly shows the central role of

information in coping with risks and in taking the right management decisions. Following Simon (1977, 1982) and Rougoor *et al*. (1998) a decision maker is not likely to change and make new decisions, unless a certain level of dissatisfaction about the current situation is reached. In line with this, Isik & Khanna (2003) concluded that the introduction of new techniques (in this case Site-Specific Technologies, SST's) is hampered by ignoring risk aversion and feelings of uncertainty in practice.
In grassland-based intensive dairy farming, there is much more information available about milk yield and quality than about herbage yield and quality. Dairy cows are milked at least twice a day, and on modern farms milk yield and quality per cow is often measured also twice a day. These measurements provide frequent feedback in the management cycle; the relationship between decisions and results is relatively clear and simple and the time lag is small. In contrast, data availibility about herbage production is poor. Herbage yield is not measured, neither in grazed nor mown grassland. Most dairy farmers do ask for measurements of silage quality (dry matter, energy and protein contents), but fresh herbage quality is seldomly measured, and is relatively expensive (Reijneveld, BLGG, pers. comm.). Commonly, grassland use and animal manure and fertiliser applications per paddock and per cut are registrated with the grassland calendar, providing insight in the growth time per cut and the options for grazing and cutting (Holshof, 1997a). Clearly, the grassland calendar has a much lower frequency of information feedback than the records of milk yield and quality from the milking parlour and dairy industry. In practice, the day-to-day grassland management is mainly steered by the information about daily milk yield (Figure 8-3). Because data availability and feedback in grassland management are relatively poor, grassland management is relatively poor compared to the management of animal nutrition and animal health.

Total annual herbage yield at farm level is often calculated in an indirect way, as the difference between energy output via milk and meat and energy input via bought roughages and concentrates. Clearly, this calculation provides an estimate of the net grassland yield which is being effectively used for milk and meat production. Everything that might affect milk production, animal performance and animal feed storage is incorporated in this estimate of grassland production. Therefore, this figure only gives a lower estimate of grassland productivity; it provides an impression of the efficiency at farm level averaged over a year. But it does not give information that can be used to develop management options to improve N efficiency on farm level.

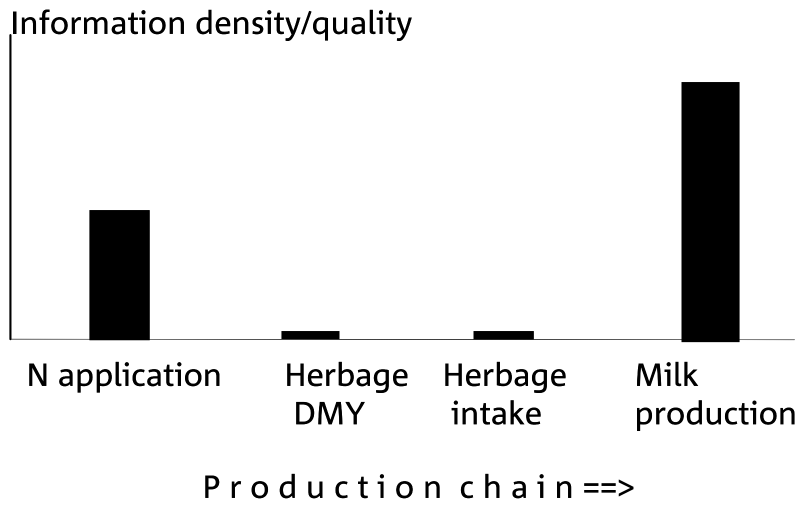

Figure 8-3. A qualitative impression of the information density and quality of the simplified production chain from N application on grassland to milk production per cow.

In general, dairy farmers do have a reasonable estimate of the accumulated DM yield of all cuts in one growing season, which is needed for the assessment of additional feed requirements. Annual variations in herbage yield and variations between sites can be in the order of 3000 to 6000 kg DM per ha (Chapters 2, 3 and 6), mainly due to variations in weather conditions, and such large variations have large consequences for the overall animal feed balance of the farm. Evidently, such variations are much larger than the estimated 300 to 600 kg DM per ha increase in herbage yield as a result of grazing and mowing in later growth stages, as estimated in the previous section, but these increases can be obainted year after year. To be able to cash in such possible increases in yield, farmers need information. To be able to realise improvements in grassland management, innovations are needed in monitoring grassland production and utilisation, and in information feedback to the farmer.

Summarising: On most dairy farms in practice, grazing takes place at a relatively young growth stage, whereby the protein content is relatively high and N utilisation low. This practice is related to risk averse behaviour of dairy farmers, because they fear a drop in milk production when dairy cows graze at high standing herbage mass. This risk averse behaviour is caused in part by lack of information; farmers have little quantitative information about herbage production, quality and utilisation per cut, i.e. at operational management level.

This suggests that improvements in grassland management can be realised through information about grassland production and utilisation.

Tools for improving operational and tactical grassland management
Recently, Stienezen *et al*. (2005) made a review of available tools for operational and tactical grassland management. They made a distinction between measurement tools and decision support tools. The measurement tools provide direct, quantitative information, while the decision support tools provide qualitative support, as they do not use much direct, on-farm measured data.

Measurement tools
Quantitative data that can be collected are herbage yield and quality, and soil information data. Weighing equipment on harvesting machines and weigh bridges are still hardly used on farms. Sward height measurements are used on 6% of the dairy farms (Stienezen *et al*., 2005), but these measurements are still inaccurate. This also holds for the electronic capacitance probe, based on differences in di-electric constants between air and herbage, (Gabriels & Van Den Berg, 1993; Harmoney *et al*., 1997; Kunnemeyer *et al*., 2001). Farmers are interested in quick measurement of herbage quality and quantity (Stienezen *et al*., 2005). In practice, measurements of fresh herbage quality are done seldomly, because they are expensive and laborious. The only quick and on-farm analysis methods for herbage quality are methods for the assessment of leaf color and nitrate in crop samples, but these have not yet been explored in practical grassland management (Geypens & Vandendriessche, 1996). Schut & Ketelaars (2003) and Stienezen *et al*. (2005) mention imaging spectroscopy as a promising new technique that can be developed within 5 years to be used in practice. With this technique, herbage yield and quality can be measured both. The method is non-destructive, which means that also during the course of growth, yield and quality can be measured.

Measurements of soil fertility and soil water provide indirect information about grassland productivity. The use of soil mineral N has been explored in research projects (e.g. Titchen *et al*., 1993; Laws *et al*., 2000), but is neither incorporated in the recommendations of N application for grassland, nor explored and used on practical dairy farms. Because part of the intensive dairy farming in The Netherlands is on drought sensitive sandy soils, which are also very susceptible to nitrate leaching, soil moisture content is an important parameter in irrigation and fertilisation management. Relatively simple measurement and sensor techniques can be used, which in part are still under developement (Stienezen *et al*. (2005).

Summarising, no quick, cheap and accurate tools for measuring herbage yield are available at this moment. In the near future, techniques and equipment will become available, and it has been indicated that farmers are interested in these tools (Stienezen *et al*. (2005).

Dynamic decision support tools

According Torssell (1994), modelling has two major goals: (i) understanding processes and effects of activities, using research models, and (ii) planning activities, using decision support models.

Nutrient cycling and optimising nutrient use efficiency in intensively managed dairy farms are complicated processes and many research models have been developed to better understand these processes. Whole farm research models aim at a better understanding of the linkages and interactions between the different compartments (i.e., animal feed, animals, animal manure and soil) of dairy farms and aim at exploring the effects of changes in strategic and tactical management (e.g., Scholefield *et al*., 1991; Ten Berge *et al*., 2000; Schröder *et al*., 2003, Van De Ven *et al*., 2003). In addition, there are research models that focus on one specific compartment of a dairy farm (e.g., soil models, grassland models, animal nutrition models). Quite a few models focus on exploring just the environmental effects of N applications, like AzoPât (Decau *et al*., 1997; Delaby *et al*., 1997), ANIMO (Hack-Ten Broeke & De Groot, 1998) and STONE (Wolf *et al*., 2003). These models are used in research and are sometimes used for supporting policy making and than focus on the strategic (and tactical) management level.
Decision support systems for farms focus on strategic and tactical management levels (e.g., Scholefield *et al*., 1991; De Haan, 2001), but also on operational management level (e.g., Carberry *et al*., 2002; Flinn *et al*., 2003; http://www.pv.wur.nl). The Decision Support Systems on operational level are all based on intensive feedback by measurement of actual conditions. Without this feedback, accounting for site specific conditions and actual weather and soil conditions, the models cannot realise a satisfactory level of accuracy (Torsell, 1994, Carberry *et al*., 2002; Flinn *et al*., 2003).
Recommendations based on simulations for average conditions must be interpreted cautiously. It has been shown frequently that model simulations based on site-specific information provide better results in fertiliser

recommendations and in calculations of N losses than in the case that average data are applied (e.g. Geypens & Vandendriessche, 1996; Makowski & Wallach, 2002; Wolf *et al*., 2003). To use models in practice, the general guidelines must be translated to each unique situation on the paddock (Carberry *et al*., 2002).

In my study, statistical models were derived on the basis of the results of various many-years field experiments that reflected a wide array of practical conditions (Chapters 2, 3 and 6). Effects of management activities, years and sites all were statistically significant, but still a large variation remained, indicating that each site-year combination harbours unique information that cannot be explained by the statistical models. The strength of statistical models using the REML procedure is that the models do reflect the variations that have been measured in the field experiments. The weakness of these statistical models is of course that these models can only be used for the conditions under which the models have been derived. Evidently, the more sites, years and management conditions measured, the better the models do reflect the actual variations in practice. My statistical models are based on four years lasting field experiments on sand, clay and peat soils, which are the three dominant soil types in The Netherlands. However, it should be noticed that in practice there is also a huge variation within these broad categories of soil types.

Dynamic recommendation systems for animal feeding take the individual animal's response in milk production to concentrate feeding into account (Van Duinkerken *et al*., 2003). Statistical analysis to separate general relationships and animal specific relationships proved to be essential in the development of these dynamic recommendation systems. Similarly, a 'dynamic' decision support system for grassland management must be based on a combination of regular measurements of herbage yield and quality, a response model as described in Chapters 2 and 3 and statistical techniques. Also the recommendations by Groot & Stuiver (2003) about using the farmers own experiences, can play a role in the development of the dynamic decision support system. Therefore, in my view, Langeveld *et al*. (2005) are to pessimistic about the possibilities to use farm data from monitoring projects.

Summarising, various simulation models about herbage yield in response to N management have been developed in the last two decades. Most of them aim at understanding the processes and only a few models have been developed for application in practice. Most of the models that are applied in practice focus on strategic management. So far, farmers lack simple decision support tools for grassland management. In my view, a combination of easy to make measurements and statistical models can be helpful in improving the operational management of grassland. The technique of imaging spectroscopy (Schut *et al.*, 2005, Stienezen *et al.*, 2005) and the models that are described in this thesis (Chapters 2, 3 and 4) can be useful components of such a dynamic decision support system.

Understanding the interaction between operational, tactical and strategic management

Results presented in Chapters 2-6 clearly show that potentially a wide range of herbage N contents can be realised through variations in N application and growth time. This wide range is constrainted by the conditions that annual herbage DM yield should be maximised and that the applied N should be economical profitable. These constraints limit the range of realistic herbage N contents, which acts subsequently as a “bottom-up” constraint in animal feeding management. It has consequences for the optimum share of maize in the animal’s diet and for the area of home grown maize. Because protein rich concentrates are relatively expensive and rich in phosphate (Anonymous, 1997b), it is also worthwile to manage the herbage N contents in such a way that only low protein concentrates have to be bought. For intensively managed, grass-based dairy farming systems, ley-maize rotations are interesting, considered from the points of view of adjusting the protein content of the diet, phosphate application via manure and the desired level of soil organic matter (Aarts *et al.*, 2000a). However, results presented in Chapter 7 indicate that aspects like nitrate leaching and emissions of CO_2 and N_2O should be considered too when transforming permanent grassland into ley-maize rotations. So far, these aspects have received little attention in grassland management in practice.

The farm budgeting program BBPR, that has been used at ‘De Marke’ (De Haan, 2001) is a decision support tool for the strategic and tactical management levels. This program also includes actions and constraints at operational level; the fertiliser application per cut, grazing and silage making per cut are the basis for the calculations on annual level (Anonymous, 1991b). Hence, the constraints and actions at operational management level are translated in BBPR into results on tactical and strategic management levels and only realistic farming situations will be simulated. A similar approach has been described by Duru & Delaby (2003) for rotational grazing systems.

The NURP-model described in Chapter 5 addresses the effects of tactical grassland management decisions on nitrate leaching. NURP includes possible interactions between tactical and operational management levels, which are also important in the decision about early housing of animals to reduce nitrate leaching from grassland (Aarts *et al.*, 1992; Lord, 1993; Titchen *et al.*, 1993). In autumn, solar radiation is relatively low, the air is moist and the grass is often “contaminated” with excreta from previous grazings. Holshof & Willems (2004) addressed the question what to do with the herbage produced after the beginning of September when grazing animals cannot utilise it properly and no good quality silage can be made anymore. Of course, poor quality silage can be fed to young stock, but only to a limited amount, because these animals also need good quality silage to realise a good growth (Vellinga & Verburg, 1995). One option is to drastically decrease N application from the second half of the growing season onwards and thereby to decrease herbage production in the second half of the growing season. A complicating factor is that farmers want to empty the manure storage facilities before the start of the new housing period. Therefore, they apply slurry to grassland till the end of August, and the organically bound N in the slurry will be released and become available for at least two to three months following application (e.g. Van Der Meer *et al.*, 1987; Chapter 3). From N utilisation point of view it is recommendable to stop slurry application at the beginning of July. This has as consequence that the manure storage capacity must be increased and that the length of the effective growing season is decreased by one or two months. Holshof & Willems (2004) calculated an extra manure storage capacity of 70-90 m^3 per average dairy farm, when cows are housed from the beginning of September.

Concentration of the N applications during the first 4 monsths instead of 6 months of the growing season enhances herbage production in the first half of the growing season. This, in turn, will have consequences for the (marginal) response to N application, the herbage N content, and the N utilisation by the grazing animal. It is worthwile to further explore concentrating N applications during the first 4 months of the growing season in terms of N utilisation and economics.

8.4 Conclusions

The agronomic and environmental performances of grassland-based intensive dairy farms in The Netherlands rely for a significant extent on the management of grassland. The management of grassland is complex, because of the large number of harvests per year, the harvesting by grazing and cutting, and the strong effects of growth time and application of N via manure and fertiliser on herbage yield and quality. The management is also complex because decisions at operational management level have conquences for the decisions to be made at tactical and strategic management levels, and vice versa. This study has shown that understanding the relationships between N application rates per cut, growth time, herbage yield and quality is prerequisite to improving operational grassland management.

The conclusions of Chapters 2-7 and the general discussion of this thesis form the basis of the following conclusions:

- Optimising N application rates per cut must be based on a combination of environmental and economic criteria.
- Grazing and cutting at an older stage than is currently practiced can improve N utilisation and annual herbage DM yield on intensive dairy farms. Possible negative effects of delaying grazing and cutting harvests are relatively small when the operational grassland management is adjusted and improved at the same time.
- Current operational grassland management is poorly supported by accurate and actual information. Improving operational grassland management should be based on data of accurate and cheap measurements combined with simulation models in “Dynamic Decision Support Systems” (DDSS).
- Knowledge about operational grassland management is essential in decisions that are taken on tactical and strategic management levels on dairy farms.

8.5 Future perspectives and recommendations

To realise further improvement in nutrient efficiency and environmentally and economically sound farming systems, more attention should be paid at the level of operational grassland management in research and extension. To be specific:

- Research into accurate, fast and cheap measurement techniques for herbage quantity and quality. In particular the quantity and quality of the ingested herbage.
- Development of decision support systems based on smart combinations of timely measurements, modelling and the farmers own experiences. The measurement resolution can vary according to the expected variation at a specific point in time and area.
- Integration of the environmental fertiliser application criteria (developed in this thesis) with the economic criteria of the current fertiliser recommendations, to arrive at multi-goal fertiliser recommendations.

- Create further awareness among farmers of the relationships between N application, growth time, herbage quantity and quality, so that it can be used to improve the economic and environmental results of the enterprise.

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Summary

During the second half of the 20^{th} century, agricultural production increased greatly in member states of the European Union (EU). The Common Agricultural Policy of the EU has significantly contributed to this development through the promotion of two main routes: an increased production level per ha and per unit of labour. This policy has certainly contributed to the intensification of grassland-based dairy farming in the EU.

In The Netherlands, grassland productivity increased through a combination of land reclamation and drainage, grassland renovation, fertilisation and mechanisation. Fertiliser nitrogen (N) input per ha doubled between 1950 and 1985, and increased faster in The Netherlands than in surrounding EU-countries. Nitrogen (N) was seen as a fertiliser and management tool to increase herbage yield and quality.

From the 1980's, it became clear that the strongly increased N inputs also led to increased N losses via ammonia volatilization, nitrate leaching and runoff, denitrification and nitrous oxide emissions. In response, the government implemented series of environmental legislations to reduce nitrogen (and also phosphorus) losses. The most important legislations relate to the EU Nitrate Directive and the EU Water Framework Directive. As a consequence, the input of N on dairy farms decreased, but environmental and ecological targets have not been met.

The implemented policies have stressed the importance of nutrient management, especially in relation to grassland management. Nutrient management is the process of handling and allocating nutrient resources so as to achieve economic and environmental objectives. Clearly, the challenge is to lower N inputs and to decrease N losses, while maintaining herbage yield and quality. To be able to realise these objectives simultaneously, improvements in the knowledge about the effects of operational, tactical and strategic grassland management measures are essential.

This thesis aims at contributing to improved decision making at the operational management level: i) by improved understanding of the relationships between N application rates, herbage yield and quality in single cuts and their effect on N use efficiency and by deriving criteria for environmentally-sound N application

recommendations; ii) the identification of tools for improved operational grassland management; and iii) by improving the understanding of the relationships between strategic, tactical and operational management.

Methodology

To be able to achieve the abovementioned objectives, various methods have been used. Data from multi-site, many-years field experiments have been analysed statistically to derive relationships between N application rates, growth time per cut, herbage yield and quality, soil mineral N and residual effects, at the level of an individual growth cycle. The field experiments have been carried out on four soil types and involved the measurements of herbage yield and N uptake and soil mineral N on mown-only grassland, as function of freshly and previously applied N, during the whole growing season. Results of these multi-site, many-years field experiments have also been used to derive criteria for N application per cut and to derive tools for decision making about N application at the operational level of grassland management. To understand the possible effects of changes in grassland management on the recovery of applied N, results of a large number of field experiments carried out on various soil types in The Netherlands over a period of sixty years have been analysed statistically. Further, a descriptive technique has been used to analyse the operational and tactical grassland management of experimental dairy farm 'De Marke'. Finally, two models have been used. Firstly, a new empirical model has been developed to estimate nitrate leaching from grassland to groundwater as a function of grazing and N application. Secondly, an existing empirical model has been extended and calibrated to estimate nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions from grassland to the atmosphere as a function of ploughing down permanent grassland and leys.

Optimising N application rates per cut

Results of the statistical analyses of the multi-site, many-years field experiments clearly indicate that N uptake and DM yield increase with increasing N application rates and with increasing growth time, in every growth cycle. The optimum N application is usually derived from applying the agronomic criterion of the marginal DM response, but this criterion does not consider the effect of N application on N losses. In this thesis, I propose to apply the herbage N content and the amount of unrecovered N after harvest as criteria for deriving the optimum N application per cut, when N losses to the environment have to be taken into account.

Results of the statistical analyses of the multi-site, many-years field experiments also indicate that a large N application at a common growth time leads to a high herbage N content, a large amount of unrecovered N and to a low marginal DM response. Increasing the growth time per cut decreases herbage N content and the amount of unrecovered N and increases the marginal DM response. This interaction between N application rate and growth time has been analysed and quantified for the whole growing season. Using the results of the statistical analyses, optimal N application rates per cut have been calculated for different target DM yields with different growth times, using marginal DM response, herbage N content and the amount of unrecovered N as criteria.

Only 20-70% of the applied N is taken up in the cut directly following application, depending on the target DM yield. The residual effects, observed as an accumulation of soil mineral N (SMN) and/or as an additional N uptake and DM yield in subsequent cuts, can be large. These effects are often poorly known in current practice, but my analyses shows that these effects must be taken into account for sound N application recommendations. On mineral soils, up to 8% of the applied N was recovered as SMN, and there was a positive relationship between SMN and additional N uptake in the subsequent cut. On the two peat soils, about 20% of the applied N was recovered as SMN, but no clear relationship between SMN and N uptake in subsequent cuts could be established. In contrast, a clear relationship was established between the amount of previously applied N and the N uptake by subsequent cuts over the complete growing season, on both the poorly and moderately well-drained peat soils and the clay and sand soils. Using these relationships, optimal N application rates have been calculated for both the agronomic (DM response) and environmental criteria (N content in the herbage and the unrecovered N). Clearly, the optimum N application heavily depends on the chosen criterion.

Analysis of data from experimental dairy farm ‘De Marke’ and from commercial dairy farms in monitoring projects show that grazing takes place after relatively very short growth times per cut. As a consequence, DM yields are low and herbage N contents are high. Due to the short growth time, N application rates per cut are higher than recommended. This leads subsequently to a suboptimal N utilisation and to suboptimal annual DM yields.

Tools for grassland management
The environmentally related criteria discussed above can be helpful in improving operational grassland management. Further, the criteria 'marginal DM response' and 'herbage N content' can be combined very well. As a result, economical and environmental sound optimal N applications can be calculated for the production of herbage that is fit for a wide range of animal diets consisting of variable portions of herbage, silage maize and concentrates.

The low recovery of applied N as SMN on mineral soils, the absence of a clear relationship between SMN and N uptake on the two peat soils, the large within field, time and random variation in SMN and the time needed to measure SMN, all suggest that SMN is not an effective tool for fine-tuning N applications. In contrast, fine-tuning N applications can be done rather easily and accurately using the relationship between the amount of previously applied N and N uptake. Further, recording of applied N in previous cuts is easy to establish in practice. In fact, recording of the amount of previously applied N has already been incorporated in the official Dutch system for N recommendations of intensively managed grasslands, using the results of my thesis as basis.

The analyses of the grassland use at 'De Marke' and commercial farms show that grazing often occurs at a (too) young growth stage of the herbage. It is argued that the grazing at a (too) young stage of the herbage is related to a risk averse attitude, which in turn is related to a lack of data in operational grassland management. In practice, DM yields per cut are only estimated roughly, and N uptake and herbage N content often are completely unknown. Until now no tools for cheap, quick and accurate assessments of herbage DM yield and N content of the standing biomass per cut exist. The availability of accurate data on herbage yield and quality is essential for improving operational grassland management and N utilisation.
The established statistical relationships, the identified criteria for fine-tuning N applications, the suggested recording system of previously applied N, and the on-site quick and accurate measurements of herbage yield and N content, altogether functionally combined in a 'Dynamic Decision Support System' seems to be an effective way to improve operational grassland management.

Interactions between management levels
The empirical model Nitrogen, URine and Pastures (NURP) has been developed as a tool for decision support at the operational and tactical management levels at

grassland-based dairy farms. The advantage of this model, in comparison to other existing models, is that annual N application rate and stocking rate are independent factors. Through this approach, more realistic management options to reduce nitrate leaching from grassland can be found than with other models. The model shows how intensive dairy farms on dry sandy soils can realise a nitrate concentration in the upper groundwater of maximally 50 mg l^{-1} by a combination of restricted grazing during the growing season, earlier housing and reduced fertiliser N input. The effect of the level of supplemental feeding and milk production per cow is relatively limited.

The increase in the Apparent N Recovery (ANR) of applied N in The Netherlands during the second half of the 20^{th} century, as deduced from the analysis of a large number of field experiments, is related to various changes in grassland use and management in practice. The ploughing down and renovation of permanent grasslands and drainage has likely contributed to a decrease in soil organic matter content and thereby to a lower soil N supply. White clover largely disappeared from the swards of most grassland, due to the increased use of fertiliser N, while the species composition and the genetic potential of perennial ryegrass, the dominant species, improved strongly. Further, the number of cuts per growing season increased, and N applications were split in various portions over the growing season. As a result, herbage N uptake and ANR increased. Although herbage N uptake tends to increase with an increased number of cuts, the herbage DM yield does not increase or might even decrease. In that case, a high ANR may even increase the risk of a poor N utilisation by the grazing animal, because of the high N content of the herbage on offer.

The effects of ploughing down permanent grassland and leys in The Netherlands during the last decades on the emissions of CO_2 and N_2O to the atmosphere were explored using an empirical model. The area of permanent grassland has been reduced considerably during the seventies and eighties of the 20^{th} century through the conversion of grassland to arable land, used for the growth of silage maize. It is expected that the area of permanent grassland will reduce further over the next 20 years, because of the likely increase of leys in rotation with arable crops (potatoes, flowers). The calculated total emissions resulting from this conversion range from 30 to 250 ton CO_2-equivalents ha^{-1}, with CO2 as the main source. Emissions are high directly after ploughing and decrease slowly during the following 50 years. Annual N_2O emissions from rotations of ley with arable crops and flowers, and from grassland renovation range from 1.8 to 11.0 ton CO_2-

equivalents per ha. The total annual N_2O emission caused by ploughing down grassland ranges from 0.5 to 0.65 Mton CO_2-equivalents ha^{-1} $year^{-1}$, which is about 10% of the total N_2O emissions from agriculture in The Netherlands. As ploughing grassland is not taken into account in the national inventory, the national N_2O-emission is underestimated. Specific emission factors and the development of mitigation options are required to account for the emissions and to realise a reduction of emissions due to the changes in grassland ploughing.

In theory, N utilisation by the grazing animal can be optimised at farm level for all possible combinations of grass, silage maize and concentrates in the diet. The protein N content of the herbage is a flexible factor in this respect, provided the applied fertiliser N can be made economically profitable. Hence, high herbage N contents by high application rates or short growth times should be avoided, because of low economic profitability and high potential for high amounts of unrecovered N and N losses to the environment. These constraints in turn, will have consequences for the optimal proportion of silage maize in the animals' diet and, on most dairy farms, for the area of home grown silage maize. Evidently, the restricted room for manoeuvre at the operational management level acts as a 'bottom-up' constraints for decisions at tactical management level as regards animal nutrition and at strategic management level as regards the area of silage maize.

Simulations with the model NURP indicate that early housing of animals is an effective way to reduce nitrate leaching from grassland. The consequences of decisions about grazing in autumn, at operational management level, can be significant. In autumn, the possibility for making good silage is limited, because of the poor wilting conditions and the less tasteful herbage. The option to concentrate the N applications during the first four months instead of six months of the growing season enhances herbage production in the first half of the growing season. This, in turn, will have consequences for the (marginal) response to N application, the herbage N content, and the N utilisation by the grazing animal. It is worthwhile to further explore concentrating N applications during the first four months of the growing season.

Conclusions

- Fine-tuning N application rates per cut can be based on a combination of environmental and economic criteria.
- The amount of SMN is not a useful tool in adjusting N application rates.
- Recording the amount of previously applied N is a simple and reliable tool to take residual effects of previously applied N into account when optimal N application rates are calculated.
- Grazing at an older stage than is currently done in practice can improve N utilisation and annual herbage DM yield on intensive dairy farms.
- Current operational grassland management is poorly supported by accurate and actual information. Improving operational grassland management should be based on results of accurate and cheap measurements and simulation models in a "Dynamic Decision Support Systems" (DDSS).
- The model NURP is a useful tool in decision making aimed at reducing nitrate leaching from grasslands on intensive dairy farms.
- Emission of nitrous oxide is underestimated in The Netherlands by omitting the effects of ploughing permanent grassland and ley.
- The increase in ANR of applied N on grassland during the second half of the 20^{th} century can be explained by changes in strategic, tactical and operational grassland management.
- Knowledge about the interaction between operational, tactical and strategic grassland management is essential in achieving economical and environmental objectives on intensive grassland-based dairy farms.

Samenvatting

In de tweede helft van de twintigste eeuw is de productie in de landbouw enorm toegenomen in alle lidstaten van de Europese Unie (EU). Het Gemeenschappelijk Landbouwbeleid van de Unie heeft hier een wezenlijke bijdrage aan geleverd en was gestoeld op twee hoofddoelen: een verhoging van de productiviteit per oppervlakte-eenheid en een toename van de arbeidsproductiviteit. Beide hebben geleid tot een sterke intensivering van het graslandgebruik op melkveebedrijven.

In Nederland is de graslandproductiviteit sterk toegenomen door een combinatie van landinrichting, drainage, graslandverbetering, bemesting en mechanisatie. Het gebruik van kunstmeststikstof verdubbelde tussen 1950 en 1985. Daarbij was er sprake van een sterkere toename in Nederland dan in de omringende lidstaten. Stikstof (N) werd gezien als een meststof, maar ook als een managementinstrument om de productie en kwaliteit van het gras te sturen.

Vanaf de jaren tachtig van de 20^ste^ eeuw werd het duidelijk dat de sterk toegenomen inzet van N, vooral op melkveebedrijven, ook tot grote N-verliezen leidde in de vorm van emissies van ammoniak en stikstofoxiden, uit- en afspoeling van stikstof en denitrificatie. Milieubeleid en –wetgeving werden ontwikkeld om de verliezen van N en ook fosfor (P) terug te dringen. De belangrijkste “wetten” op dit terrein zijn de Nitraatrichtlijn en de Kaderrichtlijn Water van de Europese Unie, die grote invloed hebben op de Nederlandse mestwetgeving. Hoewel de mestwetgeving leidde tot een forse daling van de inzet van N op melkveebedrijven, zijn de milieukundige en ecologische doelen nog niet bereikt.

Door deze ontwikkelingen is het belang van nutriëntenmanagement sterk toegenomen, vooral met betrekking tot graslandmanagement. Nutriëntenmanagement is het proces waarbij de inzet van in dit geval N zo wordt gestuurd dat zowel milieu- als inkomensdoelen worden bereikt. De kunst is de N-verliezen te verlagen door de inzet van N te verminderen, bij een gelijkblijvende opbrengst en kwaliteit van het gras. Het is dan onontbeerlijk om de effecten van beslissingen die voor de korte, middellange en lange termijn worden genomen, te kennen.

Dit proefschrift heeft als doel om het nemen van de korte termijn beslissingen over grasland- en N-gebruik, die dagelijks op een melkveebedrijf worden genomen, te kunnen verbeteren. Dat wordt gedaan door i) het beter leren kennen

van de verbanden tussen N-gift, grasopbrengst en –kwaliteit binnen een snede gras, en de invloed daarvan op de N-benutting, ii) criteria af te leiden ten behoeve van een betere besluitvorming over N-bemesting, rekening houdend met verliezen van N naar het milieu; iii) het aanwijzen van gereedschappen die het nemen van beslissingen kan ondersteunen; en iv) meer inzicht te genereren in de verbanden tussen de consequenties van beslissingen op korte middellange en lange termijnen .

Toegepaste methoden

Om bovengenoemde doelen van het proefschrift te kunnen realiseren, zijn verschillende werkwijzen toegepast. Reeksen van (meerjarige) maaiproeven op verschillende grondsoorten zijn statistisch geanalyseerd om het verband tussen N-gift, groeiduur en grasopbrengst en –kwaliteit per snede vast te stellen en om de ophoping van minerale N in de bodem en de nawerking van N in volgende sneden vast te stellen. In de veldproeven is in een serie grassneden gedurende het gehele groeiseizoen de grasopbrengst, de N-opname in het gras en de ophoping van minerale N in de bodem gemeten, bij verschillende bemestingsregimes.. De resultaten zijn gerelateerd aan de N die direct voor een snede gras werd gegeven, maar ook aan de N die in voorgaande sneden was gegeven. Het grasland werd alleen gemaaid. De resultaten van de proeven zijn ook gebruikt om criteria voor de bemesting per snede af te leiden en om zo een bijdrage te leveren aan instrumenten waarmee het dagelijkse graslandmanagement verbeterd kan worden.

Een groot aantal N-bemestingsproeven uit de periode 1934 - 1994 is geanalyseerd om te begrijpen hoe de veranderingen in graslandgebruik geleid hebben tot verandering in de N-terugwinning via het gewas van de gegeven N.

Het graslandgebruik op de proefboerderij “de Marke” is op een beschrijvende wijze geanalyseerd.

Ook zijn modellen gebruikt. Er is een model ontwikkeld om de nitraatuitspoeling te berekenen als functie van beweiding en N-bemesting. Verder is een bestaand model aangepast en zijn de parameters van de juiste waarden voorzien om de emissies van de broeikasgassen CO_2 en N_2O te kunnen schatten als permanent grasland en kunstweide worden geploegd.

Optimaliseren van de N-bemesting per snede

De N-opname van het gras en de grasopbrengst per snede nemen toe als de bemesting per snede hoger is en als de groeiduur van een snede langer is. De optimale N-bemesting is tot nu steeds berekend op basis van een bepaalde waarde voor de marginale opbrengst, de extra drogestofopbrengst per extra kilogram N. Dat criterium houdt echter helemaal geen rekening met N-verliezen naar het milieu. In dit proefschrift wordt voorgesteld om het N-gehalte van het gras en de hoeveelheid N die achterblijft in de bodem als criteria te gebruiken, omdat met deze criteria wel rekening kan worden gehouden met N-verliezen naar het milieu. Uit de geanalyseerde groeiverloopproeven blijkt dat een hoge N-gift tot een hoog N-gehalte in het gras en een grote hoeveelheid N in de bodem leidt, terwijl het marginaal effect van de als laatst gegeven kilo N laag is.. Maar als de groeiduur van een snede toeneemt, dalen het N-gehalte in het gras en de hoeveelheid N die achterblijft in de bodem en stijgt het marginaal effect. Deze resultaten zijn vervolgens gebruikt om de optimale N-bemesting per snede te kunnen berekenen bij verschillende streefopbrengsten en groeiperiodes voor sneden over het gehele groeiseizoen, bij verschillende waarden voor de drie genoemde criteria.

Slechts 20 tot 70% van de gegeven N wordt opgenomen in de snede die direct volgt op de bemesting, de N-terugwinning is afhankelijk van de grasopbrengst die wordt nagestreefd. Mogelijke resteffecten van de niet-opgenomen N zijn een ophoping van minerale N in de bodem na de oogst van een snede en een verhoogde N-opname en drogestofopbrengst in de volgende sneden. Deze resteffecten kunnen sterk zijn, maar er was kwantitatief weinig over bekend. De uitgevoerde analyses tonen aan dat je rekening moet houden met deze effecten bij het vaststellen van bemestingsadviezen voor N. De resultaten van de analyses geven aan dat op minerale gronden tot 8% van de gegeven N wordt teruggevonden als minerale N. Er was bovendien een duidelijk verband tussen de hoeveelheid minerale N in de bodem en de extra N-opname in de volgende snede. Op veengronden werd ongeveer 20% van de gegeven N teruggevonden als minerale N, maar was er geen verband met de N-opname vast te stellen. Er kon op alle gronden wel een duidelijk verband worden vastgesteld tussen de totale N-gift uit voorgaande sneden en de N-opname in de volgende snede. Dit verband is gebruikt om de optimale N-giften te berekenen bij toepassing van het landbouwkundig criterium (het marginaal effect) en van de milieukundige criteria (het N-gehalte van het gras en de hoeveelheid die achterblijft in de bodem). Het blijkt dat de afgeleide ‘optimale’ N-gift sterk afhangt van het gekozen criterium.

Analyse van het graslandgebruik op de proefboerderij “De Marke” en op praktijkbedrijven liet zien dat beweiding plaatsvindt in sneden met een korte tot zeer korte groeiduur. Het gevolg is dat de grasopbrengsten laag zijn en het N-gehalte van het weidegras zeer hoog is. Mede door de korte groeiperiodes zijn de N-giften beduidend hoger dan hetgeen geadviseerd wordt. Dat leidt tot een niet optimale benutting van de gegeven N en tot lagere grasopbrengsten per jaar dan mogelijk is.

Gereedschappen voor grasland-management

De milieukundige criteria, zoals hiervoor genoemd, kunnen bijdragen aan een verbetering van het graslandmanagement. Het blijkt dat de criteria 'marginaal effect' en 'N-gehalte van het gras' uitstekend gecombineerd kunnen worden. Het resultaat is dat economisch en milieukundig verantwoorde bemestingsadviezen berekend kunnen worden voor de productie van gras dat past in een rantsoen van gras, maïs en krachtvoer, waarbij de eiwitvoeding van de koe optimaal is.

Het meten van minerale N in de bodem is geen geschikt instrument om de N-gift mee te corrigeren. Dat blijkt uit de volgende resultaten van de proefvelden: (i) slechts een fractie van de niet-opgenomen N wordt in klei- en zandgronden teruggevonden als als minerale N, (ii) een duidelijk verband tussen minerale N en N-opname in het gras kon voor veengronden niet worden afgeleid, en (iii) er is een grote ruimtelijke variatie in minerale N in de grond, waardoor een tijdrovende grondbemonstering nodig is om te komen tot een nauwkeurige schatting van de hoeveelheid minerale N. Bovendien blijkt dat het fijnregelen van de bemesting eenvoudiger en nauwkeurig kan gebeuren door gebruik te maken van het gevonden verband tussen de totale N-gift uit voorgaande sneden en de N-opname. Registratie van N-giften is zeer eenvoudig uit te voeren in de praktijk. De hiergenoemde werkwijze wordt al toegepast in het huidige bemestingsadvies voor grasland in Nederland; de resultaten van dit proefschrift hebben daarvoor als basis gediend.

De analyse van het graslandgebruik op "De Marke" en praktijkbedrijven liet zien dat vaak in te jong stadium wordt geweid. Het weiden in een jong stadium komt voort uit 'risicomijdend gedrag', dat op zijn beurt weer verband houdt met het gebrek aan kwantitatieve informatie in het dagelijkse graslandmanagement. In de praktijk wordt de grasopbrengst per snede geschat, terwijl de N-opname en het N-gehalte van het gras meestal onbekend zijn. Er zijn tot nu toe geen gereedschappen voorhanden waarmee een snelle en nauwkeurige bepaling van opbrengst en N-gehalte van het op het veld staande gras kan worden uitgevoerd. Een snelle en nauwkeurige schatting van opbrengst en kwaliteit is essentieel om te komen tot verbetering van het dagelijkse graslandmanagement en de N-benutting van het gras.

Combinatie van de statistisch bepaalde verbanden, de criteria om de bemesting beter af te stemmen op het gewenste product, de registratie van de eerder gegeven hoeveelheid N en een snelle bepaling van grasopbrengst en –kwaliteit, kunnen in een "dynamisch beslissingsondersteunend systeem" een goede manier zijn om het dagelijkse graslandmanagement te verbeteren.

Interacties tussen management niveaus

Het empirische model Nitraat UitspoelingsReductie Programma (NURP) is ontwikkeld als een beslissingsondersteunend programma op melkveebedrijven voor beslissingen over N-bemesting en beweiding van grasland. Het voordeel van dit model ten opzichte van vele andere modellen uit de literatuur is, dat de N-gift en de veebezetting onafhankelijk van elkaar gevarieerd kunnen worden. Daardoor kunnen meer opties worden verkend om de nitraatuitspoeling onder grasland te verminderen. Het model laat zien hoe op intensieve melkveebedrijven op uitspoelinggevoelige zandgronden een nitraatconcentratie van 50 mg l^{-1} bereikt kan worden. Dat gebeurt door een combinatie van beperkt weiden, eerder opstallen en een beperkte N-bemesting. Het effect van extra bijvoedering met eiwitarme producten en van verhoging van de melkproductie blijkt vrij beperkt te zijn.

Uit de analyse van een groot aantal bemestingsproeven, uitgevoerd in de tweede helft van de 20^{ste} eeuw, blijkt dat de toename van de N-terugwinning in deze periode verband houdt met veranderingen in graslandgebruik en –management. Witte klaver is grotendeels verdwenen uit het grasland door de toegenomen N-bemesting. Tegelijk veranderde de soortensamenstelling van het grasland; Engels raaigras werd de belangrijkste en meest voorkomende soort, terwijl door veredeling het opbrengend vermogen van deze grassoort sterk is verbeterd. Daarnaast steeg het aantal sneden per seizoen en werd de N-bemesting verdeeld over meer sneden. Door deze veranderingen steeg de N-opname en de N-terugwinning. Hoewel de N-opname stijgt bij een hoger aantal sneden, neemt de drogestofopbrengst vaak niet toe of daalt zelfs. Een hogere N-terugwinning in het gras leidt in dat geval tot een hoger risico van een slechte N-benutting door het vee, omdat het gras een hoger N-gehalte heeft.

Het effect van het ploegen van oud en tijdelijk grasland (kunstweide) op de emissie van de broeikasgassen CO_2 en N_2O in Nederland gedurende de laatste tientallen jaren is onderzocht met een empirisch model. De oppervlakte oud grasland in Nederland is sterk afgenomen in de jaren '70 en '80 van de vorige eeuw door de teelt van snijmaïs op voormalig grasland. De verwachting is dat de oppervlakte oud grasland in de komende 20 jaar nog verder zal afnemen omdat de wisselbouw van gras met akkerbouw (aardappelen, bollen) zal toenemen. De berekende totale emissie door deze omschakeling bedraagt 30 tot 250 ton CO_2-equivalenten per hectare. Het broeikasgas CO_2 heeft het grootste aandeel in de totale emissie. Direct na het ploegen zijn de emissies het hoogst om vervolgens geleidelijk af te nemen over een periode van ongeveer 50 jaar. De berekende emissie van N_2O als gevolg van wisselbouw en graslandvernieuwing varieert van 1,8 tot 11,0 ton CO_2-equivalenten per hectare per jaar. De totale jaarlijkse emissie varieert van 0,5 tot 0,65 Megaton per jaar, overeenkomend met ongeveer 10% van de totale emissie van N_2O door de Nederlandse landbouw. Omdat het ploegen van grasland niet in de nationale inventarisatie is meegenomen, wordt de nationale emissie dus onderschat. Om de emissie nauwkeuriger in te schatten, moeten speciale emissiefactoren voor omploegen van grasland en graslandvernieuwing worden afgeleid. Daarnaast dienen maatregelen te worden ontwikkeld om de emissies te verminderen.

Theoretisch gesproken kan de N-benutting door weidend vee worden geoptimaliseerd voor elke combinatie van gras, maïs en krachtvoer in het rantsoen. Ook het N-gehalte van het gras kan worden geoptimaliseerd, op voorwaarde dat de gebruikte N wel economisch rendabel wordt ingezet. Hoge N-gehalten in het gras, door hoge bemestingen of korte groeiperiodes, dienen te worden vermeden, omdat het economisch rendement van de gebruikte N dan erg laag is en er relatief veel N achterblijft in de bodem. Deze beperking in N-gehalte heeft gevolgen voor het optimale aandeel van snijmaïs in het rantsoen en in veel gevallen ook voor de oppervlakte maïs die wordt verbouwd. Hieruit blijkt dat de keuzemogelijkheden in het dagelijkse graslandmanagement beperkt zijn en tevens dat die beperkte mogelijkheden als een beperking fungeren voor mogelijke keuzes in de bedrijfsvoering met consequenties voor de middellange en lange termijn. Voor de middellange termijn wordt in ieder geval de keuzeruimte voor het rantsoen beperkt en voor de lange termijn de verhouding tussen gras- en maïsland.

Berekeningen met het model NURP geven aan dat eerder opstallen van vee een effectieve manier is om de nitraatuitspoeling onder grasland te verminderen. Eerder opstallen heeft echter duidelijke gevolgen voor het dagelijkse graslandmanagement. Als het gras niet wordt geweid, moet het worden gemaaid. Maar het maken van goede graskuil in de herfst is lastig, omdat de omstandigheden voor droging slechter zijn en het gras veel minder smakelijk is. De optie om de N-bemesting in de eerste vier maanden van het jaar te concentreren, leidt tot een beperking van de periode waarin al het gras geproduceerd moet worden. Dat heeft ook gevolgen voor het marginaal effect van de gegeven N, het N-gehalte van het gras en voor de N-benutting door het vee. Uit oogpunt van een goede N-benutting op bedrijfsniveau is het zinvol om het concentreren van de N-bemesting in de eerste ver maanden van het groeiseizoen verder te onderzoeken.

Conclusies

- Het nauwkeurig regelen van de N-giften per snede kan worden gebaseerd op een combinatie van economische en milieukundige criteria.
- De hoeveelheid minerale N in de bodem is geen goede maat voor de aanpassing van de N-gift per snede.
- Het registreren van de hoeveelheid eerder gegeven N is een eenvoudige methode om de nawerkingseffecten van die N mee te laten wegen in de berekening van de optimale N-gift per snede.
- Beweiding in een ouder stadium dan momenteel gangbaar is in de praktijk kan de N-benutting en de grasproductie op intensieve melkveebedrijven verhogen.
- Het huidige graslandmanagement wordt nauwelijks ondersteund door nauwkeurige informatie. Verbetering van het graslandmanagement zou gebaseerd moeten worden op een combinatie van eenvoudige modellen en snelle en goedkope metingen in een “Dynamisch Beslissings Ondersteunend Systeem”.
- Het model NURP is een nuttig gereedschap om de nitraatuitspoeling op intensieve melkveebedrijven te verminderen.
- De emissie van lachgas (N_2O) uit de Nederlandse landbouw wordt onderschat omdat de effecten van ploegen van blijvend grasland en kunstweide niet worden meegenomen.
- De stijging van de N-terugwinning in het geoogste gras in de tweede helft van de 20^{e} eeuw kan worden toegeschreven aan veranderingen in management op dagelijks niveau, middellange en lange termijn.

- Kennis van de interacties tussen de verschillende managementniveaus (de korte, middellange en lange termijn) is essentieel om zowel economische als milieukundige doelen te realiseren op intensieve melkveebedrijven.

Gearfetting

Yn ‘e twadde helte fan ‘e tweintichste ieuw is de lânbou produksje yn de lidstaten fan de Europeeske Unie tige tanaam. It Mienskiplik Lânboubelied fan de EU hat dit stimulearre troch twa rûtes: in tanommen produksje de hectare en de man. Dit belied hat bydroegen oan de yntinsifearring fan it op greide basearre hâlden fan melkfee yn de EU.

Yn Nederlân is de produksje fan greide tanaam troch in kombinaasje fan it ferbetterjen fan lân, it better ûntwetterjen, it op ‘e nij insiedzjen fan it lân, it dongjen en in tanommen mechanisaasje. It brûken fan stikstof út keunstdong ferdûbele tusken 1950 en 1985 en naam yn Nederlân folle mear ta as yn ‘e oare lânnen fan ‘e EU. Stikstof (N) waard net allinne as dongmiddel sjoen, mar ek as in middel om de produksje en kwaliteit fan gêrs te stjoeren.

Nei 1980 waard dúdlik dat it foarse tanommen brûken fan N ek grutte ferliezen joech troch de útstjit fan ammoniak, út- en ofspieling fan nitraat, denitrifikaasje en de útstjit fan stikstofoxide. As reaksje kaam de oerheid mei ferskate regels om it ferlies fan stikstof en fosfaat te beheinen. De wichtigste maatregels binne bûn oan ‘e Nitraat Rjochtline en de Ramtrjochtline Wetter fan ‘e EU. It hie fan gefolgen dat de ynset van N op it melkfeebedriuw ôfnaam. Lykwols binne de doelen foar miljeu en natoer nog net helle.

It nije belied hat it ferbân tusken it behearskjen fan ‘e dongstoffen dy ’t nedich binne foar de groei fan gêrs en it stjoeren fan it brûken van greide wichtiger makke. De keunst fan it behear fan de dongstoffen is om dizze sa yn te setten dat ekonomyske en miljeukundige doelen beide helle wurde. It grutste doel derby is om it brûken en it ferlies fan N te ferlytsjen, wylst de produksje en kwaliteit fan gêrs net ôfnimme. Om it safier te krijen, is kennis oer it stjoeren fan it brûken fan greide op ‘e koarte, middellange en lange termyn tige wichtig.

Dit proefskrift sil benammen in bydrage jaan oan it ferbetterjen fan it nimmen fan beslúten op koarte termyn, de deistiche beslúten. Dat wurdt dien troch: i) it ferbetterjen fan ynsjoch yn it ferbân tusken N-jefte, de opbringst en kwaliteit fan gêrs yn ‘e groei fan in snee, de gefolgen dêrfan foar de effisjinsje fan it brûken fan N en troch it meitsjen fan hânfetten foar miljeukundig ferantwurde N advyzen; ii) it oanmerken fan ark om it deistich brûken fan greide te ferbetterjen en iii) it ferbetterjen fan ynsjoch yn it ferbân tusken it stjoeren fan it brûken fan greide op ‘e koarte, middellange en lange termyn.

Wurkwize

Om ta boppesteande doelen te kommen, bin ik op ferskate wizen te wurk gongen. Fjildproeven op ferskate plakken en oer mear jierren, binne statistysk analysearre om it ferbân te lizzen tusken N-jefte, gêrsopbringst en –kwaliteit yn ‘e groei fan in snee, minerale N yn ‘e grûn nei in snee en neiwurking fan ‘e N-jefte yn ‘e snee dy’t er op folget.
De fjildproeven leinen op fjouwer grûnsoarten, de gêrsopbringst, it opnimmen van N en de minerale N yn ‘e grûn binne it hiele groeiseizoen mjitten as in funksje fan ‘e N-jefte yn ‘e foargeande sneden en dy yn ‘e snee sels. De resultaten fan dizze proeven binne ek brûkt om hânfetten foar de N-jefte per snee te meitsjen en om ark te betinken dat helpe kin by it deistich stjoeren fan it brûken fan greide. Om it effekt fan feroaringen yn it brûken fan greide op it weromwinnen fan N te begrypen, is er in statistyske analyze útfierd fan in grut tal proeven die tusken 1934 en 1994 yn Nederlân oanlein binne. It stjoeren fan it brûken fan greide op ‘e deistiche en middellange termyn fan ‘e proefbuorkery “De Marke” en fan praktykbedriuwen is op ienfâldige wize beskreaun en analysearre. Der binne twa modellen brûkt. It iene is nij makke om ‘e útspieling fan nitraat nei it grûnwetter te berekkenjen as in funksje fan N-jefte it jier en it tal fan fee de hektare. It oare model is in oanpast besteand model, om it útstjitten fan stikstofoxyde (N_2O) en koalstofdioxide (CO_2) troch it ploegjen fan âlde en jonge greide te skatten.

It optimalisearjen fan it jaan fan N foar elke snee

It resultaat fan it ûndersyk lit dúdlik sjen dat it opnimmen van N en ‘e opbringst fan gêrs tanimme as mear N jown wurdt en as it tal fan groeidagen tanimt. Dat jildt foar elke snee. De optimale N-jefte wurdt yn ‘e regel op ekonomyske grûn berekkene, troch it marginaal effekt te brûken: de lêste kilo N moat nog werom fertsjinne wurde. Yn dit proefskrift wurdt foarsteld om it N-gehalte fan it gêrs en it restant oan N nei in snee as hânfetten te brûken om rekken te hâlden mei it miljeu.
De resultaten fan ‘e proeven jouwe ek oan dat by meer N it N-gehalte fan it gêrs heger wurdt, it restant oan N yn ‘e grûn tanimt en it marginaal effekt ôfnimt. By in grutter tal groeidagen nimt it N-gehalte ôf, lyk as it restant oan N, wylst it marginaal effekt tanimt. It kombinearre effekt fan N-jefte en it tal fan groeidagen op ‘e foarneamde hânfetten is brûkt omfoar it hiele groeiseizoen de optimale N-

jeften berekkenjen foar ferskate gêrs opbringsten en foar ferskate groeityden de snee.

Ofhinkelik fan ‘e gêrsopbringst wurdt ûngefear 20 ta 70% fan ‘e N-jefte daliks opnommen. It neiwurkjen kin foars wèze. Dy wurdt mjitten as minerale N yn ‘e grûn en as extra opnommen N en extra gêrsopbringst yn folgjende sneden. Yn’e praktyk is net folle bekend oer it neiwurkjen. Myn analyze lit sjen dat der wol rekken mei holden wurde moat foar goeie N advyzen. Op sân en klaai wurdt op syn heechst 8 % fan ‘e N-jefte werom fûn as minerale N. Der wie wol in dúdlik ferbân tusken de minerale N en it opnimmen van N yn ‘e folgjende snee. Op feangrûn is ûngefear 20 % fan ‘e N-jefte werom fûn as minerale N, mar wie der gjin ferbân mei it opnimmen van N yn ‘e folgjende snee. Mar op alle grûnsoarten wie der yn it hiele seizoen in dúdlik ferbân tusken de totale N-jefte út foargeande sneden en it opnimmen van N yn ‘e neifolgjende snee. Dit ferbân is brûkt om de optimale N-jefte te berekkenjen foar sawol it lânboukundig hânfet (it marginaal effekt) as foar beide miljeukundige hânfetten (it N-gehalte fan it gêrs en it restant oan N yn ‘e grûn). It optimum hinget sterk ôf fan it keazen hânfet.

De analyze fan it brûken fan greide op ‘e Marke en op praktykbedriuwen toant oan dat it weidzjen van fee faak yn tige jong gêrs bart. It hat fan gefolgen dat de gêrsopbringst leech is en it N-gehalte heech. In oar gefolg is dat de N-jefte faak folle heger is as advisearre. It benutsjen fan N en ‘e gêrsopbringst binne derom leger as mooglik is.

Ark foar greidegebruk
De hjirfoar neamde miljeukudige hânfetten kinne goed brûkt wurde yn it ferbetterjen fan it deistich brûken fan greide. Ek die bliken dat ‘e hânfetten fan it marginaal effekt en it N-gehalte fan it gêrs tige goed kombinearre wurde kinne. Dertroch kinne ekonomyske en miljeukundig ferantwurde N-jeften berekkene wurde foar gêrs mei in heger as leger N-gehalte. Sok gêrs kin brûkt wurde yn in rantsoen dat bestiet út in ferskaat oandiel oan gêrs, snijmais en krêftfoer.

It bytsje N dat werom fûn wurdt yn ‘e foarm fan minerale N op sân en klaai, it ûntbrekken fan in ferbân tusken minerale N en it opnimmen fan N op fean, de grutte fariaasje yn it fjild, yn ‘e tyd en yn’t algemien en de tyd dy’t it ferget om minerale N te mjitten, jouwe oan dat it mjitten dêrfan gjin doel hat om de N-jefte oan te passen. Dêrtsjinoer kin ‘e N-jefte ienfâldich en krekt fêststeld wurde troch rekken te hâlden mei de foargenade N-jeften. Dizze wurkwize is al tapast yn it offisjele N advys foar yntinsyf brûkte greide. De resultaten dy’t yn dit proefskrift beskreaun binne, binne dêrfoar brûkt.

De analyze fan it brûken fan greide op “De Marke” en op praktykbedriuwen toant oan dat faak yn jong gêrs weide wurdt. Neffens my hat dit jong weidzjen te krijen mei in risiko mijend gedrach. Dit hat ferbân mei in tekoart oan ynformaasje oer it gêrs. Yn ‘e praktyk wurdt de gêrsopbringst de snee faak ruchwei skatten, wylst de it opnimmen van N en it N-gehalte fan it gêrs meastentyds net bekend binne. Der is oan’t no ta gjin ark dat flot, goedkeap en krekt de opbringst en it N-gehalte fan it steande gewaaks mjitte kin. Mar de beskikberens fan sokke ynformaasje is tige needsaaklik om it stjoeren fan it deistich brûken fan greide en it benutsjen fan ‘e N te ferbetterjen.
As de statistyske ferbannen út dit proefskrift, de nije hânfettenom N-jeften te ferbetterjen, it idee om de N-jeften by te hâlden en it flot en krekt mjitten fan gêrs en N-gehalte alles mei elkoar kombinearre wurde yn in “Dynamysk Beslút Stypjend Systeem”, kin it deistich brûken fan greide effektyf ferbettere wurde.

It wikselwurkjen tusken de ferskate nivo’s fan stjoeren
It empiryske model Nitraat Utspielings Reduksje Planner (NURP) is makke as in middel om it stjoeren fan it brûken fan greide op ‘e koarte en middellange termyn te ferbetterjen. It foardiel fan dit model, yn fergelyk mei oare besteande modellen, is dat de N-jefte en it tal fan fee de hektare ûnôfhinklik fan inoar binne. Hjirtroch kin yn ‘e praktyk folle better berekknene wurde hoe ’t de útspieling fan nitraat fermindere wurde kin. It model lit sjen dat op yntinsive melkfeebedriuwen op droege sângrûn it nitraatgehalte yn it grûnwetter ûnder de 50 mg de liter komme kin troch in kombinaasje fan beheind weidzjen, earder it fee op stâl te setten en minder N te brûken. It effekt fan it mear fuorjen van mais en fan in hegere molkproduksje de ko is beheind.

Út de analyze fan in grut tal fan fjildproeven die bliken dat yn ‘e twadde helte fan ‘e tweinitichste ieuw yn ferhâlding stadichoan mear N út keunstdong werom fûn waardt yn it gêrs as foarhinne. Dit tanimmen hat te krijen mei feroaringen yn it brûken fan ‘e greide op ‘e koarte, middellange en lange termyn. It better ûntwetterjen, ploegjen en op ‘e nij insiedzjen fan greide hat nei alle gedachten soarge foar in leger gehalte oan organyske stof yn ‘e grûn en dermei foar in legere N omrin en leverânsje oan it gêrs. De wite klaver is út ‘e seade ferdwûn troch it brûken fan N út keunstdong. It nij insiedzjen fan it lân hie fan gefolgen dat it part fan Ingelsk Raaigêrs tige tanaam is. Tagelyk is troch it feredeljen de produksje fan dit gêrs folle heger wurden. Ek naam it tal fan sneden ta en is de N-jefte better ferdield oer alle sneden. Dit alles hie fan gefolgen dat it opnimmen van N út keunstdong heger waardt. Alhoewol it opnimmen fan N tanimt mei it tal fan sneden, bliuwt lykwols de gêrsopbringst gelyk of wurdt sels leger. Dan kin it bettere opnimmen fan N in neidiel wêze, om't it hegere N-gehalte yn it gêrs troch de ko minder goed brûkt wurde kin.

De opperflakte âlde greide is foars ôfnaam sûnt de sawnticher jierren fan 'e tweintichste ieuw troch it ploegjen en omsetten nei boulân, meastentyds foar snijmais. Ek keunstgreide is geregeld ploege. De gefolgen foar de de utstjit fan CO_2 en N_2O nei de loft is ûndersocht mei in empirysk model. De ferwachting is dat yn 'e oankommende tweintich ier de opperflakte âlde greide fjirder ôfnimt, om't er mear behoefte is oan keunstgreide foar wikselbou mei benammen jirpels en blombollen. De berekkene totale utstjit as gefolg fan it omsetten fan âlde greide leit tusken de 30 en 250 ton CO_2-ekwivalinten de hektare. It grutste part derfan is CO_2. De útstjit is daliks nei it ploegjen tige heech en nimt stadich ôf yn 'e rin fan fyftich ier. De ierlikse útstjit fan N_2O by wikselbou fan keunstgreide mei bou en fan greidefernijen leit tusken de 1.8 en 11.0 ton CO_2-ekwivalinten de hektare (keunst)greide.
De totale útstjit fan allinne N_2O troch it ploegjen fan greide leit tusken de 0.5 en 0.65 Megaton CO_2-ekwivalinten it jier. Dat is sawat 10 prosint fan 'e totale útstjit fan N_2O troch de lânbou yn Nederlân. Om't ploegjen net belutsen is yn 'e nasjonale ynventarisaasje, wurdt de nasjonale útstjit dus underskat. Om de gefolgen fan ploegjen better skatte te kinnen, is it nedich om aparte útstjit-sifers fêst te stellen. Ek moatte de wurkwizen komme om de útstjit te ferminderjen.

Yn theory is it brûken fan N troch de weidzjende ko tige heech te krijen foar alle kombinaasjes fan gêrs, snijmais en krêftfoer yn it rantsoen. It N-(eiwyt) gehalte fan it gêrs kin troch een goede N-jefte regele wurde, mei it betingst dat de N-jefte wol syn jild opbringt troch in hegere opbringst fan gêrs. Dizze betingst betsjut in beheining fan it N-gehalte fan it gêrs. In lyts tal fan groeidagen foar in snee of in hege N-jefte moatte mijd wurde, om 't de N net ekonomysk ynset wurdt en der te folle N efterbliuwt yn 'e groun, mei mooglike ferliezen as gefolg. It beheinde N-gehalte hat op syn bar wer gefolgen foar it bêste oandiel fan snijmais yn it rantsoen en op in protte bedriuwen ek foar de oppervlakte fan 'e eigen bou fan snijmais. It is dúdlik dat de beheinde romte yn it deistich stjoeren fan it dongjen en brûken fan greide as in beheining fan ûnderop wurket foar beslúten op middellange termyn oangeande it fuorjen fan it fee en op ‘e lange termyn oangeande de bou fan snijmais.

Earder op stâl setten fan fee is tige wurksem om it útspielen fan nitraat te beheinen, sa docht rekkenwurk mei it model NURP bliken. Dit hat fan gefolgen dat it brûken fan it greide yn ‘e hjerst feroaret. Alle gêrs moat meand wurde, mar it meitsjen fan in goeie kuil is dreeg, om ’t yn ‘e hjerst it gêrs net goed mear droegje wol en de smaak faak minder is. De mooglikhed om de N-jefte ta de foarste fjouwer moannen fan it seizoen te beheinen, hat fan gefolgen dat de gêrsproduksje folle heger wurde moat yn die tyd. Dat hat dan wer gefolgen foar it marginaal effekt fan ‘e N-jefte, foar it N-gehalte fan it gêrs en foar it benutsjen fan ‘e N troch it weidzjende fee. It is de muoite wurdich om it beheinen fan ‘e N-jefte yn ‘e foarste fjouwer moannen fan it groeiseizoen fjirder te ûndersykjen.

Konklúzjes

- Foar it fêststellen fan ‘e N-jefte foar in snee gêrs is in kombinaasje fan hânfetten beskikber dy ’t rekken hâldt mei ekonomy en miljeu.
- De minerale N yn ‘e grûn is net te brûken om ‘e N-jefte oan te passen.
- De N dy ’t yn foargeande sneden jown is, is de bêste skatting foar de neiwurking en foar it oanpassen fan ‘e N-jefte.
- Weidzjen yn âlder gêrs as yn ‘e praktyk gewoante is, kin de produksje fan gêrs en it benutjsen fan N op melkfeebedriuwen ferbetterje.
- It stjoeren fan it brûken fan greide wurdt amper stipe troch flot beskikbere en krekte ynformaasje. Ferbetterjen fan it deistich stjoeren fan it brûken fan greide kin dien wurde troch in kombinaasje fan ynformaasje oer it gewaaks en modellen yn in “Dynamysk Beslúten Stypjend Systeem”.
- It model NURP is in goed stik ark foar it nimmen fan beslúten om de útspieling fan nitraat op yntinsive melkfeebedriuwen te beheinen.
- De útstjit fan stikstofoxide yn Nederlân wurdt ûnderskat om ’t gjin rekken holden is mei de gefolgen fan ploegjen fan âlde greide en keunstgreide.
- Yn ‘e twadde helte fan ‘e tweinitichste ieuw wurdt stadichoan mear N út keunstdong werom fûn yn it gêrs. Dit hat te krijen mei feroaringen yn it brûken fan greide op ‘e koarte, middellange en lange termyn.
- Kennis oer it wikselwurkjen tusken de ferskate nivo’s fan stoering is needsaaklik foar it beheljen fan ekonomyske en miljeukundige doelen op yntinsieve melkfeebedriuwen mei greide.

Curriculum vitae

Theunis Valentijn Vellinga werd geboren op 8 juli 1959 in Harlingen. In 1977 behaalde hij het Atheneum-B diploma aan het Lienward College te Leeuwarden. Daarna studeerde hij Landbouwplantenteelt, met de specialisatie Graslandcultuur, aan de toenmalige Landbouwhogeschool te Wageningen. Hij rondde deze studie af in 1985.
In september 1985 begon hij als onderzoeker bij het Praktijkonderzoek Rundvee-, Schapen- en Paardenhouderij te Lelystad. Hij werkte bij de afdeling Weide- en Voederbouw aan de ontwikkeling van simulatiemodellen voor de grasgroei en het graslandgebruik, beweidingsystemen, het opstellen van stikstof-bemestingsadviezen voor grasland, de effecten van ontwatering van veenweidegebieden en het berekenen van de inpasbaarheid en de kosten van beheersovereenkomsten op grasland. Een deel van dit onderzoek is verwerkt in dit proefschrift.
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