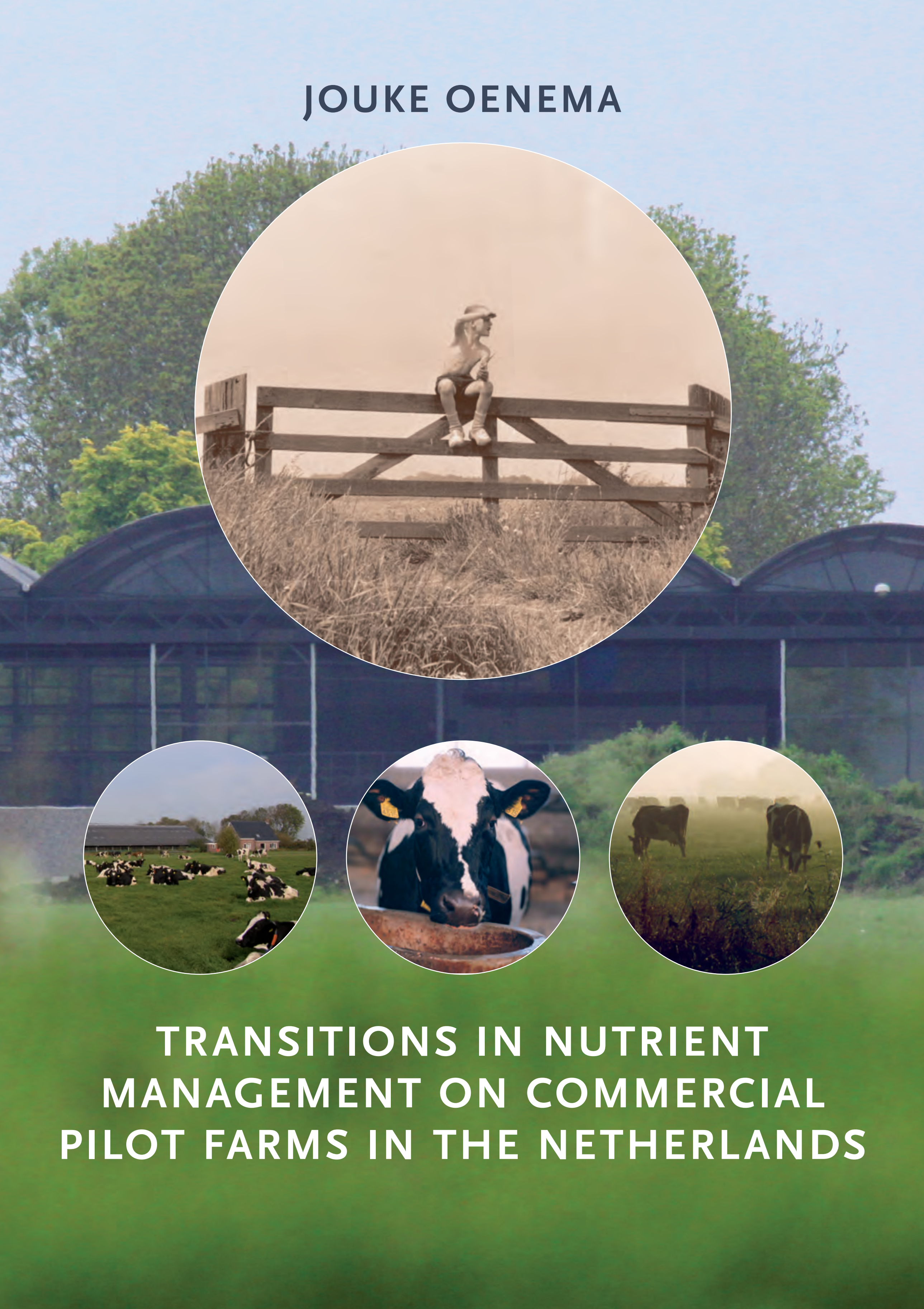
JOUKE OENEMA



TRANSITIONS IN NUTRIENT MANAGEMENT ON COMMERCIAL PILOT FARMS IN THE NETHERLANDS

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ABSTRACT

Dairy farms in the Netherlands are productive, but also have relatively high nutrient losses, which often exceed environmental targets set by the European Union. There are, however, large differences between dairy farms in performance, suggesting scope for improvement for at least a significant fraction of dairy farms. The project 'Cows & Opportunities' was initiated by the farmers' union and the government in 1998 to explore the options to meet strict environmental targets with the help of intensive coaching by researchers and extension specialists. A total of 17 commercial pilot dairy farms were invited to participate in this long-term project.

The aim of this thesis is to evaluate the transition on dairy farms with intensive coaching towards realizing environmental legislation. It describes the changes over time in the empirical relationship between farm characteristics, farm management, nitrogen (N) and phosphorus (P) surpluses and use efficiencies, and nitrate leaching during the period 1998-2011. For exploring the opportunities for each dairy farm, the method of prototyping was used, which implies an intensive 'analysis-modelling-planning-implementation-monitoring' cycle, involving active participation of farmers, researchers and extension specialists.

Changes in farm characteristics and performances were evaluated using statistical methods, such as linear and multiple regressions, and Monte Carlo simulations. The results of this thesis show that intensive coaching and interaction between farmers and researchers may lead to rapid adoption of efficient farm management practices on pilot farms.

From the start of the project in 1998 until 2002, average nutrient surpluses on the pilot farms decreased by 33% for N and 53% for P. On other commercial dairy farms in the Netherlands, nutrient surpluses decreased in the same period at similar rate for N (29%), but less for P (28%). However, on the pilot farms, nutrient use efficiency in 2002 was 34% for N and 67% for P compared with 23% (N) and 49% (P) on the 'national average' farm. In the remainder of the period (2003-2011) nutrient use efficiency continued to increase to 38% for N and 85% for P on the pilot farms and till 30% for N and 60% for P on other commercial farms.

The possibilities to improve nutrient management are farm-specific, influenced by soil type and hydrology, and depending on craftsman skills and entrepreneurship. Insight in the strengths and weakness of the nutrient use efficiency of each component of the dairy farm, (i.e., herd, manure, soil, crop/feed) guides the optimization of nutrient management.

Effective strategies to reduce farm nutrient losses are based on optimizing internal nutrient cycling in subsystems, so that external inputs of nutrients can be reduced. Adopted and implemented measures were (1) reducing the use of chemical fertilizers, (2) optimizing the use of home-produced organic manure, (3) reducing grazing time, (4) reducing the relative number of young stock, (5) lowering crude protein content in the ration, and (6) applying and managing a catch crop after maize.

Farmers in 'Cows & Opportunities' share their experiences with each other and with other farmers. The project forms a unique link in the chain of information and knowledge transfer from theoretical and experimental research to commercial dairy farms and to policy makers from both government and farmers' union.

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1




GENERAL INTRODUCTION

1 The nutrient problem in dairy farming

Agriculture and dairy farming in particular, is deeply rooted in European society. The Common Agricultural Policy (CAP) of the European Union (EU), established in 1962, stimulated intensification of agricultural production through price support (EU, 2012). In the 1980's, farms became so productive that the EU produced more food than needed. The surpluses were stored and led to 'food mountains and lakes'. Several measures were introduced to bring production levels closer to what the market needs, such as the introduction of the milk quota system in 1984. In 1992, the CAP shifted from market support to producer support. Price support was scaled down, and replaced with direct payments to farmers. In 2003, the way of payments changed due to the decoupling of subsidies and production. Farmers now receive an income support payment, on the condition that they manage the farmland properly and fulfill environmental, animal welfare and food safety standards. The most recent change was endorsed in 2011 when a new CAP reform proposal aimed to strengthen the competitiveness of the agricultural sector, promote innovation, mitigate climate change and support jobs and economic growth in rural areas.

In the Netherlands, dairy farming changed after World War II, as a result of specialization, and technological innovation (Bieleman, 2005). Scaling-up and intensification characterized the Dutch way of dairy farming since 1960. Pressure was increasing on the dairy industry, exposed to a globalizing market, in which the developments in the price of milk were insufficient to keep pace with the increasing costs of production, associated with rising energy costs. To maintain income, farmers respond by increasing milk quota and to some extent also land area, however with the net result of a higher milk production per ha and per man-hour, to reduce land and labor costs per unit milk production. In the Netherlands, the average price of agricultural land is 50 k€/ha (Anonymous, 2012). Evidently, such high land prices force farmers to intensify farming practices. Dairy farming systems rely on (1) the import of cheap chemical fertilizers to boost forage production and (2) import of animal feed to increase milk production to economically attractive levels. Only a fraction of the nutrients contained in the imported fertilizers and feed is converted to animal products exported from the farm. The remainder is excreted via dung and urine and can be utilized again for crop production or is lost to the environment. Side-effects of the intensification of dairy farming became visible and evident from the end of the 1970s and beginning of the 1980s onwards (Henkens & Van Keulen, 2001). The nutrient losses to the environment affected the quality of groundwater and surface water (e.g. Cartwright et al., 1991, Erisman et al., 2007; Galloway et al., 2008) and contributed to acid deposition (ammonia) that caused damage of forest vegetation (Steinfield et al., 2006).

Recognition of the impact of nutrient losses to the environment has resulted in the development of government policies in many European countries (e.g. De Clercq et al., 2001). The Nitrate Directive (EC, 1991), one of the EU policy frameworks, defines an application threshold of 170 kg manure-N ha^{-1} $year^{-1}$ for all Nitrate Vulnerable Areas, i.e. EU areas that have been identified as exceeding or being at risk of exceeding 50 mg NO_3 l^{-1} in the groundwater. In the Netherlands, legislation to reduce losses of nutrients from manure has been implemented since 1984. In 1998, a nutrient balance approach, the MINeral Accounting System (MINAS), was introduced as the central instrument for restricting emission of nutrients to the environment, with levy-free standards for acceptable nutrient losses (Henkens & Van Keulen, 2001; Schröder et al., 2003). In 2003, European Court of Justice rejected MINAS as policy instrument to meet the EU Nitrate Directive standards (Anonymous, 2004). In 2006, the MINAS balance approach was therefore replaced by a one-sided input approach by introducing permitted N rates (so-called 'application standards') for all crops (Schröder & Neeteson, 2008).

The environmental problems in Dutch dairy farming in the 1980s have led to the establishment of the experimental dairy farm 'De Marke' (Aarts et al., 1992). 'De Marke' aims at improving the utilization of fertilizers and feeds, by minimizing nutrient requirements, maximizing the use of nutrients in organic manure and homegrown feeds and through the targeted use of fertilizers and feed (Aarts et al., 1999). The results of 'De Marke' showed, amongst other things, that by taking a coherent set of simple measures at farm level, the input of nutrients can be drastically decreased (Hilhorst et al., 2001; Aarts, 2000; Verloop, 2013). Nitrate concentrations in the upper groundwater on the light sandy soils have decreased to a level that meets the EU Drinking Water Quality Directive of 50 mg nitrate l^{-1} (Verloop et al., 2006). Comparing the results of 'De Marke' with those of Dutch dairy farmers, there was still a huge gap between what is technically feasible and possible and what commercial dairy farmers realize in practice. The average MINAS N surplus at 'De Marke' in the period 1993-1999 was 90 kg ha^{-1} (Hilhorst & Oenema, unpublished data) compared with 304 kg ha^{-1} for all Dutch dairy farmers in 1997 (Reijneveld et al., 2000).

So far, several studies on nutrient management on Dutch dairy farms have already been done (e.g. Van de Ven, 1996; Berentsen, 1999; Aarts, 2000; Hack-ten Broeke, 2000, Verloop, 2013). These studies focus either on data collected on experimental farm 'De Marke', which was set up as an environmental prototype on sandy soil (Aarts, 2000; Verloop, 2013), or are based on a normative modelling research (Van de Ven, 1996; Berentsen, 1999; Hack-ten Broeke, 2000). Ondersteijn (2002) analysed changes in nutrient management at farm level caused by MINAS regulations on commercial farms, but the time period to monitor changes was short (three years). Many other studies are executed on commercial dairy farms. For example, Domborg et al. (2000), Nevens et al. (2006), Fangueiro et al. (2008), Treacy et al. (2008) and Gourley et al., 2012b collected data on commercial farms for a few years to derive farm-gate nutrient balances. Gourley et al., 2012a collected data on commercial farms for one year to describe N flows and transformations in the herd component. A whole-farm approach of nutrient management on farms was conducted by Spears et al., 2003a and 2003b on several commercial farms but only for one year, or for more years on one commercial farm (Lynch et at., 2003), or one experimental farm (Kobayashi et al., 2010). The study presented in this thesis focus on the transition of nutrient management in whole dairy farming systems, i.e. farm-specific analysis based on detailed and accurate data on nutrient balances at the whole farm and at the herd and soil level, on commercial pilot farms over a long time period (1998-2011).

2 Objectives of the research

The aim of this thesis is to evaluate the transition on dairy farms with intensive coaching towards realizing environmental legislation. For this purpose data of the project 'Cows & Opportunities' with pilot commercial farms are used. More specifically, the following research questions are addressed:

- Can a participatory project with pilot farms help to adopt changes in nutrient management to bridge the gap in performance between experimental and commercial dairy farms;
- How to change whole farm management to reduce nutrient losses;
- How to improve grassland management and how and which factors affect the grassland yields on commercial dairy farms;
- Can means-orientated legislation instead of goal-orientated legislation fulfill the target of 50 mg nitrate l^{-1} in groundwater;
- What is the uncertainty of nutrient flows on commercial pilot farms using a monitoring program and what is the contribution of the collected data to this uncertainty.

3 Research framework and methodology

To answer the research questions the study uses the framework outlined in Fig. 1. The figure shows a dairy farming system in its environment, to realize transitions in farm and nutrient management that are needed to comply with environmental standards and are economically viable.

The dairy farming system is central in the framework because for the analysis of the transition in nutrient management a whole-farm system approach on interactions and overall effects of integrated measures is essential, since changes introduced to remedy one loss process may exacerbate other problems (e.g. Aarts et

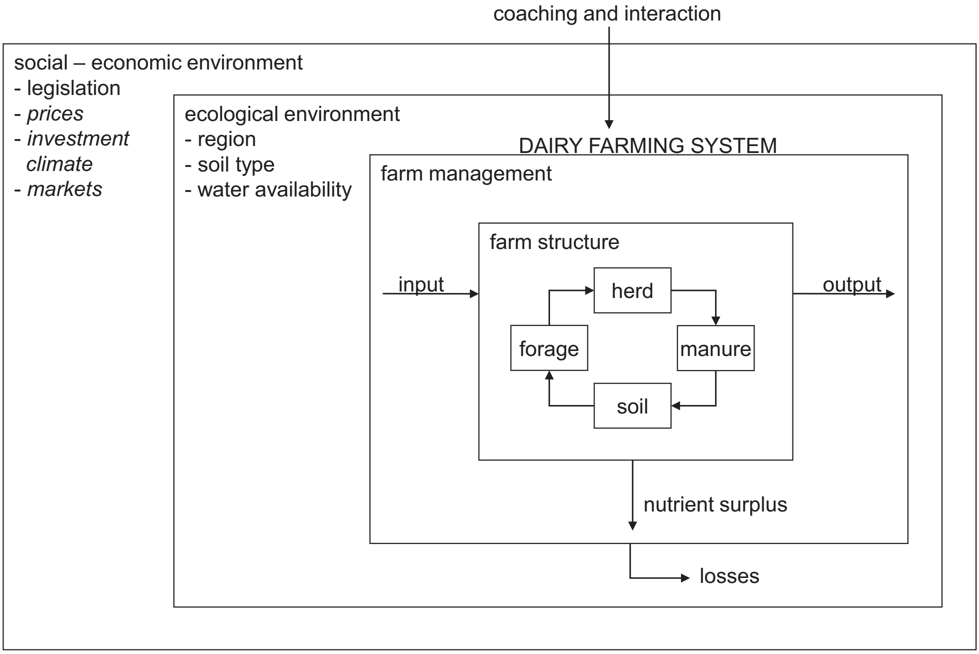

Fig. 1 *Framework of dairy farming systems analysis in its environment. The italic elements are not a topic in this study.*

al., 1992; Jarvis et al., 1996). How a dairy farming system operates depends on the farm structure (e.g. farm area, crops, milk production, number of animals etc.) and the farm management (e.g. herd & feeding management; crop & fertilizer management). Local circumstances such as region and soil type and legislation rules are the environment wherein a dairy farming systems operates.

This thesis is based on data collected on 16 commercial pilot farms in the project 'Cows & Opportunities' during the period 1998-2011. It is characterized by agreements of the research project with the farmers on realization of measurable targets and intensive coaching through frequent interaction between researchers, extension agents and farmers. For designing suitable farming systems the method of prototyping was used, which implies a combination of system modeling and system implementation. An intensive 'analysis-modelling-planning-implementation-monitoring-analysis' cycle is followed, involving active participation of farmers, researchers and extension specialists. Measurable targets for nutrients were formulated to realize the transition of improved nutrient management. At the start, each farm was thoroughly analysed to identify its strengths and weaknesses in the original situation and to analyse the opportunities. This analysis also identified the gap between the targets and the reality of the original situation. Subsequently, outlines for farm designs were formulated for each participant. Consultations between farmer and research team yielded a list of measures, based on best professional judgement. A whole-farm system model was used to simulate the effects of the new farm design to calculate the environmental and economic effects of the farm design, and to identify the best farm strategies. After modelling and adjusting the farm design, the farm development plan was constructed, approved and implemented. The data from 16 commercial pilot farms in time allow us to do statistical tests, even though the farms are not a real replication of a prototype.

The prototyping method was formalized by Vereijken (1992) to design production systems on an experimental arable farm and by Aarts et al., (1992) on an experimental dairy farm. Both authors (Vereijken, 1997; Aarts, 2000) recommended the need for prototyping on pilot farms to disseminate innovative production systems. Le Gal et al. (2011) provided an extended review about the various methods described in scientific literature to support the development of sustainable farming systems. Prototyping was one of the methods and adapted for commercial farms in various countries worldwide (Blazy et al, 2009; Kabourakis & Vassilou, 1999; Stoorvogel et al., 2004). Le Gal et al. (2011) concluded also that within the process of prototyping on commercial farms, the farmers' participation actually occurred quite late in the process, notably after researchers have defined the objectives to be reached (Sterk et al., 2007). The study presented in this thesis fulfills the recommendation of Vereijken (1997) en Aarts (2000) to apply the prototyping approach on commercial pilot farms to test and disseminate innovations for their manageability, acceptability and effectiveness. The targets were formulated by legislation and together with the farmers' aspirations, designs for new innovations were formulated by consultations between the farmer, researchers and extension agents.

4 Outline

Chapter 2 was written in 2001 for a special issue of the Netherlands Journal of Agricultural Science and found its origin in the national symposium 'Nitrate policy: research, dairy sector and policy makers', organized in November 2000 by Plant Research International (part of Wageningen UR) in collaboration with the Centre for Agriculture and the Environment (CLM, Utrecht) and Wageningen UR Livestock Research, with contributions from the Ministry of Agriculture, Nature Management and Fisheries (now part of Ministry of Economic Affairs), the Ministry of Infrastructure and Environment (I&M, formerly VROM), and the National Farmers' Association. The aim of the symposium was to evaluate the relevance of recent research results of experimental dairy farm 'De Marke' for policy makers and the dairy farming sector. The paper describes the blueprint of the project Cows & Opportunities and why this project is needed in the chain of research and knowledge exchange to commercial farms to become environmentally and economically sustainable. Results of the transition in improved nutrient management on commercial pilot farms are described and discussed in Chapters 3 to 5.

Chapter 3 analyses the development of farm management strategies to meet environmental targets to reduce nutrient surpluses. The study contributes to closing the information gap on the causes underlying the variation in system performances across specialized dairy farms and years, by systematically examining whether differences in system performance among farms can be explained by different management practices. Chapter 4 describes the development and variation in N management on grassland and explains this to differences in farm structure and soil characteristics. This can reveal opportunities to improve N management and N use efficiency on grassland on dairy farms. Chapter 5 explores the effects of farm management practices and soil and climatic conditions on nitrate leaching from grassland and maize land on sandy soils at three spatial scales: farm, field and sampling point. Results and insights of this study can be used to support further development and refinement of policy instruments. Decisions in nutrient management and environmental policy making have to be based on sound data and proper analysis of cause-effect relationships. Information on uncertainties in nutrient flows may be used for determining the risk for yield losses and exceeding environmental targets, and hence to better inform decision making as to the optimum nutrient management strategy. The experiences with monitoring data in the projects ‘De Marke’ and ‘Cows & Opportunities’ provides the opportunity to gain knowledge about studying uncertainties in nutrient flows on dairy farms. Chapter 6 presents the input-output N balance model used in ‘Cows & Opportunities’ to describe and quantify N flows in dairy farming systems. The model was used to quantify uncertainty in monitoring data and the uncertainty in and sensitivity of output from the model was quantified using a Monte Carlo approach. Results can be used to understand the uncertainty in N flows on dairy farms as a basis for policy and decision-making but also for dairy farmers to make good decisions to improve their management. Chapter 7 combines the results of the different chapters into a general discussion by presenting a synthesis of the transition in the N and P flows on commercial pilot farms, the impact of project results is presented and plans for the future are outlined. Finally, the main conclusions of this thesis are presented.

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CHAPTER 2

GUIDING COMMERCIAL PILOT FARMS TO BRIDGE THE GAP BETWEEN EXPERIMENTAL AND COMMERCIAL DAIRY FARMS; THE PROJECT 'COWS & OPPORTUNITIES'

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Abstract

In the Netherlands there is a remarkable difference in environmental performance between the average commercial dairy farm and some experimental dairy farms. Despite 15 years of policies and measures to decrease nutrient losses, experimental dairy farms based on careful nutrient management, like 'De Marke', realize much higher resource use efficiencies and much lower nutrient surpluses than the average commercial dairy farm. This paper discusses the transitions that are needed to bridge the gap between experimental dairy farms and commercial pilot farms. In the project 'Cows & Opportunities', 17 farms were selected representing the full range of conditions for dairy farming, with emphasis on dry sandy soils because of their environmental constraints. There are intensive discussions and communications between farmers, extension services, advisers from the industry, researchers and policy makers. Firstly, all farms were thoroughly analysed in terms of agronomic and environmental performance in the original situation. Secondly, opportunities for improving their performance were analysed using sustainability criteria like nutrient losses, energy and water use, emission of greenhouse gases, crop protection, accumulation of heavy metals, and nature development. Thirdly, an outline for a farm development plan was formulated to meet the nitrogen and phosphorus surplus targets set by the Dutch government. These first outlines (designs) were thoroughly discussed between farmers and researchers. After modelling the farm design to calculate the environmental and economic effects, the farm development plan was adjusted wherever needed, approved and implemented. The performance of the farm will be monitored and evaluated over the next few years. In the original situation, the MINAS nitrogen surplus on the farms ranged from 47 to 349 kg ha^{-1}, with an average of 207 kg. The modelling results indicated an average N surplus of 131 kg ha^{-1} after implementation of the farm development plans, i.e., 19 kg ha^{-1} less than the target surplus. The project 'Cows & Opportunities' demonstrates that it is possible to meet the nitrogen and phosphorus surplus targets by taking simple measures. The project yields useful information on the relations between management measures, constraints, nutrient balances and environmental performance.

1 Introduction

Intensive dairy farming systems rely on (*i*) import of fertilizers to boost forage production, and (*ii*) import of animal feed to increase milk production to economically attractive levels. Only a fraction of the nutrients contained in the imported fertilizers and animal feed is converted into animal products exported from the farm. The remainder is excreted via dung and urine and can be utilized again for crop production or is lost to the environment. It has become clear now that continued high imports of fertilizer and feed can lead to nutrient imbalances that result in emission of excess nutrients from the farm to ground- and surface water and the atmosphere, with potentially adverse environmental impacts (Jarvis et al., 1995).

Currently, there is much information about nutrient flows, transformations and losses that can be used to improve nutrient use efficiency and reduce nutrient losses from the major compartments of dairy farming systems (e.g. Aarts et al., 1992). Substantial reductions in nutrient losses can be realized immediately by improved management of animal manure (Van Der Meer et al., 1987; Rees et al., 1992; Van Der Meer & Van Der Putten, 1995; Schils et al., 1999), and improved fertilizer recommendations (Titchen & Scholefield, 1992; Oenema et al., 1992). However, for long-term success and sustainability it is essential that whole systems are considered because changes introduced to remedy one loss process may exacerbate other problems (e.g. Aarts et al., 1992; Jarvis et al., 1996).

Despite this abundance of information, nutrient surpluses from commercial dairy farms in the Netherlands (e.g. Reijneveld et al., 2000) and in many other countries and regions in the European Union (e.g. Walle & Sevenster, 1998) remain very high. In the Netherlands, the MINeral Accounting System, MINAS (Van Den Brandt & Smit, 1998; Neeteson, 2000), was introduced in 1998 as a policy instrument to reduce nitrogen (N) and phosphorus (P) losses, and to meet the standard of the EU Nitrate Directive (Anonymous, 1991) of 50 nitrate mg l^{-1} in the upper groundwater. Between 1998 and 2003, dairy farms in the Netherlands have to reduce the average N and P surpluses by a factor of 2 or more, which indeed is a major task.

There are about 35,000 dairy farms in the Netherlands, managing about 70% of the agricultural area or 1,3 million ha. These farms are in transition because of decreasing milk and meat prices and high stress on the environment (e.g. Dietz, 2000). Dairy farms are confronted ever more by constraints concerning the sustainability in ecological (e.g. stress on the environment), agro-technical (e.g. soil fertility) and socio-economic sense (e.g. WTO is decreasing product support and at the same time increasing income support in exchange for landscape maintenance).

The environmental problems in Dutch dairy farming have led to the establishment of the experimental dairy farm 'De Marke' (Aarts et al., 1992). 'De Marke' aims at improving the utilization of fertilizers and feeds by minimizing nutrient requirements, maximizing the use of nutrients in organic manure and home-grown feeds, and by importing specific fertilizers and feed (Aarts et al., 1999b). The results of 'De Marke' show, amongst other things, that by taking a coherent set of simple measures at farm level, the input of nutrients can be drastically reduced (Hilhorst et al., 2001; Aarts, 2000). Nitrate concentrations in the upper ground-water on the light sandy soils have decreased to a level that nearly meets the EU Drinking Water Quality Directive of 50 mg nitrate l^{-1} (Aarts et al., 2000; Van Keulen et al., 2000). Comparing the results of 'De Marke' with those from Dutch dairy farmers, there still is a huge gap between what is technically feasible and possible and what commercial dairy farmers realize in practice. The average MINAS nitrogen surplus at 'De Marke' in the period 1993-1999 was 90 kg ha^{-1} (Hilhorst & Oenema, unpublished data) compared with 304 kg ha^{-1} for all Dutch dairy farmers in 1997 (Reijneveld et al., 2000).

To bridge this gap requires coaching and transfer of knowledge. On experimental farms, innovative and possibly risky farm designs can be tested, adjusted and further improved easily, on the basis of the experimental results. In practice, dairy farmers are often reluctant to adjust management, because of lack of information and lack of confidence in the results. Intensive coaching and transfer of knowledge will help dairy farmers to adopt changes in management more easily. Our hypothesis is that intensive coaching and increased interaction between researchers and farmers will lead to rapid adoption of efficient farm management in practice. Currently, the following 4 levels of coaching and knowledge transfer are distinguished (see also Fig. 1):

1. Highly intensive participation of researchers, coaching of farm personnel and exchange of knowledge on experimental farms (e.g. 'De Marke').
   Intensive coaching and knowledge transfer on commercial pilot farms.
2. Extrapolating knowledge and experience gained on experimental farms (e.g. 'De Marke') to pilot farms ('Cows & Opportunities').
   A group of 17 farmers was selected to support and demonstrate transfer to suitable farming systems in practice. Participants receive weekly to monthly advice, and have to realize strict targets.
3. Extensive coaching and knowledge transfer on dairy farms in practice.
   An example is the project 'Farmers Data II' with 180 dairy farms. Participants of this project obtain advice twice a year, but there are no strict targets.
4. Incidental coaching and knowledge transfer by appointment.
   Extension specialists visit farmers on request. Knowledge transfer via agricultural magazines and discussions in farmers' study groups is also part of this type of coaching. This group is by far the largest (35,000 dairy farmers), and also is the group 'that lags behind'.

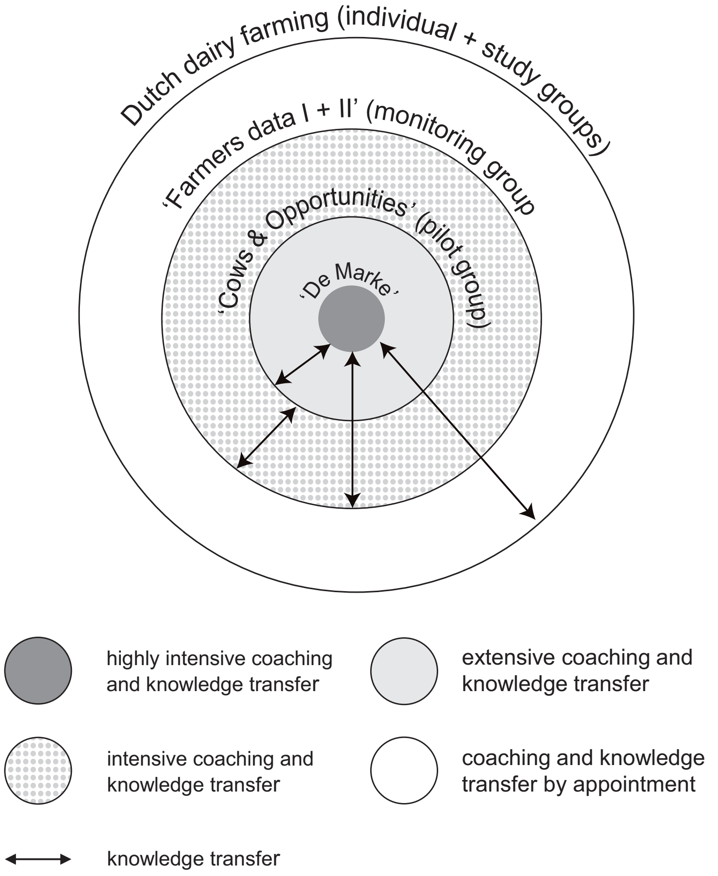

Fig. 1 *Coaching levels and knowledge exchange in Dutch dairy farming.*

This paper focuses on the intensive coaching and knowledge transfer on commercial pilot farms. The project 'Cows & Opportunities' is innovative in the collecting and transfer of knowledge. An intensive 'analysis-modelling-planning-implementation-monitoring-analysis' cycle is followed, involving active participation of farmers, researchers and extension specialists. Measurable targets (sustainability criteria) have been formulated for the following themes: nutrient losses, crop protection, energy and water use, emission of greenhouse gases, accumulation of heavy metals, and nature development. In the first three years of the project, 'nutrient losses' is the most important objective.

The purpose of this paper is (*i*) to discuss the selection of the farms in the project 'Cows & Opportunities', (*ii*) to discuss the research methodology of transition management, and (*iii*) to discuss the targets and required changes in the N balance of the farms.

2 Materials and methods

2.1 Selection of commercial pilot farms

The pilot farms must represent the full range of conditions for dairy farming to facilitate acceptance of the results from these pilot farms by other farms. Selection of the pilot farms required a number of steps. First, all dairy farms in the Netherlands were analysed in terms of agronomic performance (size, fodder production, milk production, nutrient surpluses, etc.) and environmental conditions (soil, region, etc.) to characterize the variability in dairy farming systems (Reijneveld et al., 2000). Then, the results of this study were used to determine the most important selection criteria (region, intensity, and soil type). Advertisements and articles in agricultural magazines were used for publicity and for recruitment of potential participants. After a first screening, potential participants were visited and evaluated in terms of management, motivation, specific circumstances and communication ability (Aarts, 2001). Finally, 17 farms were selected, with emphasis on dry sandy soil, because of the specific constraints. Location and some characteristics of the farms are shown in Table 1.

Table 1 *Location and characteristics of the commercial pilot farms in the Netherlands.*

	Name	Domicile	Area (ha)	Kg milk ha^{-1}
1	Post[1]	Nieweroord	33	12,200
2	Kuks	Nutter	51	10,120
3	Bomers	Eibergen	49	12,930
4	Eggink[1]	Laren (Gld.)	33	15,290
5	Menkveld & Wijnbergen	Gorssel	47	15,470
6	De Kleijne	Landhorst	29	19,820
7	Pijnenborg-van Kempen	IJsselstein	26	20,990
8	Schepens[1]	Maarheze	27	16,660
9	van Laarhoven[1]	Loon op Zand	32	15,600
10	Hoefmans[1]	Alphen (NBr)	36	15,350
11	Van Hoven	Cadier en Keer	42	15,600
12	Sikkenga-Bleker	Bedum	54	9,990
13	Miedema	Haskerdyken	40	11,820
14	Dekker	Zeewolde	47	22,840
15	Van Wijk	Waardenburg	34	16,840
16	Boekel	Assendelft	72	10,740
17	De Vries	Stolwijk	36	12,130

[1] from 1999

2.2 Research methodology

For designing suitable farming systems the method of prototyping (Fig. 2) was used, which implies a combination of system modelling and system implementation (Aarts et al., 1992; Aarts, 2000). After collecting farm data, each participating farm was thoroughly analysed to identify its strengths and weaknesses in the original situation and to analyse the opportunities (Koskamp, 2000). This analysis also identified the gap between the targets for the various sustainability criteria and the reality of the original situation. Subsequently, outlines for farm designs were formulated for each participant. Consultations between farmer and research team yielded a list of measures based on best professional judgement; farmers had a strong influence on farm design (Beldman & Zaalmink, 2000). The next step was to simulate the effects of the new farm design with the farm-budgeting model BBPR (Alem & Van Scheppingen, 1993), to calculate the environmental and economic effects of the farm design, and to identify the best farm strategies (Galama et al., 2000). After modelling and adjusting the farm design, the farm development plan (FDP) was constructed, approved and implemented (Koskamp, 2003).

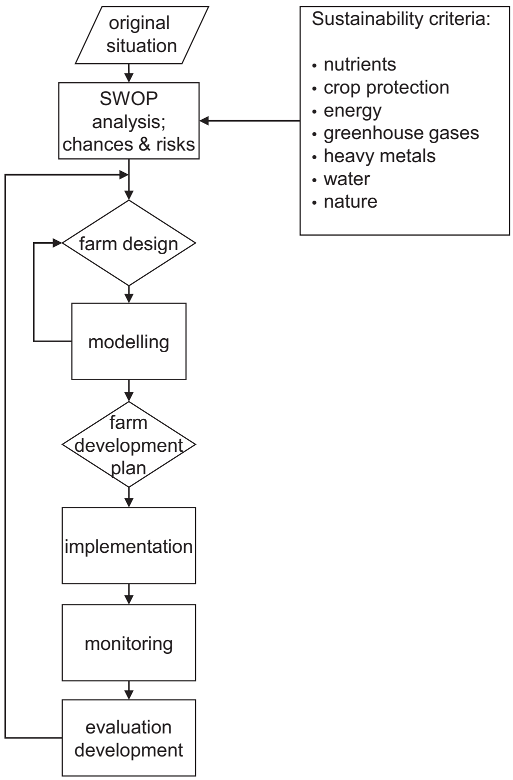

Fig. 2 *Prototyping process in 'Cows & Opportunities'.*

2.3 Targets for nutrient surpluses

The target nutrient surpluses are based on MINAS. In this system, farmers have to monitor all incoming and outgoing N and P with imported and exported products at farm level on an annual basis (Fig. 3). Surpluses of N and P (the difference between input and output) are linked to a target. Target surpluses for 2003, based on acceptable N and P losses to the soil, are shown in Table 2. Levies have to be paid if these targets are exceeded (Henkens & Van Keulen, 2001). The 'Cows & Opportunities' farms have to realize the targets for 2003 by the year 2000/2001.

Table 2 *MINAS target surpluses for nitrogen and phosphate for the year 2003, in kg ha^{-1} (Henkens & Van Keulen, 2001).*

Land use	Target surpluses (kg ha^{-1} per year)
Nitrogen	
Grassland	180
Grassland (dry sandy soil, loess)	140
Arable land	100
Arable land (dry sandy soil, loess)	60
Phosphate (P_2O_5)[1]	
All types of land use	20
Phosphate level insufficient[2]	50

[1] Inorganic phosphate fertilizers included.
[2] Only in 'Cows & Opportunities'.

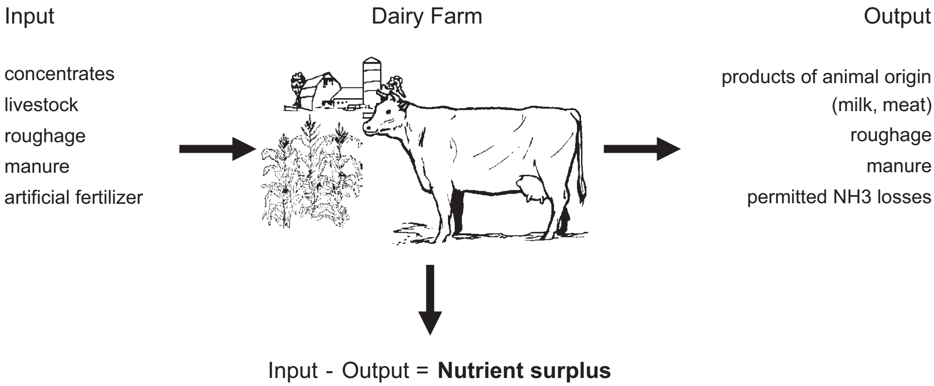

Fig. 3 *Inputs and outputs considered in the MINAS nutrient accounting system, expressed in kg N and kg P_2O_5 per ha per year.*

2.4 Targets for manure disposal

As a consequence of the implementation of the EU Nitrate Directive and the permitted amount of manure on agricultural land (Anonymous, 1991), the Dutch government will introduce a system of manure disposal agreements (Anonymous, 2000; Henkens & Van Keulen, 2001) from 2002 onwards. Farmers need a manure disposal contract if manure production at the farm exceeds the permitted quantity for application of manure on agricultural land. The calculated maximum manure production per farm is shown in Table 3.

Each farm has its specific target for N surplus and its target for maximum permitted manure production. Fig. 7 explains the consequences if targets are not realized. The horizontal axis presents the deviation from the permitted farm-specific N surplus (MINAS target). All farms attempt to realize a value below zero. The deviation from the maximum permitted manure production is presented on the vertical axis. These axes result in 4 quadrants:

1. *Bottom left: no problem*
   The MINAS targets are realized and a manure disposal contract is not necessary.
2. *Top left: (empty) manure disposal contracts*
   Manure production exceeds the permitted N application in manure, but the MINAS targets are realized. So a manure disposal contract is necessary, but no obligation to export manure to other farms.
3. *Bottom right: MINAS targets not realized*
   Manure production is lower than the permitted N application in manure, but the MINAS targets are not realized.
4. *Top right: manure disposal contract and MINAS targets not realized*
   Manure production exceeds the permitted N application in manure and the MINAS targets are not realized. A manure disposal contract is necessary, manure has to be exported to other farms and a fine has to be paid.

Table 3 *Values for the calculation of manure production per farm (Anonymous, 2000).*

	N target kg N per year
N production per animal category	
Cow	107.4
Young stock 1 year and older	73.8
Young stock up to 1 year	36.1
Maximum N application via animal manure from 2003 onwards	
Grassland (per ha)	250
Arable land (per ha)	170

2.5 Data acquisition and analysis

At the start, farmers had to complete a questionnaire for the year 1997/1998 or 1998/1999 (original situation). Most of the data were derived from existing accounting administration. In the course of the project, data collection takes place on a monthly to annual basis. All data, originating from various sources, are entered in a database, as shown in Fig. 4. Farmers themselves collect most data, half of them electronically, half on paper. Industry and services supply other data. Data from the Dutch Herd Book and from milk factories are collected through Electronic Data Interchange (EDI) and automatically stored in the central database. The third group of data is collected by the participating research organizations, which are also responsible for data flow and analysis. The results of the data analyses are also stored in the central database. Efficient data collecting and data processing have been identified as a critical success factor in this project.

Data are analysed for nutrients, economics, fertilization and soil fertility, forage production, animal nutrition and animal health, crop protection, energy, greenhouse gases, heavy metals, water, and nature development. As for nutrients, system balances at farm level are quantified (Oenema et al., 2000). These system balances provide detailed information on inputs, outputs, losses and internal recycling, usually for a number of compartments, e.g. soil, crop, herd, and manure. Depending on the level of detail required, these compartments can be further subdivided into different pools (Jarvis, 1999). A schematic representation of the N cycle is given in Fig. 5.

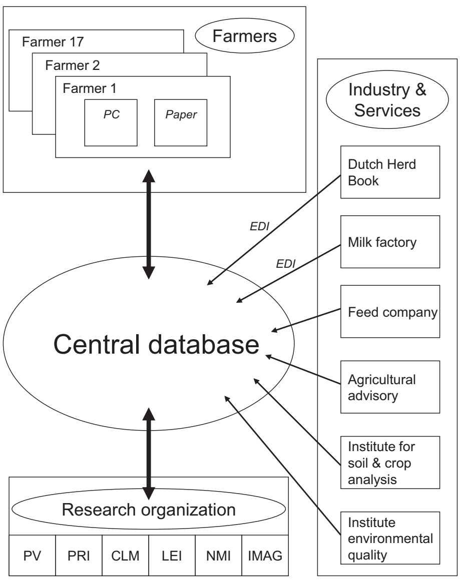

Fig. 4 *Structure of the data bank in the project 'Cows & Opportunities'.*

3 Results

3.1 N balance in original situation

The MINAS nitrogen balance in the original situation (1997/1998) for all farms is shown in Table 4. The farms have been arranged according to increasing level of milk production per ha (intensity). The N balance of 'De Marke' is given for comparison. The N surplus ranged from 47 to 349 kg ha^{-1}. The difference between the surplus in 1997/1998 and the MINAS target 2003 indicates the gap between the original situation and the objective. This difference ranges from 97 kg below to 243 above the target. Five of the 17 participating farms already realized the MINAS target. Four of these five are situated on sandy soil and one on peat soil. None of the 4 farms situated on clay soil realized the final MINAS target. Differences in surplus among farms are mainly related to differences in intensity, soil type, management and farming style.

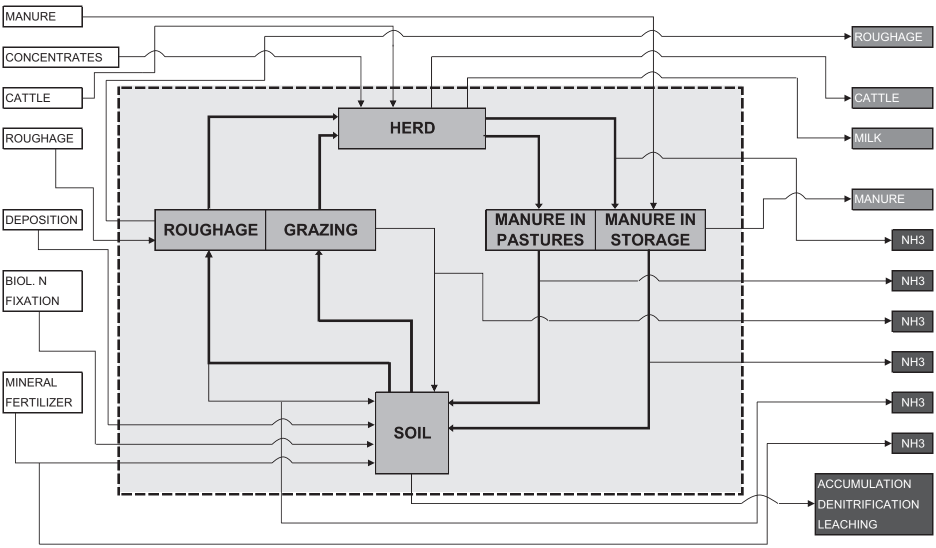

Fig. 5 *N cycle, with left the farm input, right the farm output and in de middle the internal recycling.*

Table 4 *MINAS nitrogen balance of the commercial pilot farms in the original situation (1997/1998).*

	Sikkenga – Bleker	**Kuks**	**Boekel**	**De Vries**	**Miedema**	**Post**	**Bomers**	**Eggink**	**Van Hoven**	**Hoefmans**	**Van Wijk**	**Van Laarhoven**	**Menkveld & Wijnbergen**	**Schepens**	**De Kleijne**	**Pijnenborg -Van Kempen**	**Dekker**	**De Marke**
INPUT																		
Cattle	0	5	0	1	0	0	11	0	0	0	0	0	0	0	0	0	3	0
Manure	0	10	0	4	13	0	0	2	0	27	0	0	10	74	38	48	0	0
Inorganic fertilizers	232	117	197	145	234	222	0	113	228	183	249	224	206	171	109	218	221	63
Concentrates	79	102	102	131	83	83	78	117	122	111	140	103	124	201	172	196	194	73
Imported roughage	0	0	54	12	26	13	78	33	57	7	47	66	9	68	45	47	79	10
Total	*311*	*234*	*352*	*292*	*357*	*317*	*167*	*265*	*407*	*329*	*436*	*393*	*349*	*514*	*363*	*508*	*498*	*146*
OUTPUT																		
Milk	54	55	58	63	65	65	69	76	79	82	84	84	87	93	109	113	120	63
Cattle	9	10	9	18	11	10	15	13	3	13	12	23	16	20	18	17	17	7
Manure	0	0	0	42	0	9	0	16	91	0	0	0	0	0	76	94	93	7
Permitted NH_3 losses	2	27	7	7	24	20	36	43	42	38	29	40	38	52	59	54	50	13
Total	*65*	*93*	*73*	*130*	*99*	*104*	*121*	*148*	*215*	*133*	*125*	*147*	*141*	*165*	*262*	*277*	*281*	*90*
SURPLUS	245	141	279	162	257	214	47	117	192	196	311	246	208	349	101	231	217	56
MINAS target 2003	170	142	174	180	172	135	144	120	117	110	174	128	144	106	115	160	157	132
SURPLUS – target	75	0	104	-18	85	79	-97	-3	75	86	136	118	64	243	-14	71	59	-76

3.1 Farm Development Plans (FDP)

The urgency to take measures varies among farms. Some farms already realized the final MINAS target in the original situation, while others still had to bridge a huge gap (see Fig. 6). With a few exceptions, all measures that were suggested for the participating farms (Table 5) have already been tested on 'De Marke'. However, each measure has a farm-specific interpretation and a specific effect, because of the differences in environmental conditions among farms, especially in soil type. Brief explanations of the important measures to be taken by the farms are as follows:

1 *Acquisition of milk quota and land*
Many farms have invested or intend to invest in milk quota or in land. This will change the milk production per ha in subsequent years. Intensively managed farms invest mostly in land, extensively managed farms mostly in quota.
2 *Ratio grassland/maize*
The optimal ratio for grassland to maize land varies per farm and region. Generally, it is economically attractive for the intensively managed farms on clay soil to purchase silage maize instead of producing it. Conditions for growing silage maize and for grassland on sandy soils in the south and east are different from those on clay and peat soils in the west and north of the Netherlands. It is attractive to grow maize on sandy soils. Participating farmers aim at growing both sufficient energy-rich and sufficient protein-rich fodder.
3 *Fewer cattle*
A lower number of cattle implies less manure and often lower nutrient surpluses. This also holds for young stock. A small number of young stock can be realized when the replacement rate is low and milk production per cow high. A high milk production per cow also allows keeping fewer cattle, though this may affect the feed ration and health of the cows, with possible consequences for the cost-effectiveness of a higher milk production per cow.
4 *Lower fertilizer level*
Lowering the rate of N application will ultimately lead to a reduction in crop yield. Many participants also have to reduce total phosphate application and to omit application of phosphate fertilizer. Its effect on crop yields in the short term is not yet clear. It is expected that crop yields will not or hardly decrease (Habekotté et al., 1999). The adjusted fertilization levels at the participating farms are often lower than the current official recommendations.
5 *Less purchased concentrate feed*
On most farms, the input of nutrients via purchased animal feed is very high. In the original situation it is on average 50% of total N and 75% of total P input. This is much higher than required according to the animal nutrition recommendations. So it is important to adjust nutrition to the recommendations.

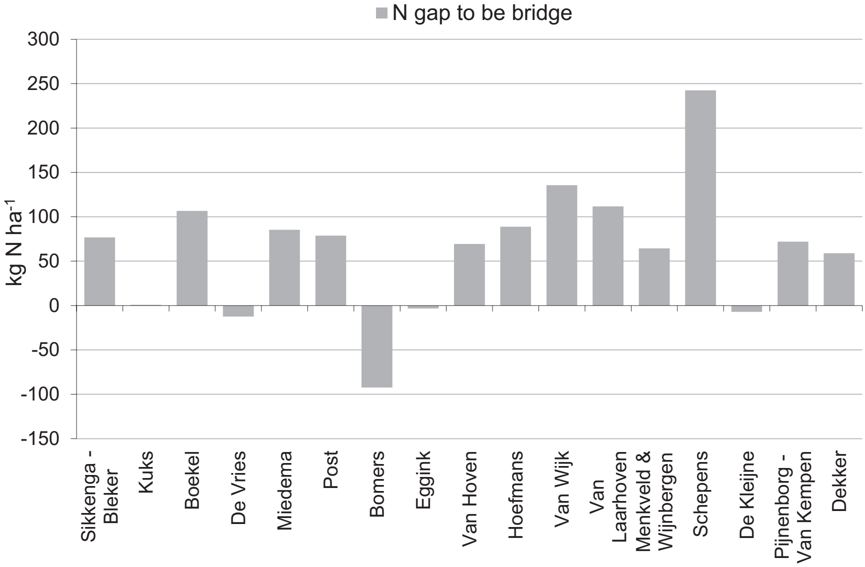

Fig. 6 *N surplus gap to be bridged by the farm development plan.*

Table 5 *List of measures per participant (farms are presented in order of increasing milk production per ha).*

Measure	**Sikkenga - Bleker**	**Kuks**	**Boekel**	**De Vries**	**Miedema**	**Post**	**Bomers**	**Eggink**	**Van Hoven**	**Hoefmans**	**Van Wijk**	**Van Laarhoven**	**Menkveld & Wijnbergen**	**Schepens**	**De Kleijne**	**Pijnenborg-Van Kempen**	**Dekker**
Changing farm lay-out																	
More milk quota	×		×	×		×		×	×	×	×					×	
More land area			×	×		×	×					×	×			×	×
More grassland less maize					×			×									
More maize less grassland	×	×				×			×		×						
(extra) nature conservation and							×					×	×				
Less grazing						×				×		×	×			×	
Sowing grass/clover mixtures	×									×							
Catch crop after maize						×			×	×							
Changing herd																	
More milk per cow					×			×		×			×		×	×	×
Less young stock		×						×		×		×		×		×	×
Farm out raising cattle																	
Changing fertilization																	
Higher improvement manure									×						×		×
Lowering N application	×	×	×		×	×		×	×	×	×	×	×	×	×	×	
Lowering inorg. phosphate appl.	×	×	×		×	×			×	×	×	×	×	×	×	×	×
No farm input manure										×							
No farm output manure													×		×		
Changing feeding regime																	
Feeding recommended mount	×	×	×	×	×	×			×		×		×	×	×	×	×
Less P in concentrates		×									×		×			×	

Table 6 *MINAS nitrogen balance after applying the proposed strategies (model calculations).*

	Boekel	Menkveld & Wijnbergen	Kuks	Eggink	Van Laarhoven	Bomers	Post	Sikkenga-Bleker	Miedema	De Vries	Van Hoven	Van Wijk	Pijnenborg - Van Kempen	Hoefmans	Schepens	Dekker	De Kleijne
INPUT																	
Cattle	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0
Manure	0	0	21	6	0	0	0	0	13	5	0	0	45	0	0	0	0
Inorganic fertilizers	115	125	133	100	104	0	100	96	173	144	188	131	143	108	141	129	89
Concentrates	73	89	75	100	93	81	114	89	57	97	99	117	134	148	98	146	113
Imported roughage	39	1	2	2	4	23	2	42	72	42	29	117	31	40	87	109	94
Total	*227*	*215*	*232*	*207*	*201*	*112*	*216*	*228*	*316*	*288*	*316*	*365*	*353*	*296*	*326*	*384*	*295*
OUTPUT																	
Milk	60	64	64	64	65	65	69	72	79	79	82	94	102	105	106	110	113
Cattle	9	7	8	10	9	11	9	10	13	8	15	16	12	13	13	13	18
Manure	0	0	0	0	0	0	4	0	0	35	84	0	68	0	0	19	12
Roughage	3	24	19	27	15	0	4	0	0	16	0	0	0	0	0	0	0
Permitted NH_3 losses	2	4	18	16	9	31	21	11	30	5	34	30	45	39	46	44	59
Total	*74*	*99*	*108*	*118*	*98*	*106*	*107*	*93*	*122*	*143*	*215*	*141*	*226*	*157*	*166*	*185*	*201*
SURPLUS	154	116	124	89	102	6	108	135	194	145	100	224	127	139	161	199	94
MINAS target 2003	175	148	153	138	136	173	134	171	165	180	129	180	150	122	109	158	115
SURPLUS - target	-21	-32	-29	-48	-33	-167	-26	-36	29	-35	-29	44	-23	17	52	41	-21

The selection of measures depends on farm-specific conditions, professional skills and entrepreneurship. For example, farmer Van Wijk will be able to realize the environmental targets with a high level of concentrate use. He manages his farm intensively and aims at a high milk production per cow. High input of concentrates instead of purchased roughage saves costs of, for example, roughage storage. This also allows realization of a more balanced feed ration over the whole lactation period. Van Wijk's feed supplier has developed a new concentrate feed with a low protein content to reduce the input of N. In contrast, farmer Miedema has adopted zero grazing to realize a higher grass production. Farmers Dekker and Schepens are using 'waste products' as purchased concentrates to reduce feed costs. On the farm of Sikkenga - Bleker (clay soil), grass-clover swards have been introduced to reduce the input of N fertilizer, even though this measure may not reduce total N input.

3.3 Model-predicted N balances: the prognosis

A prognosis of the results - e.g. the MINAS nitrogen balance - after applying the proposed strategies, was formulated for each individual farm (Table 6). The N surplus ranged from 6 to 224 kg ha^{-1}. After applying the proposed strategies, 5 farms do not yet realize the final MINAS targets. They are the most intensively managed farms, three situated on clay soil and two on dry sandy soil. Miedema and Van Wijk's farms do take many measures, but the effects of these measures are partly offset by the purchase - for economic reasons - of milk quota and the associated intensification. Miedema might realize the MINAS target by renting some additional land. In the short run, Dekker might realize the target by exporting more animal manure.

Fig. 7 displays the position of the farms with respect to the N surplus target and the target for the permitted manure production. Also the (actual) position of 'De Marke' and the position of the average Dutch dairy farmer (Reijneveld et al., 2000) are presented. Evidently, on a number of farms manure production per ha exceeds the standard for 2003. In other words, about half of the farms need a manure disposal contract. Of these farms, five also do not realize the N target. Dekker and Miedema exceed the N target by about an equal rate, but Dekker manages his farm more intensively. The physical conditions at Dekker's farm (well-drained clay soil) are better than at Miedema's farm (poorly drained clay over peat). Possible additional measures for these five farms are: (*i*) reducing chemical fertilizer, through better utilization of animal manure, (*ii*) reducing purchase of protein-rich concentrates, and (*iii*) purchasing or renting of more land, though this is very expensive. Another possible solution is to import more animal feed, instead of chemical fertilizer, but ultimately this option is not sustainable because of the externalization of the environmental costs associated with producing animal feed on other farms.

Results for the farms of De Kleijne and Pijnenburg-Van Kempen show that the N surplus target can also be realized on farms with highly intensive farm management without or with little manure output.

3.4 Nitrogen balance in 1999

Table 7 shows the average MINAS balance of the farms in 1999 compared with the original situation and as calculated (prognosis). The N surplus of the farms decreased from 207 kg per ha in the original situation (1997/1998) to 163 kg in 1999. The prognosis indicated that the average N surplus should have gone down to 138 kg ha^{-1}. In the original situation, the N surplus exceeded the MINAS target by 62 kg ha^{-1}, whereas in 1999 it was exceeded by an average of 38 kg ha^{-1}. The reduction in fertilizer input (from 180 to 150 kg N ha^{-1}) contributed most to the decrease in N surplus. Both, the purchase and the export of animal manure and organic soil amendments also decreased. Input decreased from 13 to 10 kg N ha^{-1}, while output decreased from 25 to 12 kg N ha^{-1}. This points to an attempt to improve utilization of farm-produced animal manure.

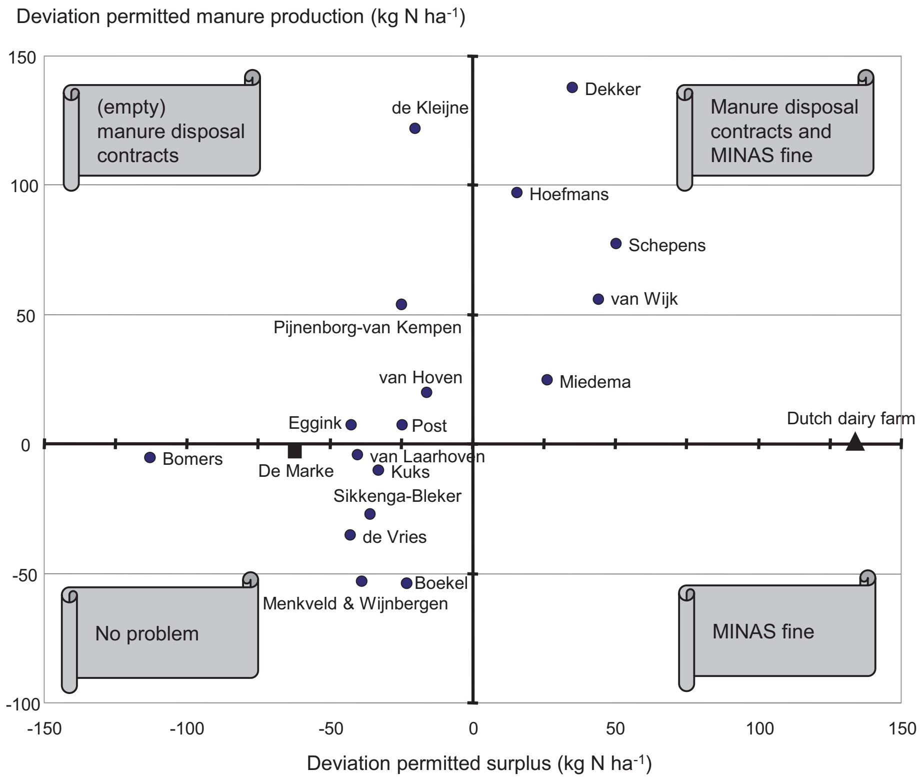

Fig. 7 *Expected deviation of the farms compared with the permitted manure production and compared with the permitted N surplus, after applying the strategy (kg N ha^{-1}).*

Table 7 *Average MINAS nitrogen balance of the commercial pilot farms in the original situation (1997/1998), in 1999, the calculated N balance in the prognosis, and the difference between 1999 and the prognosis (kg N ha^{-1}).*

	1997/1998	Range	1999	Range	Prognosis	Range	
	A		B		C		B - C
INPUT							
cattle	1	(0-11)	1	(0-9)	0	(0-8)	1
manure	13	(0-74	10	(0-29)	5	(0-45)	4
inorganic fertilizers	180	(0-249	150	(0-252)	119	(0-188)	23
concentrates	126	(78-201)	122	(69-186)	101	(57-148)	19
imported roughage	38	(0-79)	37	(7-127)	43	(1-117)	-8
Total	*358*	*(167-514)*	*319*	*(119-553)*	*269*	*(112-384)*	*40*
OUTPUT							
milk	80	(54-120)	82	(52-115)	82	(60-113)	-1
cattle	14	(3-23)	12	(6-23)	11	(7-18)	1
manure	25	(0-94)	12	(0-74)	13	(0-84)	-2
roughage	0	(0-0)	1	(0-9)	6	(0-27)	-6
permitted NH_3 losses	33	(2-59)	31	(0-54)	26	(2-59)	6
Total	*152*	*(65-281)*	*138*	*(59-255)*	*139*	*(74-226)*	*-3*
SURPLUS	207	(47-349)	181	(8-305)	131	(6-224)	25
MINAS target 2003	144	(106-180)	144	(106-180)	149	(109-180)	-12
SURPLUS - target	62	(-97-243)	38	(-136-174)	-19	(-167-52)	37

4 Discussion and conclusions

The combination of system modelling and system prototyping is an attractive method for developing strongly improved dairy farming systems (Aarts, 2000; Van Keulen et al., 2000). Results of 'De Marke' indicate that such prototypes can indeed be realized on experimental dairy farms. Prototypes of sustainable dairy farming systems have also been designed, for example, in Germany and the United Kingdom (e.g. Weisbach & Ernst, 1994; Peel et al., 1997), and for arable farming in the Netherlands (e.g. Vereijken, 1992). It is attractive also because it allows active participation of farmers and other stakeholders in the whole process from analysis to monitoring and evaluation (e.g. Fig. 2).

'Cows & Opportunities' is the practice-oriented follow-up of experimental dairy farm 'De Marke' that involves close co-operation of enterprising and future-oriented dairy farmers, researchers and other stakeholders to develop and demonstrate strategies for sustainable dairy farming. Ultimately, the project will demonstrate whether commercial dairy farmers can realize the various prototypes in practice. At the same time, it also will prove whether the current recommendations, for instance for animal nutrition, and for fertilizer and manure application, are suitable for realizing the environmental targets. 'Cows & Opportunities' should also demonstrate whether the improved dairy farming systems are economically viable. So far, results of the project demonstrate that it is possible to realize the target N surplus for the year 2003, even on intensively managed dairy farms. Results also indicate that the targets cannot be easily realized on all farms. However, various opportunities exist for these farms to further improve management and reduce nutrient surpluses.

The gap in N surplus between what is possible and what is realized in dairy farming in practice is large. At the start of 'Cows & Opportunities', the mean N surplus (MINAS) of the farms was 207 kg ha^{-1} (Table 4), which is much lower than the 304 kg ha^{-1} averaged for all Dutch dairy farms in the same period (Reijneveld et al., 2000). Both values are much higher than the N surplus (MINAS) of 90 kg ha^{-1} on 'De Marke' (Hilhorst & Oenema, unpublished data). Many dairy farmers fear that reducing the N and P surpluses to the levels required for the year 2003 (target surpluses) will be expensive, for example, because of lower forage production when reducing fertilizer application. For similar reasons farmers often buy more protein-rich animal feed than is needed for economically attractive milk production. Measures introduced on experimental dairy farm 'De Marke' to realize the environmental quality, increase the costs by almost Dfl[1]. 6 per 100 kg milk (De Haan, 2001). Moreover, farmers are worried about the impact of lower nutrient surpluses on soil fertility.

[1] Dfl. 100 = € 45.38

Farmers participating in ‘Cows & Opportunities’ share their experiences with each other and with other farmers. So these farmers closely co-operate with farmers of the project ‘Farmers Data II’, with 180 participants. Also study groups were formed around ‘Cows & Opportunities’, to ensure that participants of ‘Farmers Data II’ receive first-hand information. Farmer-to-farmer communication is the best way to transfer knowledge from research to practice. Moreover, publishing results in agricultural magazines and organizing excursions are used to contact other dairy farmers.

In conclusion, the project ‘Cows and Opportunities’ forms a unique link in the chain of information and knowledge transfer from theoretical and experimental research to commercial dairy farms. Representative dairy farms have been selected with enterprising and future-oriented farmers who are able to quickly adopt measures. As a result, these farms will also demonstrate the practical feasibility of prototype dairy farming systems developed by research. Results of monitoring in the coming years will indicate whether this promise holds, and whether the pilot farms serve indeed as examples for other commercial dairy farms.

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CHAPTER 3

PARTICIPATORY FARM MANAGEMENT ADAPTATIONS TO REDUCE ENVIRONMENTAL IMPACT ON COMMERCIAL PILOT DAIRY FARMS IN THE NETHERLANDS

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ABSTRACT

Regulations in the Netherlands with respect to nutrient use force dairy farmers to improve nutrient management at the whole-farm level. On experimental farm 'De Marke', a coherent set of simple measures at farm level has been implemented, which has resulted in a drastic reduction in input of nutrients without affecting production intensity (milk production; kg milk per ha). To promote adoption of these measures in commercial dairy farming, the project 'Cows & Opportunities' was initiated in which 16 commercial pilot farms participated. Data were collected over a 6-year period (1998-2003). This paper describes and analyses the different farm management strategies adopted on these farms, using two classifications of the farms at the start of the project (the base situation), one based on nitrogen (N) surplus (kg ha^{-1}), the other on production intensity. In both classifications, the farms were split in two equal groups. Changes over time in farm characteristics (farm development) were described through linear regression for each group and the variance among farms within a group was used to test for differences between groups. Under the influence of economic driving forces, the pilot farms, on average, expanded land area and increased their milk quota. However, the most intensive farms could comply with regulations only by reducing production intensity. From 1998 to 2002, average nutrient surpluses on the pilot farms decreased by 33% for N and 53% for phosphorus (P). Important measures were reducing the use of inorganic fertilizer, optimizing the use of home-produced organic manure, reducing grazing time, reducing the number of replacement stock and lowering crude protein content in the ration. Over the years, variation in N surpluses among farms (inter-farm variation) remained almost constant. Differences in farm management strategy could not unequivocally be related to farm typology (high/low N surplus; high/low production intensity). It was concluded that decisions by individual farmers on farm development are not always based on 'rational' arguments, but are co-determined by 'emotional' perceptions.

1 Introduction

Agriculture has been identified as a major contributor to nutrient losses to the environment (Cartwright et al., 1991; De Walle & Sevenster, 1998; Novotny, 1999; Pretty et al., 2003), especially from livestock manure. To identify attractive options for reducing nutrient losses, whole-farming system research is needed (Jarvis et al., 1996), as management interventions in one nutrient flow may affect flows elsewhere in the system (*'ceteris non-paribus'*). This holds especially for mixed farming systems, such as intensively managed dairy farming systems in Western Europe. The major constraints on long-term sustainability of these systems are economic profitability and environmental sustainability, resulting from societal demands. Cornelissen (2003) identified these 'two faces of sustainability', based on Koestler's metaphor of the Janus-faced Holon, as a common ground for sustainable development.

Pressure is increasing on the dairy industry in Western Europe, exposed to a globalizing market, in which the developments in the price of milk are insufficient to keep pace with the increasing costs of production, associated with rising energy costs. To maintain income, farmers respond by increasing milk quota and to some extent also land area, however with the net result of intensification, i.e., a higher milk production per ha and per man-hour, to reduce land and labour costs per unit milk production. In the Netherlands, the average price of agricultural land is 40 k€/ha. Evidently, such high land prices force farmers to intensify farming practices. This process of intensification is accompanied by increasing milk production per cow and off-farm rearing of young stock to specialize in milking cows.

In the Netherlands, legislation to reduce losses of nutrients from manure has been implemented since 1984. In 1998, the MINeral Accounting System (MINAS) as a balance approach was introduced as the central instrument for restricting emission of nutrients to the environment[1] (Henkens & Van Keulen, 2001). To comply with the tightening environmental standards, farmers adapted management through reducing fertilization, restricting grazing time, exporting manure, covering slurry storage, applying slurry through injection into the soil, reducing young stock and restricting feed protein content. To explore possible options for dairy farming systems on leaching-sensitive sandy soils, to increase nutrient use efficiency and reduce nutrient losses, the method of prototyping, a combination of system modelling and system implementation, was applied on the experimental farm 'De Marke' (Aarts et al., 1992). Performance of the 'De Marke' system has shown that by implementing a coherent set of simple measures at farm level, nutrient inputs to

1 In 2003, the European Court of Justice rejected the use of MINAS as an instrument to comply with the EU Nitrate Directive (cf. Anonymous, 1991). In response to this court order, in 2004, the Netherlands introduced permitted N rates (so-called 'application standards') for all crops (Schröder & Neeteson, 2008). The data in this paper cover the period 1998-2003, i.e. before the change in regulations.

the farm can be drastically reduced without affecting production intensity (kg milk per ha) (Aarts, 2000; Hilhorst et al., 2001). To promote adoption of this approach in commercial dairy farming, the project 'Cows & Opportunities' was initiated in 1999. The project builds on experiences at 'De Marke' and can be considered an extension of the prototyping method. It is characterized by agreements with the farmers on measurable targets and intensive coaching with frequent interaction between researchers and farmers (Oenema et al., 2001).

The commercial pilot farms accepted the commitment to aim for immediate compliance with national environmental standards (permitted nitrogen (N) and phosphorus (P) surpluses per ha land area) that, according to legislation, is compulsory for other commercial farmers in 3 to 5 years. Maximum permitted nutrient surpluses are farm-specific, depending on soil type, hydrology, cropping pattern and production intensity. Pilot farmers were supported during a 6-year period (1998-2003) in identifying the farming system that best matched their specific conditions and their aspirations. The objective of this paper is to describe and analyse adaptations in farm management on the pilot farms, as governed by farmers' aspirations and societal demands. We want to illustrate that the implemented measures to comply with regulations depend on production intensity and N surplus at the start of the project, taking into account the farmers' aspirations (e.g. farm income, herd or crop management). Moreover, we want to show that intensive coaching and frequent interaction between researchers and farmers on commercial pilot farms results in a higher adoption rate of modified management, resulting in promising future dairy farming systems.

2 Materials and methods

2.1 Research methodology

The most important target of the pilot farms was reducing the nutrient surpluses in a cost-effective way. An intensive annual 'analysis-modelling-planning-implementation-monitoring-analysis' cycle was followed, involving active participation of farmers, researchers and extension officers. At the start, each farm was analysed in detail to quantify the gap between its current situation and the targets, as a basis for identification of measures to bridge that gap (Oenema et al., 2001). The expected economic and environmental effects of these measures were simulated with the whole-farm dairy model DairyWise (Schils et al., 2007). Based on these analyses, farm-specific plans were designed and discussed with the various stakeholders, i.e. farmers, researchers, and extension agents involved, and the farm strategy (combination of measures) that resulted in the most complete realization of the project objectives and best matched the farmers' aspirations, was implemented.

For comparison of the representativeness of the pilot farms, a 'national average' was calculated, based on specialized dairy farms (land area > 15 ha, at least 80% grassland and fodder crops, > 30 milking cows; n=217), derived from the Dutch Farm Accountancy Data Network (FADN) (Aarts et al., 2008).

2.2 Data collection and monitoring

Data from 16 specialized pilot dairy farms were collected over a 6-year period (1998-2003). For details on farm selection and farm characteristics see Oenema et al. (2001). At the start of the project, data for the year 1998, representing the original situation, were derived from farm records and interviews with the farmers. In the course of the project, frequency of collection of the different data varied from monthly to annually. Farmers recorded most basic data, either electronically or on paper. From these primary data, internal and external nutrient flows were calculated. The calculation methods and the sources are summarized in Table 1. Mass flows entering (import) and leaving (export) the farm were derived from farm accounts. Nutrient flows in imported and exported animals were estimated from the number of animals per category (cow, calf and heifer), assuming category-specific nutrient contents (Tamminga et al., 2000). The nutrient composition of imported feeds (concentrates, roughage) was obtained from feed analysis reports and suppliers. N output in milk was quantified by frequent monitoring protein contents (mg l^{-1}) and milk production (l) by the milk processor. Field-level data on inorganic fertilizer and organic manure management, crop yields and grazing regimes were recorded daily in a computerized fertilizer recommendation programme. Dry matter yields were estimated by the farmer for each cut (mowing/grazing), using tools like a tempex disc (Keuning, 1988). A well-mixed sample was taken from the slurry pits 2 to 4 times per year and a sample from each silage heap, in which nutrient contents were determined according to standardized laboratory methods. Diet compositions were derived by monitoring the feed supply through weighing each feed lot during one week each month. During the monitoring weeks, the different feed components were sampled and analysed for nutrient contents.

Weather conditions were more or less similar for all years, except for the year 2003, when a long dry period in summer caused lower yields, especially for grassland.

Table 1 *Classification, source and calculation method (see text for more explanation) of nutrient flows in a dairy farm system (I = input; O = output; S = surplus), for the whole farm and the components herd and soil. S is defined as the (positive) difference between inputs and outputs of a (sub-)system.*

Nutrient flow	Farm balance	Component balance		Source and calculation method
		Herd	Soil	
Imported animals	I	I		Farm accounts + N content per animal category (Tamminga et al., 2000)
Imported concentrates	I	I		Farm accounts
Imported roughage	I	I		Farm accounts
Imported fertilizer	I		I	Farm accounts
Imported manure	I		I	Farm accounts
Biological N fixation	I		I	Estimated % clover in grassland × total yield (ton dry matter) × 45 (Biewinga et al., 1992)
Atmospheric deposition	I		I	Literature, region-specific (Heij & Schneider, 1995)
Intake from crops on farm		I		Gross production of crops on farm - field, conservation and feeding losses ± changes in stock
Intake during grazing		I		Balance entry of the herd balance
Net field, grazing, conservation and feeding losses			I	6% for harvesting; 10% conservation and feeding (only N); 10-20% grazing, depending on regime (restricted, unrestricted) (Anonymous, 1997)
Manure to soil [a]			I	Applied organic manure [b] + excreta during grazing [c]
Gross production of crops on farm			O	Harvested crop [b] + field and conservation losses
Gross grass production during grazing			O	Intake during grazing + grazing losses
Exported animals & milk	O	O		Farm accounts
Exported roughage	O			Farm accounts
Exported manure	O			Farm accounts
Gross production of manure		S		Manure to soil + ammonia losses from stable, storage, grazing and spreading + exported manure-imported manure + changes in stock
NH_3 losses stable & storage	S			Farm-specific model calculation (Smits et al., 2000)
NH_3 losses grazing & spreading	S			Farm-specific model calculation (Smits et al., 2000)
Accumulation of nutrients in the soil	S		S	Not determined, part of 'surplus'
Denitrification	S		S	Not determined, part of 'surplus'
Leaching and run-off	S		S	Annually measured on each farm (Oenema et al., 2010), in this study part of 'surplus'

[a] Excluding ammonia losses from stable, storage, grazing and spreading.
[b] Field registration + representative samples (see text for explanation).
[c] Derived from the manure production in stable and the length of the grazing season: hours grazing/total hours × manure in stable (including ammonia losses in stable and during storage).

2.3 Data analysis

For analysis of the dairy farming system, four major components were distinguished, i.e., herd, manure, soil and crop (Aarts, 2000; Van Keulen et al., 2000; Schröder et al., 2003). Nutrients cycle through these components, i.e., output from one component is input into another, but losses are incurred in these transfers. The nutrient balance of a component, i.e., the difference between inputs and outputs, characterizes the (in)efficiency in management of a particular nutrient in a particular part of the farm, revealing the weakest and strongest parts of the farming system. The specific type of nutrient balance selected depends on the purpose of the analysis (e.g., Schröder et al.,2003; Watson & Atkinson, 1999; Goodlass et al., 2003; Van Beek et al., 2003). We distinguished two levels in the nutrient balances: whole farm level and component level (Fig. 1). Nutrient balances at farm level (farm balance) were based on nutrients in all products that enter and leave the farm (inputs and outputs; Table 1). Within the farm, four component balances were distinguished, also taking into account the internal flows, and thus providing more specific information for locating the nutrient losses within each specific dairy farming system. A surplus, i.e., a positive difference between inputs and outputs, corrected for changes in stock, indicates nutrient losses:

$$\text{Surplus} = \text{maximum}\ (0, \text{Input} - \text{Output} + \text{Changes in stock}) \qquad (1)$$

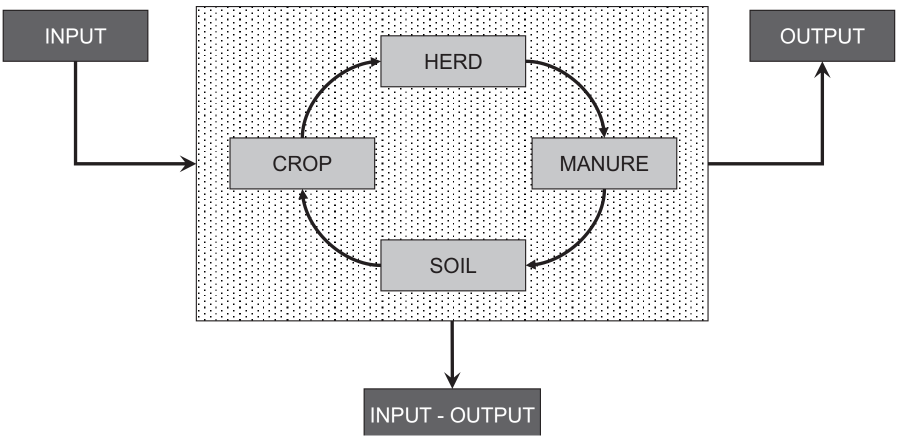

Fig. 1 *Main nutrient flows on a dairy farm.*

In order to identify whether and if so, where exactly in the system losses can be reduced, the efficiency of the whole system and the efficiencies of the underlying components must be assessed, for which nutrient use efficiency (NutUE) is used, defined as the ratio output/input (O/I).

In this paper we focus on the farm balance and on the balances for the two most important components (herd and soil) of a dairy farm (Fig. 1; Table 1). Soil balance in this study is defined as the difference in nutrient flows entering and leaving through the soil surface. Crop and manure balances can be used to identify field (grazing and harvesting), conservation and feeding losses and losses of ammonia (stable, storage, grazing and spreading), respectively, but these are not being treated in this paper. First, these balances do not provide additional information in analysing the farming systems, and second, in calculating these balances, assumptions would have to be made for the magnitude of losses that were not monitored.

The most important nutrient flows for the farm as a whole were analysed in an analysis of variance with farms and years as treatment factors. Whether differences among farms could be explained by soil type was tested using the REML algorithm (method of residual maximum likelihood) (Genstat 8 Committee, 2005).

Strategies to reduce nutrient losses are farm-specific, depending on technical and financial conditions and on the farmer's aspirations. Implementation of strategies leads to changes in various farm characteristics; the combined effect of these changes on the farming system is referred to as farm development. The dynamics of a number of these characteristics have been analysed. To analyse differences in farm development, two classifications were applied to the 16 commercial pilot farms, one on the basis of the magnitude of N surplus (kg ha^{-1}) in the original situation, the other on the basis of production intensity (kg milk per ha) in the original situation. In both classifications, the farms were split in two equal groups ('low' and 'high'; n=8).

We assumed that development of farm characteristics (C) (see next section) can be described by linear relations that might be different for the two groups. Hence, a linear regression was performed and the variance among farms within a group was used to test for differences between groups. The regression model used was:

$$C_i = \beta_0 + \beta_1 \times y + \beta_2 \times group_i + \beta_3 \times y \times group_i \quad (2)$$

where i = 1, 2 for group 'low' and 'high', respectively, $group_1 = 0$, $group_2 = 1$. y is the number of years since implementation of the strategies, and β_0, β_1, β_2 and β_3 are the parameters to be estimated. β_0 represents the starting value for group 1 (1998), β_1 the 'development rate' per year of group 1, β_2 the difference in intercept between the two groups and β_3 the difference in development rate between the two groups.

3 Results

3.1 Farm characteristics of the commercial pilot farms at the start

To characterize the commercial pilot farms at the start of the project (1998), four groups of characteristics were selected, describing the main aspects of the dairy farming system: farm size, overall N management, herd and feed management and crop management, including inorganic fertilizer regime (Table 2). Farm size was characterized by milk quota (kg) and land area (ha). Average milk quota (kg) of the pilot farms was similar to the 'national average' in 1998, but average land area was smaller. Production intensity of the pilot farms was on average higher (by around 1800 kg milk per ha) than the 'national average'. N surplus (kg ha^{-1}) on the pilot farms was lower than the 'national average', whereas Nitrogen Use Efficiency (NUE) at farm level was higher. Average milk production per cow on the pilot farms was higher than the 'national average', but with substantial variation. 'National average' inorganic fertilizer doses were higher than those on the pilot farms. Most striking was the difference in allocation of organic manure to crops: on 'national average' much more was used on maize land than on grassland, in contrast to what was the case on the pilot farms.

Table 2 *Farm characteristics of commercial pilot farms (including standard deviation (sd)) and the 'national average' farm (see text for explanation) in 1998, at the start of the project 'Cows & Opportunities'.*

	'national average'	'Cows & Opportunities'	
		Average	sd
Farm size			
Quota (kg milk)	574,006	570,339	136,213
Farm area (ha)	44	40	12
Production intensity (kg milk per ha)	13,046	14,901	3,883
Overall nitrogen management			
N surplus farm (kg ha^{-1})	381	272	63
NUE-farm (%)	17	26	5
NUE-herd (%)	19	22	3
NUE-soil (%)	51	74	11
Herd & feed management			
Number of cows	76	74	20
Number of young stock (per 10 cows)	8.3	8.0	2.1
Milk per cow (kg yr^{-1})	7,580	8,098	985
Fat content milk (%)	n.a[a]	4.37	0.18
Protein content milk (%)	n.a.	3.48	0.08
Urea content milk (mg per kg milk)	n.a.	23	4.7
Grazing time cows (hours)[b]	2,458	1,768	691
Concentrates (kg per 100 kg FPCM)[c]	28	25	4
Crude protein in winter ration (%)	n.a.	15.8	0.9
Crude protein in summer ration (%)	n.a.	18.1	1.8
Crop & fertilizer management			
Grassland area (%)	84	75	15
N fertilization grassland			
- Inorganic fertilizer (kg ha^{-1})	283	221	74
- Organic manure (kg ha^{-1})	196	221	60
N fertilization maize land			
- Inorganic fertilizer (kg ha^{-1})	55	50	52
- Organic manure (kg ha^{-1})	279	178	100
P fertilization grassland			
- Inorganic fertilizer (kg ha^{-1})	14	12	14
- Organic manure (kg ha^{-1})	31	33	9
P fertilization maize land			
- Inorganic fertilizer (kg ha^{-1})	15	14	15
- Organic manure (kg ha^{-1})	42	26	14

[a] Not available.

[b] Number of grazing days × hours per day.

[c] Fat-and-protein corrected milk.

3.2 Nutrient flows

Nutrient surpluses were not significantly different among soil types (data not shown), although N surpluses for the farms on clay were on average high compared with those for the farms on sand, peat and loess.

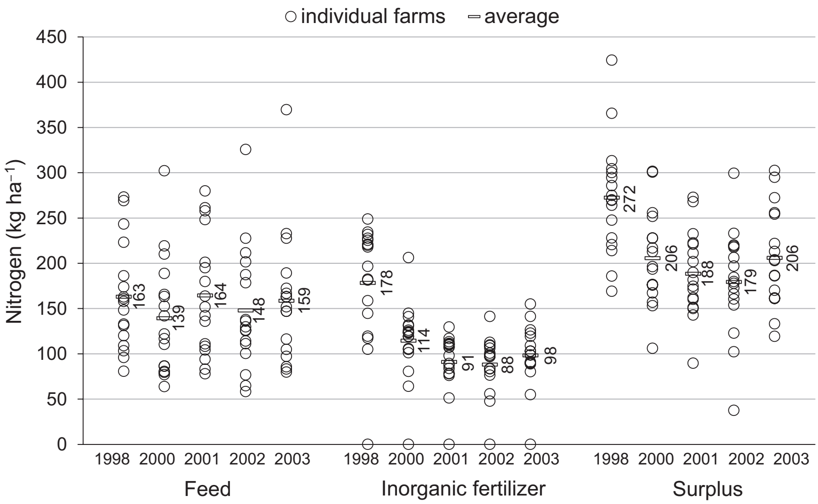

Fig. 2 *Imported nitrogen in feed and inorganic fertilizer, and farm surplus for the commercial pilot farms in 1998 (original situation), 2000, 2001, 2002 and 2003.*

Average N surplus of the farms (Fig. 2) decreased significantly (P<0.001) between 1998 and 2002, i.e., from 272 to 179 kg ha^{-1}, followed, in 2003, by an increase to 206 kg ha^{-1}. N surplus in any given year varies strongly among farms (e.g. in 1998 from 169 to 424 kg ha^{-1}), as a result of differences in management and management skills, and spatial variability. Inter-annual variability in N surplus for individual farms was also very high (largest difference between 217 and 424 kg ha^{-1}), due to differences in management and weather conditions from year to year. Inorganic fertilizer input significantly declined over time (from 178 to 98 kg ha^{-1} on average). The correlation between N surplus and inorganic fertilizer input was high (r^2=0.76), indicating that the decrease in inorganic fertilizer input contributed most to the reduction in N surplus. On the other hand, feed input was also strongly correlated with N surplus (r^2=0.61). In all years, the highest feed input was recorded on the farm with the highest production intensity (milk production between 20,000 and 25,000 kg ha^{-1}). Export of animal manure decreased (from 23 to 15 kg N ha^{-1}; data not shown), suggesting that farmers increasingly used farm-produced animal manure to reduce the cost of expensive inorganic fertilizer.

Average P surplus of the farms significantly decreased ($P<0.005$) from 19 kg ha^{-1} in 1998 to 8 kg ha^{-1} in 2000, after which it stabilized until 2002. Similarly to N, P surplus in 2003 increased to 12 kg ha^{-1}. Comparable with N, the major contribution to the reduction in surplus came from a decrease in inorganic fertilizer input: P surplus and inorganic-P fertilizer dose were more closely correlated than P surplus and feed input (r^2=0.74 and 0.36, respectively). On most farms, less than 10 kg ha^{-1} inorganic-P fertilizer was applied, but on individual farms the dose exceeded 20 kg ha^{-1}, from 2000 onwards on a single farm, located on strongly P-fixing clay soil.

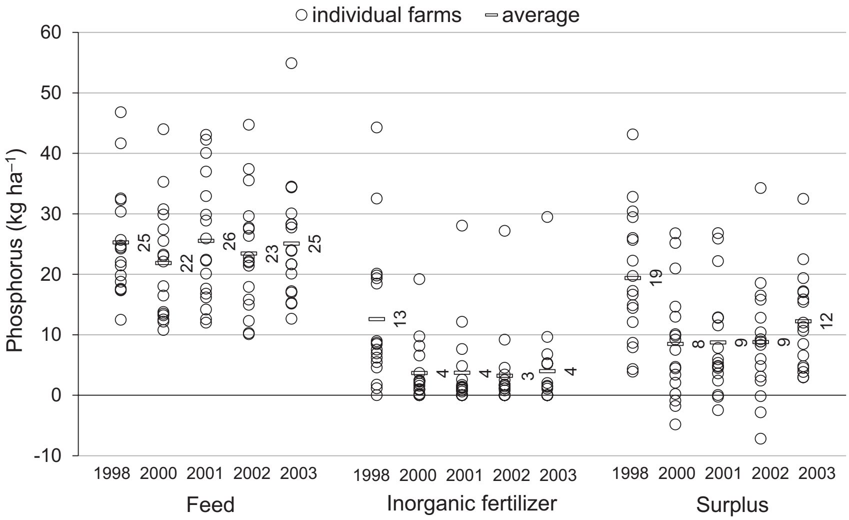

Fig. 3 *Imported phosphorus in feed and inorganic fertilizer, and farm surplus for the commercial pilot farms in 1998 (original situation), 2000, 2001, 2002 and 2003.*

No statistically significant difference was found among years in average N input into the herd in feed (concentrates, roughage and grass) (Fig. 4). The variation in annual N input among farms was very high (e.g. from 291 to 586 kg ha^{-1} in 1998), whereas inter-annual variation for individual farms was less (largest difference from 294 to 511 kg ha^{-1}). P input remained constant at around 60 kg ha^{-1}, but with a very high variation among farms within any year. Variation in nutrient output in milk and animals was much smaller than in input, and output remained constant between 1998 and 2003.

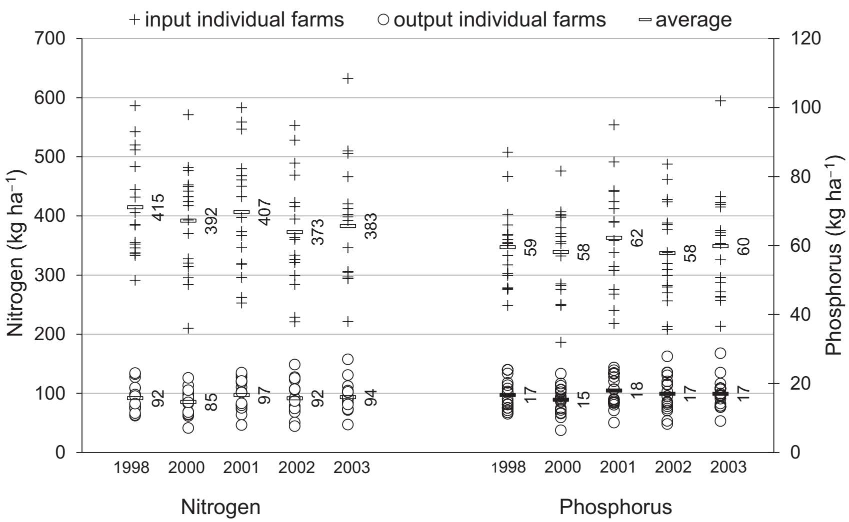

Fig. 4 *Nitrogen and phosphorus inputs and outputs of the herd for the commercial pilot farms in 1998 (original situation), 2000, 2001, 2002 and 2003.*

Average total nutrient input into the soil (Fig. 5) significantly decreased between 1998 and 2003: for N from 510 to 410 kg ha^{-1} (P<0.005) and for P from 54 to 44 kg ha^{-1} (P<0.01). In particular, inputs in inorganic fertilizer (Figs. 2 and 3) and in organic manure during grazing decreased; the latter as a result of reduced grazing time (see next section). Total crop nutrients (i.e. nutrient content before harvesting or grazing; output from the soil balance) also decreased significantly (P<0.05). Compared with the 309 kg N ha^{-1} in 1998, total crop-N in 2003 was 20% lower (250 kg ha^{-1}), mainly because of the dry summer. In 2002, N yields were 14% higher than in 2003, at the same input level. Total crop-P decreased by 11% from 1998 to 2003, but in intermediate years output was higher.

In 2003, nutrient yield on one farm, especially for N, was exceptionally high. Most likely, for this farm on peat soil, the above-average temperatures in that year have resulted in high mineralization rates and thus high soil-N availability.

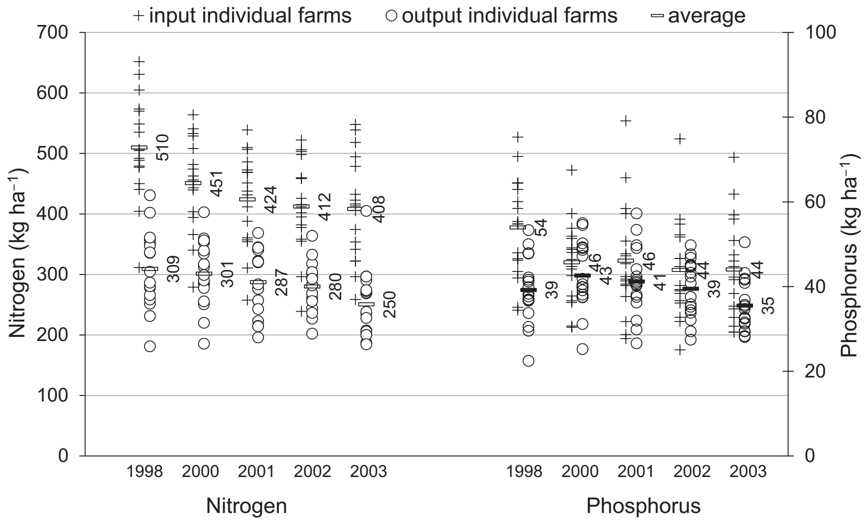

Fig. 5 *Nitrogen and phosphorus inputs and outputs of the soil for the commercial pilot farms in 1998 (original situation), 2000, 2001, 2002 and 2003.*

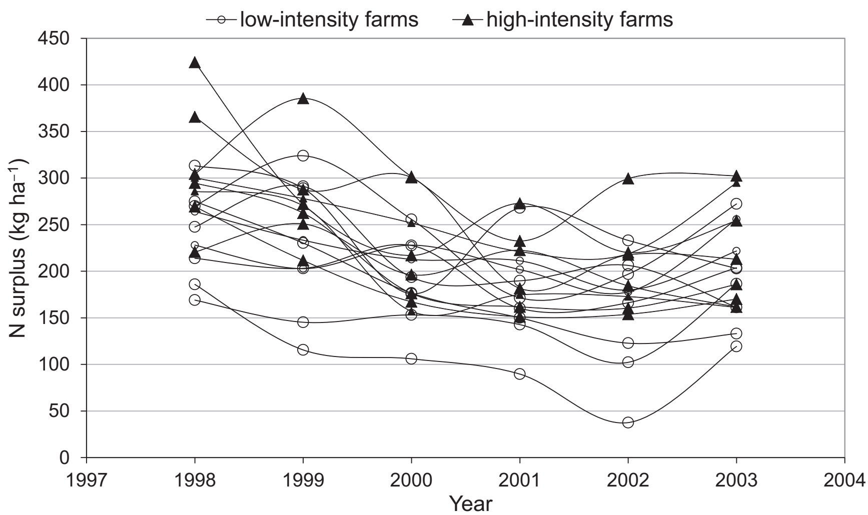

Fig. 6 *Changes over the period 1997-2004 in N surplus on commercial pilot farms. Each graph represents an individual farm. Farms classified on the basis of their intensity in 1998.*

3.3. Farm development

Development of N surplus (kg ha^{-1}) strongly varied among farms (Fig. 6). Moreover, the rate of development showed inter-annual variation. The range in N surpluses among farms remained almost constant over time. In Table 3, development of farm characteristics between 1998 and 2002 is presented for the two groups of farms, classified on the basis of N surplus level in 1998 ('low' and 'high'). The year 2003 was excluded from the linear regression because it was very dry, with consequently lower crop yields (Fig. 5) and higher N surpluses (Figs. 2 and 6).

At the start, group 'high' had a higher milk quota and smaller farm area than group 'low'. In both groups, milk quota, land area and production intensity increased over time. The difference in average N surplus between the groups at the start was 87 kg ha^{-1}, and for both groups the surplus decreased. All NUEs (-farm, -herd and -soil) from group 'low' in 1998 were higher than those from group 'high', and they all increased statistically significantly between 1998 and 2002 for farm and soil. Most pronounced developments in herd and feeding regime characteristics were a decrease in number of young stock and in grazing time, and an increase in fat content in milk. Between the groups, these developments were not statistically different (β_3). At the start, the proportion grassland on farms in group 'low' was 10% lower than that in group 'high', but the difference declined over time. N en P inorganic fertilizer doses in 1998 on grassland and maize land in group 'high' were higher than in group 'low', and decreased in both groups. At the start, group 'high' applied absolutely and relatively more organic manure to maize land, and both groups shifted manure application from maize land to grassland (group 'high' to a larger extent than group 'low').

Table 4 presents the development of farm characteristics for the two groups of farms, classified on the basis of production intensity in 1998 ('low' and 'high'). The difference in intensity between the groups in 1998 was 4.3 Mg ha^{-1}. In both groups, milk quota and land area increased, but in the high-intensity group priority was given to land area, resulting in a decrease in intensity. At the start, N surplus on the low-intensity farms was lower (60 kg ha^{-1}), as was NUE at farm level (24.9% versus 27.4%). This is in contrast to the groups of farms in Table 3, where a lower N surplus was associated with a higher NUE at farm level. The increase in NUE-farm and NUE-soil was stronger in the low-intensity group than in the high-intensity group. The difference between the groups was most pronounced for NUE-soil (3.1% versus 1.3%). The rate of development of the farm characteristics related to feeding regime (urea content in milk and crude protein (CP) percentage in the ration in summer) was higher in the low-intensity group than in the high-intensity group The patterns of N and P fertilization on grassland and maize land at the start, as well as their development, were generally the same as in Table 3, except for the inorganic-N fertilizer dose on maize land at the start: no difference between the groups classified on the basis of production intensity and almost double the dose in the group 'high surplus' compared with the group 'low surplus'.

Table 3 *Farm development of two groups of commercial pilot farms, classified (n=8) on the basis of N surplus level at the start in 1998 ('low' and 'high'). For each characteristic, the absolute starting value in 1998 is given (β_0 and $\beta_0+\beta_2$) and the average development rate per year between 1998 and 2002 (β_1 and $\beta_1+\beta_3$). (See Eq. 2 for explanation of symbols).*

	N surplus						
	Starting value in 1998		Development rate (y^{-1})		Statistical significance [c]		
	Low (β_0)	High ($\beta_0 + \beta_2$)	Low (β_1)	High ($\beta_1 + \beta_3$)	β_1	β_2	β_3
Farm size							
Quota (Mg milk)	533	583	26	40	*		
Farm area (ha)	40	36	1.6	2.5			
Production intensity (Mg milk ha^{-1})	13.7	16.4	0.2	0.1		**	
Overall nitrogen management							
N surplus farm (kg ha^{-1})	225	313	-18	-30	***	***	
NUE farm (%)	27.5	24.8	2.6	2.4	***		
NUE herd (%)	22.7	21.5	0.4	0.7			
NUE soil (%)	64	59	2.4	2.1	**		
Herd & feed management							
No. of cows	71.7	70.0	2.7	6.1			
No. of young stock (per 10 cows)	7.7	9.3	-0.2	-0.3	*	***	
Milk per cow (kg yr^{-1})	7,978	8,108	11	-96			
Fat content milk (%)	4.38	4.33	0.04	0.03	**		
Protein content milk (%)	3.49	3.51	-0.02	0.0			
Urea content milk (mg per kg milk)	20.4	24.3	0.07	-0.53		*	
Grazing time cows (hours)[a]	1,700	1,926	-154	-136	*		
Concentrates (kg per 100 kg FPCM)[b]	22.3	26.6	0.6	-1.0			*
Crude protein in winter ration (%)	15.9	16.8	-0.03	-0.3			
Crude protein in summer ration (%)	17.8	18.2	-0.3	-0.3			
Crop & fertilizer management							
Grassland area (%)	67	77	1.7	-1.5		*	
- N fertilization grassland							
- Inorganic fertilizer (kg ha^{-1})	202	262	-27	-39	***	**	
- Organic manure (kg ha^{-1})	230	235	3	13			
N fertilization maize land							
- Inorganic fertilizer (kg ha^{-1})	35	60	-1.3	-1.9			
- Organic manure (kg ha^{-1})	196	251	-15	-19			
P fertilization grassland							
- Inorganic fertilizer (kg ha^{-1})	4	17	-1	-3		***	*
- Organic manure (kg ha^{-1})	36	35	1	2			
P fertilization maize land							
- Inorganic fertilizer (kg ha^{-1})	11	18	-3	-3			
- Organic manure (kg ha^{-1})	31	37	-2	-2			

[a] No. of grazing days × hours per day.

[b] Fat-and-protein corrected milk.

[c] * $P<0.1$; ** $P<0.05$; *** $P<0.001$.

Table 4 *Farm development of two groups of commercial pilot farms, classified (n=8) on the basis of intensity (milk production per ha) at the start in 1998 ('low' and 'high'). For each characteristic the absolute starting value in 1998 is given (β_0 and $\beta_0+\beta_2$) and the average development rate per year between 1998 and 2002 (β_1 and $\beta_1+\beta_3$) (see Eq. (2) for explanation of symbols).*

	Production intensity						
	Starting value in 1998		Development rate (y^{-1})		Statistical significance[c]		
	Low (β_0)	High ($\beta_0 + \beta_2$)	Low (β_1)	High ($\beta_1 + \beta_3$)	β_1	β_2	β_3
Farm size							
Quota (Mg milk)	509	606	46	20	**	*	
Farm area (ha)	42.0	35	1.5	2.6			
Production intensity (Mg milk ha^{-1})	12.4	17.7	0.6	-0.3	*	***	**
Overall nitrogen management							
N surplus farm (kg ha^{-1})	238	299	-19	-28	**	**	
NUE farm (%)	24.9	27.4	3.1	1.9	***		
NUE herd (%)	21.8	22.3	0.5	0.6	*		
NUE soil (%)	61	62	3.1	1.3	***		
Herd & feed management							
No. of cows	70.6	71	4.2	3.7	*		
No. of young stock (per 10 cows)	7.9	9.1	-0.1	-0.4		*	
Milk per cow (kg yr^{-1})	8,054	8,029	-7	-77			
Fat content milk (%)	4.36	4.34	0.04	0.03	*		
Protein content milk (%)	3.47	3.52	-0.01	0.0			
Urea content milk (mg per kg milk)	22.7	22.1	-0.4	0.0			
Grazing time cows (hours)[a]	1,676	1,949	-146	-181			
Concentrates (kg per 100 kg FPCM)[b]	22.3	26.6	0.8	-1.3			**
Crude protein in winter ration (%)	16.6	16.1	-0.2	0.0			
Crude protein in summer ration (%)	19.1	17.1	-0.6	-0.2	**	*	
Crop & fertilizer management							
Grassland area (%)	72	73	1.2	-1.0			
- N fertilization grassland							
- Inorganic fertilizer (kg ha^{-1})	213	252	-29	-36	***	*	
- Organic manure (kg ha^{-1})	225	240	7	9			
N fertilization maize land							
- Inorganic fertilizer (kg ha^{-1})	49	47	-1	-2			
- Organic manure (kg ha^{-1})	184	260	-16	-19		*	
P fertilization grassland							
- Inorganic fertilizer (kg ha^{-1})	10	12	-3	-2	**		
- Organic manure (kg ha^{-1})	35	35	1	2			
P fertilization maize land							
- Inorganic fertilizer (kg ha^{-1})	19	11	-5	-1	**		*
- Organic manure (kg ha^{-1})	29	38	-2	-2			

[a] No. of grazing days × hours per day.

[b] Fat-and-protein corrected milk.

[c] * $P<0.1$; ** $P<0.05$; *** $P<0.001$.

3.4. Relation between intensity and nitrogen surplus

The characteristics production intensity and N surplus were used as criteria to analyse differences in farm management (Fig. 7). In a multiple linear regression model with year, production intensity and their interaction, 48% of the variance of N surplus was accounted for. For each year the *p*-value of the slope was less than 0.014, except for 1998 (*p*=0.069). In all years, the relation between these characteristics has more or less the same slope: For each Mg increase in milk yield per ha, N surplus increases by 6 to 13 kg ha^{-1}. Progress at individual farms in the course of the project was characterized by a lower surplus at a given production intensity. At a production intensity of 15,000 kg ha^{-1} mean N surplus decreased from 273 kg ha^{-1} in 1998 to 179 kg ha^{-1} in 2002. Similar relations were found on progressive Flemish dairy farms (Nevens et al., 2006).

The characteristics for the year 2003 were similar to those in 2000 as a consequence of the dry summer and the associated lower yields of grassland. The lower slope for 1998 is associated with the relatively low N surpluses realized by the most intensive farms at the start.

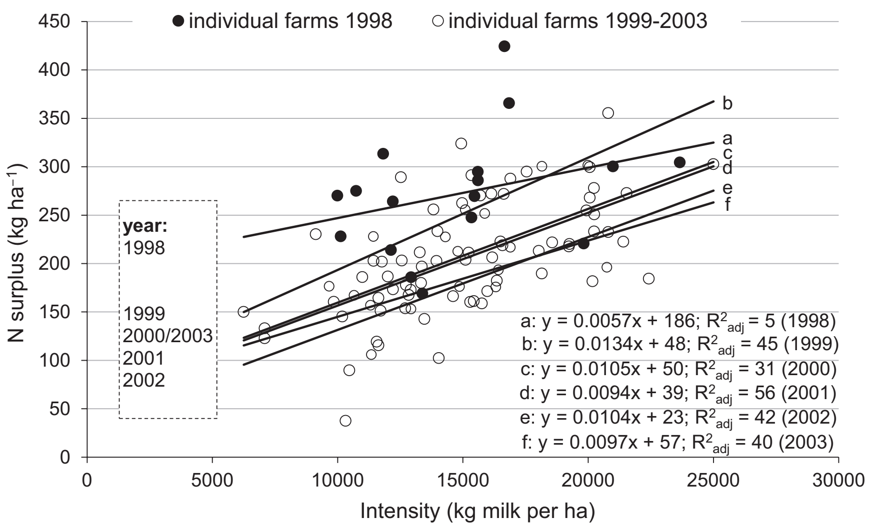

Fig. 7 *Relation between intensity and N surplus of the commercial pilot farms in the years between 1998 and 2003.*

4 Discussion and conclusions

Developments on farms are pre-dominantly governed by technical and financial conditions and farmers' aims and aspirations, but these are modified by regulations based on societal demands. From the start in 1998 until 2002, average nutrient surpluses on the commercial pilot farms in the project 'Cows & Opportunities' decreased by 33% for N and 53% for P. On the 'national average' farm (Aarts et al., 2008), nutrient surpluses decreased in the same period almost similarly for N (29%), but less for P (28%). However, on the commercial pilot farms, NutUE in 2002 was 34% for N and 67% for P compared with 23% and 49%, respectively, on the 'national average' farm. Production intensity on the 'national average' farm remained lower than on the commercial pilot farms. Intensive coaching and very frequent interaction among researchers, extension agents and farmers resulted in adoption and implementation of nutrient-efficient management in practice (see Section 4.1). Similar results were found on farms with access to advice and information systems in other developed countries (Garforth et al., 2003) and in developing countries (Haefele, 2001). Aarts (2003) reported for the same set of pilot farms that adoption of nutrient-efficient farm management, triggered by its reduced environmental impact, was stimulated by the associated increase in farmers' income (on average €3,000 over 5 years), due to reductions in purchases of feeds and inorganic fertilizer. Under the influence of economic driving forces, the pilot farms on average expanded land area and increased their milk quota, resulting in a limited increase in production intensity. This strategy is in agreement with the results of Ondersteijn et al. (2002), who concluded that farms tend to grow in size and in production intensity to survive in the current harsh economic environment. Higher production intensity results in higher N surpluses (Fig. 7), which is in contradiction with the main target of the pilot farms: reducing nutrient losses. The solution to reconciling these conflicting objectives and develop more nutrient-efficient management, is found elsewhere in the dairy farming system.

4.1 Implemented measures

Effective strategies to reduce nutrient losses are based on optimizing internal nutrient cycling in subsystems, so that external inputs of nutrients can be reduced. That was the main motive underlying implementation of MINAS (specifying permitted nutrient surpluses) as a policy instrument. The most effective measure is reducing the use of inorganic fertilizer (Figs. 2 and 3) through increased use of farm-produced animal manure (less is exported) and higher utilization efficiency through improved allocation to crops (from maize to grass; Tables 3 and 4) and timing of application. As dry matter yields hardly decreased (Oenema et al., 2002), the lower N input levels especially reduced the N content of home-produced feed

(Fig. 5), but not its energy content. So lower N yields did not increase the need for purchased feed (Figs. 2 and 3).

Another important measure is reducing grazing time (Tables 3 and 4). The disadvantage of grazing is that the composition of feed rations is difficult to manage. Grass intake, as well as its quality, are variable (weather conditions), and both are difficult to estimate quantitatively. Under grazing, field losses are higher than under harvesting as silage. However, before grass silage is ingested, losses occur during conservation and feeding. The spatial distribution pattern of manure during grazing is so unfavourable that grass hardly profits from its nutrients, and there is a high risk of excessive nitrate leaching (Scholefield et al., 1993; Verloop et al., 2006). Systems with grazing require a favourable parcelling pattern (size of plots, distance to the farm). On the other hand, grazing systems are less labour-intensive and their costs are lower, as mechanical harvesting is not needed and housing requirements are simpler. Moreover, grazing is preferable from the point of view of animal health and welfare. Also from a societal point of view there is a demand for grazing systems.

Another measure is to reduce the relative number of young stock, as they present a highly inefficient component in the nutrient balance. Each additional heifer (young stock older than 1 year) increases the farm nutrient surpluses by 51 kg N and 7 kg P (Mourits et al., 2000). Young stock management is important because of selection for replacement. Replacing a milking cow requires an 'investment' in nutrients and energy intake (Aarts et al., 1999). On the other hand, raising or fattening young stock on other farms is a case of shifting this 'investment' elsewhere.

Changing fertilization management (reduced use of mineral fertilizer, optimizing use of animal manure to crops) and grazing regime influenced the composition of home-produced feed. Crude protein (CP) content of the rations hardly decreased. At the start, average CP contents of the ration in winter (15.8%) were lower than 'national average', so further reduction has low priority. Theoretically, a CP content of 13.5% would be sufficient (Bannink et al., 2006), but that requires highly skilled management to provide a balanced dietary energy/protein ratio to sustain milk production. Most progress has been made in lowering the CP content in the ration in summer, by shortening grazing time and supplementary stall-feeding to balance the ingested protein/energy ratio. The lower CP content of the ration did not affect milk production per cow, nor fat and protein content of the milk (Tables 3 and 4).

4.2. Does strategy depend on intensity or nitrogen surplus?

This study contributes to closing the information gap on the causes underlying the variation in system performance among specialized dairy farms and years, by systematically examining whether differences can be explained by different management practices. The inter-farm variation in N surplus remained constant over time (Fig. 6). To explain differences in farm development, in this study, farms were classified on the basis of production intensity and N surplus in the base situation. Farms characterized by low N surpluses at the start still identified opportunities to reduce nutrient losses (Table 3 and Fig. 6). Explanations might be found in factors such as 'learning period' and 'degree of adaptation' (Ozanne et al., 2001; Ondersteijn et al., 2003). The 'N surplus limit' is farm(-type)-specific, and (co-) determined by agro-ecological conditions (e.g., soil type), but also by professional skills and entrepreneurship. These factors are therefore important in understanding differences in farm development. Decisions of farmers to adapt to changing conditions are not only governed by economic considerations, but also by their social and psychological characteristics (Gow & Stayner, 1995; Traoré et al., 1998; Wilcock et al., 1999).

As the classifications of farms on the basis of initial production intensity and on the basis of initial N surplus strongly overlap, because both characteristics are strongly correlated (Fig. 7), it is difficult to differentiate between the two groups. For the two classes distinguished on the basis of production intensity in the base situation, the most striking development is the reduction in intensity on the high-intensity farms (Table 4). On these farms, the ceiling has been reached in improvements in agro-ecological and socio-economic performance to comply with regulations, such as permitted nutrient surpluses.

For most characteristics, the average differences between groups declined as the project progressed, suggesting development towards a feasible limit for each characteristic, however, with some notable exceptions. For the farms classified on the basis of N surplus in the base situation, the differences between the two groups in intensity, NUE-farm and NUE-soil, relative number of young stock and grazing time persisted or even increased. For the farms classified on the basis of initial production intensity, this held for NUE-herd and NUE-soil and manure application rate to maize land. Hence, explanations for differences among farms and groups are only valid for an *average* development of farm characteristics. The inter-farm variation in farm characteristics remains high over time. This variation may be related to differences in production environments (both, agro-ecological and socio-economic) in which the farm(er)s operate (cf. Ondersteijn et al., 2002; Ondersteijn et al., 2006; Zachariasse, 1974). Further research should therefore focus on identification of the factors underlying these substantial inter-farm differences in nutrient surpluses. This requires analyses of the effects of changes in the whole dairy farming system, i.e., farm-specific analyses based on detailed and accurate data on nutrient balances at the whole farm level and at herd and soil level, combined with analyses of farm characteristics related to the herd and feeding regimes and crop and fertilizer regimes. The ceiling to production intensity to comply with regulations and societal demands is farm-specific and dependent on the willingness and skills of the farmer. Advice to individual farmers has to be situation-specific, based in the results of the farm-specific analyses, and the dairy farming systems on the commercial pilot farms presented in this paper can be used in guiding the promotion of adoption of improved farm management practices. However, differences in farm management strategy could not unequivocally be related to farm typology (high/low N surplus; high/low intensity). Decisions of individual farmers on farm development are not always based on 'rational' arguments, but are co-determined by 'emotional' perceptions.

Acknowledgements

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CHAPTER 4

IMPROVING NITROGEN MANAGEMENT ON GRASSLAND ON COMMERCIAL PILOT DAIRY FARMS IN THE NETHERLANDS

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Abstract

Nitrogen (N) use efficiency (NUE), the ratio of N output and N input, is rather low on dairy farms with high stocking densities and high N input on grassland resulting in high N losses to the environment. This study describes and analyses the development and variation in N management on grassland on 16 commercial pilot dairy farms in the project 'Cows & Opportunities' (C&O) over a 12-year period (1998-2009, with the aim that applying this knowledge to other farmers may provide insight in the (im)possibilities to improve management. Farm milk production ranged from 11 to 23 Mg ha^{-1} and grassland occupied ca. 80% of the total land area (between 63 and 97%). Mean N application rate (kg total N ha^{-1} $year^{-1}$) on grassland (in manure, chemical fertilizer, excreta during grazing, biological N fixation and atmospheric deposition) on the pilot farms decreased from 540 in 1998 to 450 in 2001, while in the remainder of the period the inter-annual variation was low (between 400 and 450). Mean dry matter yields on grassland (11 Mg ha^{-1}) varied among years and farms (between 7.7 and 16 Mg ha^{-1}), without any significant temporal trend. We observed no trend of diminishing returns of dry matter yields at farm scale up to an N application rate on grassland of ca. 600 kg ha^{-1} because farms with a high production intensity (Mg milk per ha) need more dry matter than farms with a lower intensity and were able to increase nitrogen management on grassland with high N input levels. Management options that result in improved NUE include reduced grazing time which results in increased dry matter yields and NUE as a consequence of better utilization of organic manure.

1 Introduction

Grassland-based livestock production is important throughout the world (Rotz et al., 2005). In Europe, a third of the agricultural area is covered by grasslands (Smit et al., 2008). In north-western Europe, most cattle production systems are characterized by high stocking densities and associated intensive use of grassland with high nitrogen (N) inputs through manure and chemical fertilizers (cf. Aarts, 2000). Grassland and crops use the N inputs inefficiently. Generally, more than 50% of the N applied is not assimilated by plants (Tilman et al., 2002; Mosier et al., 2004; Robertson & Vitousek, 2009), and is a potential source of environmental pollution compromising the quality of groundwater and surface water (Cartwright et al., 1991; Erisman et al., 2007; Galloway et al., 2008).

Recognition of the environmental impact of high N surpluses has resulted in the development of government policies in many European countries to reduce nutrient losses. The Nitrate Directive (EC, 1991), one of the European Union (EU) policy instruments, defines an application threshold of 170 kg manure-N ha^{-1} $year^{-1}$ for all Nitrate Vulnerable Areas, i.e. EU areas that have been identified as exceeding or being at risk of exceeding 50 mg NO_3 l^{-1} in the groundwater.

In the Netherlands, legislation to reduce losses of nutrients from manure has been implemented since 1984. In 1998, a balance approach, the MINeral Accounting System (MINAS), was introduced as the central instrument for restricting emission of nutrients to the environment (Henkens & Van Keulen, 2001; Schröder & Neeteson, 2008). In 2006, the MINAS balance approach was replaced by a one-sided input approach by introducing permitted N rates (so-called 'application standards') for all crops (Schröder & Neeteson, 2008).

Parallel to the introduction of the N application standards for crops, the Netherlands filed a request for a derogation for dairy farms (Schröder & Neeteson, 2008). In the scientifically underpinned derogation request, all dairy farms with a land use exceeding 70% grassland would be allowed to apply maximally 250 kg instead of 170 kg manure-N (total) per ha per year; it was accepted by the European Commission in Brussels for the periods 2006-2009 and 2010-2014. In the derogation request, criteria for N excretion per animal, N fertilizer replacement values of manure N and N application standards (kg plant available N per ha) for grassland and maize land were included.

More than 60% of the agricultural land in the Netherlands is used for dairy farming. Grassland is the most important source of feed, followed by silage maize. To comply with government policies while minimising costs, dairy farmers need timely, relevant, and accurate information to improve nutrient management. To explore possibilities to increase nutrient use efficiency and reduce nutrient losses, the method of prototyping, a combination of system modelling and system implementation, was applied on experimental farm 'De Marke' (Aarts et al., 1992).

Performance of the 'De Marke' system has shown that by implementing a coherent set of simple measures at farm level, nutrient inputs to the farm can be drastically reduced without affecting production intensity (kg milk per ha) (Aarts, 2000; Hilhorst et al., 2001). To promote adoption of similar systems in commercial dairy farming, the project 'Cows & Opportunities' was initiated in 1999. It is characterized by agreements with the farmers on realization of measurable targets and intensive coaching through frequent interaction between researchers, extension agents and farmers. In practice, dairy farmers are often reluctant to adjust management, because of lack of information and lack of confidence in the results. Intensive coaching and knowledge transfer is used to realize rapid adoption of efficient farm management in practice (Oenema et al., 2001).

From the start of the 'Cows & Opportunities' project, the commercial pilot farmers accepted the commitment to aim for immediate compliance with national environmental standards that, according to legislation, would be compulsory for commercial farmers in 3 to 5 years. Farm dynamics are pre-dominantly governed by biophysical, technical and financial conditions and farmers' aims and aspirations, but these are modified by regulations. From 1999 to 2002, the intensive coaching resulted in adoption and implementation of nutrient-efficient management practices (Oenema et al., 2011b), so that average farm gate nutrient surpluses on the pilot farms decreased by 33% for N and 53% for phosphorus (P). Important measures were reducing the use of inorganic fertilizer, optimising the use of home-produced organic manure, reducing grazing time, reducing the number of replacement stock and lowering crude protein content in the ration. However, over this period, the variation in N surplus among the pilot farms (inter-farm variation) was substantial and remained almost constant (Oenema et al., 2011b). This variation may be associated with differences in production environments (both, agro-ecological and socio-economic) in which the farmers operate and they may reveal different strategies (Ondersteijn et al., 2002; 2006). For extrapolation of the results to a range of farming systems, quantification and better understanding of the factors underlying these inter-farm differences in nutrient surpluses is needed. Long term detailed data of dairy farms are available from experimental farms (e.g. Aarts et al., 2000; Taube & Wachendorf, 2001; Verloop et al., 2006, 2010) but hardly from commercial dairy farms. Detailed observations and analysis from a range of different commercial dairy farming systems is an omission in the literature and will enhance understanding inter-farm differences in nutrient management as related to farm strategies. Whereas Oenema et al. (2011b) analysed the overall changes in *farm* management on commercial pilot farms during a 6-year period, this study will focus on detailed *grassland* management on commercial pilot farms over a longer period (12 years). The purpose of this study was therefore to describe the development and variation in N management on grassland on the 16 commercial dairy farms participating in the 'Cows & Opportunities' project and explain the differences by farm structure, N management and soil characteristics. Knowledge transfer of these insights can reveal opportunities to improve N management and N use (efficiency) on grassland on dairy farms.

2 Materials & Methods

2.1. Data collection and monitoring

Data for the 16 specialized pilot dairy farms were collected over a 12-year period (1998-2009). For details on farm selection and farm characteristics reference is made to Oenema et al. (2001). The characteristics of the pilot farms cover the range of conditions in intensive dairy farming in the Netherlands, to facilitate acceptance of their results by other farmers (Fig. 1; Table 1). Farms on sandy soil were over-represented because of the nitrate leaching problems on this soil type (Oenema et al., 2010). At the start of the project, data for the year 1998, representing the base situation, were derived from farm records and interviews with the farmers. In the course of the project, frequency of collection of the various data varied from daily to annually. Farmers recorded most basic data, either electronically or on paper, that were used to calculate internal and external nutrient flows. For details on calculation methods and sources of nutrient flows in a dairy farm system reference is made to Oenema et al. (2011b). Field-level data on fertilizer and manure management, dry matter yields and grazing regimes were recorded daily in a computerized fertilizer recommendation program. Grassland dry matter yields were estimated by the farmer for each cut, using the rising plate meter (Keuning, 1988). At the start of the project, farmers were instructed and tested how to use the tool. Grazing intake was recorded for each field after the animals moved to a next field by visually estimating the dry matter yield of the grass sward and/or by estimating the daily dry matter intake, knowing the amount of other feed intake indoors. At the start of the project the estimations of the grazed grass swards were calibrated by using the rising plate meter. To determine the nutritive value in organic manure and silage, a sample was taken from the slurry pits two to four times annually, following extensive mixing, and a sample from each silage heap was taken, in which nutrient contents were quantified on the basis of chemical analysis. Data of the year 1999 were not included because of missing field-level data of fertilizer and manure management, dry matter yields and grazing regimes.

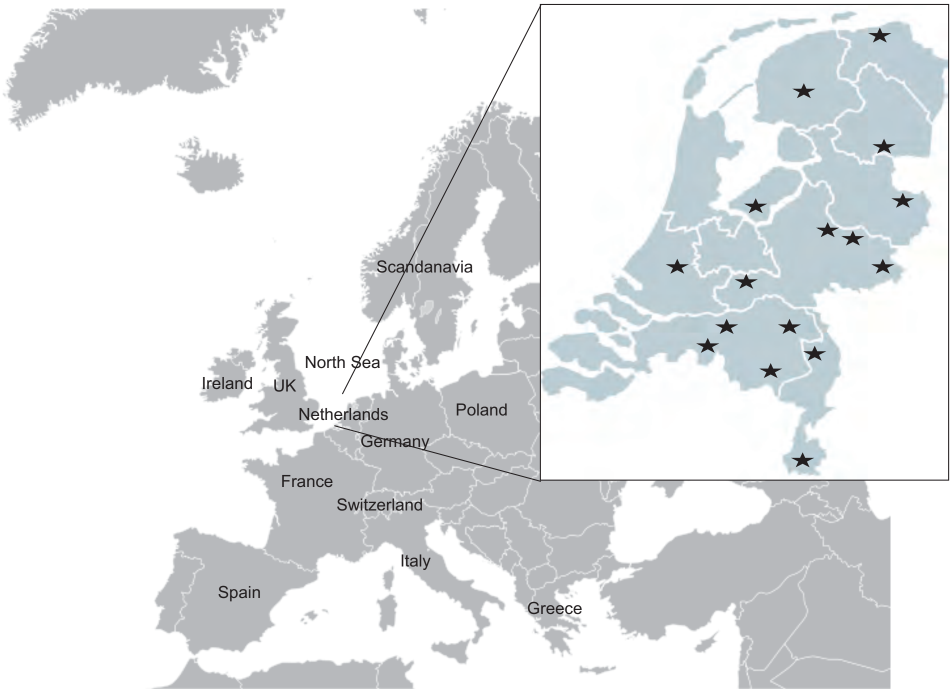


Fig. 1 *Location (stars) of the commercial pilot dairy farms included in the project 'Cows and Opportunities' in the Netherlands.*

Soils were sampled (almost) every year (grassland 0-10 cm) on all fields in the winter period, to monitor changes in soil fertility status. In each field (max. 2 ha), 40 cores were mixed into a composite sample. Total N content was determined by the Kjeldahl technique (Bremner, 1960). In soils expected to be low in organic matter, soil organic carbon (SOC) was determined through elemental C analysis, following dry combustion (Yeomans & Bremner, 1991; Soon & Abboud, 1991). On soils expected to be rich in organic matter (all grassland samples), loss on ignition (NEN 5754, 2005) was used to determine soil organic matter (SOM) directly, using corrections for inorganic carbonates and clay content. SOC was calculated as SOM × 0.5 (Reijneveld et al., 2009). Plant available P in grassland was expressed as P-AL (Van der Paauw, 1956) which indicates readily available P during the growing season.

Table 1 *General farm characteristics of commercial pilot dairy farms in the project 'Cows & Opportunities' (C&O) and the 'national average' (see text for explanation). Data of the pilot farms and the 'national averages' are averages for the period 1998-2009.*

	Soil type	Number of milking cows	Total milk production (Mg year^{-1})	Production intensity (Mg milk ha^{-1})	Milk production cow^{-1} (Mg year^{-1})	Farm size (ha)	Grassland area (%)	N in feed per Mg milk (kg)[a]	N in fertilizer per Mg milk (kg)[a]
De Marke	Sand	76	662	12.1	8.8	55	60	8	2
F1	Sand	103	697	11.1	6.8	63	65	10	0
F2	Clay	128	1036	22.7	8.1	46	76	14	7
F3	Sand	70	526	12.8	7.5	41	77	8	8
F4	Sand	87	741	18.5	8.5	40	66	11	6
F5	Loess	109	885	13.9	8.1	64	63	10	10
F6	Sand	75	651	16.4	8.7	40	68	10	4
F7	Sand	89	692	13.7	7.8	51	75	10	9
F8	Sand	84	576	12.7	6.9	45	79	8	9
F9	Sand	116	941	12.7	8.1	74	79	10	8
F10	Peat	114	824	14.0	7.2	59	84	11	8
F11	Sand	84	708	18.7	8.4	38	67	11	8
F12	Sand	81	762	17.4	9.4	44	75	13	8
F13	Sand	68	612	21.5	9.0	29	67	13	5
F14	Clay	128	1144	14.4	8.9	80	89	10	10
F15	Peat	68	572	13.8	8.4	42	97	9	9
F16	Clay	82	761	19.6	9.3	39	86	10	8
Average C&O		93	758	15.9	8.2	49	76	10	7
National average		82	638	13.1	7.7	49	83	10	12

[a] Purchased N in feed and fertilizers (organic and chemical)

The moisture supply capacity from the soils on five farms (the three 'best performing farms' and the two 'average performing farms'; see section 'data analysis') was calculated. The moisture supply capacity of soils influenced by capillary rise from the groundwater was calculated on the basis of the water deficit in the growing season of 150 days (starting April 1) in a dry year with a probability of occurrence of 10% (Bouma, 1989). The moisture supply capacity for grassland was classified in a rating table: score 1 (very high) for moisture supply above 200 mm, up to score 5 (very low) for moisture supply below 50 mm (Sonneveld et al., 2010).

To benchmark results of the pilot farms, a 'national average' was calculated for specialized dairy farms from the Dutch Farm Accountancy Data Network (FADN) (land area > 15 ha; at least 80% grassland and fodder crops; > 30 milking cows). Using FADN data, a study was carried out on fertilization, yields and nutrient use efficiency of grassland and maize land on specialized dairy farms in the period 1998-2006 (Aarts et al., 2008). Due to the acceptance of a new derogation by the EU (c.f. Schröder & Neeteson, 2008) and for a desk study for The Netherlands Action Programme (Oenema et al., 2012), the study has been extended, and the years 2007, 2008 and 2009 were added to the dataset of Aarts et al. (2008). Yields of grassland on 'national average' farms were calculated, based on the total energy requirement of the animals and by subtraction the energy of imported concentrates and other feed, and the estimated yields of home grown silage maize and other forage crops. The result is the energy intake from home grown grassland. Correction for losses (feeding, grazing, conservation) were made to calculate the net yields of grassland. The input data for this calculation were collected in a survey. A detailed description of the entire method is given by Aarts et al. (2008). This method was also applied on the pilot farms and the calculated yields were compared with the monitored yield. Based on the combined phosphorus yields of grassland and silage maize, results of the monitoring on pilot farms where slightly higher (2%) than the 'energy requirement' calculation method (Oenema et al., 2011a).

2.2. Data analysis

N application rate on grassland (kg ha^{-1} $year^{-1}$) is defined as the applied amount in organic manure (total N) and chemical fertilizer, in excreta during grazing, biological N fixation by clover (estimated from % clover in grassland x total yield (Mg dry matter) × 45 (Biewinga et al., 1992)) and atmospheric deposition minus ammonia losses during application and grazing (Smits et al., 2000; Huijsmans & Schils, 2009). The used N fixation factor (45 kg N Mg^{-1} clover) is in line with experimental results in the Netherlands from Schils & Snijder (2002) (between 39 and 58 kg N Mg^{-1} clover), lower than experimental results from Elgersma & Hassink (1997) (between 49 and 69 kg N Mg^{-1} clover), and higher than reported values from Korsaeth & Eltun (2000) (between 29 and 39 kg N Mg^{-1} clover). For comparative purposes, we take the same value for atmospheric deposition for each commercial pilot farm (36 kg N ha^{-1}) that Aarts et al. (2008) were also using in the 'national average'. N surplus on grassland is defined as N application minus N yield (derived from dry matter yield and N content grass). N surplus at the whole farm was established by registration of N inputs in imported feeds (concentrates and roughages), imported fertilizers (organic and chemical), imported animals, biological N fixation and atmospheric deposition, and N outputs in exported milk, animals, manure and roughage. NUE is defined as the ratio N output/N input (expressed as percentage), for grassland (N output in yield, N input in application rate), the whole farm (N output in milk and meat, N input in imported feeds (concentrates and roughages), imported fertilizers (organic and chemical), and biological N fixation by clover and atmospheric deposition) and for the herd component (N output in milk and meat, N input in feed).

On the basis of the relation between NUE and dry matter yield with respect to grassland (Fig. 6), some farms were classified as examples of 'best performing farms' - the highest NUE of grassland for a given dry matter yield - and 'average performing farms' - close to the 'national average' NUE of grassland for a given dry matter yield.

3 Results and discussion

3.1. Farm characteristics

Total milk production on the pilot farms was higher than the 'national average' at a similar farm size (Table 1). Hence, production intensity of the pilot farms was on average higher (by around 2,800 kg milk ha^{-1}), as was milk production per cow (approximately 500 kg). The higher milk production on the pilot farms, per farm, per ha and per cow, makes a comparison with the 'national average' not straightforward. Therefore, interpretation of results should consider these differences. Moreover, farms on sandy soil were overrepresented in the group of pilot farms. On the other hand, results of Aarts et al. (2008) show no significant differences in N application rate and dry matter yields among soil types. The proportion of grassland in land use on the pilot farms (76%) was slightly lower than the 'national average' (83%). The pilot farms purchased less N in chemical fertilizer per Mg milk produced than the 'national average' (7 versus 12 kg per Mg). Purchased N in feed per Mg milk was equal in both groups. Results of the experimental farm 'De Marke' are also given to show the possibilities of improved management (low N input from 'external' feed and fertilizer).

3.2. N application rate

Mean N application rate on grassland on the pilot farms decreased from 540 kg ha^{-1} in 1998 to 450 in 2001, while in the remainder of the period the inter-annual variation was very low (between 400 and 450 kg ha^{-1}; Fig. 2). At the onset of the project, 'national average' N application rate on grassland was higher than on the pilot farms, from 2003 to 2006 the rates were equal and from 2007 to 2009 slightly lower. The variation in N application rate among farms was very high (e.g. from 180 to 680 kg ha^{-1} in 2005), whereas the inter-annual variation for individual farms (Fig. 2) was less (between 139 and 264). The 'strategy' in N application rate varies among farms: from a 'high N application rate' (F2), via a 'moderate N application rate' (F9 and F14), to a 'low N application rate' (F1). Farm F14 shows a reduction in N application rate. This farmer decided in 2009 to transform to an organic farm and thus to discontinue the use of chemical fertilizer and increase the use of clover in grassland. The farm started already earlier to reduce the N application rate on grassland. The omission of chemical fertilizer was not fully compensated by N fixation of clover (Fig. 2).

The decline in N application rate was first (1999-2001) realized through a reduction in the use of chemical fertilizer, followed by a decrease in the excreta during grazing in the period 2001-2009 due to a decrease in grazing time (Table 2). Input of N in applied manure remained almost constant during the whole period. Developments in the 'national average' were similar: first a reduction in the use of chemical fertilizer, followed by a decrease in the excreta during grazing. Differences between the pilot farms and the 'national average' were the 'levels of N use', i.e. pilot farms applied more manure and less chemical fertilizer and a lower input in excreta during grazing. N fixation by clover was not monitored in the 'national average' and was assumed to be negligible (Aarts et al., 2008).

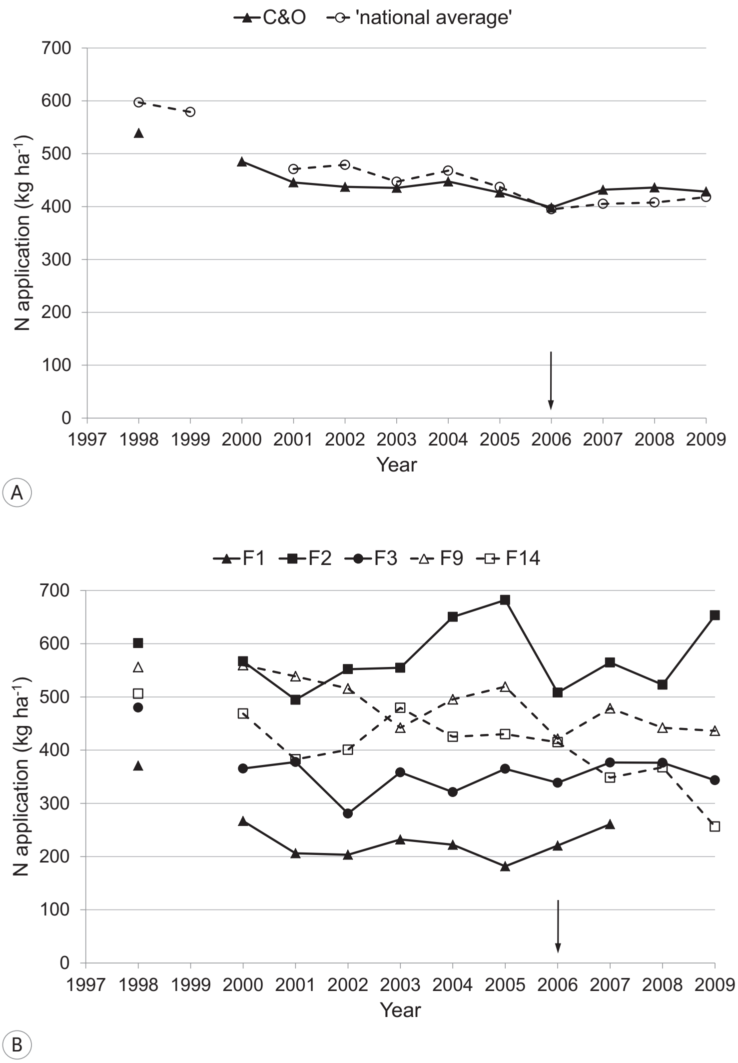


Fig. 2 *Time course of N application rate on grassland on commercial pilot dairy farms (C&O) and the 'national average' (see text for explanation), (A) on average and (B) on individual commercial pilot farms. F1, F2, and F3 represents 'best performing farms', F9 and F14 representing 'average performing farms' (see text for explanation). Before 2006, legislation was based on permitted surpluses; since 2006 legislation focuses on crop-specific N application standards.*

Table 2 *Development and type of N application rate (kg ha^{-1}) on grassland on commercial pilot dairy farms in the project 'Cows & Opportunities' (C&O) and the 'national average' (NatAver) (see text for explanation).*

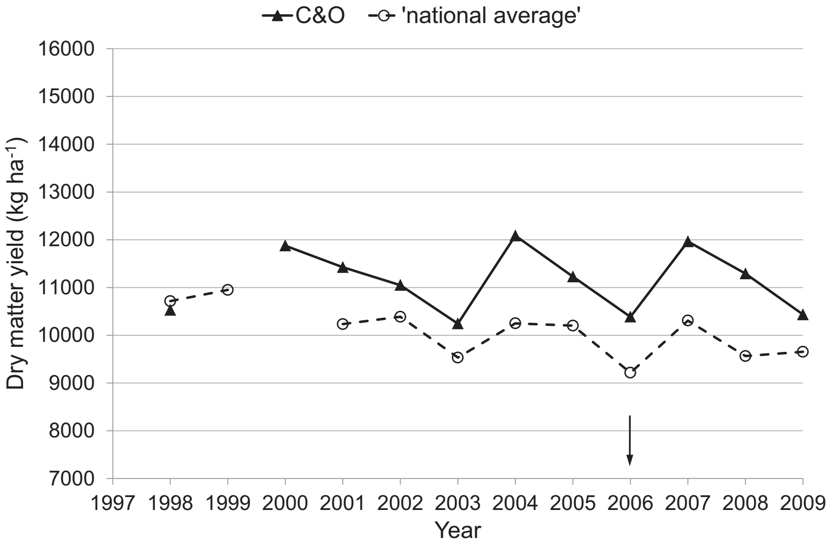
	Applied manure		Chem. fertilizer		Excreta grazing		N-fixation	
Year	C&O	NatAver	C&O	NatAver	C&O	NatAver	C&O	NatAver
1998	223	196	223	283	86	118	6	n.a.
1999	n.a.[a]	196	n.a	273	n.a.	110	n.a	n.a.
2000	231	n.a.	158	n.a.	89	n.a	7	n.a.
2001	255	210	121	186	61	75	8	n.a.
2002	248	214	117	184	61	81	12	n.a.
2003	245	201	125	168	56	78	10	n.a.
2004	230	214	143	180	63	74	12	n.a.
2005	232	196	137	175	51	66	7	n.a.
2006	219	193	127	145	45	57	8	n.a.
2007	238	180	138	150	49	75	7	n.a.
2008	249	191	138	145	41	71	7	n.a.
2009	242	205	135	143	41	70	11	n.a.

[a] not available

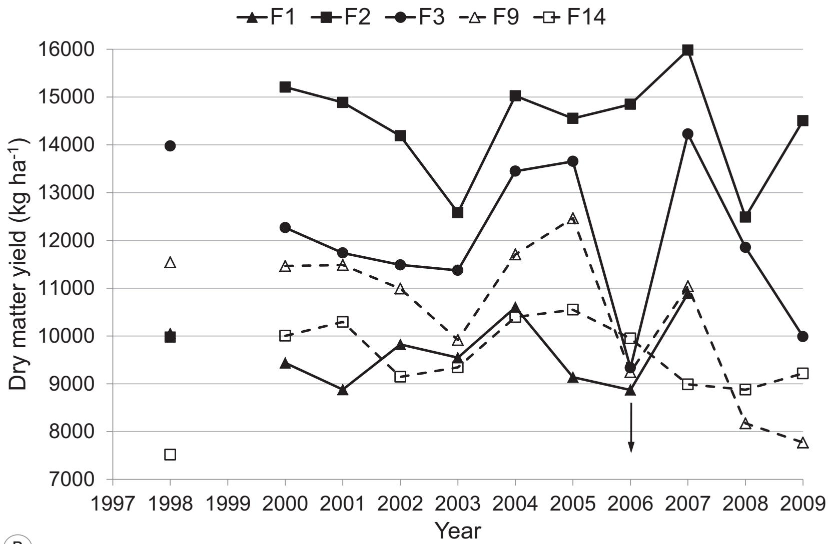
Despite compliance with the maximum use of 250 kg manure N at farm level since 2006, the actual input of N in manure (applied manure and excreta during grazing) on grassland has been higher. The maximum use of manure N is based on the average for the total area of the whole farm. However, the distribution of the manure over the fields/plots/crops can be decided by the farmer. Most of the farmers do not apply the full, permitted, amount of 250 kg manure N to maize land, so consequently more manure N is available for grassland. Moreover, the definition of the N application standard on grassland leaves room for other choices. The N application standard for grassland is differentiated only on the basis of soil type (clay and sand/loess/peat) and grassland use (cutting only and mixed use with grazing) (Schröder & Neeteson, 2008). Farmers therefore rent grassland which are managed under agri-environmental schemes, for which the N application standard for grassland applies. In practice, this grassland area is not fertilized or 'under-fertilized', and the 'surplus' fertilizer is used on the production grassland. For farmers, this is attractive for economic reasons, but environmentally it has negative consequences.

3.3. Dry matter yields

Mean dry matter yields on grassland vary among years (Fig. 3), without any significant temporal trend. In the period 2000-2009, average grassland dry matter yields on the pilot farms were close to 11 Mg ha^{-1} and 24% of the total dry matter yield was grazed. The grazing share decreased from 29% in the first years to 20% in the last years. Dry matter yields in the 'national average' were lower (10 Mg ha^{-1}) with a slightly higher share for grazing (28%). Variation among years is mostly the result of variation in weather conditions, assuming that the management was relatively constant (cf. Fig. 2). Weather conditions (temperature, rainfall) influence soil temperature and soil moisture conditions, resulting in variation in N mineralization (Oostendorp, 1962; Van Keulen, 1982). Mean annual dry matter yields on the pilot farms were higher than the 'national average' (between 0.5 and 1.5 Mg per ha; Fig. 3). Similar to the N application rate, variation in annual dry matter yields among farms (Fig. 3; e.g. from 9 to 16 Mg per ha in 2007) was larger than the inter-annual variation for individual farms (largest for farm F2 with a range from 10 to 16 Mg per ha; Fig. 3). Variation among farms in the entire dataset used for the 'national average' was even larger (Aarts et al., 2008; Oenema et al., 2011a). Farm F2 realizes almost each year the highest dry matter yield (without grazing), in combination with the highest N application rate (Figs. 2 and 3). On farm F1 (organic), with almost each year the lowest dry matter yield (<10% of grazing), N application rate was by far the lowest (Figs. 2 and 3). Dry matter yields on farms F9 and F14 (26 and 29% grazing, respectively) were mostly below the average, with a 'moderate N application rate' (Figs. 2 and 3). No statistically significant difference, nor a trend, was found in the dry matter yields on grassland between the periods with different legislation rules (before 2006 based on permissible surpluses, since 2006 based on crop-specific N application standards). Overall, there is a significant ($P<0.001$ of the slope in a linear regression on data from individual C&O farms) positive relation between dry matter yield and N application rate at farm scale (Fig. 4). Mean dry matter yields increased with 10 kg per kg N applied, which improved in the course of the monitoring period (7.8 kg per kg N in the period 1998-2003 and 13 kg per kg N in the period 2006-2009; Figs. 4b and 4c). Especially intensive farms, in terms of kg milk per ha, with high N application rates, realized increasing dry matter yields in the course of the monitoring period (F11, F12 and F13; Figs. 4b and 4c; see also Table 1). Overall, in the course of the years, farms tended to produce closer to the frontier defined by the most efficient farms (in terms of dry matter yield per unit N input; Figs 4b and 4c), which may indicate that continuing intensive coaching and knowledge transfer may have further improve nitrogen management on grassland. The relation between dry matter yield and N application rate is only valid *across* farms and not *within* farms. Individual farms operate in a limited range of the full spectrum of N application rate and dry matter yields found across farms.



A



B

Fig. 3 *Time course of dry matter yields on grassland on commercial pilot dairy farms (C&O) and the 'national average' (see text for explanation), (A) on average and (B) on individual commercial pilot farms. F1, F2, and F3 represents 'best performing farms', F9 and F14 representing 'average performing farms' (see text for explanation). Before 2006, legislation was based on permitted surpluses; since 2006 legislation focuses on crop-specific N application standards.*

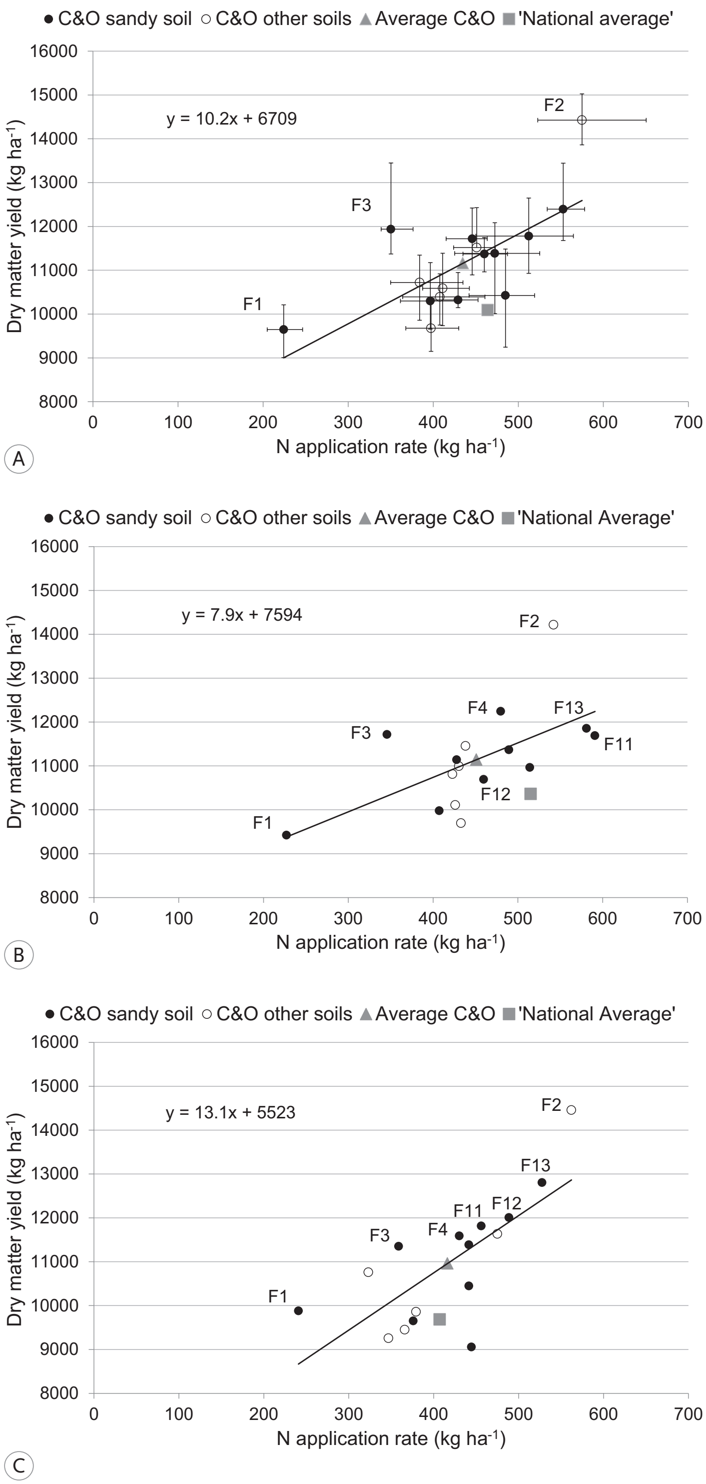


Fig. 4 *Dry matter yields on grassland as a function of N application rate on individual commercial pilot dairy farms (C&O) and the 'national average', (a) in the period 1998-2009, (B) in the period 2000-2003 and (C) in the period 2006-2009. Error bars (A) indicate interquantile range (25-75%) of the values during the period 2000-2009. F1, F2 and F3 indicate the 'best performing farms' (see text for explanation). F4, F11, F12 and F14 indicate intensive dairy farms with high N application rates on grassland. The % of variance accounted for is 51, 37 and 53, respectively; the standard error of the slope is 2.7, 2.7 and 3.3, respectively.*

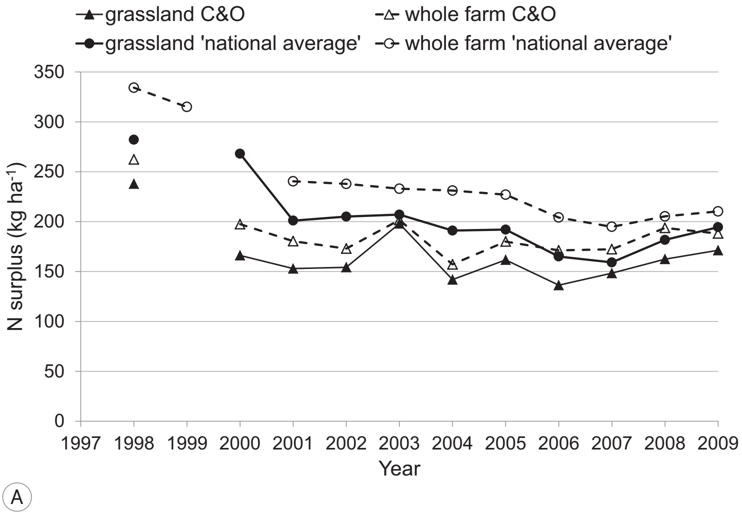
3.4. N surplus

On average, N surpluses on the pilot farms, both for the whole farm and for grassland, were lower than the 'national average' (Fig. 5a), with the exception of the year 2003 when N surpluses on grassland were almost equal. The year 2003 was warm and dry, with consequently low grassland yields, especially on sandy soils (low moisture supply capacity of the soil). From 1998 to 2005, the period with legislation based on permissible N surpluses, mean N surplus of the whole farm significantly decreased over time ($P<0.001$ of the slope in a linear regression). Due to a lower N surplus at the start on the pilot farms the reduction in N surplus during the whole period was higher on the 'national average'. Till 2006, N surpluses on the pilot farms remained lower than the 'national average'. No statistically significant difference was found among years from 2006 onwards, the period with legislation based on N application standards. Also after 2006 no differences were found in N surpluses between pilot farms and the 'national average' but the dry matter yields on grassland on pilot farms remained higher (Fig. 3). Moreover, the pilot farms have a higher milk production per ha on average (Table 1). Generally, N surplus of the whole farm increases with the milk production per ha (Nevens et al., 2006; Oenema et al., 2011b). Compared to the 'national average', pilot farms have a higher milk production per ha and similar N surplus for the whole farm and thus the average NUE of the whole farm was higher on the pilot farms than on the 'national average' (34% and 25%, respectively). While N surplus decreased till 2005 and remained constant after 2006, the NUE of the whole farm increased till 2005 and remained constant after 2006 in both groups (data not shown). Variation in N surplus on grassland across farms and years was substantial (Fig. 5b).

3.5. Variation in grassland management: the scope for improvement

In the period 2000-2009, NUE on grassland was 68% (Fig. 6) and the N surplus was around 160 kg per ha (Fig. 7). The 'national average' NUE was lower and the N surplus was higher (i.e. 59% and 204 kg per ha, respectively). Using the same definition of NUE in this study, we calculated a NUE of 80% in an experiment with different perennial ryegrass varieties and only cutting reported by Wilkins et al. (2000). Powell et al. (2010) provided in a literature review for various dairy systems a range of 16 to 77% for NUE for crops and pasture (not only grassland) and Kobayashi et al. (2010) reported a NUE of 57% for crops on dairy farms in Japan. Variation in the relations between dry matter yield on the one hand and NUE and N surplus on the other on the pilot farms is substantial. Five individual farms are included in Figs. 6 and 7: three 'best performing farms' and two 'average performing farms'. Farm F2 realized the highest dry matter yield in almost every year (Fig. 3), however, NUE was moderate and N surplus above-average. Farm F1 realized the highest NUE and lowest N surplus, but dry matter yields were also the lowest

(Fig. 3). On farm F3, dry matter yields and NUE were high and N surplus was low. On farms F9 and F14 ('average performing farms'), dry matter yields and NUE were low and N surplus high (especially on farm F9).



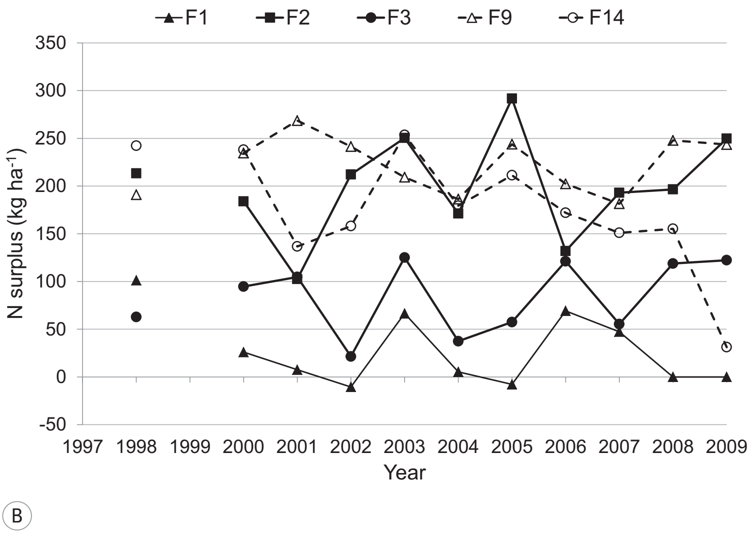


Fig. 5 *Time course of N surplus; (A) average N surplus on grassland and of the whole farm on commercial pilot dairy farms (C&O) and the 'national average' (see text for explanation), and (B) N surplus on grassland on five individual farms (black lines 'best performing farms', dashed lines 'average performing farms'; see text for explanation).*

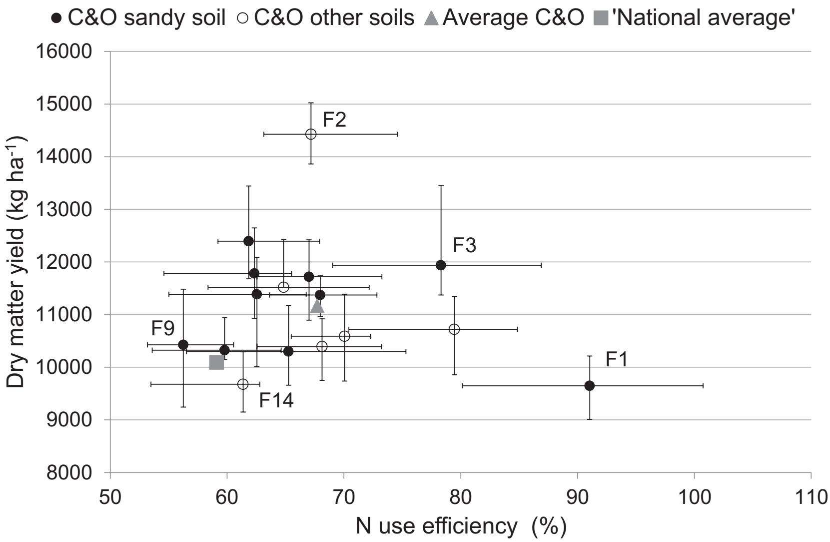


Fig. 6 *Relation between dry matter yield and N use efficiency on grassland on individual commercial pilot dairy farms (C&O) and the 'national average' (see text for explanation). Error bars indicate interquantile range (25-75%) of the values for the period 2000-2009. F1, F2, and F3 are examples of 'best performing farms', F9 and F14 of 'average performing farms' (see text for explanation).*

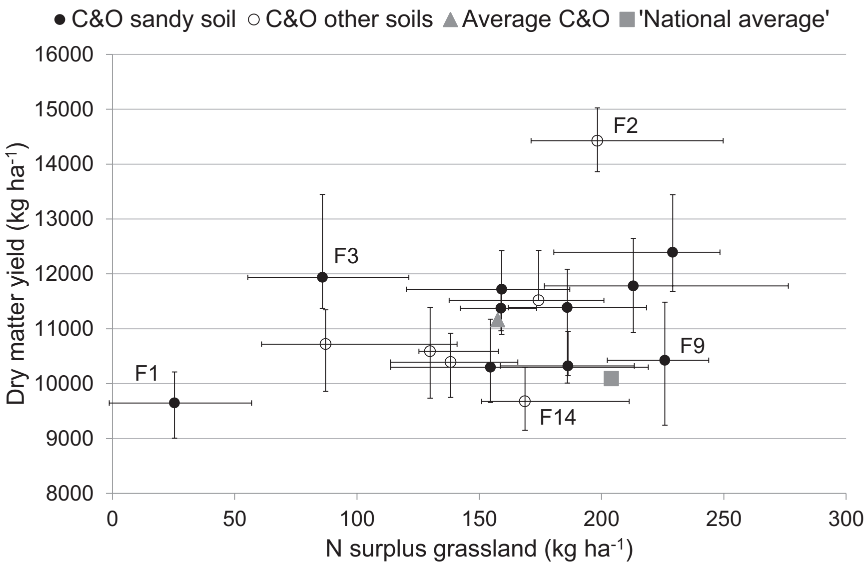


Fig. 7 *Relation between dry matter yield and N surplus on grassland on individual commercial pilot dairy farms (C&O) and the 'national average' (see text for explanation). Error bars indicate interquantile range (25-75%) of the values for the period 2000-2009. F1, F2, and F3 are examples of 'best performing farms', F9 and F14 of 'average performing farms' (see text for explanation).*

3.6. Can variation be explained?

How to explain the differences among farms? What makes the positions of farms F1, F2 and F3 in Figs. 6 and 7 so special? On F2, N application rate is high; however, this farm is located in one of the 'new polders' on a clay soil with excellent growing conditions (moisture supply capacity) for any crop (Table 3). The high NUE on F1 is associated with the low N input on this organic farm (Table 3). Management on F3 can be considered an 'optimum strategy': above-average dry matter yield, high NUE and low N surplus. Beside farm specific conditions - like soil type - an explanation of the grassland management on F3 can be found by professional skills and entrepreneurship of the farmer. On F9, N application on grassland in manure was above the maximum permitted 250 kg per ha. This farm includes a substantial area of grassland managed under agri-environmental schemes (Table 3) that is not included in the analysis. The maximum permitted use of manure-N on this grassland is also 250 kg per ha, but in practice less manure is applied here, allowing higher applications on 'productive grassland'. Despite this high N application, dry matter yields were relatively low, resulting in low NUEs and high N surpluses, partly the result of the low moisture supply capacity (Table 3), making water availability the limiting factor for dry matter production. Over the period 2000-2009, F14 almost doubled its farm size and milk quota, step by step (data not shown). These 'strategic measures' influenced grassland management and hence its nitrogen regime, partly for 'logistic reasons' (time management) and partly because of the addition of land with low soil fertility (data not shown).

Another important difference in grassland management between 'best performing farms' (F1, F2, F3) and 'average performing farms' (F9, F14) is the grazing intensity. Low grazing intensity leads to a combination of high dry matter yields and high NUEs (F2 and F3), whereas a substantial grazing intensity results in lower dry matter yields and lower NUEs, as in systems with intensive grazing nutrient losses are high (e.g., Ball & Ryden, 1984; Haynes & Williams, 1993; Whitehead, 1995; Verloop et al., 2006). Moreover, systems without grazing are logistically easier to handle, i.e. the risk of 'mismanagement' is lower (e.g. plot size, avoiding soil compacting, a constant feed supply). On the other hand, grazing systems are less labour-intensive and their costs are lower, as mechanical harvesting is not needed and housing requirements are simpler. Charlton et al. (2011) reviewed the pros and cons between grazing systems and indoor housing systems. It is generally assumed that grazing provides cattle with better welfare compared to indoor housing systems. Moreover, over the past years in the Netherlands, a strong societal demand for grazing systems emerging.

Table 3 *Farm characteristics of commercial pilot dairy farms in the project 'Cows & Opportunities'. Data are averages for the period 2000-2009. For more characteristics of the farms, see Table 1.*

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	Avg
Farm size (ha)																	
Area																	
- grassland	43	31	33	28	44	23	38	27	36	47	26	27	18	78	41	33	36
- grassland with restrictions[a]	0	4	0	0	0	7	0	10	24	7	0	8	0	0	0	0	4
- maize land	13	11	4	13	18	11	12	10	11	5	12	8	8	3	1	6	9
- other crops	8	0	5	0	4	0	0	0	5	4	0	0	0	3	0	1	2
Overall N management																	
N surplus farm (kg ha^{-1})	98	252	154	196	168	157	210	165	163	188	230	213	241	220	164	240	191
N surplus grassland (kg ha^{-1})	25	198	86	159	138	155	186	159	226	130	213	186	229	169	87	174	158
NUE farm (%)	42	37	35	37	33	38	30	33	32	32	34	35	37	29	36	33	34
NUE herd (%)	23	24	24	27	24	26	22	24	24	22	24	25	26	24	22	26	24
NUE grassland (%)	91	67	78	67	68	65	60	68	56	70	62	63	62	61	79	65	68
Herd & grassland management																	
Grazing time cows (h)[b]	477	32	0	853	1,614	1,580	866	2,062	1,134	695	1,798	573	1,496	2,003	2,652	597	238
Crude protein in ration (%)	14.2	15.4	15.5	15.2	15.5	13.9	15.0	16.3	15.4	15.8	15.4	15.5	16.0	17.0	17.2	16.2	15,6
N fertilization grassland (kg ha^{-1})																	
- applied manure	164	318	239	250	172	243	223	249	255	284	239	259	301	190	176	256	238
- excreta grazing	20	2	0	50	82	68	56	81	54	31	102	52	94	66	104	32	56
- chemical fertilizer	0	245	111	137	147	63	144	130	175	93	170	158	150	119	104	156	131
- N fixation clover	40	11	1	8	7	23	6	1	0	3	3	3	8	23	1	8	9
Soil characteristics																	
Moisture supply capacity (mm $year^{-1}$)[c]	3,5	2	3,7	n.a.	n.a.	n.a.	n.a.	n.a.	4	n.a.	n.a.	n.a.	n.a.	3	n.a.	n.a.	
Organic matter (%)	4,1	4,4	5,3	4,6	4,4	4,6	4,8	5,1	5,5	17,3	8,3	9,2	4,0	9,1	47,4	9,1	9,2
P_AL (mg P_2O_5 (100 gr $soil)^{-1}$)	45	46	54	53	28	51	42	44	45	26	39	41	50	114	50	16	47
N_total (mg N (100 gr $soil)^{-1}$)	1,669	2,470	1,938	1,658	2,149	1,567	1,871	2,002	2,268	8,090	2,437	2,490	1,439	4,841	1,9314	5,004	3,825
C:N ratio	15	11	16	17	12	18	16	15	14	12	20	23	17	11	15	10	15

[a] agri-environmental scheme's
[b] No. of grazing days x hours per day
[c] Classification of moisture supply capacity (mm) : 1: > 200; 2: 150-200; 3: 100-150; 4: 50-100; 5: <50

Grassland on the commercial pilot farms occupies almost 80% of the total area. Hence, grassland performance has a major impact on the overall performance of the farm. NUEs of the whole farm were higher on 'best performing farms' than on 'average performing farms' (Table 3), with higher NUEs for the grassland components and equal values for herd NUE. Average NUE of the whole farm on the pilot farms was 34%. In other countries, such as Scotland (Domburg et al., 2000), Ireland (Treacy et al., 2008), Japan (Kobayashi et al., 2010) and Italy (Segato et al., 2009) NUE of the whole farms were lower (28%, 20%, 25% and 27%, respectively). Only on Flemish 'progressive dairy farms' NUE of the whole farm were similar (38%; Nevens et al., 2006). Powell et al. (2010) reported an indicative range between 20 and 35% for NUE of the whole farm on various dairy farms. Average NUE of the herd on the pilot farms was 24% and was similar on dairy farms in Japan (Kobayashi et al., 2010). Courley et al. (2012) and Powell et al. (2010) reported a range for feed NUE from 15 to 35%. This feed NUE was based on only the lactating cows, young stock was not included.

Another important issue in grassland management is the timing of manure application in the course of the growing season. On average, about 45% of the manure was applied in the period February-April as fertilization for the first cut (Fig. 8a). After September 15, application of manure is prohibited. In the course of the period 2001-2009, manure application shifted to some extent (not significantly) from March (first cut) to May (mostly second cut). The distribution of manure application varies substantially among farms (Fig. 8b). For the first cut, F1 gave priority to application in March and F2 in February. The proportion of applied manure for the first cut is similar on both farms. Compared to the average distribution, F3 applied less manure for the first cut. Timing of the manure application on both F9 and F14 is similar to the average timing on the pilot farms. Apparently, not one single 'best strategy' exists in the distribution of manure application to grassland. Improvements in manure management on grassland must therefore be found in the fine-tuning of distribution of manure among fields.

Soil characteristics organic matter, N_total, P_AL and C:N ratio were not detected as factors in explaining variation in grassland performance. C:N ratio were the same on F1 with the high dry matter yields as on F14 with the low dry matter yields. On farms with high C:N ratio (F6, F11, F12) - suggesting that N is not easy available - NUE of grassland was not detected as relatively too low. On average, the levels of P_AL in the soil were high (a level of 20 is classified as low). A relation between P_AL and NUE and dry matter yield was not found. Even on F16 with the lowest P_AL level in the soil, NUE and dry matter yield were 'on average'. This farm applied extra P with chemical fertilizer to compensate the demand of P (data not shown).

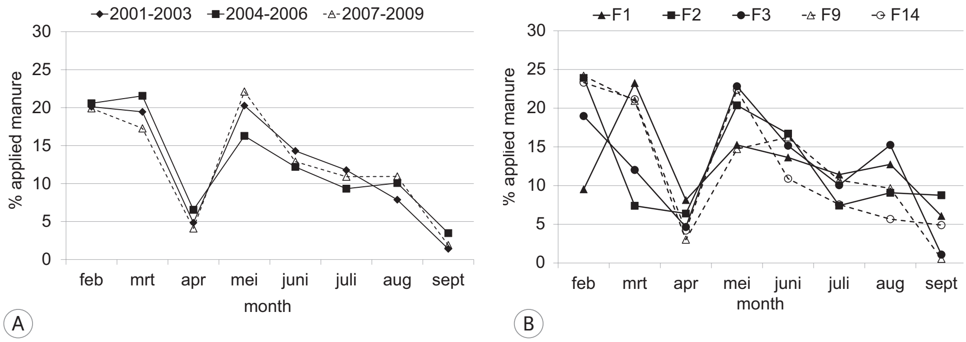


Fig. 8 *Distribution of applied manure on grassland in the course of the growing season on commercial pilot dairy farms in the project 'Cows and Opportunities': (a) as averages for three periods (2001-2003, 2004-2006 and 2007-2009), and (b) as average for the period 2001-2009 for five individual farms (black lines 'best performing farms', dashed lines 'average performing farms'; see text for explanation).*

3.7 How to interpret NUE?

A high NUE is one of the key features of environmentally and economically sustainable agricultural production systems (Ryan et al., 2010; Powell et al., 2010). The basic principle of using NUE as a performance indicator is to get insight in N management and losses to the environment. However, use of NUE as performance indicator can lead to misinterpretation. Definitions differ, depending on the perspective (Mosier et al., 2004). Environmental NUE can be quite different from agronomic or economic efficiency (Roberts, 2008). Dibb (2000) and Roberts (2008) include also the requirements for crop/food production, in combination with available land, in their definition of 'efficiency' as indicator, so, there must be a balance between environmental NUE and optimum crop production. Roberts (2008) and Powell et al. (2010) pointed out that NUE in dairy farming systems follows the 'law of diminishing returns' in low input systems, i.e. NUE is highest at the lowest N input, both at whole farm level (N output in milk and meat, N input in imported feeds - concentrates and roughages -, imported fertilizers - organic and chemical -, biological N fixation by clover and atmospheric deposition) and at field/crop level (N output in yield, N input in application rate). Interestingly, we observed no diminishing returns of dry matter yields on grassland at farm scale up to an N application rate of ca. 600 kg ha^{-1} (Fig. 4a). This is possible because the higher input levels are associated with both better soils and improved management. Clearly, the need for high input levels and improved management is more stringent on farms with a high production intensity (Mg milk per ha) allowing them to produce the higher dry matter yields needed for such farms.

From an agronomic point of view, F2 is the 'best' farm in terms of dry matter yields. F1 realizes the highest NUE, but at a low production. Results of a specific farm cannot be interpreted without the context of the farm because that may lead to wrong interpretations and recommendations for farmers and other stakeholders.

Identification of opportunities to improve N management on grassland requires a systems approach, i.e. consideration of farm characteristics, including grazing regime and 'site-specific conditions', such as soil characteristics.

4 Conclusions and further research

Possibilities for improvement of nitrogen (N) management on grassland of dairy farms are bounded by site-specific biophysical conditions, such as weather patterns and soil moisture supply. However, analysis of the variability in realized dry matter yields and NUE on commercial pilot farms over the 1998-2009 period indicates that substantial improvements in N management on grassland are possible on many commercial dairy farms, but strategies differ among farms.

In our sample of 16 farms we observed at farm scale no trend of diminishing returns of dry matter yields up to an N application rate on grassland of ca. 600 kg ha^{-1}. Farms with a high production intensity (Mg milk per ha) need more dry matter than farms with a lower intensity and were able to increase nitrogen management on grassland with high N input levels.

In the course of the years, farms tended to produce closer to the frontier defined by the most efficient farms (in terms of dry matter yield per unit N input). This leads to the suggestion that continuing intensive coaching and knowledge transfer may further improve nitrogen management on grassland. Making use of the variation of management on grassland and on the whole farm on pilot farms may provide farmers outside the project insight in the (im)possibilities to improve N management on grassland. Further research is needed about the adaptation of improved management on dairy farms in practice (farmers who participate in study groups and/or farmers with less coaching). Management options that result in improved NUE include reduced grazing time which results in increased dry matter yields and NUE as a consequence of better utilization of organic manure (less excreta voided during grazing and more collected manure which can be distributed and applied when needed). We assumed that the timing of manure application in the course of the growing season would also be important for improving nitrogen utilization on grassland, but this was not confirmed in our study. Application of manure in the Netherlands is restricted to the period from Feb. 1 to Sept. 15. Approximately 45% of the manure is applied for the first cut. Variation in the distribution of manure application is substantial among farms, but seems not to affect the utilization efficiency of nitrogen on grassland. More detailed monitoring of manure application in an experimental design is needed to investigate the effect of timing of manure application on grassland.

Legislation based on nutrient surpluses as applied in the period 1998-2003 was very effective in reducing N surplus and improving NUE. The legislation based on N application standards, introduced in 2006, was not effective in further reducing N surplus on grassland, at least partly caused by the fact that the derogation for dairy farms did not result in further reduction of N application rates on grassland.

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CHAPTER 5

MULTI-SCALE EFFECTS OF MANAGEMENT, ENVIRONMENTAL CONDITIONS AND LAND USE ON NITRATE LEACHING IN DAIRY FARMS

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Abstract

Nitrate leaching in intensive, grassland- and silage maize-based dairy farming systems on sandy soil is a main environmental concern. Here, statistical relationships are presented between management practices and environmental conditions and nitrate concentration in shallow groundwater (0.8 m depth) at farm, field and point scales in the Netherlands, based on data collected in a participatory approach over a seven-year-period at one experimental and 8 pilot commercial dairy farms on sandy soil. Farm milk production ranged from 10 to 24 Mg ha^{-1}. Soil and hydrological characteristics were derived from surveys, and weather conditions from meteorological stations. Statistical analyses were performed with multiple regression models. Mean nitrate concentration at farm scale decreased from 79 mg l^{-1} in 1999 to 63 in 2006, with average nitrate concentration in groundwater decreasing under grassland, but increasing under maize land over the monitoring period. The effects of management practices on nitrate concentration varied with spatial scale. At farm scale, nitrogen (N) surplus, grazing intensity and the relative areas of grassland and maize land significantly contributed to explaining the variance in nitrate concentration in groundwater. Mean nitrate concentration was negatively correlated to the concentration of dissolved organic carbon in the shallow groundwater. At field scale, management practices, soil, hydrological and climatic conditions all significantly contributed to explaining the variance in nitrate concentration in groundwater under grassland and maize land. We conclude that on these intensive dairy farms, additional measures are needed to comply with the EU water quality standard in groundwater of 50 mg nitrate l^{-1}. Most promising measures are omitting fertilization of catch crops and reducing fertilization levels of first-year maize in the rotation.

1 Introduction

The availability of relatively cheap nitrogen (N) fertilizers has greatly contributed to the boost in crop production and indirectly also in animal production since the 1950s, especially in affluent and rapidly developing countries (Smil, 2001; Mosier et al., 2004). However, the use efficiency of applied fertilizer N, in terms of increased dry matter, is rather low in most current production systems, and, as a consequence, N losses to the wider environment are relatively high, with significant local and global ecological implications (e.g. Cartwright et al., 1991; Novotny, 1999; Pretty et al., 2003; Mosier et al., 2004; Galloway et al., 2008).

N surplus (i.e. input minus output on a balance) is a key indicator for the pressure of agricultural N use on the environment. N use efficiency in crop production greatly depends on crop type, environmental conditions and N application rate (Ladha et al., 2005). In crops with dense and year-round soil cover such as perennial grasses N use efficiency is usually high, while in crops with short growing seasons it is usually low. Furthermore, N use efficiency tends to decrease with increasing N application rate (Roberts, 2008). In animal production systems, N use efficiency strongly depends on animal category and management, and manure management. Especially in intensive animal production systems, N use efficiency is relatively low and N losses are high (Rotz et al., 2005; Powell et al., 2010). N loss pathways are governed by fertilizer type (animal manure, chemical fertilizer), climate, soil-hydrological conditions and N loss mitigation measures (Hatfield & Follet, 2009). Main N loss pathways are leaching, denitrification and ammonia volatilization, the latter process mainly associated with urea fertilizers and animal manures.

Nitrate leaching from agricultural land is a major concern, as it leads to pollution and eutrophication of groundwater and surface waters and thus negatively affects their quality at local, regional and supra-regional scales (Matson et al., 1997). To protect groundwater and surface waters from pollution by nitrates from agriculture, the European Union (EU) has adopted the Nitrates Directive (EC, 1991), which obliges Member States to implement measures that guarantee nitrate concentrations in groundwater and surface waters not exceeding the standard of 50 mg l^{-1}.

In the Netherlands, more than 60% of agricultural land is used for dairy farming. Grass is the most important crop, followed by silage maize. Especially on sandy soils, nitrate leaching is an important N loss pathway (Vellinga et al., 2001; Fraters et al., 2005). Nitrate leaching on dairy farms can be reduced by optimizing farm management (e.g. Aarts et al., 1992; Di & Cameron, 2002; Verloop et al., 2006), as various management practices affect nitrate leaching, such as timing of fertilizer application, application method of animal manure and rate of N application (Cameron et al., 1996; 1999; Ledgard et al., 1999; Van Es et al., 2006), grazing management (Scholefield et al., 1993; Owens & Bonta, 2004), cropping sequences and age of the grassland sward (Eriksen et al., 2004). Many management practices have been tested in field and lysimeter experiments (Scholefield et al., 1993; Cameron et al., 1996; 1999; Ledgard et al., 1999; Eriksen et al., 2004; Van Es et al., 2006) or in a farming system perspective (Verloop et al., 2006). Various strategies to reduce nitrate leaching have been analyzed (e.g. Dinnes et al., 2002; Di & Cameron, 2002; Nangia et al., 2008), and it has been frequently observed that the effectiveness of management practices strongly depends on weather patterns and soil characteristics (e.g. Lund et al., 1974; Boumans et al., 2005).

To meet the EU standard for nitrate leaching, it is important to know which management practices effectively reduce nitrate leaching on different farms and to gain insight in the extent to which management practices are effective under different soil characteristics and climatic conditions. In practice, the complexity is even larger, as management measures are implemented as a package of farm-specific measures. So far, only few packages have been analyzed at field and farm scales, mainly on experimental farms, such as the experimental dairy farm 'De Marke' (Aarts et al., 1992; Verloop et al., 2006), at which the variability in soil characteristics is limited.

The current study was set-up with the purpose of exploring the effects of a range of management practices on nitrate leaching and other nutrient losses on commercial dairy farms. The set-up of the study and the background of the project 'Cows & Opportunities' have been described by Oenema et al. (2001), while the effects of management practices on N and P surpluses were presented in Oenema et al. (2011). This paper addresses the effects of farm management practices and soil and climatic conditions on nitrate leaching from grassland and maize land on sandy soils at three spatial scales, i.e. farm, field and sampling point. Land use in these systems consists for 95% of grassland and maize. We used data collected over a six-year-period at one experimental and eight commercial dairy farms. Results and insights of this study can be used to support further development and refinement of policy instruments in The Netherlands to comply with the EU Nitrate Directive.

2 Materials & Methods

2.1. Origin of data

Data were collected on experimental dairy farm 'De Marke' (Aarts et al., 1992; Aarts, 2000) and on 8 out of a total of 16 pilot commercial dairy farms from the project 'Cows & Opportunities' (Oenema et al., 2001). The pilot farms cover the full range of conditions in intensive dairy farming in the Netherlands, to facilitate acceptance of the results from these pilot farms by other farmers. For this study, only farms on sandy soils, located in the east and south of the Netherlands, were selected, on which an identical procedure for groundwater monitoring was applied (Fig. 1).

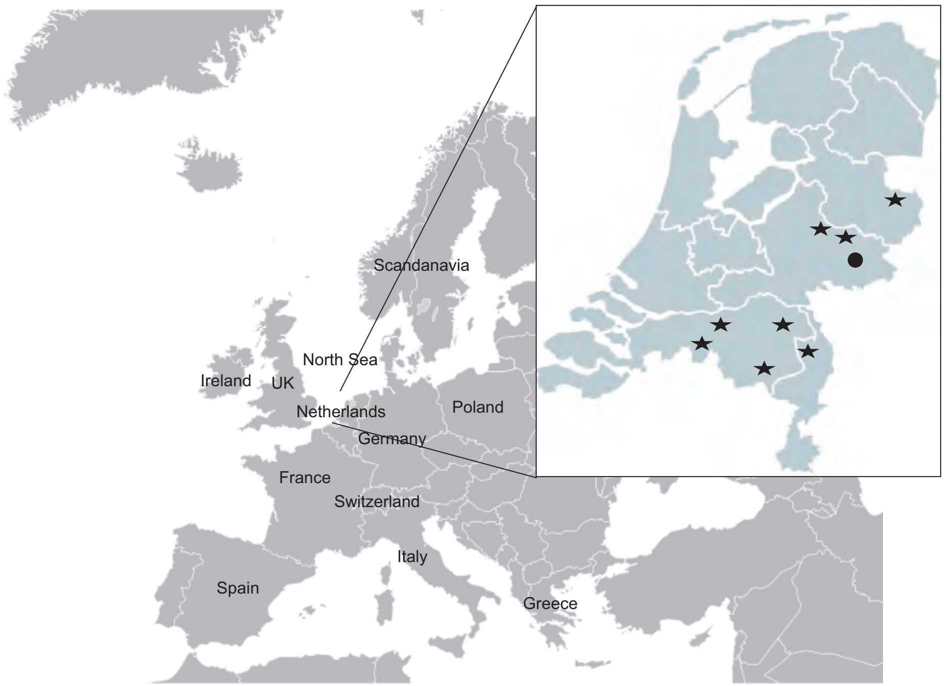

Fig. 1 *Location of the farms in The Netherlands. Stars indicate commercial pilot farms. The circle indicates the experimental dairy farm 'De Marke'.*

Table 1 *Data collected at the farms with their means and ranges at the spatial scale of measurement.*

Variable	Explanation	Scale[†]	Mean	Range
	Groundwater			
DOC	Water soluble organic matter content in groundwater ($mg\ l^{-1}$)	WF	22	(5 - 59)
Sulfate	Sulfate concentration in groundwater ($mg\ l^{-1}$)	WF	55	(14 - 148)
GWT	Groundwater table depth at the time of sampling groundwater (cm below soil surface)	P	190	(30 - 500)
	Hydrology and soil properties[‡]			
MHW	Mean highest groundwater table sampling point in summer (depth below soil surface; cm)	P	89	(20 - 251)
MLW	Mean lowest groundwater table sampling point in winter (depth below soil surface; cm)	P	200	(100 - 320)
SOM	Soil organic matter content upper layer (%)	P	4.3	(1.5 - 13)
DeptSom	Depth of presence of soil organic matter (cm below soil surface)	P	97	(25 - 320)
SOMmhw	Soil organic matter below MHW (0 = absent; 1 = present)	P	0.4	(0 - 1)
SOMmlw	Soil organic matter below MLW (0 = absent; 1 = present)	P	0.22	(0 - 1)
Peat	Peat layers in subsoil (0 = absent; 1 = present)	P	0.06	(0 - 1)
CN	Carbon-Nitrogen ratio in organic matter (see text for explanation)	F	16.6	(10.5 - 25.6)
LoamMHW	Average loam content above MHW (%)	P	13	(0 - 40)
LoamMLW	Average loam content between MHW and MLW (%)	P	18	(0 - 61)
	Mean weather conditions			
Pseason[§]	Cumulative precipitation March 1 - October 31 (mm)	WF	573	(404 - 880)
Pwinter	Cumulative precipitation November 1 - February 28 (mm)	WF	298	(199 - 390)
Pwinter_1[§]	Cumulative precipitation November 1 - February 28 (mm)	WF	300	(162 - 390)
Tautumn[§]	Mean daily temperature October 1 - November 30 (°C)	WF	13.4	(9.7 - 15.0)
Twinter	Mean daily temperature November 1 - February 28 (°C)	WF	4.0	(2.5 - 4.9)
	Farm management[§]			
Intens	Farm intensity ($Mg\ milk\ ha^{-1}$)	WF	14.9	(9.8 – 24.9)
frGrass	Relative area of grassland on farms (0-1)	WF	0.68	(0.53 - 0.92)
NsrpFarm	N surplus on the farm balance ($kg\ ha^{-1}$)	WF	192	(86 - 300)
NsrpCrop	N surplus on the field balance ($kg\ ha^{-1}$)	F	178	(-149 - 504)
GrazingH	Grazing pressure (cow hours ha^{-1})	F	154	(0 - 985)
NinpTot	Total N input in animal manure, mineral fertilizer and clover ($kg\ ha^{-1}$)	F	400	(0 - 876)
NinpMan	N input in animal manure ($kg\ ha^{-1}$)	F	229	(0 - 582)
NinpFert	N input in chemical fertilizer ($kg\ ha^{-1}$)	F	111	(0 - 301)
AgeCrop	Years of continuously growing crops or years of crop in rotation	F	7.5	(1 - 37)
FirstCrop	First year crop in a crop rotation (0 = no; 1 = yes)	F	0.13	(0 - 1)
Reseed	Plowing up and reseeding permanent grassland (0 = no; 1 = yes)	F	0.02	(0 - 1)

[†] Sampling point (P), field (F) and whole farm (WF).
[‡] Invariable between years.
[§] Year prior to nitrate sampling.
[¶] Number of animals per ha × number of grazing days × (hours per day/24) × Animal Units (AU), where 1 milking cow = 1 AU; 1 young stock > 1 year = 0.439 AU; 1 young stock < 1 year = 0.22 AU.

Table 2 *Farm (n=9) characteristics in 1998 and 2005; means, ranges and the differences between means in the two years.*

General farm characteristics	1998		2005		Difference (%)
	Mean	Range	Mean	Range	
Milk production (intensity) (Mg ha^{-1})	15.0	(10.1 - 21.0)	14.3	(9.7 - 24.9)	-5
Land area (ha)	41.3	(22 - 60)	50.8	(23 - 81)	19
AU† (ha^{-1})	2.6	(1.9 - 3.7)	2.0	(0.0 - 3.2)	-30
Grassland (fraction)	0.6	(0.53 - 0.80)	0.7	(0.60 - 0.90)	13
Milk yield. (kg cow^{-1})	7915	(6343 - 10151)	8000	(6500 - 9500)	1

† Animal unit: 1 milking cow = 1 AU; 1 young stock > 1 year = 0.439 AU; 1 young stock < 1 year = 0.22 AU.

Information on farm characteristics and farm management was collected annually from 1998 to 2005. Farm management characteristics were obtained through frequent registration by the farmers and extension agents and through measurements (Oenema et al., 2011), either at field or whole farm scale (Table 1). N surplus at farm scale (NsrpFarm) was established by registration of N inputs in imported feeds (concentrates and roughages), imported fertilizers (manure and chemical fertilizer), imported animals, biological N fixation and atmospheric deposition, and N outputs in exported milk, animals, manure and roughage. Other characteristics at farm scale are farming intensity (intens), expressed as milk production per ha and the relative area of grassland within a farm (frGrass). All other farm management practices refer to the field scale. General farm characteristics and farm management characteristics are given in Table 2.

Groundwater was sampled between May and October and analyzed on each farm once per year from 1999 to 2006. The magnitude of nitrate leaching from soils is best reflected in the nitrate concentration in shallow groundwater. Based on 30-years meteorological data, we assume a net precipitation surplus in winter of 300 mm per year. Further, we assume that on these sandy soils soil moisture content at field capacity is about 100 mm in the root zone (50 cm) and also 100 mm between root zone and depth of the groundwater table, which is on average at 100 cm below the soil surface. Most of the residual nitrate in the soil at the end of the growing period will leach to the shallow groundwater during autumn and winter, due to the precipitation surplus. Annual and regional variations in precipitation surplus and mean groundwater level are substantial, and as a consequence, it may take between 1 and 3 years before all residual nitrate in the soil profile has reached the shallow groundwater. On each of seven pilot farms, 48 boreholes were made, randomly distributed, proportionally per field, based on field size. On one farm, only 16 boreholes were made. Samples were taken each year at about the same locations, if possible. At 'De Marke', three samples were taken per hectare (in total about 170), each year at about the same locations (Boumans et al., 2001). The 170 samples at 'De Marke' were reduced to 48 by grouping samples on the basis of nearest samples. Groundwater was sampled from boreholes, made with an auger to 0.8 m below the groundwater table, using a perforated PVC-tube connected to a pump with a filter. Nitrate concentration values were determined instantaneously with test strips and a Nitrachek Reflectometer (Fraters et al., 1998). Per spot, two strips were used to measure nitrate concentration. A third strip was used when the variation in concentration between the two strips exceeded 10% (Boumans et al., 2001). At each sampling point, the actual depth of the groundwater table was monitored. For cost efficiency reasons, further chemical analyses (including phosphorus, calcium, chloride, sodium, cadmium, copper, dissolved organic carbon and sulfate) were performed on bulked samples per farm by mixing all samples of all fields and crops. Dissolved organic carbon (DOC) and sulfate concentration (sulfate) were used as explanatory variables for nitrate concentration in groundwater, because of their indicator value for denitrification (and pyrite oxidation through nitrate reduction) (Burford & Bremmer, 1975; Bijay-Singh et al., 1988; Postma et al., 1991). As about 70% of the fields were in grassland, DOC and sulfate concentration in groundwater at farm scale reflect predominantly their concentrations in groundwater under grassland.

Daily temperature and rainfall were taken from the nearest meteorological stations of the Royal Netherlands Meteorological Institute (www.knmi.nl), for each farm. In total 9 stations were involved (Table 3). For the purpose of regression analysis, we transformed rainfall and temperature data to cumulative and average values, respectively (see Table 1).

Table 3 *Annual precipitation and temperature per year, averaged for the 9 farms.*

Year	Precipitation (mm)				Daily temperature (°C)			
	Pseason†		Pwinter		Tautumn		Twinter	
	Mean	sd	Mean	sd	Mean	sd	Mean	sd
1998	812	77	313	38	12.0	0.4	3.6	0.3
1999	501	30	330	26	14.1	0.1	4.6	0.1
2000	642	58	287	30	13.3	0.3	4.6	0.3
2001	641	49	369	24	13.7	0.2	4.6	0.1
2002	522	48	287	21	11.8	0.5	3.1	0.7
2003	469	37	322	33	10.6	0.6	4.6	0.3
2004	561	52	271	29	13.1	0.3	3.5	0.2
2005	528	53	221	30	14.6	0.5	3.0	0.3

† See Table 1 for explanation of the variables.

General soil characteristics (Table 1) were obtained from soil surveys carried out once at virtually all groundwater boreholes (Dekkers, 1992; Velthof et al., 2004). The C:N ratios (CN) were calculated from soil analyses at field scale, and were invariable for each sampling point within a field. Soils were sampled annually (grassland 0-10 cm; arable land 0-20 cm) on all fields in the winter period, to monitor changes in soil fertility status. Total N content was measured by the Kjeldahl technique. In soils expected to be low in organic matter, soil organic carbon (SOC) was determined through elemental C analysis, following dry combustion (Yeomans & Bremner, 1991; Soon & Abboud, 1991). On s General farm characteristics oils expected to be rich in organic matter (all grassland samples), loss of ignition (NEN 5754, 2005) was used to determine SOM directly, using corrections for inorganic carbonates, and percentage clay in the soil. SOC was calculated as SOM × 0.5 (Reijneveld et al., 2009). Each field was characterized by a single CN-value, averaged over all years.

The total dataset consisted of 69 data points at whole farm scale (number of farms x years), 750 at field scale for grassland (number of fields with grassland x years), 230 at field scale for maize land, 1509 at sampling point scale for grassland, and 523 at sampling point scale for maize land.

2.2. Data analysis

Relationships between explanatory variables and nitrate concentration were studied at three spatial scales: whole farm, field and sampling point. At sampling point scale and at field scale, two crops were distinguished: grass and maize. A field (and sampling point) was characterized by the crop grown (either grass or maize) in the season before sampling groundwater. For the whole farm scale, the corresponding data of fields and sampling points within the farm were averaged to that scale. Depending on variable type, aggregated variables are expressed as means or fractions.

The statistical analyses were performed with multiple regression models. We established regression models for nitrate concentration using the variables from Table 1 as potential explanatory variables (regressors). The relevance of variables was tested using the RSEARCH procedure in GenStat (all possible subset selection; Genstat 12 (2009)). Only variables of Table 1 that are sufficiently uncorrelated ($r<0.70$) have been included in the selection process to avoid the problem of colinearity (Ott & Longnecker; 2010). In case of high correlations, one of the variables was selected for inclusion in the selection process. To identify the best parameter combinations, the percentage of variance accounted for (R^2_{adj}, i.e. adjusted for the number of parameters), the value of Mallows' C_p (Ott & Longnecker, 2010), and the p-value of the parameter estimates were evaluated. We selected models with the highest R^2_{adj} and low C_p ($C_p<p'+3$, with p' the number of parameters in the model) and significant parameters ($P<0.05$).

At whole farm scale, the first model (Model 1) was based on a selection of variables monitored at farm scale. A second model (Model 2) was based on a selection of variables monitored at farm and field scale, followed by a third model (Model 3) based on a selection of all variables. At field scale - both for grassland and maize land - models were selected based on a selection of variables monitored at farm and field scale (Models 4 and 6, respectively) and in a second step based on all variables (Models 5 and 7, respectively). At sampling point scale - both for grassland and maize land - Model 1 was fitted, followed by the selected models at field scale.

Because datasets were unbalanced and include observations at different scales, the parameter estimates of the regression models at different scales were compared with those of the REML algorithm (method of residual maximum likelihood; Genstat 12 (2009)). The REML algorithm estimates treatment effects and variance components in a linear mixed model with both fixed and random variables (random = (farm×year)/field).

To investigate the effect of *all* variables, they were added one by one to the most basic model at sampling point scale ('base model'), both for grassland (Model 1) and maize land (Model 6), and the effect was calculated as the difference between the nitrate concentration estimated at the 25%-quantile and the 75%-quantile of that variable.

3 Results

3.1 Observed nitrate concentration

Fig. 2 summarizes observed nitrate concentration in the groundwater (medians plus ranges) at farm scale (A) and at field scale for grassland (B) and maize land (C). Due to the (large) variation among farms within a year, there was no significant time trend at farm scale. Mean nitrate concentration in groundwater at farm scale decreased from 79 mg l^{-1} in 1999 to 59 mg l^{-1} in 2003, followed by an increase to 66 mg l^{-1} in 2005, and again a decrease to 63 in 2006. Nitrate concentration in groundwater was higher on maize land than on grassland. Mean nitrate concentration on grassland showed a significant decrease over time ($p=0.02$ of the slope in a linear regression), whereas the concentration on maize land showed a significant increase ($p=0.04$) (Fig. 2). At farm scale, averaged for all years, 75% of the measured nitrate concentration values exceed the limit of 50 mg l^{-1}, but this percentage varies over time (Table 4). The percentage of measured nitrate concentration values exceeding the limit of 50 mg l^{-1} at field scale is lower on grassland (52%) than on maize land (80%). The pattern is similar at sampling point scale, but at lower levels of exceedence (48 and 72%, respectively). The frequency distributions of nitrate concentration values at field and sampling point scale are skewed to the right, resulting in relatively high averages at farm scale. The standard deviation at sampling point scale (within a farm and year) was 49 mg nitrate l^{-1} on grassland and 57 on maize land. The standard deviation at field scale was 42 on grassland and 47 mg nitrate l^{-1} on maize land. The variation in nitrate concentration among farms was less (sd=25 mg nitrate l^{-1}).

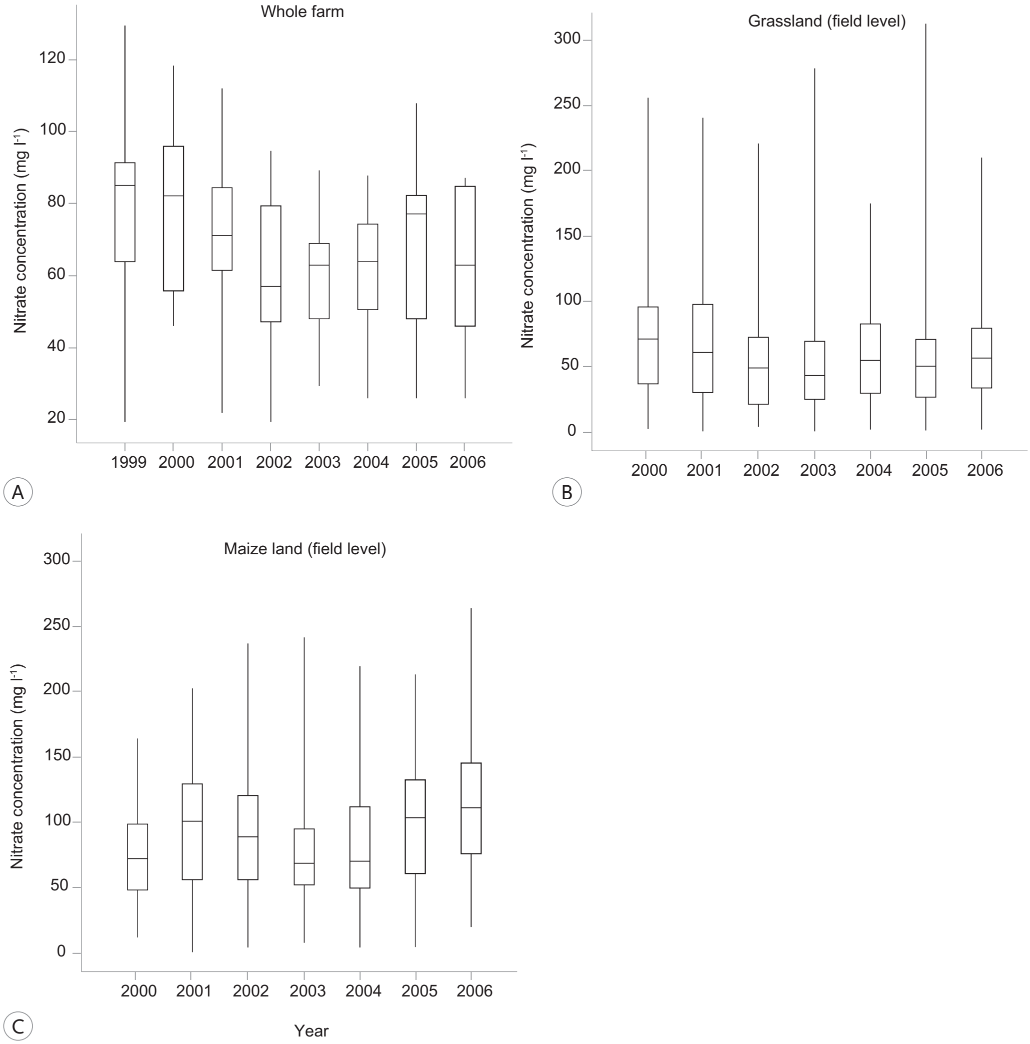

Fig. 2 *Distribution of average nitrate concentration in upper groundwater in box-and-whisker plots for eight years for the whole farm (A), for grassland at field level (B) and maize land at field level (C). The box covers the interquantile range (25% to 75%) of the values, so that the middle 50% of the data are within the box, with a line indicating the median. Whiskers indicate minimum and maximum observed values.*

3.2. Models at whole farm scale

The best model - based on highest R^2_{adj} and low Mallows' C_p - on a selection with only uncorrelated explanatory variables monitored at whole farm scale is:

$NO_3 = 26.3 + 0.27 \times NsrpFarm - 0.49 \times DOC$ *Model 1*

Additional statistical information on the model is given in Table 5. For ranges of the variables, see Table 6. Nitrate concentration increased with 27 mg l^{-1} per 100 kg N ha^{-1} surplus at farm scale. Dissolved organic carbon concentration reduced the nitrate concentration with 0.49 mg l^{-1} per mg l^{-1} DOC.
A selection with uncorrelated variables monitored at whole farm and field scales results in the model:

$NO_3 = 38.8 + 0.12 \times NsrpFarm - 0.52 \times DOC + 0.13 \times GrazingH$ *Model 2*

Variables NsrpFarm, NsrpCrop and NinpTot were correlated and NsrpFarm is selected for inclusion as explanatory variable, because intuitively a better relationship with nitrate concentration was expected. Variable GrazingH was added in model 2. Because of the positive correlation between NsrpFarm and GrazingH (r=0.65), part of the contribution of NsrpFarm to nitrate concentration is taken into account through GrazingH. Model 2 indicates that the nitrate concentration decreases with 13 mg l^{-1} with each 100 cow hours ha^{-1} reduction in grazing intensity.
A selection with all uncorrelated variables results in the model:

$NO_3 = 55.9 - 79 \times frGrass + 0.17 \times GrazingH + 0.38 \times MHW + 0.09 \times DeptSOM$
Model 3

Variables SOM, CN and peat were correlated and SOM is used in the selection as explanatory variable. Variables DeptSOM, SOMmhw and SOMmlw were correlated and DeptSOM was selected for inclusion as explanatory variable, because intuitively a better relationship with nitrate concentration was expected. NsrpFarm and DOC are replaced by frGrass, MHW and DeptSOM. Dissolved organic carbon concentration is correlated with MHW (r=0.65) and is therefore replaced. Model 3 indicates that the nitrate concentration decreases by 7.9 mg l^{-1} when the relative area of grassland increases by 10%. DeptSOM increases the nitrate concentration by 0.09 mg l^{-1} per cm increase in the presence of SOM in the soil profile.

Table 5 *Estimated regression coefficients (a through k) with standard error (se), percentage of variance accounted for (R^2_{adj}), and standard error of the model (se, mg nitrate l^{-1}) for 6 models for the analysis with nitrate concentration at the whole farm (A), at field scale (B and C) and at sampling point scale (D and E). See Table 6 for values of ranges of the parameters.*

(A) Analysis at the whole farm scale

	Model 1		Model 2		Model 3	
Parameter	**estimate**	**se**	**estimate**	**se**	**estimate**	**se**
C	26.3**[§]	8.8	38.8***	8.9	55.9***	14
a (NsrpFarm)	0.27***	0.04	0.12*	0.05		
b (DOC)	-0.49**	0.15	-0.51***	0.14		
c (frGrass)					-79***	20
d (GrazingH)			0.13***	0.03	0.17***	0.03
e (MHW)					0.38***	0.08
f (DeptSOM)					0.09*	0.03
R^2_{adj}	43		54		59	
sd	18		15		15	
n	69		64		64	

(B) Analysis at field scale: grassland

	Model 1		Model 4		Model 5	
Parameter	**estimate**	**se**	**estimate**	**se**	**estimate**	**se**
C	40***	5.4	38.3***	5.7	6.3	8
a (NsrpFarm)	0.17***	0.03			0.15***	0.04
b (DOC)	-0.54***	0.11	-0.42***	0.11		
d (GrazingH)			0.04***	0.01	0.05***	0.01
e (MHW)					0.23***	0.03
g (NsrpCrop)			0.06**	0.03	0.06**	0.02
h (NinpFert)			0.06*	0.03		
f (reseed)			25*	10		
i (SOM)					-4.7	1
R^2_{adj}	6		10		17	
sd	43		42		41	
n	750		748		748	

Table 5 *Continued*

(C) Analysis at field scale: maize land

	Model 6		Model 7	
Parameter	**estimate**	**se**	**estimate**	**se**
C	-18.5	32	59.2***	15
e (MHW)			0.22***	0.06
f (DeptSOM)			0.29***	0.04
i (SOM)			-11***	3.3
j (NinpTot)	0.11**	0.04	0.10*	0.04
k (Tautumn)	6.7**	2.5		
l (FirstCrop)			25***	7.4
R^2_{adj}	6		24	
sd	49		44	
n	230		230	

(D) Analysis at sampling point scale: grassland

	Model 1		Model 4		Model 5	
Parameter	**estimate**	**se**	**estimate**	**se**	**estimate**	**se**
C	28.7***	5.4	34.5***	4.6	5.8	6.5
a (NsrpFarm)	0.22***	0.03			0.17***	0.03
b (DOC)	-0.42***	0.09	-0.30***	0.09		
d (GrazingH)			0.05***	0.009	0.05***	0.009
e (MHW)					0.20***	0.03
g (NsrpCrop)			0.06***	0.02	0.06***	0.02
h (NinpFert)			0.06*	0.02		
f (reseed)			29***	8.5		
i (SOM)					-4.8***	0.9
R^2_{adj}	6		9		13	
sd	50		49		48	
n	1509		1505		1505	

(E) Analysis at sampling point scale: maize land

	Model 6		Model 7	
Parameter	**estimate**	**se**	**estimate**	**se**
C	-34.7	26	60.9***	12
e (MHW)			0.28***	0.05
f (DeptSOM)			0.30***	0.03
i (SOM)			-13***	2.6
j (NinpTot)	0.09**	0.03	0.09**	0.03
k (Tautumn)	8.13***	2		
l (FirstCrop)			22***	6.1
R^2_{adj}	5		20	
sd	61		56	
n	523		523	

§ Significance of the regression coefficient of the variable: * P<0.1; ** P<0.05; *** P<0.001.

3.3 Models at field scale

When Model 1, based on data at the whole farm scale, is fitted to the grassland dataset, R^2_{adj} decreases and the model error increases (Table 5). Fitting model 1 to the maize land dataset yields no significant parameter estimates.
The best models for grassland are:

NO_3 = 38.2 + 0.06 × NsrpCrop - 0.42 × DOC + 0.04 × GrazingH + 0.06 × NinpFert + 25 × Reseed *Model 4*

NO_3 = 6.3 + 0.15 × NsrpFarm + 0.06 × NsrpCrop + 0.05 × GrazingH - 4.7 × SOM + 0.23 × MHW *Model 5*

The best models for maize land are:

NO_3 = -18.5 + 0.11 × NinpTot + 6.7 × Tautumn *Model 6*

NO_3 = 59.2 + 0.10 × NinpTot + 0.22 × MHW - 11 × SOM + 0.29 × DeptSOM + 25 × FirstCrop *Model 7*

Model 4 (grassland) is the result of the best parameter combination in a selection of uncorrelated variables monitored at whole farm and field scales. Correlated variables were NsrpCrop and NinpTot, and NsrpCrop is used as explanatory variable. Variable NsrpFarm is not selected in the model and is replaced by NsrpCrop, GrazingH, NinpFert and Reseed. The effect of GrazingH is weaker than in the models at whole farm scale (Models 2 and 3). Model 5 is the result of the best parameter combination in a selection with all uncorrelated variables. Correlated variables were MHW and MLW, DeptSOM and SOMmlw, with MHW and DeptSOM being used as explanatory variables. Similar to the farm scale (Model 3), DOC is replaced by MHW. Variable NsrpFarm is again selected, together with NsrpCrop and GrazingH. The model is completed with SOM and MHW, monitored at sampling point scale.

Model 6 (maize land) is the result of the best parameter combination in a selection of uncorrelated variables monitored at whole farm scale and field scale. Variables NsrpCrop, NinpMan and NinpTot were correlated, but on maize land, the latter was more closely correlated to nitrate concentration and is therefore used as explanatory variable. Model 7 is the result of the best parameter combination in a selection with all uncorrelated variables. Variables MHW and MLW were correlated, as were DeptSOM, SOMmhw and SOMmlw, and SOM and peat. Rather subjectively, variables MHW, DeptSOM and SOM are selected for inclusion as explanatory variables. Compared to model 6, Tautumn is replaced by MHW, SOM, DeptSOM and FirstCrop. The latter, monitored at field scale, is only selected in combination with soil and hydrological variables monitored at sampling point scale.

3.4 Models at sampling point scale

When variables of Model 1 (whole farm scale), Model 4 (whole farm and field scale) and Model 5 (all) are fitted to the grassland dataset at sampling point scale, parameter estimates remain quite similar (Table 5). When Models 1, 6 and 7 are fitted to the maize land dataset, none of the parameter estimates of Model 1 are significant, while those of Models 6 and 7 remain quite similar.

3.5. REML analysis

Results of fitting Model 1 in a REML model to the grassland dataset at sampling point scale are different from those of the multiple regression analysis. The parameter estimate for NsrpFarm decreases from 0.22 to 0.03, i.e. the slope of the relation between nitrate concentration and NsrpFarm within farms is less steep than across farms. Subsequent regression analysis of the relation between nitrate concentration and NsrpFarm within individual farms shows the variation in this relation: Farms are characterized by either combinations of low nitrate concentration and low NsrpFarm or combinations of high nitrate concentration and high NsrpFarm. No single farm contains (across years) the full range of NsrpFarm values found in the entire dataset. Within farms showing a substantial range in NsrpFarm values across years (>100 kg N ha^{-1}), parameter estimates for NsrpFarm are similar to those in Model 1 across farms. Results of fitting other models at field and sampling point scale in a REML analysis are comparable to those of the multiple regression analysis (i.e. the same variables are significant with similar slopes). Hence, results from the multiple regression analysis are essentially similar to those from the REML analysis (individual farms), when the ranges in values of variables (NsrpFarm, management practices and/or soil and climatic conditions) are substantial.

3.6 Effects of all variables on nitrate concentration on grassland and maize land

The effect of the mean lowest groundwater table depth (MLW) on nitrate concentration in groundwater is stronger on maize land than on grassland (Table 6).

The effect of SOM on nitrate concentration is quite similar for maize land and grassland. The effect of CN is stronger on maize land than on grassland. Variable DeptSOM only affects the nitrate concentration on maize land. Presence of peat has a decreasing impact on the nitrate concentration on both grassland and maize land, but on the latter the effects are twice as strong (or more).

Variable Pwinter negatively affects the nitrate concentration on maize land. Higher Tautumn increases the nitrate concentration on grassland, but more strongly on maize land.

On grassland, N surplus variables, GrazingH and NinpTot are positively correlated with the nitrate concentration. On maize land, effects of N surplus variables and N rate variables (NinpMan, NinpFert) are omitted from the analysis because of confounding effects with the reference model. Plowing up grassland has a positive effect on nitrate leaching, both for reseeding grassland (reseed) and for maize as the subsequent crop in the rotation (FirstCrop). The effect of adding the latter to Model 6 is half as strong when FirstCrop is selected in the model, which is based on a selection with all uncorrelated variables (Model 7; see Table 5).

Table 6 *Effects of variables (see Table 1 for explanation) on nitrate concentration in the upper groundwater (mg L[1]), derived from regression analysis performed at the scale of sampling points (grassland and maize land). Effects were quantified across the range from the 25% (Q25) to the 75% (Q75) quantiles by addition of variables to the 'base model' (Model 1 for grassland, Model 6 for maize land).*

	Grassland				Maize land			
Variable	**Q25**	**Q75**	**Effect (mg l-1)**	**Sign§**	**Q25**	**Q75**	**Effect (mg l-1)**	**Sign§**
Groundwater								
DOC†	13	36	-10	***	8	33	6.6	
Sulfate	37	71	-0.5		41	71	-1.8	
GWT	140	220	2.7		140	226	12	***
Hydrology and soil properties								
MHW	60	115	11	***	55	110	11	***
MLW	165	235	17	***	160	234	33	***
SOM	3	4.5	-6	***	3	4	-6.5	**
DeptSOM	45	130	2		40	150	25	***
SOMmhw			-4.6				6.5	
SOMmlw			1.6				18	***
Peat			-31	***			-68	***
CN	15.6	18.5	-3.5	**	15.2	19.5	-10	*
LoamMHW	10.3	14.4	-2.2		11.2	17.3	2.4	
LoamMLW	12	20.2	-2.8	**	11.9	22.2	3.9	
Weather conditions								
Pseason	478	594	0.5		472	573	-3.5	
Pwinter	255	324	-0.4		250	318	-11	**
Pwinter_1	281	332	2.8		278	320	3.6	
Tautumn‡	12.2	13.9	3.8	*	12.2	13.9	13	***
Twinter	3.3	4.7	1.8		3.7	4.8	-5.3	
Farm management								
NsrpFarm†	146	219	10	***	154	223		
NsrpCrop	143	270	11	***	33	120		***
GrazingH	21	292	15	***				
NinpTot‡	374	530	9.5	***	170	255	7.6	
NinpMan	213	288	0		136	201		***
NinpFert	89	155	3.1	*	0	54		***
AgeCrop	3	10	3.2	**	2	7	5.7	
FirstCrop			-0.7				12	*
Reseed			23	**				

† Variable in reference model in grassland.
‡ Variable in reference model in maize land.
§ Significance of the regression coefficient of the variable: * $P<0.1$; ** $P<0.05$; *** $P<0.001$.

4 Discussion

Farm management and soil and climatic conditions strongly affect nitrate concentration in the shallow groundwater of grassland and maize land on intensively managed dairy farms, but the effects depend on the spatial scale (farm, field or sampling point). Our study shows for the first time that, due to the highly skewed frequency distribution of nitrate concentration, especially on grassland, but also on maize land, has a strong influence on the mean nitrate concentration at farm level. Also the high proportion of data points exceeding the limit of 50 mg l^{-1} at field and farm levels is the result of this frequency distribution.

4.1 Analysis

In the method of multiple regression (MR) there is only one term for the variance, whereas in REML a more complex structure of the variance can be part of the model. So, variables can be tested against the variance of their measurement level. However, the REML method cannot be combined with the RSEARCH procedure (see section 'data analysis') to identify the best parameter combinations, in contrast to MR. Therefore, the REML method was used only to compare with the results of MR. The results of MR and the REML method are contradictory in terms of the relation between nitrate leaching and Nsrpfarm, as the differences in Nsrpfarm among farms are large and consistent over the years, in contrast to the differences in Nsrpfarm over the years on a specific farm. The REML method detects that there is no positive correlation between Nsrpfarm and nitrate concentration in the shallow groundwater at farm scale. The MR method, which is ignorant of the origin of the data, cannot detect this relation. The REML method combines the information from within and among farms which results in a smaller effect of Nsrpfarm on nitrate concentration than the among farms effect only (MR method).

Unfortunately, for all models developed at field and sampling point scale, the resulting R^2_{adj} was low. Since the objective of the study was to identify variables influencing the nitrate concentration at different spatial scales, and not to establish predictive models, these results are useful.

4.2 Spatial variation and travel time

Table 4 shows that for both the sampling point and the field scale, the percentage of data points exceeding the limit of 50 mg nitrate l^{-1} was on average much higher on maize land than on grassland during the measuring period of 7 years. Interestingly, the percentage exceedence at farm scale is similar to that for maize land, while the mean area of maize land is much smaller than that of grassland. This apparent anomaly is caused by the large spatial variation in nitrate concentration on grassland and its highly skewed frequency distribution. Nitrate concentration in groundwater below urine patches is very high, while most of the grassland is not covered by urine patches and nitrate concentration in the groundwater below this area is relatively low. It has been well established that urine patches are a major source of nitrate leaching in grazed grassland (Cuttle et al., 2001; Ryden et al., 1984). Also in ley-arable farming systems, the spatial variation in nitrate concentration is substantial, especially when leys are grazed (Cuttle & Scholefield, 1995; Francis et al., 1998).

Estimated travel time of the residual soil N in autumn to groundwater varies between 1 and 3 years (see section 'origin of data'). The low variance (R^2_{adj}) in our regression models is partly the result of the uncertainty in estimated travel time. We assume in our models that the travel time of residual soil N to the sampled groundwater is approximately 1 year, in agreement with Derby et al. (2009). Verloop et al. (2006), however, showed that land use changes 2 to 4 years earlier had an effect on nitrate concentration in groundwater, and hence, on the relationships between N input variables and nitrate concentration. So, historical effects, originating more than 2 years earlier, can (at least partly) be responsible for the low R^2_{adj} of our models.

4.3 Farm management

It has been well established that the excreta of grazing animals contribute to nitrate leaching (Ball & Ryden, 1984; Haynes & Williams, 1993; Whitehead, 1995; Jarvis, 2000; Eriksen et al., 2004; Verloop et al., 2006). In our analysis at whole farm scale (Models 2 and 3), as well as at field and sampling point scales on grassland (Models 4 and 5), grazing intensity affects nitrate concentration. Improving grazing practice (intensity, timing) is one of the most important management practices to reduce nitrate leaching on dairy farms on sandy soil. Especially minimizing grazing intensity in autumn may contribute to reduced nitrate leaching, as the utilization by the crop of nitrogen from urine and dung deposits declines with the progression of the growing season (Cuttle & Bourne, 1993; Titchen et al., 1993, Lord, 1993; Verloop et al., 2006). However, grazing is preferable from the point of view of animal health and welfare. Moreover, grazing is appreciated for its contribution to an attractive rural landscape. Other important management practices that affect nitrate leaching are expressed in the N rate variables NinpTot and NinpFert. Nitrate leaching appears less sensitive to NinpMan than to NinpFert. Stoddard et al. (2005) also found, in the short term, a higher nitrate leaching risk from chemical fertilizer, but after three years, nitrogen originating from animal manure contributed more to nitrate leaching than that from chemical fertilizer. In intensive grassland- and maize land-based dairy farming systems it may be expected that regular additions of animal manure to land will contribute to a high basal soil organic nitrogen mineralization rate (Trindade et al., 2001; Sørensen, 2004; Schröder et al., 2005a). A high mineralization rate of accumulated manure-derived organic nitrogen increases nitrate leaching potential, especially in periods with little or no N uptake by the vegetation. Unfortunately, past animal manure applications on the farms in our study are unknown, but may have been large and substantially different among farms and among fields within a farm. As a consequence, the estimated effects of the N rate variables may be biased because of the unaccounted for residual effects of past manure applications.

Chemical N fertilizer application significantly affects nitrate leaching on maize land (Table 6). In general, chemical N fertilizer on maize land is mostly applied on nearly bare land as a starter application, in addition to an application of animal manure. Experiments in farming system 'De Marke' have shown that omission of the chemical fertilizer decreases nitrate leaching, without negatively affecting maize yields (Aarts, 2000; Verloop et al., 2006).

Plowing up grassland for rotational cropping has been shown to increase nitrate leaching (Whitmore et al., 1992; Hoffman, 1999). Our study also indicates that plowing up grassland for rotational cropping with maize or for reseeding to grassland, leads to increases in nitrate leaching. On first-year maize land (FirstCrop), the nitrate concentration is about 25 mg l^{-1} higher than in subsequent years (Model 7). The technology for converting grassland to maize land should be improved. In practice, after grassland is ploughed up, chemical N-fertilizer is applied before maize is sown. This application can be omitted, because the release of N from the ploughed-in grass sod is sufficient to meet the requirements of maize (Verloop et al., 2006).

Reseeding grassland presents a huge risk to nitrate leaching (reseed, Model 4) and should be avoided as much as possible. In practice, farmers use their own criteria to decide on reseeding. Extension officers should explicitly emphasize the risks associated with reseeding grassland. Moreover, reseeding in autumn represents a greater risk for nitrate leaching than reseeding in spring (Velthof & Hoving 2004; Seidel et al., 2004). On the other hand, reseeding in spring increases the risk of weed infestation, requiring more frequent use of herbicides.

4.4. Management of a catch crop

Since 2006, in the Netherlands, growing a catch crop following maize is compulsory on sandy soil. In our dataset, on almost 90% of the maize fields a catch crop was cultivated for the whole period. From 2002 onwards, 60% of the fields with a catch crop were fertilized in the period February-March for harvesting the catch crop before plowing up (no data were recorded about the timing of fertilizer application on maize fields before 2002). Adding the variable 'catch crop fertilization' (yes/no) to Model 6 (n=320), indicated that nitrate concentration increased by 33 mg l^{-1} when the catch crop was fertilized. This dramatic effect suggests substantial scope for reducing nitrate leaching on maize land by simply withholding N application to the catch crop. It has been shown that the utilization efficiency of residual soil N by the catch crop after the harvest of maize is highly dependent on its sowing date (Brinsfield & Staver, 1991). A successful strategy has been developed on experimental farm 'De Marke', in which the catch crop is sown between the maize rows in early summer and is neither fertilized, nor harvested in the following spring. However, the pilot farmers have not adopted this strategy yet, because of the risk of maize yield loss due to the competition between catch crop and maize seedlings for light, nutrients and water, when seeding the catch crop too early.

4.5. Soil and climatic conditions

Soil properties have substantial effects on the mean nitrate concentration in groundwater on the dairy farms examined, even though all farms were located on well-drained sandy soil. The effects of soil characteristics on nitrate concentration were stronger on maize land than on grassland.

Content of SOM was a main explanatory soil variable, negatively correlated to nitrate leaching, both for grassland and for maize land. The negative effect of CN on nitrate concentration can be explained by higher immobilization of N with increasing CN (Hassink, 1994; Schipper et al., 2004). Neither SOM nor CN were selected at farm scale, presumably because of the small differences among the means of the farms. The positive effect of the variables DeptSOM and SOMmhw, especially on maize land, was unexpected. Presence of SOM below MHW can stimulate denitrification under anaerobic conditions (e.g. McCarty & Bremner, 1992), as well as mineralization under aerobic conditions (Hadas et al., 1989; Weier & MacRae, 1993). The latter contributes more to nitrate leaching if the roots can not absorb the N released.

Hydrological variables were only selected at field and sampling point scale for both crops. As for soil properties, at whole farm scale these variables were not significant, because of their small ranges in farm averages.

4.6 Dissolved organic carbon

Dissolved organic carbon (DOC) concentration in groundwater is rather critical in predicting nitrate concentration in groundwater. DOC concentration is negatively correlated to the mean nitrate concentration at farm scale (Models 1 and 2) and at field and sampling point scale on grassland (Model 4). Note that DOC is invariable on grassland at field and sampling point scale. When using DOC concentration as the response variable, 75% of the variation in DOC concentration at farm scale can be explained by the model:

$$DOC = 128 + 24.4 \times frGrass - 0.22 \times MHW - 0.33 \times MLW - 4.9 \times SOM - 0.07 \times NsrpFarm$$

Model 8

Content of SOM, hydrology, type of crop and NsrpFarm affect DOC concentration in the groundwater on dairy farms. As an alternative to monitoring DOC concentration, this model can be used to predict DOC concentration in our models.

4.7 N surplus versus N standards

To comply with the obligations of the EU Nitrate Directive, the Netherlands introduced soil- and crop type-specific N (and P) application standards in 2006, as part of the Dutch Action Plan. The application standards replaced the mineral accounting system MINAS with permissible N (and P) surpluses at farm level as policy instrument (Henkens & Van Keulen, 2001; Schröder & Neeteson, 2008). The results of our study allow verification of the specific N application standards and N surpluses for grassland and maize land on sandy soil, as instruments to restricting the nitrate concentration in the groundwater to values below 50 mg l^{-1}.

Based on Model 1 for the whole farm, and assuming an average DOC concentration of all farms and years in our dataset (22 mg l^{-1}), the limit for NsrpFarm is equivalent to 120 kg N ha^{-1}. Fig. 3 presents the relation between observed NsrpFarm and nitrate concentration in groundwater at farm scale, and the fitted one, as function of the DOC concentration (Model 1). Depending on mean DOC concentration, maximum NsrpFarm to limit the nitrate concentration in groundwater to 50 mg l^{-1} ranges between 100 and 140 kg N ha^{-1} (Fig. 3).

For deriving recommended N application limits for grassland, we can use the alternative Model 4 (without reseed) at field scale, yielding parameter estimates for the constant (39), NsrpCrop (0.07), DOC (-0.43) and GrazingH (0.038). For farms with 100% grassland and zero grazing, maximum NsrpCrop assumes the value 185 kg ha^{-1}. For farms practicing grazing (assuming 100 cow hours ha^{-1}, based on all farms and years in our dataset), maximum NsrpFarm decreases to 128 kg ha^{-1}. To convert farm NsrpCrop to N standard, the following steps have been taken:

- NsrpCrop = soil N surplus
- Soil N surplus + N yield crop = N input soil = N standard

Average N yield on grassland on these farms was 260 kg ha^{-1} (data not shown), i.e. the maximum amount of N applied to grassland on farms without grazing was 445 kg ha^{-1} and with grazing 388 kg ha^{-1}. These rates are very similar to the actual N application standards for grassland in 2009 (440 and 400 kg ha^{-1}, respectively; Schröder & Neeteson, 2008).

For deriving N application limits for maize land, Model 6 has been selected. Assuming an average value for Tautumn (13), the nitrate concentration limit of 50 mg l^{-1} is exceeded by 19 mg l^{-1}. This is a surprising result and not in agreement with the actual N application standard for maize land of 150 kg *crop-available* N ha^{-1}. The N application standards were derived under the assumption that the nitrate concentration limit of 50 mg l^{-1} is not exceeded when growing maize in a crop rotation of 3 years of grassland, following 3 years of maize, including cultivation of a catch crop without fertilizer application (Schröder et al., 2005b). As we pointed out above, in practice, as in our dataset, 60% of the catch crop *was* fertilized. Furthermore, the release of N from the ploughed-in grass sod in first-year maize land has not been taken into account.

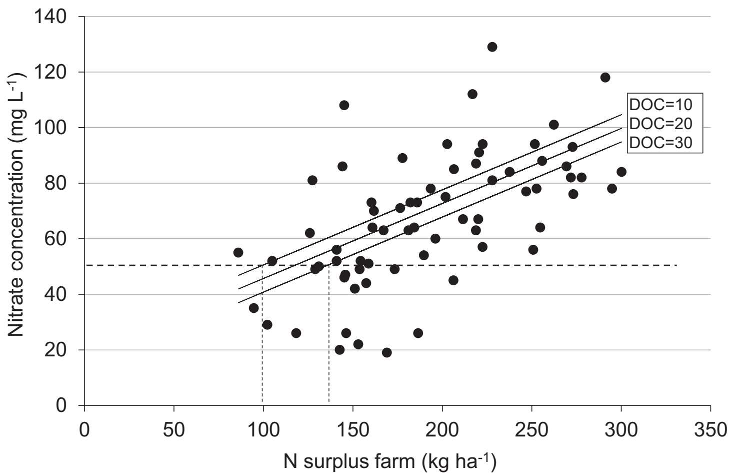

Fig. 3 *Observed relation between N surplus at the farm scale (kg ha^{-1}) and mean nitrate concentration in groundwater (mg l^{-1}) at farm scale and the fitted relation (solid lines) depending on dissolved organic carbon concentration (DOC) in groundwater (mg l^{-1}) (R^2_{adj}=65%). Dashed horizontal line indicates the limit of 50 mg nitrate l^{-1}.*

5 Conclusions

We investigated the interactions between management-related factors and soil and climate characteristics on nitrate concentration in shallow groundwater under grassland and maize land on eight intensively managed dairy farms at multiple scales during a seven-year period. At all farms, the agreed objective was to decrease nitrate leaching and to aim for immediate compliance with national legislation (permitted nutrient surpluses, N application standards), which is compulsory for other commercial farmers in 3-5 years. Mean nitrate concentration tended to decrease during the first years after modification of management, but subsequently increased again somewhat. On grassland, mean nitrate concentration tended to decrease from 2000 till 2003 and on maize land, mean nitrate concentration tended to increase from 2004 till 2006.

The risk of exceeding the concentration of 50 mg l^{-1} is higher on maize land than on grassland, and also higher at farm scale than at field or sampling point scale on grassland. Hence, the effects of farm management practices and soil and climatic conditions are spatial scale-specific. At farm scale, the most important variables affecting nitrate leaching are average N surplus, grazing intensity, the relative area of grassland and the DOC concentration in the groundwater. In grassland at field and sampling point scale, additional variables are plowing up the grassland sward, soil organic matter content and mean highest groundwater level. On maize land, total N input, the first crop in the rotation and catch crop fertilization are important management variables.

Our results indicate that the recommended N application standard for grassland is roughly adequate for restricting the maximum nitrate concentration in the shallow groundwater to 50 mg l^{-1}. In contrast, our results suggest that the recommended N application standard for maize land is too high to restrict the maximum nitrate concentration in the shallow groundwater to 50 mg l^{-1}. To realize the water quality standard for nitrate, farmers have to improve management, for instance by omitting fertilization of catch crops and reducing fertilization rates of first-year maize in rotation.

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CHAPTER 6

STOCHASTIC UNCERTAINTY AND SENSITIVITIES OF NITROGEN FLOWS ON DAIRY FARMS IN THE NETHERLANDS

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Abstract

Decisions in nutrient management and environmental policy making have to be based on sound data and proper analysis. Uncertainty in effects of nutrient management may lead to confusion and wrong conclusions. Annual data collection and monitoring are wrought with uncertainties that need to be addressed. An input-output N balance model was developed to describe and quantify N flows in dairy farming systems. Input for this model was based on monitored data in 2005 from one experimental and 14 pilot commercial dairy farms. A Monte Carlo approach was used to quantify effects of uncertainty in input data on annual farm N surplus, soil N surplus and N intake during grazing, followed by a sensitivity analysis to apportion the different sources in the uncertainty. Uncertainties in data input were described with probability density functions. Farm N surplus among farms ranged between 81 and 294 kg ha^{-1}, soil N surplus between 35 and 256 kg ha^{-1} and N intake during grazing between 27 and 108 kg ha^{-1}. The uncertainties in N flows - both relative (coefficient of variation; cv) and absolute (standard deviation; sd) - increase from farm N surplus (cv=8%; sd=15 kg N ha^{-1}) via soil N surplus (cv=12%; sd=16 kg N ha^{-1}) to N intake during grazing (cv=49%; sd=28 kg N ha^{-1}). Nitrogen flows on dairy farms pertaining to the whole farm balance ('external flows') are less uncertain than N flows pertaining to the component balances from herd and soil ('internal flows'). Uncertainties in N flows can be reduced by focusing on the most uncertain input, in combination with the relative contribution of these inputs to the balance. Nitrogen fixation by clover and the annual stock changes of roughage and manure are main sources for the variation in farm N surplus and soil N surplus. Estimates of N fixation by clover can be improved by using effective tools to estimate the clover content in grassland, and by better estimates of a farm-specific N fixation factor. Establishing uniform protocols and guidelines for farmers to estimate changes in stocks of roughage and manure may contribute to lower the uncertainty in the changes of these stocks.

1 Introduction

Recognition of the environmental impact of high nutrient surpluses in agricultural systems has resulted in many countries in the development of government policies to reduce nutrient losses (e.g. De Clercq et al., 2001). Central to many of these policy approaches has been the definition and on-farm implementation of nutrient balances (e.g. Henkens and Van Keulen, 2001; Mulier et al., 2003; Gourley et al., 2012). A range of nutrient balance approaches of varying complexity, including whole-farm (also called farm gate), soil surface and soil system balances, has been advocated to increase system understanding, as a method for on-farm nutrient management, or as policy instruments (Öborn et al., 2003; Oenema et al., 2003).

For policy makers, aiming at regulating nutrient losses, the farm gate approach is more attractive than that of the soil surface, because the farm gate balance integrates both crop and animal production and is more accurate and easier to quantify than the soil surface balance (Oenema and Heinen, 1999; Watson and Atkinson, 1999). However, there are significant "internal" nutrient flows that characterize weaknesses in the system (Aarts et al., 2000; Van Keulen et al., 2000), and that through improved management, could lead to higher nutrient use efficiencies and reduced losses (Öborn et al., 2005).

Decisions in nutrient management and environmental policy making have to be based on sound data and proper analysis of cause-effect relationships. Uncertainty may lead to confusion and wrong conclusions, to delays in the decision-making process, and to inefficient nutrient management. Annual data collection and monitoring are wrought with uncertainties that need to be addressed in results of any type of analysis (at national, regional or farm level), and in policy and decision-making. Data can be obtained from four types of monitoring: counting, measurement, estimation and using default/fixed rate from literature. Insight in the uncertainty in the collected data gives an actor (from policy maker to individual farmer) more confidence in interpreting the results.

Different types of monitoring schemes and research programs have been initiated to investigate the effects of improved management on nutrient losses from agricultural systems (e.g. Lord et al., 1999; Fraters et al., 2005; Schröder et al., 2007). In the Netherlands, the concern for environmental problems associated with nutrient surpluses in dairy farming, has led to the establishment of the experimental dairy farm 'De Marke', aiming at exploration of the possible options to increase nutrient use efficiency and reduce nutrient losses of dairy farming systems on leaching-sensitive sandy soils (Aarts et al., 1992). To promote adoption of similar systems in commercial dairy farming, the project 'Cows & Opportunities' was initiated in 1999. It is characterized by agreements of the research project with the farmers on realization of measurable targets and intensive coaching through frequent interaction between researchers, extension agents and farmers (Oenema et al., 2001; 2011).

Information on uncertainties in annual nutrient flows may be used for determining the risk for yield losses and exceeding environmental targets, and hence to better inform decision making as to the optimum nutrient management strategy. Various studies have investigated and quantified the uncertainties in whole-farm nutrient balances (e.g. Mulier et al., 2003; Payraudeau et al., 2007; Gourley et al., 2012), or in nitrogen (N) losses (De Vries et al., 2003; Payraudeau et al., 2007). However, these studies did not take into account the uncertainty in total N inputs in the system (De Vries et al., 2003) or they studied only a few uncertain N input sources (Payraudeau et al., 2007). There is lack of information about quantified uncertainty of N flows in dairy farming systems, especially the "internal" N flows.

In this study, we developed an input-output N balance model to describe and quantify N flows in dairy farming systems. Data from two monitoring programs differing in detail were used as input for this model. Model outputs of interest were farm N surplus, soil N surplus and N intake during grazing, the balancing items of, respectively, the farm balance, soil balance and herd balance (Fig. 1; Table 1). The uncertainty in and sensitivity of the model output due to uncertainty in the annual monitoring data, were quantified using a Monte Carlo approach. An uncertainty analysis quantifies the overall uncertainty associated with the model output as a result of uncertainties in the model inputs (e.g. results of monitoring) and a sensitivity analysis is the study of how the variation in the output can be apportioned to different sources of input variation (Saltelli et al., 2000).

2 Materials & Methods

2.1 Model concept

For analysis of the dairy farming system, four major components are distinguished, i.e. herd, manure, soil and crop (Aarts et al., 1992; Schröder et al., 2003). Nitrogen cycles through these components, i.e. output from one component is input into the other, but losses are incurred in these transfers (Fig. 1).

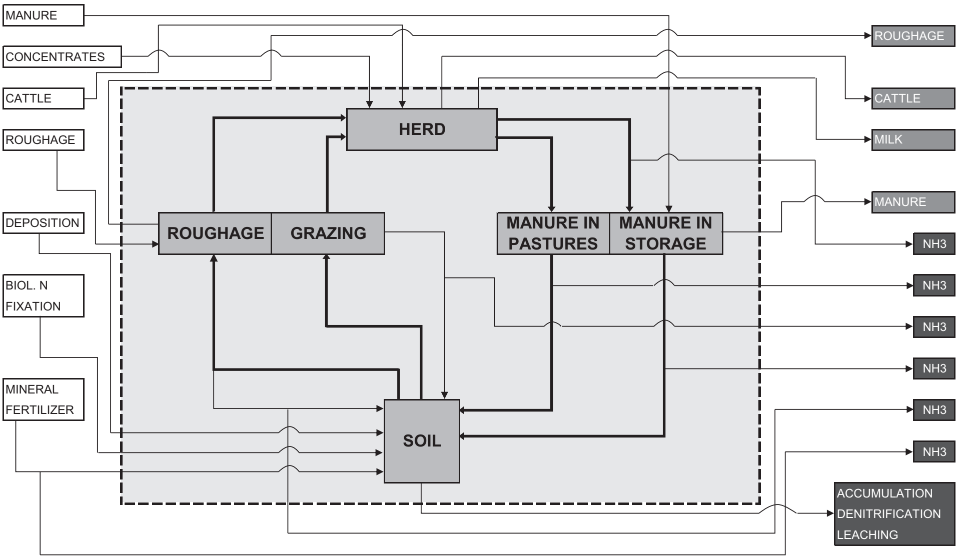

Fig. 1 *N flows through a dairy farm, with on the left hand side farm inputs, on the right hand side farm outputs and losses, and in the middle internal recycling through the four major components: herd, manure (manure in pastures, manure in storage), soil and crop (roughage, grazing).*

In the input-output N balance model, we distinguish two levels in the N balances: whole farm level and component level. The N balance at farm level (farm balance) is based on N in all products that enter and leave the farm (inputs and outputs; Table 1). The four component balances take into account the internal flows and provide more specific information for locating the N losses in each specific dairy farm component. A surplus, i.e. a positive difference between inputs and outputs, corrected for changes in stock, indicates N losses:

$$\text{Surplus} = \text{maximum}\ (0, [\text{Input} - \text{Output} + \text{Changes in stock}]) \qquad (1)$$

The soil balance is defined here as the difference in N flows entering and leaving through the soil surface. We assume "a steady state" in soil N, so changes in soil N are attributed to the balancing item (soil N surplus). Therefore, the soil N surplus includes and accounts for accumulation, depletion, denitrification and leaching. Crop balances were used to identify field (grazing and harvesting), conservation and feeding losses and manure balances to identify the losses of ammonia (from stable and storage, during grazing and spreading). Assumptions on the field, conservation, feeding and ammonia losses have to be made. Appendix I provides a description of the used model and data sources for the calculation of N flows. Three model outputs were distinguished: (1) the N surplus of the farm - balancing item of the farm balance - (2) the N surplus of the soil - balancing item of the soil balance - and (3) the N intake of the herd during grazing - balancing item of the herd balance (Fig. 1; Table 1).

Table 1 *Classification of N flows in a dairy farm system (I = Input; O = Output; S = surplus), for the whole farm and the components herd and soil. S is defined as 'losses' of nitrogen from either the farm balance, or the component balances herd and soil. N flows indicated in grey are the balancing item of each balance (model output).*

N flow	Farm balance	Component balance	
		Herd	Soil
Imported animals	I	I	
Imported concentrates	I	I	
Imported roughage	I	I	
Imported fertilizer	I		I
Imported manure	I		I
Biological N fixation	I		I
Atmospheric deposition	I		I
Applied manure to soil[a]			I
Excreta during grazing[b]			I
Net field, grazing, conservation and feeding losses			I
Intake from crops on farm[c]		I	
Intake during grazing		I	
Gross production of crops on farm[d]			O
Gross grass production before grazing			O
Exported animals	O	O	
Exported milk	O	O	
Exported roughage	O		
Exported manure	O		
Gross production of manure[e]		S	
Surplus farm[f]	S		
Surplus soil[g]			S

[a] Excluding ammonia losses from animal houses and during spreading.
[b] Excluding ammonia losses during grazing.
[c] Intake homegrown silage (grass, maize, other).
[d] Gross N yield (silage, grazing); including harvesting, conservation, feeding and grazing losses.
[e] Including ammonia losses from animal houses, during grazing and during spreading.
[f] Including all ammonia losses, accumulation in the soil, denitrification, leaching and run-off.
[g] Including accumulation in the soil, denitrification, leaching and run-off.

2.2 Data collection and monitoring

Data from two monitoring programs were used, (1) intensive data collection as adopted at experimental farm 'De Marke', and (2) less intensive data collection as adopted on pilot commercial farms in 'Cows & Opportunities' (C&O) (Fig. 2). In the monitoring programs, four types of data collection are distinguished: counting, measurement, estimate and fixed rate. The frequency of data collection varied from daily to annually. Data from 'De Marke' are dominated by measurements and less by estimates while data from C&O are more based on estimates instead of measurements. Data from the 14 C&O dairy farms were obtained from registrations by the farmers and extension agents and through measurements. Farmers recorded most basic data, either electronically or on paper. For this study, data from the year 2005 were used, seven years after the start of the project C&O, so we assume by that time farmers had learned to collect proper data of their farms. Furthermore, weather circumstances in 2005 were close to average.

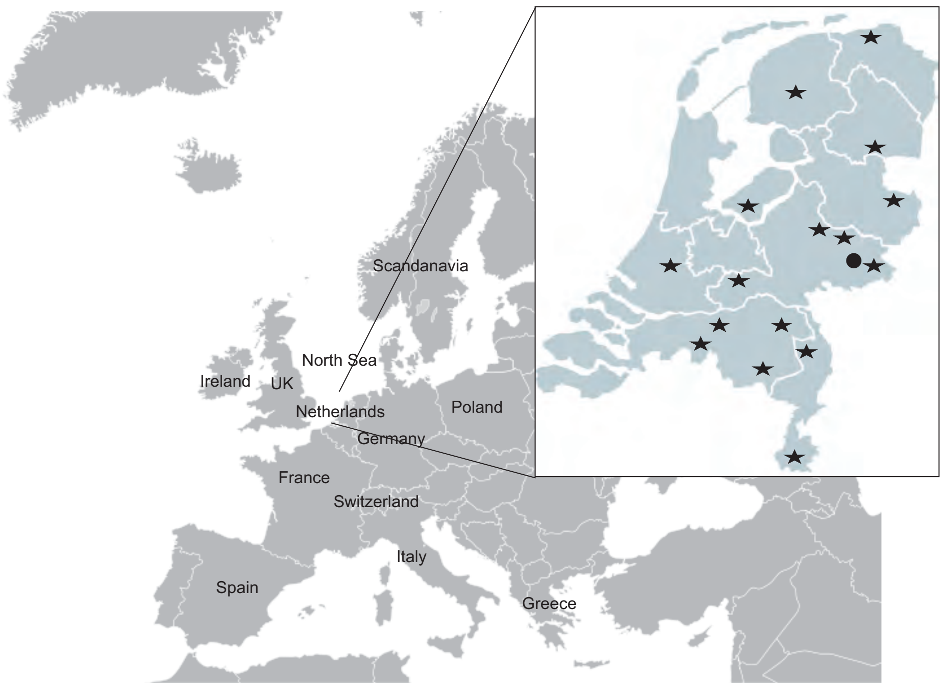

Fig. 2 *Location of the farms in The Netherlands. Stars indicate pilot commercial farms in 'Cows & Opportunities'. The circle indicates experimental dairy farm 'De Marke'.*

In both monitoring programs, mass flows entering (import) and leaving (export) the farm were derived from farm accounts. Nitrogen flows in imported and exported animals were estimated from the number of animals per category (cow, calf and heifer), assuming category-specific nutrient contents (Tamminga et al., 2000). The nutrient composition of imported feeds (concentrates, roughage) in C&O was obtained from feed analysis reports and suppliers. At 'De Marke', samples of the imported feeds were taken to determine their nutritive value. In both monitoring programs, N output in milk was quantified by frequent monitoring of protein contents (mg l^{-1}) and milk production (l) by the milk processor.

Field-level data on fertilizer and manure management, dry matter yields and grazing regimes were recorded daily in a computerized fertilization recommendation program. In C&O, grassland dry matter yields were estimated by the farmer for each mowing and grazing cut, using the rising plate meter (Keuning, 1988). At the start of the C&O project, farmers were instructed how to use the tool. Silage maize dry matter yields were estimated by the farmer after harvest, either by counting the number of loads (assuming an average weight per load), or by weighing the loads. At 'De Marke', the mass of harvested grass and maize for silage were determined on the weighing bridge. In both monitoring programs, samples from each silage heap were taken to determine their nutritive value by chemical analyses. Similarly, samples were taken from the slurry pits two to four times annually, following extensive mixing, and nutrient contents were determined. At 'De Marke', frequency of sampling manure was higher (10 times per year) than at the pilot farms. Also, at 'De Marke' the N content of wilted grass before ensilage was measured at each harvest and each field, by Near Infrared Spectrometry (Williams & Norris, 1987). At 'De Marke', ammonia volatilization from animal houses was measured continuously in the period 1995-1999, and volatilization during grazing was derived from calculation using farm specific input data (Koskamp et al., 2003). Ammonia volatilization following manure application at 'De Marke' was measured during two growing seasons (1999 and 2000) (Koskamp et al., 2003). The measurements and calculations were used to derive fixed rate values for ammonia volatilization from animal houses, during grazing and following manure application. On farms in C&O, fixed rate values for ammonia volatilization from animal houses and during grazing were derived from simulations using farm-specific input data (Smits et al., 2001). For the ammonia volatilization following application of manure, the national fixed emission factors from Huijsmans and Schils (2009) were used.

2.3 Monte Carlo uncertainty and sensitivity analyses

The uncertainty and stochastic sensitivity analyses are based on a Monte Carlo approach, using an ordinary random sampling procedure for each of the input parameters. The approach consisted of six steps: (1) select input parameters for inclusion in the analysis, (2) assign probability density functions (PDFs) to each input parameter, (3) generate an input matrix, (4) calculate the model output, (5) analyze the model output (uncertainty analysis), and (6) assess the influence of each input parameter on the output (sensitivity analysis).

Step 1: select input parameters
An analysis was performed using 48 input parameters from the monitored data. All monitored data of the types 'counting', 'estimate' and 'measured' were selected and the most important ones of the type 'fixed rate'. A summary of these parameters is given in Table 2.

Step 2: assign probabilistic distribution of input variables
The uncertainties in input data selected are characterized with probability density functions (PDF's), defined through their mean, coefficient of variation (cv) and type of probabilistic function. Mean values (result of the monitoring) of important input parameters and farm characteristics of the year 2005 for each farm are shown in Table 3. Some of the mean values are the result of a group of input parameters and/or farm characteristics. For example, imported feed (kg N ha^{-1}) comprises the values of input parameters imported concentrates (kg), N-content imported concentrates (kg N kg^{-1}), imported roughage (kg dry matter) and N-content imported roughage (kg N (kg dry matter)$^{-1}$). A four-member expert panel, with experience in both monitoring programs, generated for each input variable the cv and a PDF (Table 2), based on literature, knowledge of observations from the monitored data (bookkeeping, analyses of feed and manure samples) and/or expert judgment. First, each member estimated a cv for each input variable and secondly, a definitive cv was derived after comparison and discussion of the estimates from each member. Estimated cv's of input parameters by different experts were similar. Generally, cv's of the input parameters of the type 'measure' is lower than those of the input parameters of the type 'estimate'. Also, cv from mass flows expressed as kg *product* (concentrates, mineral fertilizer) is lower than that from mass flows expressed as kg *dry matter* (roughage). The monitoring program on 'De Marke' is more intensive (higher frequency of measurements) than the monitoring program in C&O. In general, lower cv's of input parameters were assumed on 'De Marke' than in C&O.

Table 2 *Parameter uncertainty (coefficient of variation; cv) and assumed probabilistic density functions (PDF) based on expert knowledge in a monitoring program at 'De Marke' and in Cows & Opportunities (C&O)*

Type of monitoring	Description of parameter	Unit	PDF	Uncertainty (cv)	
				De Marke	C&O
Count	Animals, imported and exported	number	lognormal	0	2
	Animals, changes in stock	number	normal	2.5	2.5
Measure	Concentrates, imported[a]	kg	lognormal	2.5	2.5
	Chemical fertilizer, imported	kg	lognormal	2.5	2.5
	Roughage, imported and exported	kg dm[b]	lognormal	5	7.5
	Manure, imported and exported	Mg	lognormal	5	5
	Milk production	kg	lognormal	1	1
	Protein content milk	%	lognormal	2	2
	N[c]-content manure, imported and exported	kg N Mg^{-1}	lognormal	5	7.5
	N-content manure for application	kg N Mg^{-1}	lognormal	5	7.5
	N-content roughage[d]	kg N $(Mg\ dm)^{-1}$	lognormal	5	7.5
	N-content harvested yield grassland	kg N $(Mg\ dm)^{-1}$	lognormal	2.5	7.5
	N-content harvested yield crops	kg N $(Mg\ dm)^{-1}$	lognormal	2.5	5
	Grassland and crop area	ha	lognormal	0	5
Estimate[e]	Concentrates, changes in stock	kg	normal	10	10
	Chemical fertilizer, changes in stock	kg	normal	5	7.5
	Roughage, changes in stock	kg dm	normal	10	15
	Manure, changes in stock	Mg	normal	10	20
	N-content manure, changes in stock	kg N Mg^{-1}	lognormal	7.5	10
	Applied manure	Mg	lognormal	5	10
	Excreta during grazing	kg N	lognormal	20	20
	Harvested yield	Mg dm	lognormal	5	10
	Total yield grassland	Mg dm	lognormal	5	15
	Average clover content grassland[f]	fraction	lognormal	4.5	25
Fixed rate	N-content animals	kg N $animal^{-1}$	lognormal	5	5
	N-content chemical fertilizer	kg N kg^{-1}	lognormal	2.5	2.5
	N-content concentrates, imported[a]	g N kg^{-1}	lognormal	2.5	2.5
	N-content concentrates, changes in stock	g N kg^{-1}	lognormal	5	5
	N-fixation factor clover	kg N $(Mg\ dm)^{-1}$	lognormal	30	30
	Atmospheric deposition[g]	kg ha^{-1}	lognormal	17	17
	NH_3-N losses[h]	fraction	lognormal	10	10

[a] Based on data from feed supplier company 'For Farmers' (personal communication Bertho Bosweger)
[b] dm = dry matter; [c] N = nitrogen
[d] On 'De Marke', N content of each feed lot is measured. In C&O, N content of imported grass silage and maize silage is measured and for other types of imported roughage fixed rates were assumed.
[e] Classification for the estimated group of parameters is based on the monitoring program in C&O. On 'De Marke' most of these parameters were measured. See text for explanation of the differences.
[f] Based on data from experiments (adjusted from Schils and Snijders, 2002)
[g] Based on assumed minimum and maximum values (95%) around mean values.
[h] Model parameters: NH_3-N losses in stable and storage, during application and during grazing

Step 3: generate an input matrix
The input matrix was generated using the random sampling procedure for all combinations of monitored model input parameters. The input matrix in the present study consisted of 5000 samples for each farm. The random sampling of all combinations of input parameters was independently drawn per farm on the basis of their PDF's. No correlations between input parameters in the sampling of a farm were assumed; for each farm all values for input parameters were sampled independently. Even for a well-known relation as that between N fertilization and dry matter yield, we assumed no correlation within the range of their PDF's, i.e. variation in this relation is of the same order of magnitude as the variation that may be found within a farm. Assuming no correlations between input parameters leads to a maximization of the uncertainty of the output variables (Björkland, 2002), while a Monte Carlo approach can still be used to analyse uncertainty when independence of parameters is assumed (Sandars et al., 2003).

Step 4: calculate model output
For each farm, model outputs (farm N surplus, soil N surplus and N intake during grazing) were calculated for each Monte Carlo ordinary random sample using the calculation rules in Appendix I.

A model restriction for the calculation N intake during grazing was introduced (N intake during grazing > 0) and negative values were reported as 'missing values'. N intake during grazing is the balancing item of the herd balance (See Fig. 1, Table 1). In a sample where the gross production of manure ('surplus' herd balance) was relatively low and where the intake from concentrates and intake from crops on farm (input herd balance) were relatively high, calculated N intake during grazing may become negative, especially on farms with a minimal grazing regime. Due to the model restriction, the number of missing values (Table 4) varied among farms (between 5 and 1363). Since the number of runs is high (5000), the effect of missing values on the results is considered small.

For 'De Marke', two Monte Carlo runs were performed: one based on input uncertainties of the 'De Marke' monitoring program and one based on input uncertainties of the 'C&O' monitoring program.

Table 3 *General farm characteristics and mean values of important input parameters on 'De Marke' (DM) and on the pilot Commercial Farms (CF) in Cows & Opportunities in the year 2005*

	Farm size (ha)	Grassland area (ha)	Production intensity (Mg milk ha^{-1})	Imported N[a] feed (kg ha^{-1})[b]	Imported N fertilizer (kg ha-[1])[c]	N fixation (kg ha^{-1})[d]	Application manure grassland (kg N ha^{-1})[e]	N stock change roughage (kg ha^{-1})[f]	N stock change manure (kg ha^{-1})[g]
DM	55	33	11.9	113	0	31	189	-10	-2
CF1	70	49	9.7	113	0	23	167	42	17
CF2	44	31	16.9	153	109	6	244	7	0
CF3	56	38	13.9	122	97	9	187	4	-5
CF4	49	34	12.4	102	30	12	180	-3	-20
CF5	50	38	14.5	138	112	4	287	-44	-23
CF6	54	42	11.4	94	55	0	282	7	-5
CF7	76	59	12.1	120	102	0	190	35	-5
CF8	79	66	11.5	102	55	6	228	26	-28
CF9	42	30	16.5	195	138	0	212	29	-34
CF10	57	41	15.5	192	117	2	229	-4	-14
CF11	27	19	24.9	348	159	5	225	112	-5
CF12	86	86	14.9	128	204	5	191	7	-14
CF13	45	39	13.4	89	104	0	249	-34	-15
CF14	42	34	18.6	148	157	10	281	1	-20

[a] N = nitrogen

[b] imported concentrates (kg) × N content concentrates (kg N kg^{-1}) + imported roughage (kg dry matter) × N content roughage (kg N $(\text{kg dry matter})^{-1}$)

[c] imported chemical fertilizer (kg) × N content fertilizer (kg N kg^{-1})

[d] clover content grassland (fraction) × yield grassland (kg dry matter) × N fixation factor (kg N $(\text{kg dry matter})^{-1}$)

[e] manure application grassland (Mg ha^{-1}) × N content manure (kg N Mg^{-1})

[f] stock change roughage (kg dry matter) × N content roughage (kg N $(\text{kg dry matter})^{-1}$)

[g] stock change manure (Mg) × N content manure (kg N Mg^{-1})

Step 5: uncertainty analysis

The aim of the uncertainty analysis is to quantify the overall uncertainty in the output as a result of uncertainties in the inputs. The mean, standard deviation (sd) and cv of each output variable were calculated for each farm separately, and used as a measure of the uncertainty in model output. These statistics were calculated from the 5000 samples of the Monte Carlo simulations (Table 4).

Step 6: sensitivity analysis

The relative effect of the individual input parameters on each model output was assessed using variance decomposition. In variance decomposition the variance reduction in the model output, that would occur if the input would be fully known, is calculated. This reduction is called the top marginal variance (TMV) of an input parameter (Jansen et al., 1994), the first-order sensitivity index or the correlation ratio (Brus and Jansen, 2004). In a regression-based sensitivity analysis, the relation between the model output and the input parameters is approximated by a multiple regression model. A linear regression model was used and the quality of the approximation was established using the percentage variance accounted for in the full linear model (R^2 adjusted for sample size and number of parameters). The R^2 in all cases exceeded 98%, so almost all variance in the output was accounted for. The sensitivity analysis was performed with USAGE 2.0, a collection of GenStat algorithms for sensitivity and uncertainty analyses (Goedhart and Thissen, 2009; GenStat, 2009).

3 Results

3.1 Uncertainty analysis

Frequency distributions of 5000 calculated values for farm N surplus, soil N surplus and N intake during grazing for 2 farms (CF1 and CF13) are visualized in Fig. 3. On both farms, farm N surplus and soil N surplus follow a normal distribution. Nitrogen intake during grazing shows a different pattern, i.e. on farm CF13 a normal distribution and on farm CF1 skewed to the right. On the latter farm, grazing intensity was low and due to the restriction on N intake during grazing (>0), the number of 'missing values' was high (Table 4), resulting in this skewed distribution. The number of 'missing values' (1363 and 11, respectively) has no effect on the distribution patterns for farm and soil N surplus.

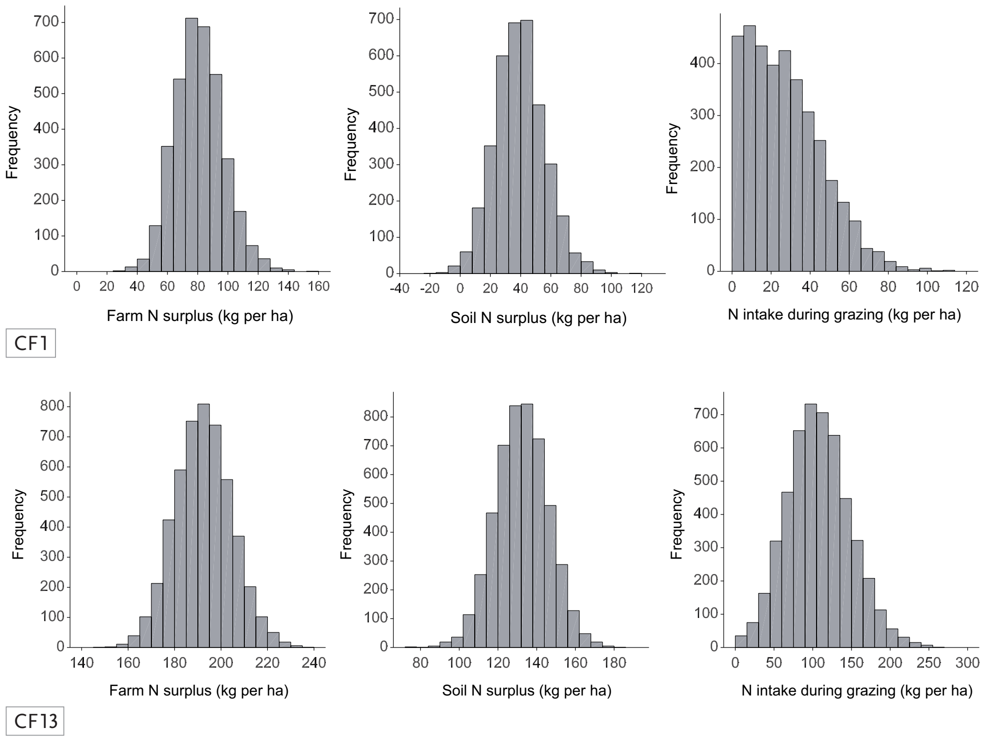

Fig. 3 *Frequency distributions of 5000 calculated values for 2 pilot commercial farms (CF1 and CF13) of farm N surplus (left), soil N surplus (middle) and N intake during grazing (right).*

The mean, standard deviation (sd) and coefficient of variation (cv) for each output (N surplus farm, N surplus soil, N intake during grazing) and each farm are presented in Table 4. The calculated farm N surplus on the commercial pilot farms ranged between 81 and 294 kg ha^{-1} with a sd between 10 and 18 kg ha^{-1}, except for farm CF11 with a sd of 29. Soil N surplus (between 35 and 256 kg ha^{-1}) is lower than farm N surplus, but sd is similar, indicating a relatively larger uncertainty (higher cv). The high sd on farm CF11 is related to the high production intensity with high levels of imported feed and fertilizer and high level of N stock change in roughage (Table 3).

Table 4 *Mean, standard deviation (sd) and coefficient of variation (cv) of farm N surplus, soil N surplus and N intake during grazing (all in kg N ha^{-1}), and 'missing values' for each farm (DM = De Marke; CF = pilot Commercial Farm from Cows & Opportunities) based on average output of 5000 samples of input values*

	Farm N surplus			Soil N surplus			N intake during grazing			'Missing'
	Mean	sd	cv	Mean	sd	cv	Mean	sd	cv	values
DM_A[a]	108	12	11	79	13	17	33	17	51	168
DM_B[b]	108	15	14	78	15	19	44	27	61	532
CF1	81	16	20	35	18	51	27	19	70	1363
CF2	156	12	8	115	12	10	46	28	61	523
CF3	149	11	7	107	12	11	83	27	33	5
CF4	145	13	9	107	14	13	66	25	38	14
CF5	272	17	6	225	19	8	60	34	56	288
CF6	146	10	7	113	10	9	38	22	58	418
CF7	158	12	8	111	14	13	49	25	51	251
CF8	152	12	8	105	14	13	60	31	52	215
CF9	238	18	8	188	21	11	62	30	48	165
CF10	197	14	7	149	16	11	34	23	68	1142
CF11	222	29	13	175	29	17	93	39	42	51
CF12	294	17	6	256	16	6	76	34	45	83
CF13	192	12	6	132	14	11	108	41	38	11
CF14	224	16	7	155	20	13	56	34	61	555
Average C&O	178	15	8	133	16	12	58	28	49	

[a] Monte Carlo run 'De Marke' based on input uncertainties from 'De Marke' monitoring program
[b] Monte Carlo run 'De Marke' based on input uncertainties from Cows & Opportunities monitoring program

Calculated N intake during grazing on the commercial pilot farms varied between 27 and 108 kg ha^{-1} with a sd between 19 and 41 kg ha^{-1}. The relative uncertainty (cv) for N intake during grazing is higher than that for the farm and soil N surplus. On most farms, cv of N intake during grazing exceeds 50%.

The sd of farm and soil N surplus for 'De Marke' hardly differs when input uncertainties are based on 'De Marke' monitoring program (DM_A) or based on C&O monitoring program (DM_B). Despite the higher input uncertainties of the C&O monitoring program, the difference in uncertainty in soil N surplus is small (13 kg ha^{-1} with 'De Marke' input uncertainties and 15 kg ha^{-1} with 'C&O' input uncertainties). 'De Marke' shows a high value for N fixation with clover (Table 3) resulting in high uncertainty in farm N surplus and soil N surplus, mainly caused by the high uncertainty of the N fixation factor (cv=30%), despite a more certain estimate of the clover content in the 'De Marke' monitoring program (cv=4.5% on 'De Marke' and 25% on C&O; Table 2. For the calculated N intake during grazing, the differences in mean value (33 and 44 kg ha^{-1}, respectively) and sd (17 and 27 kg ha^{-1}, respectively) are substantial.

3.2 Sensitivity analysis

The results of the sensitivity analysis with the most important (groups of) input parameters for the variation in farm N surplus and soil N surplus are shown in Table 5 and for N intake during grazing in Table 6. De TMV's given in Tables 5 and 6 show the sensitivities associated with a particular (group of) input parameter(s). For example, a TMV of 10% for imported feed on 'De Marke' (DM_A) denotes that 10% of the variation in farm N surplus is caused by uncertainty in imported feed. Some input parameters were grouped by summarizing the individual TMV's, e.g. imported feed is the sum of the TMV's of the input parameters imported concentrates, N content concentrates, imported roughage and N content imported roughage. Fig. 4 shows the average TMV for each individual input parameter for all C&O farms to illustrate the relative importance of individual input parameters in a group.

For almost all farms, uncertainty in atmospheric deposition is the main source of variation in farm N surplus and soil N surplus (Table 5). On average, 30% of the calculated variation in farm N surplus originates from the uncertainty in atmospheric deposition.

The importance of other input parameters differs per farm. Farms with a substantial mean value for N fixation (Table 3) have high TMV for N fixation, both in farm N surplus and soil N surplus. The uncertainty in input parameters N fixation factor clover and average content clover in grassland are the main sources of this uncertainty (see Fig. 4).

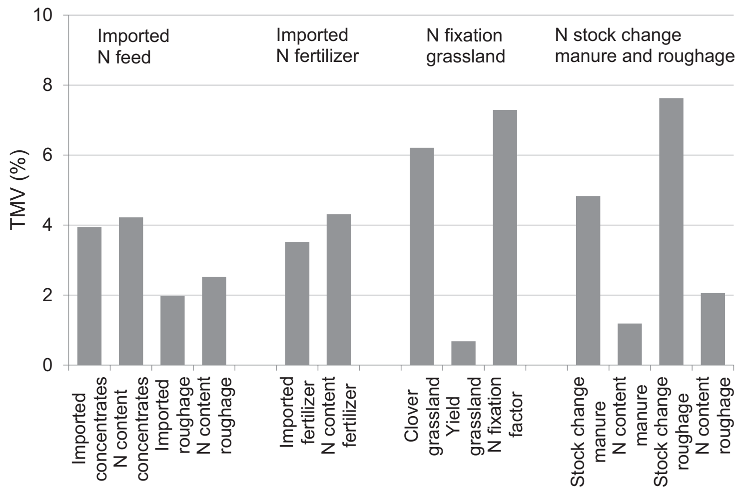

Fig. 4 *Average top marginal variance (TMV; %) of farm N surplus for four groups of uncertain input parameters on the pilot commercial farms in 'Cows & Opportunities'.*

Similar to N fixation, the TMV for the grouped input parameters N stock change manure and N stock change roughage was substantial for some farms (Table 5) due to the high mean values in these N stock change (Table 3). The uncertainties in input parameters stock change manure (ton) and stock change roughage (kg dry matter) are the main sources in the grouped TMV from N stock change manure and roughage (see Fig. 4).

Application of manure to grassland is only a source for uncertainty in soil N surplus and not for farm N surplus. For the other (groups of) input parameters shown in Table 5, TMV's per farm were almost equal for farm N surplus and soil N surplus, indicating no differences in the contribution of these input parameters to the variation in farm N surplus and soil N surplus.

The TMV in imported feed and stock changes of roughage and manure for N intake during grazing (Table 6) is much lower than for farm N surplus and soil N surplus (Table 5). Application of manure to grassland is the main source of variation in N intake during grazing for each farm, followed by N yield grassland and N excretion during grazing (Table 6). At first sight, it appears strange that application of manure is related to N intake during grazing. However, it follows from the way in which the N flows in this study are calculated (Table 1 and Appendix I). More manure production ('surplus' herd balance) means more N in feed intake (input). More N in feed intake may lead to more N intake during grazing, and more manure production may lead to more application of manure. The N excretion during grazing varies among farms due to the variation in grazing intensity (data not shown). In general, on the C&O farms, mean values for N excreta during grazing are lower than the N application of manure to grassland.

Table 5 *Top marginal variance (TMV; %) of farm N surplus (Farm) and soil N surplus (Soil) of the most important uncertain (groups of) input parameters for 'De Marke' (DM) and for pilot commercial farms (CF) in Cows & Opportunities.*

	Imported N feed[a]		Imported N fertilizer[b]		N fixation[c]		Atmospheric deposition		Application manure grassland[d]		N stock change roughage and manure[e]		Grassland area	
	Farm	Soil	Farm	Soil	Farm	Soil	Farm	Soil	Farm	Soil	Farm	Soil	Farm	Soil
DM_A[f]	10	11	0	0	62	52	20	17		8	1	1	4	2
DM_B[g]	7	6	0	0	69	66	14	14		4	2	2	3	1
CF1	11	10	0	0	30	25	32	26		5	20	19	1	0
CF2	20	19	10	9	5	5	43	41		6	1	1	11	4
CF3	17	17	9	8	10	9	35	31		8	1	1	11	4
CF4	8	8	1	1	15	14	57	52		5	10	11	6	2
CF5	8	8	6	5	2	1	22	17		13	28	29	29	15
CF6	12	11	4	3	0	0	64	59		7	2	2	7	3
CF7	12	11	9	6	0	0	40	28		16	24	21	13	4
CF8	8	7	3	2	4	4	20	17		12	35	33	18	6
CF9	14	14	8	6	0	0	30	22		7	21	23	12	5
CF10	20	18	9	6	1	0	18	14		6	4	4	17	7
CF11	26	26	4	3	0	0	12	11		1	43	43	4	2
CF12	6	7	19	20	2	2	12	13		5	3	5	58	48
CF13	7	6	9	7	0	0	17	14		24	29	26	35	13
CF14	10	8	13	8	7	5	32	21		23	6	6	19	5
Average C&O	13	12	8	6	14	12	30	25		9	16	15	16	8

[a] Sum of TMV's from imported concentrates + N content concentrates + imported roughage + N content roughage
[b] Sum of TMV's from imported chemical fertilizer + N content fertilizer
[c] Sum of TMV's from clover content grassland + yield grassland + N fixation factor
[d] Sum of TMV's from manure application grassland + N content manure
[e] Sum of TMV's from stock change roughage + N content roughage + stock change manure + N content manure
[f] TMV's 'De Marke' based on input uncertainties from 'De Marke' monitoring program
[g] TMV's 'De Marke' based on input uncertainties from Cows & Opportunities monitoring program

Table 6 *Top marginal variance (TMV; %) of N intake during grazing of the most important uncertain (groups of) input parameters for 'De Marke' (DM) and for pilot commercial farms Cows & Opportunities (CF).*

	Imported N feed[a]	Application manure grassland[b]	Application manure crops[c]	N excreta during grazing	N yield harvested grass[d]	N yield crops[e]	N stock change roughage and manure[f]
DM_A[g]	4	54	1	11	11	3	0
DM_B[h]	1	52	1	3	14	3	0
CF1	2	25	2	1	20	1	5
CF2	2	42	2	2	23	2	0
CF3	3	38	4	19	27	3	0
CF4	2	42	15	8	19	6	3
CF5	1	53	3	4	14	2	4
CF6	1	48	4	4	16	3	0
CF7	2	42	3	3	26	3	3
CF8	1	50	1	6	20	1	5
CF9	4	33	4	9	20	4	7
CF10	2	37	2	0	12	2	1
CF11	13	24	2	6	19	1	21
CF12	1	46	0	17	25	0	1
CF13	1	47	0	26	19	1	3
CF14	1	46	0	1	22	0	1

[a] Sum of TMV's from imported concentrates + N content concentrates + imported roughage + N content roughage
[b] Sum of TMV's from manure application grassland + N content manure
[c] Sum of TMV's from manure application crops + N content manure
[d] Sum of TMV's from yield harvested grass + N content grass
[e] Sum of TMV's from yield harvested crops + N content crop
[f] Sum of TMV's from stock change roughage + N content roughage + stock change manure + N content manure
[g] TMV's 'De Marke' based on input uncertainties from 'De Marke' monitoring program
[h] TMV's 'De Marke' based on input uncertainties from Cows & Opportunities monitoring program

4 Discussion

4.1 Methodological aspects

The objective of this paper was to quantify uncertainties in and sensitivities of important annual N flows on dairy farms using a Monte Carlo approach. Describing PDF's for input data is often mentioned as a major difficulty when MC is used as an approach for the development of uncertainty analysis (Björklund, 2002; Heijungs and Huijbregts, 2004; Payraudeau et al., 2007; Basset-Mens et al., 2009). In general, there is a lack of information underlying the description of the PDF's for input data. Description of PDF's is mostly based on expert judgment (minimum and maximum values) and in some cases on literature and/or general statistical data. Using knowledge of farm-specific data (bookkeeping, analyses of feed and manure samples) may lead to a better description of PDF's to calculate uncertainty in N flows on dairy farms. The projects 'De Marke' and C&O allowed us to gain knowledge to make a better description of PDF's to calculate N flows on dairy farms. Hence, results of this study can be used to understand the uncertainty in annual N flows on dairy farms as a basis for policy and decision-making but also in convincing and stimulating dairy farmers to improve their management.

We assumed a long-term 'steady state' in soil N, despite the annual fluctuations in soil N at farm level due to management activities (crop rotations, ploughing, resowing grassland). These fluctuations (due to accumulation or depletion) are assumed part of the soil N surplus. In case the steady state assumption does not hold, the computed soil N surplus is still valid, but there is a shift between the items accumulation, depletion, denitrification and leaching, resulting in a net change of soil N).

4.2 Uncertainty in nitrogen flows

The uncertainties in annual N flows on dairy farms - both relative and absolute - increase from farm N surplus (cv=8%; sd=15 kg N ha^{-1}) via soil N surplus (cv=12%; sd=16 kg N ha^{-1}) to N intake during grazing (cv=49%; sd=28 kg N ha^{-1}). Quantification of these uncertainties confirms the hypothesis that the uncertainties in internal N flows (soil N surplus and N intake during grazing) exceed those in N flows at the whole-farm level (farm N surplus) (Watson and Atkinson, 1999; Oenema et al., 2003; Öborn et al., 2003). High N surpluses are not always associated with high absolute and relative uncertainties. For example, on a farm with a low farm N surplus (CF1, 81 kg N ha^{-1}; Table 4), the absolute and relative uncertainty are high (sd=16 kg N ha^{-1}; cv=20%, respectively), whereas on a farm with a high N surplus (CF5, 272 kg N ha^{-1}), the absolute uncertainty is similar (sd=17 kg N ha^{-1}), but the relative uncertainty is lower (cv=6%) than that of the farm with a low N surplus. The low absolute uncertainty on the farm with a high N surplus can be explained by the fact that the contribution of N flows with low input uncertainties to the N farm balance was relatively high.

Farm structure and farm characteristics, such as production intensity, N fixation and N stock changes (e.g. Table 3) have a strong influence on the absolute and relative uncertainty of important N flows (Table 4), but also on the relative importance of uncertain N flows (Tables 5 and 6). For example, results of uncertainties in N surpluses are different when a farm relies on the use of chemical fertilizer (accurate data) than when it relies on a large contribution of N fixation by clover (less accurate data). Also, large transports (imports and/or exports) of animal manure (Payraudeau et al., 2007) and large stock changes in roughages and manure are important factors in explaining high uncertainties in N surpluses.

From the three output variables studied, the uncertainty in N intake during grazing was by far the largest (Table 4). Calculating N intake during grazing (the balancing item from the herd balance) is less accurate than calculating soil N surplus (the balancing item from the soil balance), while both balancing items belong to the 'internal N flows' on a dairy farm. In an N cycle for a dairy farm, internal N flows through each component should be 'closed' (Fig. 1), except for N losses from the soil balance. The magnitudes of other losses from the N cycle (in this case only NH_3) are estimated and form part of the input data (Table 2). Therefore, N intake during grazing is not only the balancing item of the herd balance, but also the 'balancing item' of the whole N cycle, with the consequence that all estimated errors are part of this N flow. This - in combination with the uncertainty in input parameters of the balance items on the herd balance - explains the large variation in N intake during grazing.

4.3 Reducing uncertainty in nitrogen flows

Uncertainty in manure production (in stable and excreta during grazing) can be reduced by comparing manure production with N excretion rate values per animal type (Tamminga et al., 2004). The N excretion rate values for milking cows depend on the milk production per cow and feed ration (indicated as urea content in the milk (mg l^{-1})). Other animal types (e.g. calves and heifers) have fixed values for N excretion.

Uncertainty in N intake during grazing can be reduced by verifying the calculated value with the value based on information from monitored data, such as applied grazing regimes, estimated standing dry matter during grazing and the N-content in grazed grass (analyzed or fixed value). Comparing the results from both methods may support the value of N intake during grazing.

Atmospheric deposition, N fixation by clover and the annual stock changes of roughage and manure are the main sources of variation in farm N surplus and soil N surplus. The PDF for atmospheric deposition is based on assumed minimum and maximum values around the mean (Table 2), resulting in an uncertainty of cv =

17%, which matches results of an uncertainty assessment of Dutch emission data (Van Gijlswijk et al., 2004). Reducing the uncertainty in estimating atmospheric deposition is hardly possible. However, the contribution of atmospheric deposition to the uncertainty in N surplus has decreased because of the reduction in atmospheric deposition in the Netherlands by more than 30% in the past 30 years (Buijsmans et al., 2010) and will further reduce due to the expected reduction in the future (Velders et al., 2010).

Similar to the recommendation of Payraudeau et al. (2007), uncertainty in the value for N fixation by clover can be reduced by a more accurate estimate of the clover content in mixed pastures (e.g. Vertès and Simon, 1991), using practical tools for such estimates, such as a picture card (De Visser and Philipsen, 2002) or a 0.25 m^2 quadrat (Schils et al., 1999). The cv of the estimated clover content in grassland in C&O is more than 5 times that on 'De Marke' (25 versus 4.5), because of its higher frequency of monitoring, for each cut and each field, compared to between 1 and 3 times per year for all grassland in C&O. The uncertainty in N fixation factor (kg N Mg^{-1} clover) is high (cv=30%), and based on data from experiments in the Netherlands (Schils and Snijders, 2002). The mean N fixation factor was set to 45 kg N Mg^{-1} clover (Biewinga et al., 1992), in line with Schils and Snijders (2002) (between 39 and 58 kg N Mg^{-1} clover), lower than experimental results from Elgersma and Hassink (1997) (between 49 and 69 kg N Mg^{-1} clover), and higher than reported values from Korsaeth and Eltun (2000) (between 29 and 39 kg N Mg^{-1} clover). Other studies also used a linear equation to calculate N fixation by clover, but included an intercept (e.g. Carlsson et al., 2009; Hogh-Jensen et al, 2004; Phelan et al., 2013). A comprehensive literature study would be needed to improve estimates of farm-specific N fixation factors by clover using more easily available data, such as soil type and grassland management (e.g. fertilization level, grazing and mowing regimes).

The uncertainty in changes in stocks can be reduced by improvements in the quantification of stock changes of roughage and manure by establishing uniform protocols and guidelines for farmers to assess these stock changes. Farmers should be convinced that measurements are not only associated with 'costs', but that they yield useful information relevant for improved cost-effective nutrient management, resulting in lower N losses to the environment.

The differences in uncertainty in farm N surplus and soil N surplus between the two monitoring programs were small due to the high uncertainty of the N fixation factor. Thus, an intensive monitoring program using more measurements instead of using fixed values will not always result in a better quantification of N surpluses in case N fixation with clover is important for a farm. The added value of an intensive monitoring program is a more precise quantification of the internal N flows on dairy farms, especially the N intake during grazing. Hence, calculations show that on farms with no N fixation, an intensive monitoring program does result also in a less uncertain quantification of N surpluses. For instance, the uncertainty of farm N surplus and soil N surplus on CF11 decreases with 23% when the monitoring program of 'De Marke' is applied instead of the C&O monitoring program. The uncertainty in N intake during grazing decreases even more, i.e.30%.

5 Conclusions

N flows on dairy farms pertaining to the whole farm balance ('external flows') are less uncertain than N flows pertaining to the component balances from herd and soil ('internal flows'). The uncertainties in N flows - both relative and absolute - increase from farm N surplus (cv=8%; sd=15 kg N ha^{-1}) via soil N surplus (cv=12%; sd=16 kg N ha^{-1}) to N intake during grazing (cv=49%; sd=28 kg N ha^{-1}). High N surpluses are not always associated with high absolute and relative uncertainty. Uncertainty in output (N surplus) is explained from the contribution of input parameters associated with low or high uncertainties.

In the two monitoring program, four types of data collection are distinguished: counting, measurement, estimates and fixed rate. We found that a monitoring program based on more measurement instead of estimates and/or fixed rate values from literature, will not always result in a better quantification of N surpluses, but the uncertainty of internal N flows will decrease, especially the N intake during grazing.

Atmospheric deposition, N fixation by clover and the annual stock changes of roughage and manure are the main sources for uncertainty in farm N surplus and soil N surplus. The relative importance of uncertain N flows varies per farm. The magnitude of the importance of a source depends on the contribution of an N flow to the balance, in combination with the input uncertainty.

Uncertainty in N flows can be reduced by focusing on the most uncertain input, in combination with the relative contribution of these inputs to the balance. Estimates of N fixation by clover can be improved by using effective tools to estimate the clover content in grassland, and by a better estimation of a farm-specific N fixation factor. The importance of the uncertainty in atmospheric deposition will reduce by the reduction of the absolute values of atmospheric deposition in the near future. Establishing uniform protocols and guidelines for farmers to estimate changes in stocks of roughage and manure may contribute to lower the uncertainty in the changes of these stocks.

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Appendix 1: Calculation of N flows on dairy farms

Characteristic for dairy farming systems is the combination of plant and animal production. By exchanging manure and forage between the plant and animal components, nitrogen (N) cycles through the system, but N losses also occur (Aarts et al., 1992). Fig. 1 presents a schematic representation of N flows in a dairy farming system. Here, we present the calculations of N flows on a dairy farm on an annual, hectare, basis (kg N ha^{-1} yr^{-1}). We distinguish between external N flows (farm balance) and internal N flows (component balances).

External N flows (imports and exports)

The quantity of N imported with animals (Ni_an) is calculated as:

$$\text{Ni\_an} = \Sigma\ (\text{number of imported animals}_i \times \text{N content animal}_i) \quad (1)$$

where *i* is a category of animal (cow, calf, heifer, etc). The N contents of animals (kg N $animal^{-1}$) have been taken from literature (Tamminga et al., 2000).
N imported in concentrates, roughages, fertilizer and manure (Nimp) is all calculated in the same way:

$$\text{Nimp} = \Sigma\ (\text{product}_j \times \text{N content product}_j) \quad (2)$$

where *j* denotes imported loads (kg) of concentrates, roughage, fertilizer or manure.
Biological N fixation is derived from the estimated clover content in grassland. For the quantity of N fixed by clover we assume 45 kg N per Mg dry matter of clover (Biewinga et al., 1992):

$$\text{Nfix} = \Sigma\ (\%\ \text{clover}_k \times \text{yield\_dm}_k \times 45) \quad (3)$$

where %clover is the estimated proportion of clover in plot *k*; yield_dm is the total yield of dry matter (Mg) in plot *k*.
N deposition for each farm (region–specific) is taken from literature (Hey & Schneider, 1995).
Export of N in animals (No_an) is calculated similar to that in imported animals:

$$\text{No\_an} = \Sigma\ (\text{number of exported animals}_i \times \text{N content animal}_i) \quad (4)$$

The quantities of N exported in milk, roughage and manure (Nexp) are calculated as:

$$\text{Nexp} = \Sigma\ (\text{product}_j \times \text{N content product}_j) \quad (5)$$

where *j* denotes exported loads of milk, roughage or manure (kg).
Changes in stock of manure, concentrates, roughage and fertilizer (Nstock) are calculated as:

Nstock = Σ ((product$_j$ end period – product$_j$ begin period) $\times$ N content product$_j$))6)
where *j* denotes the amount of manure, concentrates, roughage or fertilizer (kg).

Internal N flows

N applied in chemical fertilizer (Nfert_soil) is the sum of the applications to the different crops/plots:

$$\text{Nfert\_soil} = \Sigma\ (\text{fert}_{m,n} \times \text{N content fert}_{m,n}) \quad (7)$$

where fert$_{m,n}$ is the quantity of applied fertilizer *m* (kg) to crop/plot *n*.
The quantity of applied manure N (Nman_soil) is calculated as:

$$\text{Nman\_soil} = \Sigma\ (\text{man}_{m,n} \times \text{N content man}_{m,n} \times (1\text{-frac\_vol\_app})) \quad (8)$$

where man$_{m,n}$ is the quantity of applied manure *m* (kg) to crop/plot *n*, N content man excludes ammonia losses from the stable, frac_vol_app is the fraction of ammonia lost during application (depending on application method; Huijsmans et al., 2007).
N field losses (Nloss_field) consist of harvesting, grazing and conservation losses:

$$\text{Nloss\_field} = \Sigma\ (\text{Ngrass\_silage} \times \text{loss\%gr\_sil}) + (\text{N\_int\_grazing} \times \text{loss\%gr\_gr}) \quad (9)$$

where Ngrass_silage is total net N yield of cut grass (see below), loss%gr_sil is an assumed percentage of harvesting and conservation losses (15%), N_int_grazing is total N intake during grazing (balance item on the herd balance, explained below), loss%gr_gr is an assumed percentage of grazing losses, depending on grazing system (restricted 15%; unrestricted 20%).
Output from the soil is the sum of gross N yields of crops, before cutting or grazing (Np_crop):

$$\text{Np\_crop} = \Sigma\ (\text{yield}_{p,n} \times \text{N content crop}_{p,n}) + \text{Nloss\_field}_{p,n} \quad (10)$$

where yield$_{p,n}$ is the net yield of dry matter of crop *p* (kg) on plot *n*.
The calculation of N flows in the herd balance is different from those in the farm and soil balances. In the farm and soil balances, the balancing item is N surplus (see Table 1). Nitrogen surplus of the herd (gross production of manure; Np_man) is calculated as:

$$\text{Np\_man} = \text{Np\_man\_stable} + \text{Nman\_gr} \quad (11)$$

where Np_man_stable is the (gross) manure production in the stable and Nman_gr denotes the N excreta during grazing. Np_man_stable is calculated as:

$$\text{Np\_man\_stable} = \text{Nman\_soil} / (1\text{-frac\_vol\_stable}) \quad (12)$$

where frac_vol_stable is the ammonia volatilization fraction from stable and storage (see text for explanation).

Nman_gr is derived from manure production in the stable (Np_man_stable) and length of the grazing season (hours_grazing):

$$hours\_grazing = \Sigma\ (\text{number of grazing animals}_i \times hours\_day_i \times days_i) \qquad (13)$$

where *i* is a category of animal (cow, calf, heifer, etc.), hours_day is average grazing time during a day of animals of category *i*, days is the number of days of the grazing period for animals of category *i*. The hours are corrected for the category of animal (cow = 1; heifer = 0.7; calf = 0.3). Nman_gr is now calculated as:

$$Nman\_gr = hours\_grazing/(hours\_total - hours\_grazing) \times Np\_man\_stable \qquad (14)$$

where hours_total is total number of herd hours on the farm, calculated as:

$$hours\_total = \Sigma\ (\text{total number of animals}_i \times 24 \times 365) \qquad (15)$$

where *i* is category of animal (cow, calf, heifer, etc.). As for hours_grazing, hours are corrected for the category of animal (cow = 1; heifer = 0.7; calf = 0.3).
N intake in concentrates by the whole herd (Nint_conc) is the difference between the imported N in concentrates (Ni_conc) and the change in N in the stock of concentrates (Nstock_conc):

$$Nint\_conc = Ni\_conc \pm Nstock\_conc \qquad (16)$$

N intake in crops/roughage (Nint_rough) by the herd is calculated as:

$$Nint\_rough = Ni\_rough + Nnet\_crop \pm Nstock\_rough \qquad (17)$$

where Ni_rough is the imported N in roughage, Nnet_crop is the net N yield of home produced crops, calculated as:

$$Nnet\_crop = Np\_crop - Nloss\_field \text{ (see above)} \qquad (18)$$

Finally, N intake during grazing (Nint_grazing) is calculated as the balancing item of the herd balance:

$$Nint\_grazing = Np\_man + Nman\_gr - Nint\_conc - Nint\_rough \qquad (19)$$

CHAPTER 7

GENERAL DISCUSSION

1 Introduction

The overall objective of this study was to evaluate the transition of nutrient management on dairy farms with intensive coaching towards realizing environmental legislation. Relationships between farm characteristics, farm management, nutrient use efficiency and environmental quality were quantified. This research objective was approached with data of 16 commercial farms participating in the project 'Cows & Opportunities'. The project was initiated to bridge the gap in resource use efficiency between experimental dairy farms, such as 'De Marke' (Aarts, 2000) and commercial farms. So far, in the project three periods have been distinguished, each period with a different focus of research questions. In the first period (1999-2003) the prototyping method was applied (Chapter 2) with the focus on reducing nutrient surpluses. In the second period (2004-2008) the target for permitted surpluses was replaced by crop-specific nutrient application standards. In the third period (2009-2013) reducing ammonia volatilization and greenhouse gases (especially methane) were important issues. The project started with a group of 17 motivated farmers. In 2003, one farm left the project because of difficulties in collecting data. In 2009, on request of the financers, five farms were renewed.

Driven by legislation and changing conditions on a farm (availability of a successor, financial situation, age of the farmer, availability of (cheap) land), farm structure (milk production, land area) on the pilot farms was changed during the project period. In general, under the influence of economic driving forces, the pilot farms expanded land area and increased their milk quota, resulting in a (limited) increase in production intensity. Farms tended to grow in size and production intensity to survive the current harsh economic environment (Ondersteijn et al., 2002).
This last chapter is dedicated to the elaboration of different emerging issues in the transition of nutrient management on commercial pilot farms. First, a synthesis of the transition in the N and P flows on commercial pilot farms is presented and discussed. Next section addresses methodological issues of prototyping research, representativeness of the pilot farms, and pros and cons of the used data, methods and statistics. The third section address issues on the impact of the project 'Cows & Opportunities' for dairy farming in the Netherlands and an outlook. Finally, the main scientific findings of this thesis are presented.

2 Development of N and P flows in 'Cows & Opportunities'

This section presents a synthesis of the transition in N and P flows on commercial pilot farms during the period 1998-2011. Some results of analysis presented in the preceding chapters are extended with the latest available project results (Gerjan Hilhorst, unpublished data). Developments in N and P flows in 'Cows & Opportunities' are compared with those in the 'national average' of commercial farms (see Chapters 3 and 5 for explanation) and also extended with the latest available data (Co Daatselaar, unpublished data).

2.1 Targets for nutrient use

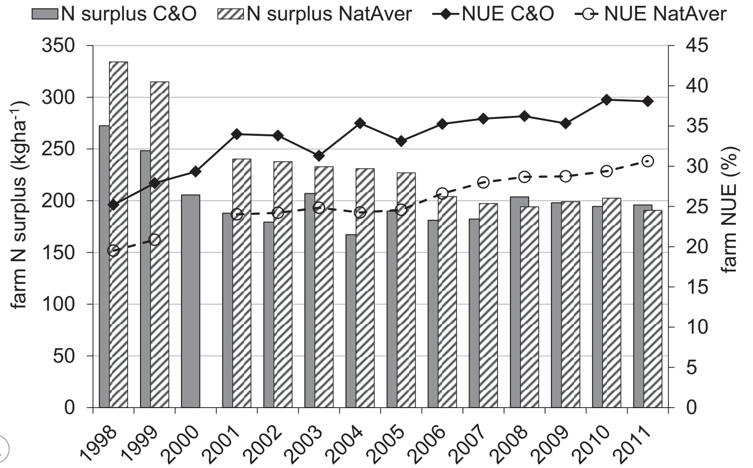
At the start of the project, measurable targets (sustainability criteria) have been formulated to reduce for example nutrient surpluses, pesticide use, energy and water use in a cost-effective way. Nutrient use was the most important target, based on legislation. The pilot farmers accepted the commitment to aim for immediate compliance with the national environmental standards which is compulsory for other commercial farmers in 3-5 years. From 1999 till 2005 the target for nutrient use was formulated by permitted surpluses: the MINAS system (Henkens & Van Keulen, 2001), followed by crop-specific nutrient application standards (Schröder & Neeteson, 2008).

2.2 Development of N and P flows at farm level

On average, in 'Cows & Opportunities' farm N and P surplus was lower and N and P use efficiency was higher than in the 'national average' (Fig. 1a, b). From 1998 to 2002, the period with legislation based on permissible nutrient surpluses, mean farm N surplus significantly decreased over time ($p<0.001$ of the slope in a linear regression). Since 2005 on the pilot farms and since 2007 in the 'national average, N surplus has remained almost constant. Due to a higher farm N surplus at the start on the 'national average' the reduction in farm N surplus during the whole period was higher on these farms. However, despite the higher level at the start, N use efficiency on the pilot farms increased more than on the 'national average': from 25 % to 38% on the pilot farms and from 20% to 30% on the 'national average' in the period 1998-2011. Patterns in development in farm P surplus and P use efficiency on the pilot farms and 'national average' was more or less similar like in N, with a few exceptions. First, the high farm P surplus on the pilot farms in 1999: one farm applied sludge with a very high P concentration. Second, at the start in 1998, P use efficiency on the pilot farms and 'national average' were almost similar.

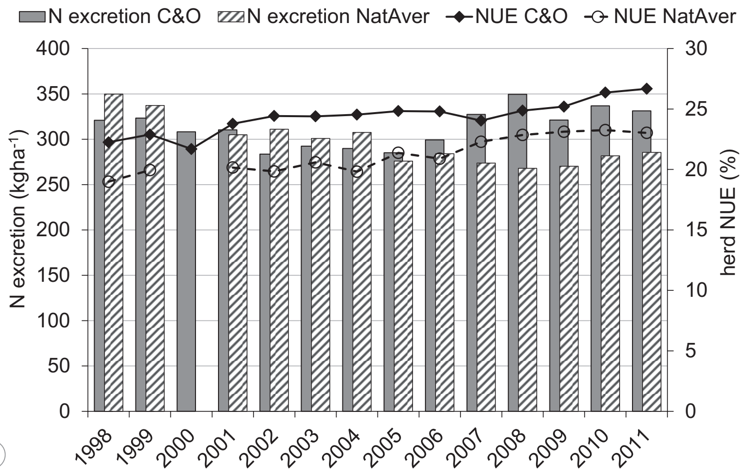
In the period 1998-2011, the pilot farms tended to grow more in size and production intensity than the 'national average' (Table 1). It has been well established that higher production intensity results in higher nutrient surpluses (e.g. Chapter 2;

farm



A

herd



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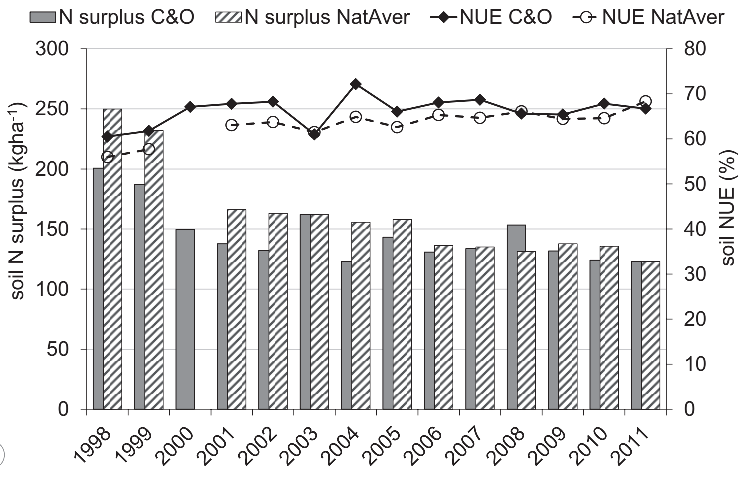

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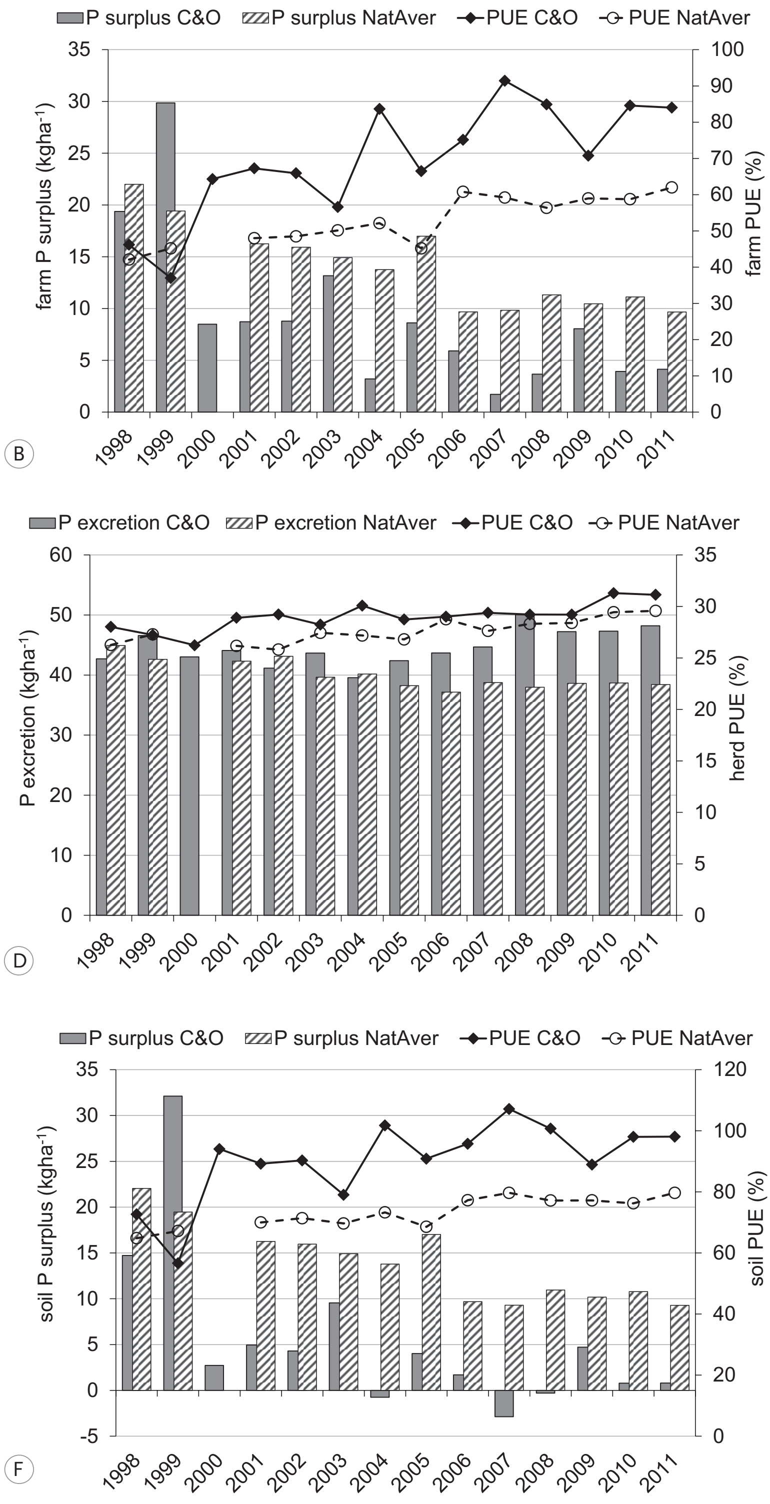

Fig. 1. *Development of (a) N and (b) P flows at farm level (surplus and use efficiency; UE), (c) N and (d) P flows at herd level (excretion and use efficiency; UE) and (e) N and (f) P flows at soil level (surplus and use efficiency; UE) on the commercial pilot farms in 'Cows & Opportunities' (C&O) and the 'national average' (NatAver) in the period 1998-2011.*

Dalgaard et al., 1998; Børsting et al., 2003; Nevens et al., 2006; Beukes et al., 2012). Despite this mechanism, the pilot farms realized equal or lower farm nutrient surpluses than the 'national average' with higher nutrient use efficiencies. The reasons for these differences can be found elsewhere in the dairy farming system: the farm components herd and soil.

Table 1. *A two-years average of the development of general farm characteristics of commercial pilot farms in the project 'Cows & Opportunities' (C&O) and the 'national average' (NatAver) in the period 1998-2011 with standard deviations between brackets for C&O.*

		'98-'99	**'00-'01**	**'02-'03**	**'04-'05**	**'06-'07**	**'08-'09**	**'10-'11**
Total milk production (Mg year^{-1})	C&O	574 (129)	646 (137)	722 (174)	776 (211)	835 (225)	941 (266)	1,048 (262)
	NatAver	580	573	614	626	669	701	791
Farm size (ha)	C&O	39 (9)	43 (13)	48 (14)	53 (16)	55 (20)	55 (21)	56 (23)
	NatAver	45	44	47	49	52	53	56
Production intensity (Mg milk ha^{-1})	C&O	15.1 (3.6)	15.6 (3.5)	15.6 (3.7)	15.2 (4.3)	16.2 (5.2)	18.4 (5.9)	19.9 (5.6)
	NatAver	13.0	13.0	13.1	12.7	12.9	13.2	14.1
Grassland area (%)	C&O	73 (14)	71 (14)	73 (13)	77 (11)	82 (10)	85 (10)	80 (12)
	NatAver	83	83	83	82	85	84	85
Number of milking cows	C&O	76 (18)	81 (19)	90 (23)	96 (25)	106 (27)	116 (31)	123 (35)
	NatAver	76	77	81	82	84	89	99
Milk production per cow (Mg year^{-1})	C&O	8.0 (1.0)	8.1 (1.0)	8.1 (1.0)	8.0 (0.8)	8.0 (1.0)	8.1 (0.8)	8.6 (0.9)
	NatAver	7.7	7.4	7.6	7.6	7.9	7.9	8.0

2.3 Development of N and P flows at herd level

Fig. 1c, d show the results of N and P excretion (expressed as kg per ha) and N and P use efficiencies of the herd. N and P excretion on pilot farms first decreased and then increased again while the 'national average' tended to decrease till 2005 and from then it remained fairly constant. As explained above, the pilot farms increased their production intensity (more milk per ha) more than the 'national average' (Table 1) resulting in a higher and increased N and P excretion per ha. Nutrient use efficiency, especially N, was on the pilot farms higher than the 'national average' and tended to increase in time. With the change in legislation from permitted nutrient surpluses to crop-specific nutrient application standards, farms with high production intensity became more conscious to improve the herd and feeding management to lower the nutrient excretion rate per animal. From 2006 onwards, on average farms have to export manure because of a manure production higher than permitted (maximum 250 kg N with animal manure per ha; see Schröder & Neeteson, 2008). Manure production on dairy farms was calculated with fixed N and P excretion rate values per animal type (Tamminga et al., 2004). N excretion rate values for milking cows depend on the milk production per cow and feed ration (indicated as urea content in the milk (mg l^{-1})). P excretion rate only depends on the milk production per cow. For other animal types (e.g. calves and heifers) fixed values for N and P excretion were assumed (Tamminga et al., 2004). However, in practice, there is more variation in manure production than indicated by the (fixed) N and P excretion rate values. The surplus of manure produced on a farm, which cannot be applied to crops has to be exported, which costs money. Highly intensive farms with lower actual N and P excretion than the fixed values have to export more manure than necessary resulting in more costs and less N and P with manure available for crops than allowed. Therefore, a tool (Excretion Calculator) was developed in 'Cows & Opportunities' to calculate farm-specific N and P excretion rates (Anonymous, 2010; Sebek, 2011). The tool calculates the specific N and P excretion from dairy cattle on farm level (as the difference between feed input and output of milk and extra bodyweight/calf). The acceptation to use Excretion Calculator as policy instrument in 2009 stimulates farmers to improve the herd management. The tool was first tested and applied in 2007 on the pilot farms and from then onwards, nutrient use efficiency on these farms tended to increased more than on the 'national average'. The increase of the P use efficiency from 2010 was due to the agreement among the farmers' union and feed supplying industry to lower the P surpluses of animal manure in the Netherlands by increasing the P use efficiency of the herd. The feed supplying industry increased its supply of feed with low P-contents and at the same time, farmers became conscious to buy this type of feed. Making use of the Excretion Calculator by farmers will stimulate them to lower the N and P excretion rates per cow.

2.4 Development of N and P flows at soil level

Results of the soil component are shown in Fig. 1e, f. Soil N surplus on the pilot farms decreased from 200 kg per ha in 1998 to 125 kg per ha in 2004, while in the remainder of the period it remained fairly constant. In the 'national average' soil N surplus decreased till 2006, and in the remainder of the period it remained fairly constant. On average, levels of N surpluses on pilot farms and 'national average' were similar, except the first two years, resulting in similar N use efficiency. However, despite equal *average* soil N surplus and soil N use efficiency, yields of *grassland* (dry matter and N) and N use efficiency of grassland on the pilot farms were higher than the 'national average' (Chapter 4). Moreover, the level of soil N surplus on the pilot farms was realized with higher N input to the soil (organic manure, chemical fertilizers, N fixation, atmospheric deposition) and higher N output (crop N yield) than in the 'national average'. Roberts (2008) and Powell et al. (2010) pointed out that N use efficiencies in dairy farming systems follow the 'law of diminishing return' in low input systems, i.e. N use efficiency is the highest at the lowest N input. Despite this 'law' soil N use efficiencies on the pilot farms were similar than those on the 'national average' but with a higher N input to the soil. The equal soil N use efficiency and higher N use efficiency on grassland on the pilot farms means that N use efficiency from other crops on the farms was lower than the 'national average'. For P, soil surplus on the pilot farms was on average lower and P use efficiency higher than the 'national average'. From 2015, the Netherlands promised the EU a P-equilibrium strategy on soils. Since 2004, the levels of soil P surplus on the pilot farms are already low and close to equilibrium.

2.5 Implemented measures

The development in N and P flows on the pilot farms is the result of adapted and implemented measures. The transition in nutrient management on the pilot farms is the result of the prototyping process described in Chapter 2. It is attractive because it allows active participation of farmers and other stakeholders in the whole process from analysis to monitoring and evaluation (Fig. 2, Chapter 2). 'Cows & Opportunities' is the practice-oriented follow-up of experimental dairy farm 'De Marke. 'De Marke' demonstrates, among other things, that by taking a coherent set of simple measures at farm level, the input of nutrients can be drastically reduced (Aarts, 2000; Hilhorst et al., 2001; Verloop, 2013). An important step in the prototyping process was the construction of a Farm Development Plan (FDP), with suggested measures to realize the targets and improved nutrient management (see Table 4, Chapter 2). Almost all suggested measures were already tested on 'De Marke', but each measure had a farm-specific interpretation and a specific effect because of the differences in agro-ecological conditions among farms (e.g. soil type). So, not 'copy and paste' but adjusted measures were used which fit on a farm taking into account the local circumstances but also the professional skills and entrepreneurship of the farmer(s). Decisions of farmers to adapt to changing conditions are not only governed by economic considerations, but also by their social and psychological characteristics (Chapter 3). From the suggested measures to reduce nutrient losses, the most attractive and effective adapted and implemented measures were:

1 *Reducing the use of chemical fertilizers.*
An easily and quickly implemented measure was to lower the nutrient application rate to crops by reducing the use of chemical fertilizers, both for N and P (Figs 2 and 3, Chapter 3). Reducing the use of chemical fertilizer contributed most to the reduction in nutrient surpluses in the first five project years, the period in which legislation was controlled with permitted nutrient surpluses (Chapter 4). On most farms, use of chemical P fertilizer was less than 5 kg per ha. In 2002, N use of chemical fertilizer was the lowest (Chapter 3 and 4), followed by an increase till 2004 and then it was stable in the remainder of the period (Chapter 4). From 2006 onwards, the use of chemical fertilizers was controlled by the crop-specific application standards.
2 *Less purchased feed by lowering crude protein (CP) and P-content of the ration.*
The second-best measure to reduce nutrient surpluses in the first five project years was the reduction of nutrients in imported feed (Chapter 3). Lowering the N import with feed was possible due to a decrease of the CP content in the ration, especially during the summer by shortening grazing time (see next measure) and supplementary stall-feeding to balance the indigested protein/energy ratio (Chapter 3). The reduction of the CP content in the ration was especially realized in the first part of the project, lowering the P-content of the ration was an important issue during the last few years (see Fig. 1d and the explanation). Initially, the project had the ability to be more independent from imported feed and fertilizers by using less chemical fertilizers and by a better use of home-produced manure and higher crop yields, to be more self-sufficient in feeding animals. A reduction in the use of chemical fertilizers was realized but not a significant increase of crop yields, especially from grassland (Chapter 4). The yields of grassland were still higher than on the 'national average' but the expected increase was not realized. Therefore, the research in 'Cows & Opportunities' should focused on analyzing the crop production to find ways to increase crop production with the same amount in use of fertilizers (organic, chemical and/or N fixation by clover).
3 *Reducing grazing time.*
The pros and cons of grazing are well described in Chapters 3, 4 and 5. The grazing time on the pilot farms was reduced resulting in a better environmental

performance in nutrient surpluses (Chapter 3), dry matter yields in grassland (Chapter 4) and nitrate leaching (Chapter 5). The last few years, grazing time was further reduced due to the increase of the farm size (Table 1) which causes logistic and especially labour problems to sustain a extensive grazing regime. Also the introduction of milking robots (on 4 pilot farms) reduced grazing time.

4 *Reducing the relative number of young stock*.
This measure was initiated because of a highly inefficient component in the nutrient balance, i.e., each additional heifer (young stock older than 1 year) increases the farm nutrient surpluses by 51 kg N and 7 kg P (Mourits et al., 2000). Young stock management is important because of selection for replacement. Replacing a milking cow requires an 'investment' in nutrients and energy intake (Aarts et al., 1999). A few pilot farms chose for off-farm rearing of young stock, which in case of nutrient management for that farm is very efficient. On the other hand, raising or fattening young stock on other farms is a case of shifting this 'investment' to elsewhere.

5 *Optimizing use of home-produced organic manure*.
At the start of the project in 1998 it was common in Dutch dairy farming to export some home-produced animal manure and/or import pig manure. Export of animal manure during that time was not associated with many costs. Moreover, animal manure was not valued as a useful fertilizer. Results of 'De Marke' showed, among other things, that through a better use of organic manure, less additional chemical fertilizer is needed to sustain the same crop yields or even to increase crop yields (Hilhorst et al., 2001; Aarts, 2000). Therefore, optimizing the use of home-produced organic manure by keeping the manure on the farm (as much as possible), optimizing the distribution to crops, and optimizing the time and method of application was suggested. From 2006 onwards, the use of home-produced manure was restricted due to the change in legislation from permitted nutrient surpluses to crop-specific application standards. For farms with a derogation (more than 70% of the land use on a farm is grassland) maximum use of animal manure for all land was 250 kg N per ha (applied manure and excreta during grazing) instead of 170 kg N per ha (Schröder & Neeteson, 2008). Hence, on average, there was no change in the total use of applied manure to grassland compared to the period with permitted nutrient surpluses (MINAS), but there was a shift from excreta during grazing to applied manure due to the reduced grazing time (Chapter 4). On the other hand the pilot farms have to export more manure due to the increasing production intensity (more cows per ha). In general, most adopted changes in optimizing use of animal manure were: (1) lowering manure application to maize land and shift to grassland (Chapter 4), (2) postponing the first application from February 1 to at least two weeks later (Oenema et al, 2008), and (3) a shift of a part of the manure application for the first grass cut (applied in March) to the second grass

cut (applied in May) (Chapter 4). Lowering manure application to maize land was proven to be promising in reducing nitrate leaching (Chapter 5). Postponing the first manure application has till now not been proved as a measure to increase nutrient use efficiency and reducing the risk for nitrate leaching. Yet, it has been argued by Aarts et al. (2000) and Verloop et al. (2006) that postponing the first manure application to mid-March is an effective measure in improving nutrient management. Also, it has not shown that optimizing the distribution of the application of manure during the growing season is an important strategy to improve nutrient use efficiency and/or increasing crop yields. More research is needed on to the effect on crop yields and environmental impact of fine-tuning the distribution of manure (and chemical fertilizers) among crops and fields.

6 *Catch crop after maize.*
Since the beginning of 'Cows & Opportunities', all pilot farms on sandy soil have been using a catch crop after maize. From 2006 onwards, growing a catch crop on sandy soil has been compulsory in the Netherlands for all maize land on sandy soils. Management of a catch crop on the pilot farms was diverse: using different types of catch crops (e.g. Italian rye grass, winter rye), fertilization of catch crop in February/March (yes or no), harvest of catch crop (yes or no), grazing of the catch crop (yes or no). Some farmers tried to adopt the system which was successfully applied on 'De Marke' where the catch crop is sown between the maize rows in early summer instead of after the maize harvest and is neither fertilized nor harvested in the following spring. It was argued that managing the catch crop this way will lead to a better catch crop with high biomass capable of catching N during the winter and spring (Verloop et al., 2006). However, in practice (on the pilot farms) problems occurred during the timing of sowing the catch crop (suitability of the machinery and/or contractor) and the risk of maize yield loss due to the competition between the catch crop and maize seedlings for light, nutrients, and water when seeding the catch crop too early. The applied strategies for catch crops on the pilot farms still lead to high levels of nitrate concentrations in groundwater below maize fields (Chapter 5). For example, our analysis demonstrates that a fertilized catch crop increases nitrate concentration with 33 mg l^{-1}. Because of the high nitrate concentrations below maize fields in the Netherlands (Willems et al., 2012), 'Cows & Opportunities' initiated together with stakeholders demonstration fields, to promote the 'De Marke' strategy for management of catch crops. This strategy is not only efficient with respect to nitrate leaching but has also advantages for organic matter dynamics in maize fields on sandy soils. We assumed that with sowing a catch crop between maize rows in early summer instead of after the maize harvest provides higher above and below ground crop yield and increases or sustains the organic matter content in the soil after destroying and plowing the (catch) grass sod before sowing a new (maize) crop.

3 Methodological aspects of prototyping

3.1 Prototyping on commercial farms

The project 'Cows & Opportunities' builds on experiences obtained at experimental dairy farm 'De Marke' and can be considered as the practice-oriented follow-up of the prototyping method (Chapter 2). Prototyping on an experimental farm always needs a follow-up with pilot farms to elaborate a range of variants of the prototype (Vereijken, 1997).The combination of system modeling and system prototyping is an attractive method for developing strongly improved dairy farming systems (Aarts, 2000; Van Keulen et al., 2000; Sterk et al., 2007). The most important difference in the prototyping method applied on an experimental farm and on commercial farms is the step of 'system modeling'. Whereas on an experimental dairy farm the most promising prototype system is entirely implemented (Aarts et al., 1992; Vereijken, 1992), on commercial dairy farms system modeling is used to adjust parts of existing farming systems to realize the targets (Chapter 2). The advantage of 'Cows & Opportunities' is the use of 16 prototyping dairy farming systems instead of one (Aarts, 2000; Verloop, 2013) which gives the possibility to use statistical tests, which will be discussed below.

The pilot farms are willing to test new innovations on their farms, such as slurry separation (Verloop et al., 2013), which always presents risks of failures. 'Cows & Opportunities' provides a platform for testing and improving new innovations which can then be adopted by other farmers. But during the test phase there are risks of lower environmental performances in (parts of) the nutrient cycle on (some of) the pilot farms.

The introduction of a Farm Development Plan (FDP) has been identified as a critical success factor in this project. Developing a plan forced farmers in collaboration with researchers and extension agents to look critically at the performances of the farm. Moreover, a FDP is farm-specific in finding ways in what is possible in improving nutrient management. Not only agro-ecological conditions are involved in this process but also the professional skills and entrepreneurship. Decisions of individual farmers on transition in farm and nutrient management are not always based on 'rational' arguments, but are co-determined by 'emotional' and/or 'social' perceptions. The FDP is also used in the Dairyman project – an European project aiming to enhance the environmental and economic sustainability of the dairy sector in seven countries in northwest Europe (Belgium, France, Germany, Luxembourg, Ireland, the United Kingdom and The Netherlands) by sharing knowledge and transfer of experiences (Aarts, 2012). A standardized FDP was applied on a network of 130 progressive commercial pilot farms, to guide them to meet both economic and environmental targets.

After implementation of the plan on the Dutch pilot farms and monitoring results, the prototypes of improved dairy farming systems were evaluated. For this process a integrative Farm Evaluation Report (FER) was developed: a comprehensively report of farm and environmental indicators in which results of implementation were compared with the targets. Around the kitchen table, results were discussed and adjusted plans were developed. That was the idea. But, in practice the FER was too complicated and all members involved in this process did no longer see the wood for the trees. At that moment, (1) it was too early for such an evaluation report, (2) there was a lack of reference values (benchmarking), and (3) the evaluation and further improvement was on a voluntary basis, i.e. it was not compulsory with legislation and/or financial incentives. Currently (2013), the government and all stakeholders in dairy farming are looking for a similar type of evaluation report, which is initiated in the project 'Cows & Opportunities'. It is called ANCA and will be discussed below.

3.2 Representativeness of pilot farms

Selection of farmers was based on representation of the full range of farming conditions and possibilities for dissemination of pilot farms to other farms (Chapter 2). The selection procedure was precise and comprehensive and involved a number of steps resulting in a selection of 17 dairy farms. From the start, the condition of representation of soil type was more focused on sandy soils because of the nitrate leaching problems in the Netherlands during that time. The production intensity on the selected pilot farms was at the start higher than the 'national average' (Table 1), which conflicts with representativeness. On the other hand, production intensity is not that an important condition to disseminate possibilities for improved dairy farming systems. Dairy farming systems in the Netherlands, pilot farms and other farms tend to grow in productions intensity (Table 1), so other farms can still 'learn' from 'comparable' pilot farms in the past. Other conditions, such as regional aspects are more important than production intensity in the chain of information and knowledge transfer from theoretical and experimental research to commercial dairy farms (Vereijken, 1997). Farms with lower production intensity can learn from farms with higher production intensity how to improve the internal cycle (herd & feeding management and soil & crop management). On farms with high production intensity there is a higher need to improve the internal cycle because of the feed needed on such farms (Chapter 4).

3.3 Data collection and monitoring: consistency and uncertainty

The research in this thesis was based on data collected in the project 'Cows & Opportunities'. So far, the project gained data over a period of 14 years, which renders more insight in long-term effects of nutrient management changes. Each chapter contains a section data collection and monitoring, depending of the objective and scope. At the start of the project, data acquisition and analysis were identified as a critical success factor (Chapter 2). A structure for a comprehensive central data bank was set up to store all data and results from data analysis (see Fig. 4, Chapter 2). After a few years of experiences in using such a sophisticated central data bank, the main conclusion was that such a system was not working properly. This was caused by (1) time and money consumption in controlling the process of collecting data, (2) access problems of the data due to the diversity of participants (research organizations), (3) problems to get data from the central data bank due to the lack of knowledge in using sophisticated software, and (4) problems with controlling and validating the data (who is responsible?; accessibility of the central data bank). All these problems led to the failure in using a central data bank in this project. On the other hand, a good and simple working central data bank for such projects can be very important in efficient data collection and handling. Projects in the future can learn from the lessons in this project. In general, data collection and monitoring is not only 'collection', validation and accessibility are also important components. For the research in this thesis, we had the opportunity to have direct access to the data through using simple excel-files to collect, control and validate the data.

This PhD-thesis was not a main target at the start of the project but was initiated in 2005. Research questions were formulated on the basis of availability of the data. Ondersteijn (2002) experienced the same problems in her thesis on the basis of data in the project 'Farm Data in Practice'. Rigidity in bookkeeping-rules and unfamiliarity with administration of data causes problems in quality of the data. In our project, we solved these problems as much as possible by setting up protocols for collecting data but also - and even more important - guiding the farmers and extension agents in data collecting and monitoring (Chapters 3, 4, 5 and 6). Data errors on farms in practice are almost unavoidable, due to the capability, willingness and accuracy of the farmers and/or extension agents. Therefore, data checks are needed to validate the data. This project is an example of dairy farming system research where feedbacks in N and P flows between the sub systems herd, manure soil and crop can be explored (Chapters 3 and 6). To demonstrate the importance and added value of dairy farming system research in validating data, two examples are given: a simple data check and a more complex one. The recorded field-level data for the use of chemical fertilizer should be equal to the imported amount of chemical fertilizer, corrected for changes in stock. In case of differences, next step is to find out which one is not correct: the recorded field-level data, the imported amount of chemical fertilizer or the recorded changes in stock. A more complex example is the N intake during grazing, which is the balance entry of the herd balance but also the balance entry of the whole N cycle (see Chapter 6). This value for N intake during grazing can be verified with the calculated value based on information from monitored data, such as applied grazing regimes, estimated standing dry matter during grazing and the N-content in grazed grass (analyzed or fixed value). The accuracy of the value for N intake during grazing can be further improved by using the P intake during grazing (calculated in the same way as the N intake during grazing) to calculate the N/P ratio. When the ratio is outside a certain range, original and collected data need an adjustment. These adjustments were done through a check with the 'farmer's opinion' or else by expert judgment.

3.4 Used methods and statistics

Prototyping research in dairy farming can be considered as very complex, due to the combination of animal and crop production. In the 'classical way of research', experiments are set up to study the effect of (a) factor(s) on the basis of the objective of research. Careful designs of the experiments allow the use of statistical tests to study the effect of the(se) factor(s). However, interactions with other factors in a dairy farming system are not investigated in such experiments, which in reality are very important to adopt and implement results of these experiments in systems. Prototyping research on an *experimental* farm can be considered as a compromise where the experimental farm should provide both the relevance and the conditions to clarify the effect of individual factor(s) on whole system performance (Verloop, 2013). However, the problem of research on one experimental farm is the lack of replication and representativeness for other types of farms. This should be solved by executing this type of research on commercial (pilot) farms like in 'Cows & Opportunities', the case study of this PhD-thesis.

Linear regression models were used to analyze development of farm management strategies in time (Chapter 3) and to explore the effects of farm management practices and soil and climatic conditions on nitrate leaching (Chapter 5). In Chapter 3 we aimed to understand the development in system performance among specialized dairy farms, by systematically examining whether differences among farms can be explained by different management practices. An approach based on an analysis on each individual farm was not possible due to the unsteady farm development caused by the annual decisions by farmers and the yearly variation in weather conditions. These problems were solved by splitting the farms in two equal sized groups and then the difference between the groups was tested by using the variance among farms within the group. Ideally, methods like Data Envelopment Analysis (DEA) or Stochastic Frontier Analysis (SFA) are preferred in Chapters 3 and 4. To improve nutrient management it is essential to learn from successful colleagues who can act as benchmark, rather than focusing on average performance of a group (Ondersteijn, 2002). Our dataset was too small and the used characteristics too many for using such methods (Chambers et al., 1998; Tauer & Hanchar, 1995).

Chapter 5 applied multiple linear regressions (MR) to understand the effects of a range of management practices on nitrate leaching on sandy soils, taking into account the environmental conditions on a farm. Because of the unbalanced datasets and data observations at different levels (farm, field and sampling point) the method of REML (Residual maximum likelihood) was preferred above MR. The REML algorithm estimates treatment effects and variance components in a linear mixed model with fixed and random variables. In MR there is only one term for the variance, whereas in REML a more complex structure of variance can be part of the model. In REML, input data used as explanatory variable for nitrate leaching can be tested using that variance at their measurement level. However, the REML method cannot be combined with the selection of variables (e.g. the RSEARCH procedure in Genstat (Genstat, 2009)), in contrast to MR. The selection of variables procedure identifies the best parameter combinations in explaining the levels of nitrate concentrations in groundwater. Therefore, the REML method was used only to compare with the results of MR.

4 Outlook

4.1 Knowledge exchange and communication

Transfer of knowledge gained at experimental and commercial pilot farms was an important target in 'Cows & Opportunities' (Chapter 2). It was argued that intensive coaching and transfer of knowledge will help dairy farmers to adopt changes in management more easily. Projects like 'Cows & Opportunities' play an important role in the 'information dissemination' diagram (Fig. 1, Chapter 2) to make the link between research and practice. It was argued by Vereijken (1997) that prototyping research on several commercial farms is essential for wide-scale dissemination because of region-specific ranges in soil, climate and management conditions which are crucial for adaptation and transition in nutrient management. Moreover, a group of capable and motivated farmers provides an indispensable technological and social base for an innovation project, which should include dissemination throughout the region (Vereijken, 1997; Sterk et al., 2007). Farmers participating in 'Cows & Opportunities' shared their experiences with each other and with other farmers by organizing excursions and study groups. Farmers need proper information for improved decision making (Churi et al., 2012) and effective communication with farmers is essential to change their behavior (Jansen et al., 2010). For example, extension agents have an important role in communication to and with farmers (Garforth et al., 2003; Ofuoku et al., 2012). Farmer-to-farmer communication is the best way to transfer knowledge from research to practice. Moreover, publishing results in agricultural magazines is used to contact other dairy farmers (e.g. Bratt, 2002). In 2012, frequency of direct communication to stakeholders by farmers and researchers via excursions, presentations, lectures was around 140, reaching about 5000 people. Frequency of written (short) communication in (agricultural) magazines was around 125 and via websites around 80. So far, the project delivered around 70 extensive research reports.

The information and knowledge gained in this project was not only used for communication to other farmers but also used for policy support at national and EU level. For example, results of the environmental performance on the pilot farms were used for the request for a derogation for dairy farms to apply a maximum of 250 kg instead of 170 kg manure-N (total) per ha per year (Schröder & Neeteson, 2008).

4.2 Spin-off of 'Cows & Opportunities'

A spin-off of the project is the development and testing of tools to calculate farm-specific performances. The Excretion Calculator (see Section 3.3) - accepted as a policy instrument for dairy farmers to calculate the farm specific manure production - is now used by more than 60% of the dairy farmers (Anonymous, 2012). Another example is the Ammonia Calculator, based on the Dutch methodology to calculate ammonia emissions from agriculture (Velthof et al., 2009), which calculates the farm-specific ammonia emission from housing, storage, grazing, manure application and mineral fertilizers. Yet another example is the P yield Calculator, which calculates the farm-specific P crop yield from grassland and maize land (Oenema et al., 2011). The Netherlands has the intension to use the P yield indicator as policy instrument to derive farm-specific crop P application standards (the Dutch government will ask permission from the European Commission for including in the 5th Action programme for the period 2014-2017). Farmers should choose either for the generic or the farm-specific P application standards.

Besides the use of the tools as policy instrument, the tools have proven their value as management instrument to improve environmental performance on the pilot farms. For example, the N and P use efficiency on the herd level increased after the introduction of the Excretion Calculator in 2007 (see Figs 1c and 1d and Section 3.3).

Another spin-off of the project is a new project called 'Annual Nutrient Cycling Assessment (ANCA)'. The objective of this project is the development of the instrument ANCA, presenting a scientific, integrated, unambiguous, and fraud-proof picture of the N, P and C cycles of the individual dairy farm. This results in a number of indicators, that enable the dairy farmer to justify his/her farm management towards authorities and milk processing industry as well as to optimise his/her management. This might offer policy makers and authorities' possibilities for replacing generic legislation by farm-specific regulations which would give dairy farmers more management freedom. And it may offer the milk processing industry possibilities for making the sustainability strategy concrete, and accepted by dairy farmers. Almost all stakeholders in Dutch dairy farming are involved in this project: farmers' unions, supplying and processing industries, knowledge organizations and governments. The ANCA project is developed in close cooperation with the project 'Cows & Opportunities'.

4.3 How to proceed?

Improving resource management in dairy farming systems and knowledge transfer and exchange are still issues for the future research and dissemination. Research should be demand-driven and provide farms with knowledge that is applicable in farm management (Aarts, 2000). Over the last decade, concerns about greenhouse gases have been increasing and they are an important topic on the agenda for policy makers but also for stakeholders, such as milk processors FrieslandCampina in the Netherlands (www.frieslandcampina.com) and Arla Foods in Denmark and Sweden (Schmidt & Dalgaard, 2012). Therefore, calculating the carbon footprint at farm level is important for the dairy farming sector. In the DAIRYMAN project, a tool was developed to calculate the on-farm and off-farm greenhouse gases emissions (from cradle to farm gate) for dairy production systems. The DAIRYMAN GHG calculator uses the IPCC guidelines 2006 for Tier 1 and Tier 2 level (www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html) and translated these to farm level. The tool was applied and tested on a network of 130 progressive commercial pilot farms throughout northwest Europe and the first results indicate that the tool was very useful but improvements are needed. One improvement is the need of a method on Tier 3 level to calculate a more farm-specific carbon footprint on farm level. This method provides not only a more precise calculation of the carbon footprint, but provides also information to farmers how to improve the carbon footprint on their farms. Tier 1 and Tier 2 calculation of the carbon footprint are too generic for farm level, because changes in farm management will not always lead to a change in carbon footprint. In the third project period of 'Cows & Opportunities' (2009-2013) we started with developing a methodology for the farm-specific carbon footprint on a Tier 3 level with the focus on methane emissions from animals. At the same time, FDP's were made to decrease greenhouse gases emissions on the farms. The first experiences indicate that farmers do not have much affinity with managing greenhouse gases compared with managing nutrients because of (1) lack of incentives, (2) lack of knowledge about levels of greenhouse gases, (3) costs of implementation of measures. Another problem of improving the greenhouse gas emissions on farm level is the interaction with other environmental issues like ammonia emissions, i.e. conflicts between measures (Shepherd & Chambers, 2007). For example: decreasing methane emissions from animals may lead to increasing levels of ammonia emissions. Therefore, an integrative approach of different environmental performances on dairy farms is needed: ANCA. The carbon footprint should be added to ANCA to provide the complete picture of the technical and environmental performance (N, P and C cycle) on dairy farms. To improve the technical and environmental performances, benchmarking of results is very important (e.g. Van Calker, 2005). To benchmark (reference values), information of the Dutch Farm Accountancy Data Network (FADN) can be used to obtain averages and/or info on the 10 and 25% 'best' dairy farms. For comparative purposes, results should be provided for different farm types, based on e.g. soil type and production intensity. Another category of benchmarking is to provide target and/or normative values for environmental issues like nutrient surpluses, ammonia emissions, carbon footprint.

To comply with environmental standards and societal demands imposed by policy makers but also by milk processors, improving resource use efficiency is the way forward for the dairy production industry in the future. Essential for this process is continuing knowledge exchange between policy makers, researchers, farmers, advisors and stakeholders. New innovations in dairy farming systems need to be tested with prototyping on experimental dairy farms, like De Marke, before their dissemination with pilot farms. Furthermore, a platform with pilot farms is also needed to test and improve tools and instruments such as ANCA.

5 Main scientific findings

The project 'Cows & Opportunities' forms an important link in the chain of information and knowledge transfer from theoretical and experimental research to commercial dairy farms.

The results of Chapter 3 and the general discussion (Chapter 7) about development in farm management form the basis of the following conclusions:

- From the start in 1998 until 2002, average nutrient surpluses on the commercial pilot farms in the project 'Cows & Opportunities' decreased by 33% for N and 53% for P. On the 'national average' farm, nutrient surpluses decreased in the same period almost similarly for N (29%), but less for P (28%). However, on the commercial pilot farms, nutrient use efficiency in 2002 was 34% for N and 67% for P compared with 23% and 49%, respectively, on the 'national average' farm. In the remainder of the period (2003-2011) nutrient use efficiency continued to increase to 38% for N and 85% for P on the commercial pilot farms and till 30% for N and 60% for P on the 'national average'.

- Decisions of individual farmers on farm development are not always based on 'rational' arguments, but also co-determined by 'emotional' perceptions.
- Intensive coaching and very frequent interaction among researchers, extension agents and farmers resulted in adoption and implementation of nutrient-efficient management in practice. Important measures were reducing the use of mineral fertilizer, optimizing the use of home-produced manure, reducing grazing time, reducing the number of replacement stock, lowering crude protein and phosphorus content in the ration, and managing a catch crop after maize.

The variation in farm N surplus among the commercial pilot farms remained high over time during the first six project-years. The variation may be related to differences in production environments (both agro-ecological and socio-economic) in which the farm(er)s operate. This requires analysis of detailed and accurate data on nutrient balances at the whole-farm level and at the herd level and feeding regimes and crop level and fertilizer regimes. Grassland is the most important source of feed on dairy farms in the Netherlands and Chapter 5 describes and analyses the development and variation in N management on grassland on the commercial pilot farms. The main conclusions were:

- Possibilities for improvement of nitrogen (N) management on grassland of dairy farms are bounded by site-specific biophysical conditions, such as weather patterns and soil moisture supply. However, analysis of the variability in realized dry matter yields and NUE on commercial pilot farms over the 1998-2009 period indicates that substantial improvements in N management on grassland were possible on many commercial dairy farms, but strategies differ among farms, such as N fertilization levels and regimes, and grazing intensity.
- Making use of the variation of management on grassland and on the whole farm on pilot farms may provide farmers outside the project insight in the (im)possibilities to improve N management on grassland.

The high N losses in the Netherlands affected the quality of groundwater, especially on sandy soils. In the selection procedure of the commercial dairy farms, there was a strong focus on farms on sandy soils. From the 16 pilot farms, eight farms were located on sandy soils, and these gave the opportunity to study the effects of farm management practices and soil and climatic conditions on nitrate leaching (1999-2006) from grassland and maize land on sandy soils at three spatial scales: farm, field and sampling point (Chapter 6). The main conclusions were:

- The most important variables affecting nitrate leaching at farm scale are farm N surplus, grazing intensity, the relative area of grassland and the dissolved organic matter concentration in the groundwater. In grassland at field and sam-

pling point scale, additional variables are plowing up the grassland sward, soil organic matter content and the mean highest groundwater table in winter. On maize land, total N input to the soil, the first year crop in a crop rotation (yes/no) and catch crop fertilization (yes/no) are important management variables.
- Additional measures are needed to realize the EU water quality standard in groundwater on sandy soil of 50 mg nitrate l^{-1}. Most promising measures are omitting fertilization of catch crops and lowering fertilization levels of first-year maize in the rotation.

Decisions in nutrient management and environmental policy making have to be based on sound data and proper analysis. An input-output N balance model was developed to describe and quantify N flows in dairy farming systems (Chapter 6). The main conclusions were:

- N flows on dairy farms pertaining to the whole farm balance ('external flows') were less uncertain than N flows pertaining to the component balances from herd and soil ('internal flows'). The uncertainties in N flows - both relative (coefficient of variation; cv) and absolute (standard deviation; sd) - increased from farm N surplus (cv=8%; sd=15 kg N ha^{-1}) via soil N surplus (cv=12%; sd=16 kg N ha^{-1}) to N intake during grazing (cv=49%; sd=28 kg N ha^{-1}).
- Uncertainties in N flows can be reduced by focusing on the most uncertain input, in combination with the relative contribution of these inputs to the balance. N fixation by clover and the annual stock changes of roughage and manure are main sources for the variation in farm N surplus and soil N surplus.

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SUMMARY

1 Introduction

Dairy farming in the Netherlands has changed after World War II, as a result of specialization, and technological innovation. Scaling-up and intensification characterized the Dutch way of dairy farming since 1960. To maintain income, farmers responded by increasing milk quota and to some extent also land area, however with the net result of a higher milk production per ha and per man-hour to reduce land and labour costs per unit milk production. Due to the intensification dairy farming systems rely on *(i)* import of cheap chemical fertilizers to boost forage and *(ii)* import of animal feed to increase milk production to economically attractive levels. Only a fraction of the nutrients contained in the imported fertilizers and feed is converted to animal products exported from the farm. The remainder is excreted via dung and urine and can be utilized again for crop production or is lost to the environment. The nutrient losses to the environment affected the quality of groundwater and surface water and contributed to acid deposition (ammonia) that caused damage of forest vegetation.

Recognition of the impact of nutrient losses to the environment has resulted in the development of government policies in many European countries. The Netherlands implemented in 1998 a nutrient balance approach, the MINeral Accounting System (MINAS), as the central instrument for restricting emission of nutrients to the environment, with levy-free standards for acceptable nutrient losses. In 2006, the MINAS balance approach was replaced by a one-sided input approach by introducing permitted N rates (so-called 'application standards') for all crops. The present study focus on the transition of nutrient management in the whole dairy farming systems, i.e. farm-specific analysis based on detailed and accurate data on nutrient balances at the whole farm and at the herd and soil level, on commercial pilot farms over a long time period (1998-2011).

The aim of this thesis is to evaluate the transition on dairy farms with intensive coaching towards realizing environmental legislation. For this purpose data of the project 'Cows & Opportunities' with pilot commercial farms were used. More specifically, the following research questions were addressed:

- Can a participatory project with pilot farms help to adopt changes in nutrient management to bridge the gap in performance between experimental and commercial dairy farms;
- How to change whole farm management to reduce nutrient losses;
- How to improve grassland management and how and which factors affect the grassland yields on commercial dairy farms;

- Can means-orientated legislation instead of goal-orientated legislation fulfill the target of 50 mg nitrate l^{-1} in groundwater;
- What is the uncertainty of nutrient flows on commercial pilot farms using a monitoring program and what is the contribution of the collected data to this uncertainty.

2 The project 'Cows & Opportunities'

The environmental problems in Dutch dairy farming have led to the establishment of the experimental dairy farm 'De Marke', aiming to improve the utilization of fertilizers and feeds, by minimizing nutrient requirements, maximizing the use of nutrients in organic manure and homegrown feeds and through the targeted use of imported fertilizers and feed. When comparing the results of 'De Marke' with those of Dutch dairy farmers, there was still a huge gap between what is technically feasible and what commercial dairy farmers realize in practice.

The project 'Cows & Opportunities' assumed that to bridge the gap in environmental performance between the experimental dairy farm and commercial farms intensive coaching and transfer of knowledge is required (Chapter 2). The project 'Cows & Opportunities' is the practice-oriented follow-up of experimental dairy farm 'De Marke' that involves close co-operation of enterprising and future-oriented dairy farmers, researchers and other stakeholders to develop and demonstrate strategies for sustainable dairy farming. For designing suitable farming systems the method of prototyping was used, which implies a combination of system modeling and system implementation. An intensive 'analysis-modelling-planning-implementation-monitoring-analysis' cycle was followed, involving active participation of farmers, researchers and extension specialists. Measurable targets for nutrients were formulated to realize the transition of improved nutrient management. At the start, each farm was thoroughly diagnosed to identify its strengths and weaknesses in the original situation and to analyse the opportunities. This analysis also identified the gap between the targets and the reality of the original situation. Subsequently, outlines for farm designs were formulated for each participant. Consultations between each farmer and the research team yielded a list of measures, based on best professional judgement. A whole-farm system model was used to simulate the effects of the new farm design, to calculate the environmental and economic effects, and to identify the best farm strategies. After modelling and adjusting the farm design, the farm development plan (FDP) was constructed, approved and implemented. Farmers in 'Cows & Opportunities' share their experiences with each other and with other farmers. Study groups were formed around 'Cows & Opportunities', to ensure that other farmers receive first-hand information. The project 'Cows and Opportunities' forms a unique link in the chain of information and knowledge transfer from theoretical and experimental research to commercial dairy farms.

3 Results

Nutrient use was the most important target on the 16 commercial pilot farms in 'Cows & Opportunities'. The pilot farmers accepted the commitment to aim for immediate compliance with the national environmental standards (either permitted nutrient surpluses or crop-specific nutrient application standards) which would become compulsory for other commercial farmers in 3-5 years.

Linear regression models were used to analyze development of farm management strategies in the period 1998-2003 (Chapter 3). From the start in 1998 to 2002, average nutrient surpluses on the commercial pilot farms decreased by 33% for N and 53% for P. On the 'national average' farm (average specialized dairy farm, based on data from the Dutch Farm Accountancy Data Network (FADN), nutrient surpluses decreased in the same period almost at the same rate for N (29%), but less for P (28%). However, on the pilot commercial farms, nutrient use efficiency in 2002 was 34% for N and 67% for P compared to 23% and 49%, respectively as the 'national average' farm (Chapter 3). In the remainder of the period (2003-2011) nutrient use efficiency continuously increased till 38% for N and 85% for P on the commercial pilot farms and till 30% for N and 60% for P on the 'national average' (Chapter 7). Production intensity (Mg milk ha^{-1}) on the 'national average' farm remained lower than on the pilot commercial farms. Intensive coaching and very frequent interaction between researchers, extension agents and farmers resulted in adoption and implementation of nutrient-efficient management in practice. Effective strategies to reduce nutrient losses are based on optimizing internal nutrient cycling in subsystems, so that external inputs of nutrients can be reduced. Adopted and implemented measures were (1) reducing the use of chemical fertilizers, (2) optimizing the use of home-produced organic manure, (3) reducing grazing time, (4) reducing the relative number of young stock, (5) lowering crude protein content in the ration, and (6) applying and managing a catch crop after maize. To explain differences in farm development, farms were classified on the basis of intensity and N surplus at the start of the project. Farms characterized by low N surpluses at the start still identified opportunities to reduce nutrient losses. Between 1998 and 2003, the variation in N surplus among farms remained constant. The possibilities to improve nutrient management is farm(-type)-specific, and (co-)determined by agro-ecological conditions (e.g. soil type), but also by professional skills and entrepreneurship. Identification of the factors underlying these substantial variations in N surpluses is needed and requires analysis of the effect in changes in nutrient management in the whole dairy farming system (Chapter 3).

Grassland is the most important source of feed on dairy farms in the Netherlands, followed by silage maize. Chapter 4 describes the development and variation in N management on grassland in the period 1998-2009 and relates this to differences in farm structure and soil characteristics. This can reveal opportunities to improve N management and N use efficiency on grassland on dairy farms. Mean N application rate (kg total N ha^{-1} $year^{-1}$) on grassland (in manure, chemical fertilizer, excreta during grazing, biological N fixation and atmospheric deposition) on the pilot farms decreased from 540 in 1998 to 450 in 2001, while in the remainder of the period the inter-annual variation was low (between 400 and 450). Mean dry matter yields on grassland (11 Mg ha^{-1}) varied across years and farms (between 8 and 16 Mg ha^{-1}), without any significant temporal trend. We observed no trend of diminishing returns of dry matter yields at farm scale up to an N application rate on grassland of ca. 600 kg ha^{-1} because farms with a high production intensity (Mg milk per ha) need more dry matter than farms with a lower intensity and were able to maintain N use efficiency on grassland with high N input levels. Moreover, the most intensive farms were mostly located on good and fertile soils. In the period 2000-2009, N use efficiency (NUE) on grassland was 68% and the N surplus was around 160 kg per ha. The 'national average' NUE was lower and the N surplus was higher (i.e. 59% and 204 kg per ha, respectively). Possibilities for improvement of N management on grassland of dairy farms are bounded by site-specific biophysical conditions, such as weather patterns and soil moisture supply. However, analysis of the variability in realized dry matter yields and NUE on commercial pilot farms over the 1998-2009 period indicated that substantial improvements in N management on grassland are possible on many commercial dairy farms, but strategies differ among farms, such as N fertilization levels and -regimes, and grazing intensity.

Multiple linear regressions was used to understand the effects of farm management practices and soil and climatic conditions on nitrate leaching in the period 1999-2006 from grassland and maize land on sandy soils at three spatial scales: farm, field and sampling point (Chapter 5). Results and insights of this study can be used to support further development and refinement of policy instruments. Mean nitrate concentration in upper groundwater at farm scale decreased from 79 mg l^{-1} in 1999 to 63 mg l^{-1} in 2006, with average nitrate concentration in groundwater decreasing under grassland, but increasing under maize land over the monitoring period. The effects of management practices on nitrate concentration varied with spatial scale. At farm scale, farm N surplus and grazing intensity significantly contributed (positive) to explaining the variance in nitrate concentration in groundwater. Mean nitrate concentration was negatively correlated to the concentration of dissolved organic carbon in the shallow groundwater and the relative area of grassland on a farm. At field scale, management practices, soil, hydrological and climatic conditions significantly contributed to explaining the variance in nitrate concentration in groundwater under grassland and maize land. We conclude that on the pilot farms, additional measures are needed to comply with the EU water quality standard in groundwater of 50 mg nitrate l^{-1}. Most promising measures are omitting fertilization of catch crops and reducing fertilization levels of first-year maize in the rotation.

Decisions in nutrient management and environmental policy making have to be based on sound data and proper analysis. Uncertainty in effects of nutrient management may lead to confusion and wrong conclusions. Data collection and monitoring are wrought with uncertainties that need to be addressed. An input-output N balance model was developed in ‘Cows & Opportunities’ to describe and quantify N flows in dairy farming systems (Chapter 6). Input for this model was based on monitored data in 2005 from one experimental and 14 pilot commercial dairy farms. A Monte Carlo approach was used to quantify effects of uncertainty in (monitored) input data on annual farm N surplus, soil N surplus and N intake during grazing, followed by a sensitivity analysis to apportion the different sources in the uncertainty. Results can be used to understand the uncertainty in N flows on dairy farms as a basis for policy and decision-making but also in convincing and stimulating dairy farmers to improve their management. Farm N surplus ranged between 81 and 294 kg ha^{-1} across farms, soil N surplus between 35 and 256 kg ha^{-1} and N intake during grazing between 27 and 108 kg ha^{-1}. The uncertainties in N flows - both relative (coefficient of variation; cv) and absolute (standard deviation; sd) - increase from farm N surplus (cv=8%; sd=15 kg N ha^{-1}) via soil N surplus (cv=12%; sd=16 kg N ha^{-1}) to N intake during grazing (cv=49%; sd=28 kg N ha^{-1}). N flows on dairy farms pertaining to the whole farm balance (‘external flows’) are less uncertain than N flows pertaining to the component balances from herd and soil (‘internal flows’). Uncertainties in annual N flows can be reduced by focusing on the most uncertain input, in combination with the relative contribution of these inputs to the balance. N fixation by clover and the annual stock changes of roughage and manure are main sources for the variation in annual farm N surplus and soil N surplus. Estimates of N fixation by clover can be improved by using effective tools to estimate the clover content in grassland, and by better estimates of a farm-specific N fixation factor. Establishing uniform protocols and guidelines for farmers to estimate changes in stocks of roughage and manure may contribute to lower the uncertainty in the changes of these stocks.

4 Experience with prototyping on commercial pilot farms

The project 'Cows & Opportunities' builds on experiences with the prototyping method obtained at experimental dairy farm 'De Marke'. Whereas on an experimental dairy farm the most promising (modeled) prototype system is entirely implemented, on commercial dairy farms modeling is used to adjust parts of existing farming systems to realize the targets. The advantage of 'Cows & Opportunities' is the use of 16 prototyping dairy farming systems instead of one, which enhanced elaboration of a range of prototype variants for wide-scale dissemination.

The introduction of a Farm Development Plan (FDP) has been identified as a critical success factor in this project. Developing a plan forced farmers in collaboration with researchers and extension agents to look critically at the performances of the farm. Moreover, a FDP is farm-specific in finding ways in what is possible in improving nutrient management. Not only agro-ecological conditions are involved in this process but also the professional skills and entrepreneurship. Decisions of individual farmers on transition in farm and nutrient management are not always based on 'rational' arguments, but are co-determined by 'emotional' and/or 'social' perceptions (Chapter 3).

Knowledge exchange and communication plays an important role in the prototyping method and was an important target in 'Cows & Opportunities'. Intensive coaching and transfer of knowledge will help dairy farmers to adopt changes in management more easily. Prototyping research on several commercial pilot farms is essential for wide-scale dissemination because of region-specific ranges in soil, climate and management conditions which are crucial for adaptation and transition in improved nutrient management. Farmer-to-farmer communication is the best way to transfer knowledge from research to practice. Moreover, publishing results in research reports and in agricultural magazines is used to reach other farmers and stakeholders. Thousands of people involved in Dutch dairy farming - farmers, researchers, extension agents, policy makers and other stakeholders - receive information each year about experiences and progress in farming system research in 'Cows & Opportunities'.

5 The future

A spin-off of the project is a new project called 'Annual Nutrient Cycling Assessment (ANCA)'. The objective of this project is the development of the instrument ANCA, presenting a scientific, integrated, unambiguous, and fraud-proof picture of the N, P and C cycles of the individual dairy farm. This results in a number of indicators, that enable the dairy farmer to justify his/her farm management towards authorities and milk processing industry as well as to optimize his/her management. This might offer policy makers and authorities' possibilities for replacing generic legislation by farm-specific regulations which would give dairy farmers more management freedom. And it may offer the milk processing industry possibilities for making the sustainability strategy concrete, and accepted by dairy farmers. Almost all stakeholders in Dutch dairy farming are involved in this project: farmers' unions, supplying and processing industries, knowledge organizations and governments. The ANCA project is developed in close cooperation with the project 'Cows & Opportunities'.

To comply with environmental standards and societal demands imposed by policy makers but also by milk processors, improving resource use efficiency is the way forward for the dairy production industry in the future. Essential for this process is continuing knowledge exchange between policy makers, researchers, farmers, advisors and stakeholders. New innovations in dairy farming systems need to be tested with prototyping on experimental dairy farms, like 'De Marke', before their dissemination with pilot farms.

SAMENVATTING

1 Inleiding

De Nederlandse melkveehouderij is zich na de Tweede Wereldoorlog steeds meer gaan specialiseren, ondermeer door het inpassen van technologische vernieuwingen. Het melkveebedrijf wordt mede daardoor sinds de jaren zestig gekarakteriseerd door groei. Om voldoende inkomen te halen uit het bedrijf werden er meer koeien gemolken en, in minder mate, werd grond aangekocht of gepacht met als gevolg dat de melkproductie per ha en per arbeidskracht toenam. Op die manier werden de productiekosten per liter melk laag gehouden. Het gevolg van deze intensivering was dat er meer voer nodig was. Daarom kochten boeren (goedkope) kunstmest, om meer gewas van hun eigen land te halen, en (kracht)voer. De mineralen in aangekocht kunstmest en voer werden maar voor een klein gedeelte omgezet in melk en vlees. Het overgrote deel van de mineralen kwam terecht in de mest op stal of in mestflatten en urine tijdens het weiden van de dieren. De mineralen in deze mest werden weer door het gewas opgenomen of gingen verloren als ammoniak en lachgas naar de lucht of als nitraat en fosfaat naar het grond- en oppervlaktewater. Deze verliezen brachten schade toe aan bossen en andere vegetaties, door verzuring (ammoniak) en eutrofiëring van water of droegen bij aan broeikasgasemissies.

De bewustwording van de gevolgen van mineralenverliezen uit de landbouw heeft in veel Europese landen geleid tot wet- en regelgeving. Nederland introduceerde in 1998 de mineralenbalans voor landbouwbedrijven middels het MINeralen Aangifte Systeem (MINAS). Met dit systeem wilde Nederland de emissies en verliezen uit de landbouw naar de omgeving terugdringen door bedrijven te verplichten hun overschot te beperken tot een door de overheid vastgesteld maximum. Volgens de Europese Unie voldeed dit systeem niet aan de Europese richtlijnen en daarom werd in 2006 de balansmethode vervangen door gebruiksnormen voor meststoffen (dierlijk en kunstmest). Dit proefschrift behandelt een bedrijfssysteembenadering met analyses van de transitie in mineralenbeheer op de voorloperbedrijven van het project 'Koeien & Kansen'. Daarbij is gebruik gemaakt van gedetailleerde gegevens die daar gedurende de periode 1998-2011 verzameld werden.

De doelstelling van dit onderzoek is het evalueren van de transitie van melkveebedrijven die voldeden aan wet- en regelgeving wat betreft het milieu en daarvoor intensief werden begeleid door onderzoekers en voorlichters. In het bijzonder gaat het om de volgende onderzoeksvragen:

- Kan een project met voorloperbedrijven in een participatieve benadering er voor zorgen dat de kloof in mineralenbeheer tussen een experimenteel bedrijf als 'De Marke' en de brede praktijk kleiner wordt door aanpassingen door te voeren in de bedrijfsvoering van voorloperbedrijven;

- Welke maatregelen nemen melkveebedrijven om mineralenverliezen te beperken;
- Wat zijn de belangrijkste factoren die de graslandopbrengst beïnvloeden en hoe is het beheer van grasland te verbeteren;
- Kan regelgeving op basis van middelvoorschriften, als alternatief voor doelvoorschriften, voldoen aan de doelstelling van de kwaliteitsnorm van 50 mg nitraat l-1 in het grondwater;
- Wat zijn de onzekerheidsmarges van gemonitorde stikstofstromen op melkveebedrijven en welke bedrijfsgegevens dragen het meest bij aan die onzekerheid.

2 Het project 'Koeien & Kansen'

De problemen in Nederland rondom het milieu hebben eind jaren tachtig geleid tot het project 'De Marke'. Het experimentele bedrijfssysteem 'De Marke' richt zich op het zodanig verbeteren van de benutting van meststoffen, water en voer op een droogtegevoelige zandgrond dat voldaan wordt aan stringente milieunormen. Tien jaar na de introductie van 'De Marke' waren de verschillen in milieuprestaties en technische mogelijkheden tussen 'De Marke' en de brede praktijk nog steeds groot. Dit heeft in 1999 geleid tot het project 'Koeien & Kansen', waarin voorlopers en 'De Marke' participeren

Het doel van het project 'Koeien & Kansen' is het ontwikkelen en demonstreren van voorbeelden van maatschappelijk gewenste bedrijfssystemen voor een breed spectrum van bedrijven in Nederland onder intensieve begeleiding om op die manier de kloof tussen 'De Marke' en de brede praktijk zoveel mogelijk te dichten (Hoofdstuk 2). Het project 'Koeien & Kansen' is een praktijkgerichte verbreding van het onderzoek op proefbedrijf 'De Marke' waarin de samenwerking tussen onderzoekers, melkveehouders, voorlichters en andere belanghebbenden centraal staan. Bij het onderzoek in 'Koeien & Kansen' wordt evenals op 'De Marke' de methode prototyping toegepast, een combinatie van berekeningen met bedrijfsmodellen en het uitvoeren van een systeem in de praktijk. In een samenwerkingsverband tussen een melkveehouder, onderzoekers en voorlichters, wordt per bedrijf een cyclus van 'analyse-doorrekenen-planning-uitvoering-monitoring-evaluatie' meerdere malen doorlopen. Harde doelen voor mineralen werden geformuleerd om de transitie naar het verbeteren van het mineralenbeheer in beweging te brengen. Van elk bedrijf is het functioneren in de uitgangssituatie grondig geanalyseerd. Daaruit werd duidelijk hoever de praktijk verwijderd is van de geformuleerde doelen, dus welke afstand door bedrijfsontwikkeling moet worden overbrugd. Vervolgens werden ontwikkelingsrichtingen ontworpen waarmee, naar verwachting, aan de doelen kan worden voldaan. Deze ontwikkelingsrichtingen werden per bedrijf afgestemd op de specifieke omstandigheden (grondsoort, quotum, beschikbare arbeid, enz.). Belangrijk is ook dat de veehouder zich er prettig bij moet voelen. Voor elk bedrijf werd één van deze 'blauwdrukken' omgezet in een bedrijfsontwikkelingsplan (BOP), dat tot uitvoer werd gebracht. De ervaringen en resultaten van aanpassingen in de bedrijfsvoering worden tussen de deelnemende melkveehouders met elkaar gedeeld. Daarnaast worden er open-dagen georganiseerd op de voorloperbedrijven en zijn er studiegroepen gevormd rondom 'Koeien & Kansen'-deelnemers om de kennis en ervaringen 'uit eerste hand' door te laten stromen naar de rest van de Nederlandse melkveehouderij. Het project 'Koeien & Kansen' vormt een unieke brugfunctie in de keten van onderzoek en kennisverspreiding tussen theorie en praktijk.

3 Resultaten

Het verbruik en de benutting van mineralen zijnde belangrijkste thema op de 16 voorloperbedrijven. De bedrijven committeren zich vanaf het begin aan de wet- en regelgeving in het mestbeleid (eerst de MINAS-overschotten, daarna gebruiksnormen) die pas over 3 tot 5 jaar verplicht worden voor de brede praktijk.

In hoofdstuk 3 is met gebruik van lineaire regressie een analyse uitgevoerd van de ontwikkeling in bedrijfsvoering in de periode 1998-2003. Tussen 1998 en 2002 zijn de mineralenoverschotten op de voorloperbedrijven gedaald met respectievelijk 33% voor stikstof (N) en 53% voor fosfor (P). Op het gemiddelde bedrijf in Nederland (afgeleid uit het Bedrijven-InformatieNet (BIN) van het LEI met een selectie van het gespecialiseerde melkveebedrijf) was de daling van het N-overschot in dezelfde periode vrijwel gelijk aan die van de voorloperbedrijven (29%) maar de daling van het P-overschot was beperkter (28%). Anderzijds was de benutting van mineralen op de voorloperbedrijven in 2002 met respectievelijk 34% voor N en 67% voor P hoger dan op het gemiddelde bedrijf in Nederland (23% voor N en 49% voor P). In de daaropvolgende jaren (2003-2011) nam de benutting van mineralen continu toe tot respectievelijk 38% voor N en 85% voor P op de voorloperbedrijven en tot 30% voor N en 60% voor P op het gemiddelde bedrijf in Nederland (Hoofdstuk 7). De gemiddelde melkproductie per ha op het gemiddelde bedrijf in Nederland bleef lager dan op de voorloperbedrijven. Intensieve begeleiding en discussies tussen onderzoekers, melkveehouders en hun voorlichters hebben geleid tot het nemen van emissiebeperkende maatregelen op de voorloperbedrijven met als gevolg een toename van de benutting van mineralen. Doeltreffende strategieën om mineralenverliezen te beperken zijn gebaseerd op het optimaliseren van de bedrijfsonderdelen in de mineralenkringloop om zodoende minder afhankelijk te zijn van de aanvoer van mineralen via voer en kunstmest. Maatregelen die door de voorloperbedrijven zijn aangenomen en uitgevoerd, zijn (1) het verlagen van het kunstmestgebruik, (2) het optimaal gebruik maken van de eigen dierlijke mest, (3) de weidegang verminderen, (4) minder jongvee aanhouden, (5) het verlagen van het ruweiwitgehalte in het rantsoen, en (6) het toepassen en beheren van een vanggewas op maïsland. Om verschillen in de ontwikkeling in bedrijfsvoering te verklaren zijn de 16 bedrijven twee keer verdeeld in twee gelijke groepen van 8; één keer op basis van het N-overschot in de uitgangssituatie in 1998 en één keer op basis van de melkproductie per ha in de uitgangssituatie in 1998. De groep van bedrijven die in 1998 al een laag N-overschot hadden konden en wilden nog steeds maatregelen nemen om de mineralenverliezen verder te verminderen. Ondanks dat alle voorloperbedrijven de mineralenverliezen verlaagden in de periode 1998-2003, bleef de *variatie* in N-overschot tussen de bedrijven gelijk. De mogelijkheden om het mineralenmanagement te verbeteren zijn bedrijfsspecifiek en worden beïnvloed door lokale omstandigheden en technische mogelijkheden (b.v. grondsoort) maar ook door de kunde en het ondernemerschap van de melkveehouder. Voor het identificeren van de factoren welke de verschillen in N-overschot tussen de bedrijven verklaren is nodig een grondige analyse van de effecten van veranderingen in mineralenmanagement in het hele bedrijfssysteem (Hoofdstuk 3).

Grasland is de belangrijkste bron van ruwvoer op melkveebedrijven in Nederland en maïsland de tweede. Hoofdstuk 4 beschrijft de ontwikkeling en variatie in N-management van grasland op de voorloperbedrijven in de periode 1998-2009 en verklaart die variatie door verschillen in bedrijfsstructuur en bodemkenmerken. De uitkomsten hiervan bieden mogelijkheden voor andere melkveebedrijven om hun beheer en N-benutting van grasland te verbeteren. Op de voorloperbedrijven nam de gemiddelde N-aanvoer op grasland (met stalmest, weidemest, kunstmest, N-binding door klaver en N-depositie; kg N-totaal ha^{-1} $jaar^{-1}$) af van 540 in 1998 tot 450 in 2001. In de daaropvolgende jaren (tot 2009) bleef de jaarlijkse variatie in N-aanvoer klein (tussen 400 en 450). Over de gehele periode bedroeg de drogestof-opbrengst van grasland gemiddeld 11 ton ha^{-1} met een grote variatie tussen jaren en bedrijven (tussen 8 en 16 ton ha^{-1}), zonder dat een duidelijke trend kon worden waargenomen. Het verband tussen N-aanvoer naar grasland en de drogestof-opbrengst bleef tot een aanvoer van ca. 600 kg ha^{-1} positief lineair. Dat een afnemende meeropbrengst op bedrijfsniveau niet werd waargenomen komt omdat op bedrijven met een hoge melkproductie per ha de grasbehoefte groter is dan op bedrijven met een lagere melkproductie per ha, en omdat deze bedrijven in staat zijn om ook bij hoge N-aanvoer niveaus hoge N-benuttingen te blijven realiseren. Bovendien hebben de meest intensieve bedrijven relatief goede landbouwgrond. De resultaten laten verder zien dat in de periode 2000-2009 de gemiddelde N-benutting van grasland op de voorloperbedrijven 68% bedroeg met een N-overschot van rond de 160 kg per ha. Op het gemiddelde bedrijf in Nederland was de N-benutting lager (59%) en het N-overschot hoger (204 kg per ha). De mogelijkheden tot verbetering van het N-management van grasland zijn begrensd door biofysische omstandigheden zoals het weer en de mineralen- en vochtbeschikbaarheid van de bodem. Maar desondanks laat de analyse op de voorloperbedrijven zien dat in de grote waargenomen variatie in drogestof-opbrengst en N-benutting van grasland tussen de bedrijven, er voor het doorsnee melkveebedrijf nog genoeg mogelijkheden zijn om voor verbetering. De wijze waarop zal per bedrijf verschillen.

Multiple lineaire regressie is gebruikt voor het begrijpen van de effecten van de bedrijfsvoering, weersomstandigheden en bodemkenmerken van zandgrond op de nitraatuitspoeling van grasland, van maïsland en van het gehele bedrijf. Hiervoor zijn (jaarlijkse) gegevens gebruikt over de periode 1999-2006 en is gewerkt met 3 schaalniveaus: het bedrijf, het perceel en het meetpunt (Hoofdstuk 5). De uitkomsten en inzichten van deze studie bieden mogelijkheden voor het verder ontwikkelen en bijstellen van wet- en regelgeving. Op bedrijfsniveau nam de gemiddelde nitraatconcentratie in het grondwater af van 79 mg l^{-1} in 1999 tot 63 mg l^{-1} in 2006, waarbij de nitraatconcentratie onder graslandpercelen significant afnam en onder maïslandpercelen toenam. De effecten van de bedrijfsvoering op de nitraatconcentratie in het grondwater verschillen per schaalniveau. Op bedrijfsniveau was er een positief verband tussen de nitraatconcentratie in het grondwater met het N-bedrijfsoverschot en met de beweidingsintensiteit. Het verband tussen de concentratie van opgelost organisch-gebonden koolstof (DOC) en de nitraatconcentratie in het grondwater was negatief, evenals dat tussen het relatieve aandeel grasland op een bedrijf en de nitraatconcentratie. Op perceelniveau verklaarden zowel factoren die betrekking hebben op de bedrijfsvoering als factoren die gerelateerd zijn aan bodem, hydrologie en weer, significant de variatie in nitraatconcentratie in het grondwater onder grasland en maïsland. Uit het onderzoek is gebleken dat zeker op droogtegevoelige zandgrond aanvullende maatregelen nodig zijn om te voldoen aan de kwaliteitsnorm van 50 mg l^{-1} in het grondwater. Veelbelovende maatregelen zijn (1) het weglaten van een bemesting op het vanggewas in het vroege voorjaar en (2) het verlagen van de bemesting op eerstejaars maïsland in een rotatie met grasland, door rekening te houden met het vrijkomen van mineralen in de bodem na het onderploegen van de graszode.

Een voorwaarde voor het nemen van beslissingen voor maatregelen op mineralengebied op bedrijfsniveau, maar ook voor de keuzes die overheden maken op het gebied van wet- en regelgeving is dat deze onderbouwd moeten zijn met betrouwbare gegevens. Onzekerheden in de effecten van maatregelen kunnen leiden tot verwarring en ongewenste effecten met als gevolg dat het vertrouwen bij melkveehouders en overheden afneemt. De gegevens van melkveebedrijven kunnen behoorlijke foutenmarges hebben wat zeker aandacht verdient. In ‘Koeien & Kansen’ is een model ontwikkeld dat de N-kringloop beschrijft op basis van zoveel mogelijk bedrijfseigen gegevens (Hoofdstuk 6). Een vernieuwde Monte Carlo analyse is gebruikt om de effecten van onzekerheden in het verzamelen van bedrijfseigen gegevens te kwantificeren en om na te gaan wat de invloed daarvan is op het jaarlijkse N-bedrijfsoverschot, N-bodemoverschot en de N-opname van weidegras. Vervolgens is met een gevoeligheidsanalyse bepaald welke factoren het meest bijdragen aan die jaarlijkse onzekerheid in N-bedrijfsoverschot, N-bodemoverschot en N-opname weidegras. Invoer van het N-kringloop model waren de verzamelde bedrijfsgegevens in 2005 op 14 voorloperbedrijven uit het monitoringsprogramma van ‘Koeien & Kansen’ en die van het monitoringsprogramma op proefbedrijf ‘De Marke’. De resultaten van deze studie kunnen bijdragen aan het begrijpen van de onzekerheden in N-stromen op melkveebedrijven en als kennis worden meegenomen in de besluitvorming van overheden bij wet- en regelgeving, maar kunnen ook dienen om melkveehouders te overtuigen hun bedrijfsvoering te verbeteren. De onzekerheid in de N-stromen - zowel relatief (variatiecoëfficiënt; vc) als absoluut (standaardafwijking; sd) - neemt toe van N-bedrijfsoverschot (vc=8%; sd=15 kg N ha^{-1}) via N-bodemoverschot (vc=12%; sd=16 kg N ha^{-1}) naar N-opname van weidegras (vc=49%; sd=28 kg N ha^{-1}). In het algemeen zijn de N-stromen die voorkomen op de bedrijfsbalans (‘externe stromen’) nauwkeuriger bepaald dan de N-stromen op de veestapel- en bodembalans (‘interne stromen’). De variatie in onzekerheden in N-stromen kunnen kleiner gemaakt worden door het nauwkeuriger monitoren van bedrijfsgegevens die het meest onnauwkeurig zijn in combinatie met hun relatieve belang op de balans. N-binding door klaver en de jaarlijkse voorraadsverandering van ruwvoer en dierlijke mest dragen het meest bij aan de onzekerheid in de schatting van het jaarlijkse N-bedrijfsoverschot en N-bodemoverschot. Het schatten van de N-binding door klaver kan verbeterd worden door gebruik te maken van hulpmiddelen voor het schatten van de hoeveelheid klaver in het grasbestand en door het bedrijfsspecifiek maken van de N-binding factor van klaver. Het bepalen van de jaarlijkse voorraadsverandering van ruwvoer en dierlijke mest kan verbeterd worden door het beschikbaar stellen van een goed protocol met handleiding voor de bepaling van de voorraadsverandering.

4 Ervaringen met prototypering op voorloperbedrijven

Het project ‘Koeien & Kansen’ maakt gebruik van de ervaringen die op proefbedrijf ‘De Marke’ met de onderzoeksmethode prototypering zijn opgedaan. Op ‘De Marke’ is het theoretisch meest geschikte prototype bedrijfssysteem in zijn geheel uitgevoerd als ‘nieuwe’ praktijk, terwijl in ‘Koeien & Kansen’ de berekeningen met computermodellen zijn gebruikt om verkenningen te doen om het bestaande bedrijfssysteem aan te passen om de geformuleerde doelen te realiseren. De meerwaarde van ‘Koeien & Kansen’ is het toepassen en uitwerken van 16 prototype bedrijfssystemen in plaats van één ‘De Marke’ wat mogelijkheden biedt om op grotere schaal prototypes te verspreiden.

Het opstellen van een BedrijfsOntwikkelingsPlan (BOP) wordt gezien als één van de succesfactoren in dit project. Het maken van zo'n plan, al dan niet in samenspraak met een onderzoeker en/of voorlichter, dwingt een melkveehouder kritisch naar zijn bedrijfsprestaties te kijken. Bovendien is een BOP toegespitst op het specifieke, unieke bedrijf, in de zoektocht naar (on)mogelijkheden de bedrijfsvoering op het gebied van mineralen te verbeteren. Niet alleen de agrarisch-ecologische voorwaarden worden meegenomen in dit proces maar ook de kennis en het ondernemerschap worden daarbij betrokken. Beslissingen en keuzes van individuele melkveehouders zijn niet altijd op basis van 'rationeel denken' maar 'emoties' en 'sociale aspecten' beïnvloeden de besluitvorming eveneens (Hoofdstuk 3).

Communiceren en het laten doorstromen en uitwisselen van kennis naar en met de praktijk is een belangrijke doelstelling in het project 'Koeien & Kansen' en een wezenlijk onderdeel in het prototype onderzoek. Het intensief begeleiden en uitwisselen van kennis draagt er aan bij dat melkveehouders gemakkelijker aanpassingen in hun bedrijfsvoering accepteren op het gebied van mineralenbeheer. Het uitvoeren van onderzoek volgens de methode prototypering op meerdere voorloperbedrijven is van wezenlijk belang voor het verspreiden en accepteren van verbeterde, bedrijfssystemen vanwege de verschillen in (on)mogelijkheden en lokale omstandigheden tussen regio's, zoals grondsoort, draagkracht van de bodem of verkaveling. Het overbrengen van kennis uit onderzoek naar de praktijk via het 'boer-tot-boer' kanaal is de meest effectieve manier van communiceren. Verder is het schrijven van rapporten en artikelen in landbouwbladen een manier om kennis uit onderzoek bij melkveehouders en andere belanghebbenden in de melkveehouderij te brengen. Jaarlijks ontvangen duizenden belanghebbenden uit de melkveehouderij in Nederland - melkveehouders, voorlichters, onderzoekers, beleidsmedewerkers en medewerkers van toeleverend en verwerkend bedrijfsleven - informatie over de ervaringen en vorderingen in het project 'Koeien & Kansen'.

5 De toekomst

Het nieuwe project 'KringloopWijzer' is voortgekomen uit de kennis en ervaringen die in 'Koeien & Kansen' zijn opgedaan. Het doel van het project is het ontwikkelen van een instrument 'KringloopWijzer' dat de N-, P- en C-kringlopen wetenschappelijk verantwoord, integraal, eenduidig en fraudebestendig in beeld brengt. Dat resulteert in een aantal kengetallen waarmee de melkveehouder zijn bedrijfsvoering kan verantwoorden naar overheden en melkverwerker, en zijn management kan optimaliseren. Voor de overheid biedt dit wellicht mogelijkheden generieke wetgeving deels te vervangen door maatwerk, waardoor de veehouder meer vrijheid krijgt in bedrijfsvoering. Voor de melkverwerker is het wellicht mogelijk de met haar melkveehouders afgesproken duurzaamheidsstrategie te concretiseren. Bij de uitvoering van het project zijn vrijwel alle partijen betrokken die belang hebben bij de melkveehouderij: standsorganisaties, toeleverend en verwerkend bedrijfsleven, kennisinstellingen en overheden. In het project wordt nauw samengewerkt met 'Koeien & Kansen'.

Om ook in de toekomst te voldoen aan wensen en eisen van de maatschappij blijft de zoektocht naar het efficiënt gebruik van grondstoffen belangrijk om te overleven. Het is belangrijk dat in deze zoektocht wordt samengewerkt door alle belanghebbende partijen. Voor het testen en verspreiden van nieuwe ideeën blijft prototype onderzoek nodig op een proefbedrijf zoals 'De Marke' en op voorloper-bedrijven.

DANKWOORD

Bijna 50 jaar oud en dan nog promoveren? Waarom gaat iemand op latere leeftijd nog aan een promotieonderzoek beginnen? Omdat het leuk en uitdagend is! De kiem van mijn promotieonderzoek werd gelegd in 2001, op het symposium over het Nitraatbeleid in Hotel Haarhuis te Arnhem. Onder leiding van Herman van Keulen hebben we twee dagen gediscussieerd over nitraatuitspoeling op melkveebedrijven en over het mestbeleid, mede aan de hand van de resultaten van proefbedrijf 'De Marke'. Dit symposium heeft geleid tot een special issue over dit onderwerp in het 'Netherlands Journal of Agricultural Sciences', waarin ook een bijdrage van mij, samen met Gerjo Koskamp en Paul Galama over het project 'Koeien & Kansen': mijn eerste artikel. De volgende stap richting daadwerkelijk 'promotietraject' was een verblijf in 2002 van drie maanden in de USA op Pennsylvania State University, onder begeleiding van Dr. Al Rotz. Dear Al, thank you very much for your hospitality and for the wonderful time Lucienne, Silke and I had, and the confidence you gave.

Op het instituut (Plant Research International) kreeg ik het vertrouwen van Frans Aarts, Jacques Neeteson en Pieter van de Sanden, om als senior assistant onderzoeker te beginnen aan mijn promotieonderzoek. Beste Herman, de contouren van 'het boekje' werden steeds duidelijker door jouw enthousiaste, kritische begeleiding en waardevol commentaar. Helaas liet jouw gezondheid het niet toe om de begeleiding tot het einde vol te houden. Ik prijs mij gelukkig dat Martin van Ittersum bereid is geweest de begeleiding over te nemen. Beste Herman en Martin, heel hartelijk bedankt voor jullie begeleiding en vooral ook voor de manier waarop jullie de vaart er in hebben weten te houden, zonder te veel te pushen.

Het project 'Koeien & Kansen' ligt aan de basis van dit proefschrift. Het project is een samenwerkingsverband van de overheid (Ministeries van Economische Zaken en Infrastructuur & Milieu), de melkveesector (LTO-Nederland en het Productschap Zuivel) en Wageningen Universiteit en Research. Beste Frans, vanaf het begin was je de inhoudelijke coördinator van dit project; ik wil je heel hartelijk bedanken voor de ruimte die ik kreeg om naast mijn 'projecttaken' ook te werken aan 'wetenschappelijke publicaties'. Een project moet ook bestuurd worden. Carel de Vries, Jaap Gielen en Michel de Haan, graag wil ik ook jullie bedanken voor jullie ondersteuning.

Aan de basis van het promotieonderzoek stonden de deelnemers van het project 'Koeien & Kansen'. Zonder jullie gegevens was dit onderzoek niet tot stand gekomen; heel veel dank voor jullie waardevolle en onmisbare bijdragen. Hierbij wil ik ook de voorlichters en adviseurs betrekken; met elkaar hebben we geprobeerd om zo zorgvuldig mogelijk de bedrijfsgegevens boven tafel te krijgen. Dat twee deelnemende boeren mij 15 november moreel komen ondersteunen zegt al genoeg over de goede samenwerking en verstandhouding in het project. Jan Kuks en Jos de Kleijne bedank ik dan ook voor hun bereidheid om als paranimf op te treden.

In het project 'Koeien & Kansen' participeerden vele onderzoekers van vele instituten. Ook hen wil ik graag bedanken voor hun bijdragen. Barbara Habekotté, Arjan Reijneveld, Gerjan Hilhorst, Zwier van der Vegte, Léon Šebek, Eddy Teenstra, René Schils, Cees Jan Hollander, Rianne Kroes, Hans van den Heuvel, Gidi Smolders, Jelle Zijlstra, Jantine van Middelkoop, Alfons Beldman, Gerben Doornewaard, Joan Reijs, Dirk Jan den Boer, Wilfried Vergeer, Robert Bakker, Harm van der Draai, Gerard Velthof, Falentijn Assinck, Gert-Jan Monteny, Michel Smits, Nico Middelkoop, Anton Kool, Leo Boumans, Dico Fraters, Cor de Jong, Arno Hooijboer, het was geweldig.

Vele jaren heb ik mijn kamer mogen delen met Peter Uithol, die helaas niet meer in ons midden is. In gedachten bedank ik ook hem. Peter, je was in meerdere opzichten mijn maatje. Irene Gosselink werd mijn nieuwe kamergenoot en ook haar wil ik graag bedanken voor de voortdurende support en 'het gedogen' van mijn stem. Koos Verloop was mijn 'promotiemaatje'. Wij hebben elkaar de afgelopen jaren gestimuleerd, met onze boekjes als resultaat. Bedankt dat je met mij de competitie wilde aangaan. Mijn 'grote broer' Oene Oenema wil ik bedanken voor het 'over de schouders' kritisch meekijken bij het schrijven van mijn proefschrift. Ben Verwijs wil ik bedanken voor het verzorgen en op de goede plek zetten van punten, komma's en spaties bij het afronden van dit boekje.

Helaas heeft Heit het resultaat van mijn promotieonderzoek niet kunnen meemaken. Ongetwijfeld zou hij kritische opmerkingen hebben geplaatst, maar hij zou ook trots zijn geweest. Welke boer, met alleen lagere school, kan bogen op twee kinderen die zijn gepromoveerd tot doctor in de wetenschap? Lieve Mem, je bent de spil van de familie en mag vol trots gaan vertellen dat jouw jongste zoon nu ook doctor is. Lieve Lucienne, wat ben ik dankbaar dat jij mijn echte 'maatje' bent. De praktische en sociale verplichtingen worden vlekkeloos door jou ingevuld. Voor onze pareltjes Silke en Hidde: 'pap zal weer normaal doen'. Tot slot: 'it giet oan!'

Jouke

CURRICULUM VITAE

Jouke Oenema was born on February 28, 1965 in Wyckel (Friesland), the Netherlands, and has grown up on the parental dairy farm. After secondary education on the HIM in Sneek he started in 1984 the study agriculture on the University of Applied Sciences in Leeuwarden. Practical trainings were done on dairy farms in Germany and Switzerland, followed by a trainee soil science by the former Dienst Getijdewateren in Middelburg. He finished this study in 1987 in the specialization dairy farming and soil science. In November of that year he started to work as research and education assistant on the former Department of Farm management on the Wageningen Agriculture University. In 1999 he shifted to the former institute for Agro-biological and soil science research (AB-DLO, now Plant Research international, Wageningen UR) and was added as senior research assistant to the group for Sustainable Farming Systems. At that time, the project 'Cows & Opportunities' started and he became responsible for the assessment of the nutrient cycling on the commercial pilot farms. In 2002 he worked for 3 months at the Pasture Systems & Watershed Management Research Unit in Pennsylvania, part of the United States Department of Agriculture. His job was to calibrate and validate their whole-farm dairy system model for European circumstances by using data from experimental dairy farm 'De Marke' in the Netherlands. In 2005 he started with the present PhD-thesis. At this moment he is a member of the Business Unit Agro Systems Research from Plant Research International, part of Wageningen UR, and worked on the development of sustainable dairy farming systems.

PE&RC PhD Training Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)
- Nutrient management on pilot commercial farms in the Netherlands

Writing of project proposal (4.5 ECTS)
- Nutrient management on pilot commercial farms in the Netherlands

Post-graduate courses (3.6 ECTS)
- PHLO Course applied statistics; WUR (2005)
- Uncertainty and sensitivity analysis for model; Biometris, WUR (2007)

Laboratory training and working visits (4.5 ECTS)
- Collaboration; Pasture Systems and watershed Management Laboratory, Pennsylvania State University (2002

Invited review of (unpublished) journal manuscript (2 ECTS)
- Agr. Ecosys. Env.: the nitrogen balance of three long-term agroecosystems on a boreal soil in Western Canada (2007)
- Agr. Ecosys. Env.: predicting productivity of trembling aspen on boreal transition ecoregion of Saskatchewan (2009)
- Agr. Ecosys. Env.: ammonia volatilization after application of biogas residues to energy crops in a coastal marsh of Northern Germany (2010)
- Pedosphere: nitrate dynamics and N budgets in a rice-wheat cropping system in the Taihu Lake region, (2011)
- Journal of Soil Science and Plant Nutrition: effect of the stocking rate and land slope on nitrogen losses on a grazed pasture of Southern Chile (2011)
- Pedosphere: implication of gross N transformation rates fertilizer-N use efficiency in two paddy soils under intensive rice-wheat rotation cultivate (2013)

Competence strengthening / skills courses (3.3 ECTS)
- Excel 97 programmeren; Broekhuis (1999)
- Effectief presentateren; KLV professional match (2002)
- Basis ANSI SQL; Computrain (2003)
- Techniques for writing and presenting a scientific paper; WGS (2007)
- Projectmanagement; VROM in house (2012)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.2 ECTS)
- Het nitraatbeleid: de wetenschap, de sector en het beleid ; symposium (2000)
- Graslanden: een dynamisch ecosysteem - 50 jaar Ossekampen Grasland Experiment; symposium (2008)
- Seminar on Nutrient Management (2012)

Discussion groups / local seminars / other scientific meetings (7.5 ECTS)
- Dairy Farming Systems working group; Maastricht (2005)
- Dairy Farming Systems working group; Gent (2007)
- Yearly project: Cows & Opportunities meetings (2002-2013)
- Yearly project: Dairyman meetings (2010-2013)

International symposia, workshops and conferences (9 ECTS)
- ASA General meeting; Denver (2003)
- EGF Meeting; Badagoz, Spain (2006)
- ASA General meeting; Houston (2008)
- 4th General meeting: Dairyman; Limirick Junction, Ireland (2011)
- Dairyman workshop; Lublin, Poland (2012)
- Dairyman stakeholder meeting; Gent, Belgium (2012)

Lecturing / supervision of practical's/ tutorials (3 ECTS)
- Nutrient management on experimental and commercial dairy farms on sandy soil: on the origin of feed; Wageningen UR (2008)
- College over duurzaamheid + practium; van Hall Larenstein (2011-2012)
- Colleges over duurzaamheid voor HAS, MAS en docenten (2011-2012)

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