CHAPTER 4

NUTRIENT MANAGEMENT UNDER GRAZING

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Abstract. This chapter reviews nutrient management of intensively managed grasslands used for dairy farming in The Netherlands, with emphasis on research but with linkages to practice. Firstly, it provides an overview of the changes that have taken place in nutrient management research and practice during the 20th century. Secondly, it presents the current concept of nutrient management with application to grazed grassland. Finally, it discusses nitrogen (N) management of pastures and the tools to improve N management at operational level.

Nutrient management under grazing has evolved from merely optimizing manure and fertilizer applications for high herbage yield towards improving nutrient use efficiency at farm level whilst maintaining productivity. Nutrient management under grazing is highly complex, because of the uneven distributions of nutrients in pastures, the difference in nutrient element requirements for herbage growth and dairy production, and the difference in mobility between nutrients and the tendency of especially N to escape from the system. Furthermore, boundary conditions of nutrient management in practice change frequently due to changes in manure policy.

The economic costs of nutrients in dairy farms have decreased during the 20th century, but the time and costs associated with nutrient management in practice have increased, mainly because of the manure policy. Nutrient balance sheets have greatly contributed to increased understanding of nutrient cycling and nutrient management in dairy farming, as they provide guidance to improving nutrient use efficiency. Emphasis in nutrient management under grazing has been on N and to a much lesser extent on P, K and Mg. The emphasis on N follows from its impact on productivity and the environment. In the near future, there will be increasing attention also for P and micro-nutrients like copper and zinc as they tend to accumulate in intensively managed grassland soils to levels critical for the environment and animal and human health.
Keywords: dairy farming; dung; grassland; Netherlands; nitrogen; phosphorus; potassium; urine

A. Elgersma, J. Dijkstra and S. Tamminga (eds.), Fresh Herbage for Dairy Cattle, 63-83.

INTRODUCTION

Management is often called the 'fourth production factor' in agriculture, in addition to land, labour and capital. It is usually defined as the process of allocating and utilizing resources to achieve specific goals through a sequence of specific activities (analysis, decision-making, planning, implementation, monitoring and assessment). The importance and complexity of management has greatly increased during the last decades due to technological development and the rapidly changing decision environment. Nutrient management has become particularly important in grass-based dairy-farming systems, as nutrient use efficiency[1] strongly influences their agronomic and environmental performances (Aarts et al. 1992; Jarvis et al. 1995; Oenema and Pietrzak 2002), while changes in government policies increasingly challenge and even force dairy farmers to improve these performances (Henkens and Van Keulen 2001; Oenema and Berentsen 2005).

At least 13 nutrient elements have been identified as being essential for herbage production and 18 for animals (Marschner 1995; Whitehead 2000), but the emphasis in nutrient management in dairy farming systems is on nitrogen (N) and phosphorus (P), because of their key roles in both crop production (yield-limiting) and environmental impacts[2] (Tamminga 1996; 2003). However, the efficiency of N and P utilization in crop and animal production also depends on the availability of other nutrients, and neglecting these can be counterproductive. Soil and weather conditions, drainage, irrigation, grazing and sward management also influence herbage production and nutrient dynamics, and hence nutrient losses and nutrient utilization.

Nutrient management in grass-based dairy-farming systems is complex, also because the harvested herbage is an intermediate product in dairy and beef production. Only a fraction of the nutrient elements in the feed (herbage and purchased concentrates) offered to dairy cows ends up in dairy and beef products; the major part is excreted via dung and urine, and is recycled within the dairy-farming system. This creates opportunities for the nutrient elements (especially N) to escape from the system into the wider environment, the magnitude depending in part on management. Nutrient management is even more complex under grazing, because of the heterogeneous distribution of animal excrements in pastures and the effects of treading and camping, which contribute to local soil compaction and increased nutrient losses (Haynes and Williams 1993).

Most grassland in The Netherlands is used for milk production and is intensively managed, with single-species grass swards, receiving split applications of animal slurry and chemical fertilizer. Grassland utilization usually comprises 4 to 8 grazing and mowing cycles, including production of silage for use during the winter season (approximately 6 months). The dairy herd is fed silage maize and concentrates in addition to the grass (silage). Most grassland is grazed twice or three times per year (rotational grazing), each time for two to four days. In 2001, 54 % of the national dairy herd (1.35 million animals) grazed during daytime only (restricted grazing), 36 % during day and night, and 10 % was housed year-round (Van den Pol-van Dasselaar et al. 2002). However, regional differences exist, with relatively more restricted grazing (61-68 %) on sandy soils in the southern and eastern parts of the country, and relatively more day and night grazing (71 %) in the western part. The dominant grazing system for young stock (1.2 million) is day and night grazing, while most beef cattle are permanently housed. Zero-grazing systems for dairy cows are increasing because of the introduction of automated milking systems (AMS or milk robots), increasing herd size and in response to the increasingly tighter environmental policies forcing farmers to utilize N and P more efficiently (Van den Pol-van Dasselaar et al. 2002).

This chapter provides a brief overview of nutrient management under grazing, with a focus on intensively managed grasslands in The Netherlands. For a basic overview of nutrients in grasslands we refer to Rotz et al. (2005) and Whitehead (2000). First, we present an overview of the developments in nutrient management during the 20th century, followed by a discussion of the concept of nutrient management for grass-based dairy farms, as well as the implications of its implementation in practice. Finally, we will present some concluding remarks.

HISTORICAL OVERVIEW

The chemist Justus von Liebig (1803-1873) has played a key role in plant nutrition, though other scientists in the 18th and 19th century also contributed to improved understanding of nutrient-cycling processes (Smil 2001). Since von Liebig, numerous so-called dose–response experiments have addressed one or more of the following five basic questions that have dominated research in ‘nutrient management’ (Van Noordwijk 1999): (i) to what extent are nutrients limiting crop yield and quality? (ii) how many nutrients are supplied by the soil? (iii) what are effective fertilizers? (iv) how much fertilizer and animal manure should be applied? and (v) what is the environmental impact of the use of fertilizers and animal manure?

From the early 1980s onwards, the term ‘nutrient management’ gradually replaced terms such as ‘plant nutrition’, ‘fertilizer use’, ‘fertilization’ and ‘manuring’. Initially, the focus was on management of particular nutrient sources, such as chemical N fertilizer and/or manure. The notion ‘integrated’ nutrient management emphasizes the need for an approach in which all nutrients and their various sources must be considered simultaneously, and both agronomic effects, i.e. crop yield and quality and soil fertility, and environmental effects, i.e. nutrient losses and resource use efficiency, must be taken into account. Integration is further hampered by the fact that ‘nutrients’ in animal husbandry and animal nutrition are defined in different ways. As a consequence, the term ‘nutrient management’ is still ill-defined and perceived, and is used more often in conceptual than in practical terms. The concepts refer both to what different farmers do and are supposed to do. Concepts of nutrient management and their practical implementation are often perceived differentially by scientists, farmers, policy makers and the public, which also contributes to the confusion. Communication among these stakeholders is further hampered by the associated ‘images’ in (news)papers, public reports and television broadcasts, both intentionally and unintentionally. These images strongly influence the public and policy makers. For example, the slurry spreader in the mud, widely used in television broadcasts during the 1990s has contributed to the public (mis)perception of (lack of) 'nutrient management' (Bloemendaal 1995; Lowe and Ward 1997).

We discuss the changes in research on and perceptions of 'nutrient management' in grass-based dairy-farming systems, with a focus on grazing systems, schematically distinguishing three periods: (i) before 1950; (ii) 1950-1985; (iii) 1985 to present. These periods are characterized by differential agricultural development patterns, in numbers of animals and farms, farm size and structure (Bieleman 2000), and the use of N, P and K fertilizers (Table 1).

***Table 1**. Changes in some characteristics of agriculture of The Netherlands in the period 1880 – 2000, all expressed in millions (from Oenema and Berentsen 2005)*

Characteristic	1880	1910	1920	1930	1940	1950	1960	1970	1980	1990	2000
Area agricultural land, ha	2.1	2.2	2.2	2.3	2.3	2.3	2,3	2,2	2,1	2,0	2,0
Milking cows, number	0.9	1.1	1.2	1.3	1.5	1.4	1,6	1,9	2,4	1,9	1,5
Pigs, number	0.4	1.0	1.5	2.0	1.2	2	2	6	10	14	13
Poultry, number	2.5	6.7	5.8	12.9	21	11	45	55	81	93	105
Horses, number	0.3	0.3	0.4	0.3	0.3	0.3	0.1	0.05	0.05	0.1	0.2
Fertilizer N, kg	1	15	20	53	103	156	224	396	485	412	340
Fertilizer P, kg	2	24	33	46	47	52	49	48	36	33	27
Fertilizer K, kg	1	27	48	88	111	128	115	107	93	81	70

Before 1950

The total area of agricultural land and the number of farms peaked in the late 1940s. Before 1950, most farms were mixed crop–livestock farms, especially on sandy soils (Van Keulen and Schiere 2004). Animal manure, collected during the winter season, was mainly used on arable crops. Fertilizer use on grassland was low, though appreciably higher than in surrounding countries. Research focused on the first four basic questions, i.e. (i) to what extent are nutrients limiting crop yield and quality? (ii) how many nutrients are supplied by the soil? (iii) what are effective fertilizers? (iv) how much chemical fertilizer and animal manure should be applied? Early nutrient management research has been summarized by Kolenbrander and De la Lande Cremer (1967) for animal manure, by Frankena (1957; 1958) for N fertilizers, and by Van der Paauw and De la Lande Cremer (1951) for P and K fertilizers. Similarly to arable crops, manure and fertilizers were applied as a basic dressing in spring, as the soil was considered a sufficient buffer, also for N. Fertilization increased yields, but often with considerable negative side-effects, including changes in sward composition (reduction in clover density), poor re-growth following heavy cuts, more treading and trampling damage, changes in herbage quality, seasonal patterns of herbage availability, residual effects, and soil acidification following the use of ammonium-sulfate fertilizers. Moreover, responses to fertilizer application strongly varied between grazed and mown-only grassland, among different soils and among different types of fertilizers, but the cause–effect relationships were often unclear. To profit from the increased grassland productivity, changes were required in farm structure, i.e. increasing farm size and intensified management. It was realized that to facilitate adoption of the new technology, the effects of fertilization should be studied within the farming system: the first experimental dairy farms were established in 1935. Establishment of pilot farms for N research in 1949 by the fertilizer industry has greatly contributed to increased understanding of the effects of N-fertilizer use on the agronomic performance of grass-based dairy-farming systems in the period 1950-1985 (Frankena 1960).

Period 1950 - 1985

Following two World Wars, a serious economic crisis and food shortages, policies in European countries after World War II aimed at stimulating the economy and boosting industrial and agricultural productivity (Meester et al. 2005). Establishment of the European Economic Community (EEC; the current European Union, EU) in 1957 was a direct consequence of these policy objectives. The focus of the Common Agricultural Policy (CAP) of the EU on increasing productivity, the establishment of common markets and parity income for farmers triggered strong intensification and specialization of agricultural production. Price support provided financial security to farmers, and subsidies stimulated investments in technological innovation. Mechanization led to increasing labour productivity, resulting in outflow of labour, which was absorbed in the concurrently expanding and labour-demanding industry and service sectors. The fertilizer-induced increase in forage production (in first instance grass, later followed by silage maize) and the large-scale import of cheap animal feed from outside the EU allowed dramatic increases in animal production. These developments resulted in the disappearance of mixed farming systems that specialized in dairying, with the arable crops being replaced by silage maize, and/or in intensive pig and poultry production. Intensive livestock farmers, with little or no land, considered animal manure as a waste, instead of as a resource (Van der Meer et al. 1987).

In the 1970s and early 1980s, critical publications started to appear. In a review on grassland in The Netherlands, Van Burg et al. (1980) observed that the increasing concentrate supplementation of grazing dairy cows is “an alarming development, as herbage can provide enough energy for high-yielding dairy cows”. They indicated an increase in average concentrate supplementation to dairy cows during the grazing period (May-October) from 100 kg per cow in 1965 to 850 kg in 1979, and estimated a conversion efficiency of 0.4 kg of milk per kg of concentrate. They argued that supplemental feeding led to reduced utilization efficiency of grass, though it was acknowledged that highly intensive farms also fed concentrates to save grass for silage making. However, this increased supplementation greatly contributed to the increased inputs in and surpluses of N, P and K in dairy-farming systems. Currently, supplemental feeding of grazing dairy cows has become common practice, in part to optimize the nutritional balance of the diet and to improve N use efficiency.

Concentrates in the 1960s and 1970s contained on average 28, 6 and 15 g per kg for N, P and K, respectively (Van Burg et al. 1980). The composition of standard concentrates has been rather stable over the period 1970-2005, with N, P and K contents ranging from 25 to 29, 4.6 to 5.1, and 13 to 15 g per kg, respectively, while those of protein-rich concentrates were 31-39, 5-6 and 13-17 g per kg (www.CBSstatline.nl; Cor van Bruggen, CBS 2006, pers. comm.). Hence, P contents in current concentrates are lower than in those used in the 1960s and 1970s, and could even be further reduced (Valk 2002). The composition of purchased concentrates is a determinant factor in composition of animal manure and thus in its nutrient utilization efficiency in grassland.

Nutrient management research on grassland in the period 1950-1985 focused on the questions ‘how much fertilizer and animal manure should be applied, what are the limits, and what are the effects on herbage composition and animal performance?’ To generate answers, dose–response trials were carried out on animal slurries and various fertilizers (e.g. Van Burg 1962; Van Burg et al. 1980; Prins 1983; Henkens 1985; Lantinga 1985; Van der Meer et al. 1986; Vellinga and André 1999). Results of these trials were translated into fertilizer recommendations (e.g. Commissie Bemesting Grasland en Voedergewassen 2002; Agterberg and Henkens 1995) and transferred to farmers via pilot farms and extension services. In general, transfer of knowledge from research to practice was effective (Bieleman 2000), but compliance with fertilizer recommendations was modest in practice (Van der Meer et al. 1987). Fertilizer N doses strongly increased, to a peak in 1985. In contrast, applications of fertilizer P and K decreased (Table 1), especially on grassland, because of the increasing availability of animal manure. Application of K fertilizer was especially reduced, following increased incidence of tetany in grazing milking cows (Kemp and Geurink 1978).

In the 1950s and 1960s, grass tetany (or hypomagnesaemia) became a serious problem for grazing dairy cows. Extensive studies by Kemp and others (e.g. Kemp and Geurink 1978) indicated this to be associated with Mg deficiency due to insufficient Mg intake and/or availability, and that Mg availability was regulated by the K and N contents of the diet (Mg content should increase proportionally to the product of K x N contents). To increase Mg content in the diet, Mg-containing fertilizers were applied to pastures and Mg-enriched concentrates were fed to dairy cows. The tetany case marks a change in the notion on nutrient management (or fertilization as it was called at that time) in dairy farming, i.e., from merely increasing soil nutrient availability to increase herbage yields, towards contributing to correcting nutritional disorders in dairy cows. The latter, however, appeared more effective via modification of the composition of purchased concentrates, and as a consequence K-rich ingredients like molasses were excluded from concentrates. Since the 1970s, grass tetany is controlled through a combination of restricted N and K contents and higher Mg contents in cattle diets, and interest in K vanished (Van de Ven 1990; Van Boheemen et al. 1991). Changes in botanical and mineral composition of herbage on pilot farms, following the increased fertilizer use from 1950 onwards, have been discussed by Keuning (1974; 1994).

In addition to the studies on grass tetany and the mineral composition of herbage, nutrient management studies on grazed grassland in the period 1950-1985 dealt with effects of grazing management and N fertilizer and cattle slurry applications on herbage yield and quality, herbage intake, urine scorching and sward quality (Meijs 1981; Lantinga 1985; Van der Meer et al. 1987; Deenen 1994). Main conclusions were that herbage yield, grassland utilization and N use efficiency were (much) lower under grazing than under cutting, and that intensive grazing in combination with high N inputs accelerated sward deterioration and thus increased the need for grassland reseeding. Moreover, they indirectly showed that results of field experiments with simulated grazing (i.e. cutting at early growth stages) cannot be translated easily to the practice of grazed grasslands.

Period of 1985 to present

Growing surpluses of many agricultural commodities in the EU and increasing awareness of the negative environmental impacts of the intensification of agricultural production resulted in structural changes in the Common Agricultural Policy and led to the implementation of increasingly tighter environmental policies from the mid-1980s onwards (Henkens and Van Keulen 2001; De Clercq et al. 2001; Meester et al. 2005). Introduction of the milk quota system (1985) and of policies on animal manure and fertilizer use resulted in declining animal densities and in reduced use of N and P fertilizers (Table 1). The number of dairy cows started to decrease in 1985[3]. Insufficient alleviation of the environmental pressure led to further tightening of legislation through introduction (in 1998) of the MINeral Accounting System (MINAS) for N and P, combined with a manure quota system (Henkens and Van Keulen 2001). This tightening of legislation forced farmers to further reduce inputs of N and P via fertilizers, animal feed and animal manure, and to increased N and P use efficiencies. These latter policies were rather effective (RIVM 2002; 2004).

These drastic changes in agriculture and government policy were in part a response to the increasing evidence of the unsustainable nature of the intensification of animal production. Reports had appeared about surpluses of N, P and K on intensive animal farms (Frissel and Kolenbrander 1977), toxic levels of copper (Cu) in heavily manured soils (Lexmond and De Haan 1977), nitrate leaching from intensively managed grassland (Kolenbrander 1969; 1973; Ryden et al. 1984), ammonia volatilization from animal production systems (Bussink 1996; Monteny 2000; Huijsmans 2003), soil acidification through deposition of ammonia derived from animal production systems (Van Breemen et al. 1982), nitrous-oxide emissions from intensively managed grasslands (Velthof 1997; Oenema et al. 1997), and use of fossil energy (Van Dasselaar and Pothoven 1994) and groundwater (Aarts 2000).

Wilkinson and Lowrey (1973) were among the first emphasizing nutrient recycling from soil via herbage and cattle to manure and soil again in grass-based dairy-farming systems, indicating the large differences in use efficiency in the various compartments of this chain. In early nutrient balances of whole dairy-farming systems in The Netherlands, Frissel and Kolenbrander (1977) pointed at the large differences between inputs and outputs of N, P and K of especially intensively managed dairy farms. This nutrient-budget approach was adapted and further refined to the mineral-balance approach in the 1980s (Aarts et al. 1992), which from then on has played a dominant role in nutrient management research and government policy. Hence, the focus in nutrient management changed from a largely field-based approach to a whole-farming system approach, more or less concomitantly with the emergence of the manure policy in The Netherlands (Henkens and Van Keulen 2001; Oenema and Berentsen 2005).

Various studies addressing nutrient balances and nutrient use efficiencies of whole dairy-farming systems (Van de Ven 1996; Aarts 2000; Ondersteijn 2002; Schröder et al. 2003) have shown that nutrient use efficiency can strongly be increased by reducing nutrient inputs and improving the use efficiency of nutrients from animal manure. Animal-manure management and grazing management turn out to be key factors. Low-emission storage and low-emission application of animal manure have become obligatory on commercial farms, following extensive studies on N losses from dairy-farming systems via ammonia volatilization (Bussink 1996; Monteny and Erisman 1998; Monteny 2000; Huijsmans 2003). Restricted grazing contributes to increasing nutrient use efficiency at farm level, through (i) minimizing grazing losses, (ii) better utilization of animal excrements (lower losses), and (iii) more balanced animal feeding (Aarts et al. 1992; Van de Ven 1996; Aarts 2000; Van den Pol-van Dasselaar et al. 2002). As a consequence, dramatic changes in manure and grazing management have been introduced in commercial dairy-farming systems over the last 20 years.

More recently, the scope has been broadened further, in response to societal needs and possible pollution swapping, due to the implementation of policies and measures aiming at mitigation of particular emission sources. These studies focus simultaneously on economic viability, environmental soundness and social acceptability of dairy farming systems and their management (Ten Berge et al. 2000; Bos 2002; Ondersteijn 2002; Van Calker 2005). Grazing and nutrient management are important elements in the sustainability concept in these studies.

NUTRIENT MANAGEMENT OF PASTURES

The nutrient management concept

The focus in nutrient management is now on synchronization and synlocalization of plant-available nutrients with the demand of nutrients by crops and animals, i.e., the required nutrients in the appropriate amounts at the right time in the right place, taking economic, environmental and social boundary conditions into account. Schematically, nutrient management can be presented as an iterative series of six activities (Beegle et al. 2000; Oenema and Pietrzak 2002):

1. *Analysis*, i.e. analyses of nutrient requirements and nutrient pools and sources, and of constraints set by labour, capital, policies and regulations.
2. *Decision-making* process, i.e. (i) identification of options on the basis of the preceding analyses, (ii) assessment of the consequences of the various options, and (iii) selecting the best option for achieving both agronomic and environmental targets.

3. *Planning*, i.e. identifying the necessary actions and measures; when, where, how, and how much. This step results in the actual nutrient management plan.
4. *Execution*, i.e. implementation of the nutrient management plan in practice, taking into account actual environmental conditions, and best management guidelines and recommendations.
5. *Monitoring*, i.e. collecting data on yield and quality and on nutrient losses.
6. *Assessment*, i.e. verification and examination of achievements relative to the objectives.

This cycle of nutrient management activities has to be considered in a whole-farm perspective (Figure 1), because of its strong impact on crop and animal productivity and on environmental performance of agro-ecosystems. Therefore, the activities have to be consistent with farm strategy, i.e. the long-term goals of the farm. A farm is a dynamic enterprise that continuously changes as a result of the farmer's decisions in response to developments inside and outside the farm. These management decisions take place first at strategic, subsequently at tactical and finally at operational level (Beegle et al. 2000; Oenema and Pietrzak 2002). Strategic decisions deal with long-term agronomic and economic goals of the farm, i.e. with investments and structural changes in type, size and intensity of the farm. Strategic management is the "art of formulating, implementing and evaluating decisions that enable the farm to achieve its objectives" (David 2001). Environmental targets have to be fully considered at strategic level, to enable effective and efficient nutrient management at tactical and operational levels. Tactical management deals with the implementation of strategic objectives; the annual nutrient management plan is established at this level. Operational management deals with implementing the nutrient management plan in practice, i.e. with activities on a day-by-day basis: when to do what and how in the field.

Nutrient distribution in grazed pastures

Grazed grasslands are aggregates of grazed and ungrazed areas, urine patches, dung patches, compacted hoof holes, camping areas and their mixtures. At the end of the growing season of intensively grazed grassland, a paddock consists of a mosaic of fresh and old, single, overlapping and possibly mixed urine and dung patches covering up to 40 % of the total area (Lantinga et al. 1987). The spatial distribution of patches containing faecal and urinary N, P and K is very heterogeneous (Haynes and Williams 1993). Urine patches contain very high concentrations of urea-N and relatively high concentrations of K, Na and Cl, while dung patches contain relatively high concentrations of P, Ca, Mg, metals like Cu and Zn, and organic N (Haynes and Williams 1993). Urine and dung patches have a high potential for emitting gaseous N compounds (NH_3, NO, N_2O and N_2) into the atmosphere, relative to urine- and dung-free areas (Velthof 1997; Oenema et al. 1997). Moreover, urine patches have a high potential for nitrate-leaching losses (Ryden et al. 1984; Hack-ten Broeke 2000; Vellinga 2006). Urine patches contribute to acidification of sandy soils, while dung adds acid-neutralizing capacity to the soil (Oenema 1990). As a consequence, the spatial variability in N losses via gaseous emissions and nitrate leaching, and of soil fertility in grazed grasslands is extremely high.

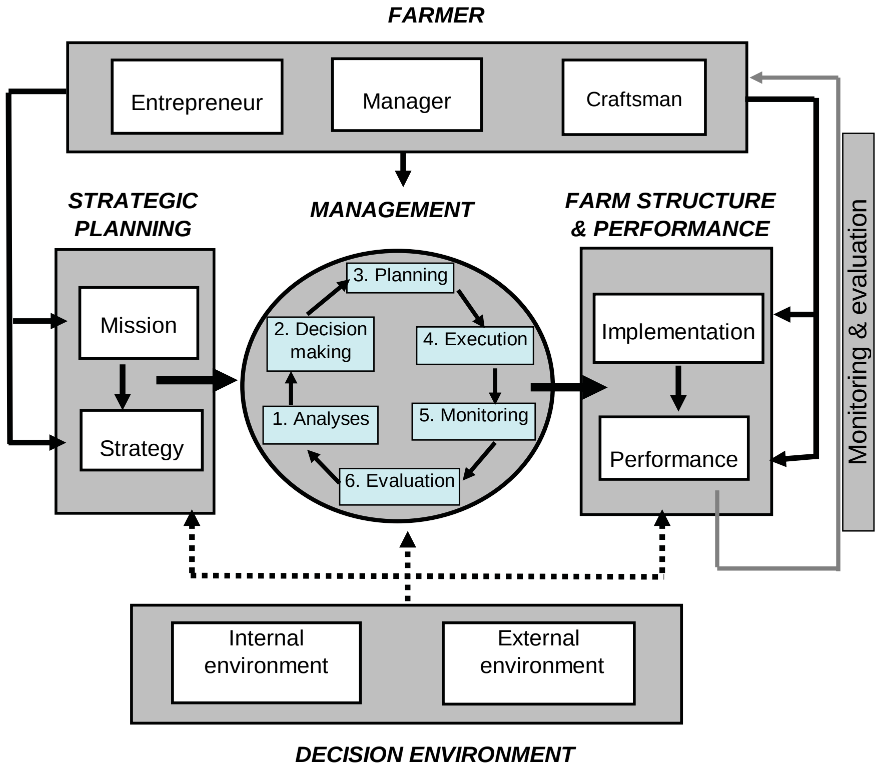

Figure 1*. Nutrient management considered from a whole-farm perspective. After David (2001) and Ondersteijn et al. (2002)*

The uneven distribution of urine and dung patches in pastures has important consequences for the utilization of mobile nutrients like N. The supply of N via dung and urine is usually too high for its effective utilization by pasture in the season of its deposition (Deenen 1994). In temperate climates with a precipitation surplus in winter, usually all excess N is lost via leaching and denitrification. On the other hand, fewer mobile nutrients such as P, Ca, Mg and to a lesser extent K, are retained by the soil and may become available to the herbage in subsequent growing seasons. A special case of heterogeneity in pastures is the camp site, where cattle assemble, for example under a tree, near a drinking place, the milking parlour, and the entrance to a pasture or simply in a corner. Usually, camp sites are highly enriched with nutrients and ‘hot spots’ for nutrient losses, actual values depending on intensity of camping and the mobility of the nutrients (Haynes and Williams 1993).

Rotational grazing and especially strip-grazing are effective practices to increase herbage utilization efficiency, minimize camping and distribute dung and urine more randomly, which ensures that all spots are equally affected and enriched in the long term, especially in intensively managed pastures. Pasture floating, following grazing, spreads out dung over larger areas and thus contributes to reducing heterogeneity. Intermediate mowing cuts also contribute to reducing heterogeneity, as nutrient enriched herbage in and around urine and dung patches is removed. Despite these efforts, heterogeneity in nutrients in grazed pasture soils remains high.

Soil testing is the basis for correcting nutrient disorders in soils and for formulating manure and fertilizer recommendations. For routine soil testing, minimally 40 samples (0-10 cm depth) are taken per 2 ha, following a zigzag grid and neglecting camping sites and dung patches. The samples are bulked and homogenized for analyses (Agterberg and Henkens 1995; Commissie Bemesting Grasland en Voedergewassen 2002). Routine soil testing is usually repeated every 4 years, but not more than half of the dairy farmers in The Netherlands regularly monitor the soil fertility status of grasslands (Arjan Reijneveld, BLGG 2005, pers. comm.). Soil testing is performed when pastures are reseeded, i.e., on average once in 5-10 years (Vellinga 2006). Until their privatization in the 1990s, overviews of the soil fertility status of grassland soils and arable soils were published by the extension services of the ministry of Agriculture, Nature and Food Quality. Recent overviews by the National Environmental Agency (RIVM-MNP) focus on soil P, because of its influence on P-leaching loss and eutrophication of surface waters. The overviews indicate that a significant fraction of the grassland area has a high P status (RIVM 2002; 2004), and does not need P fertilization. Application of P to grassland, especially in spring, has long been justified on the grounds that herbage P content should be at least 4 g per kg to satisfy the requirements of dairy cows (Agterberg and Henkens 1995), but this value has recently been challenged (Valk 2002), suggesting that the target soil P status can also be lowered.

Nutrient management in grazed pastures

Nutrient management of grazed pastures resembles ‘managing the uncontrollable’. The uneven distribution of nutrients in grazed pastures, the difference in mobility among nutrients, and the difference between herbage and dairy cattle in nutrient requirements (e.g., for N, P, K and Mg), necessitates compromise solutions. Total inputs of N and total outputs of N, including N losses, in grazed grasslands usually do not balance. The N unaccounted for tends to increase with increasing N input: up to 50 % of the total N input can be missing (Garrett et al. 1992). This suggests inaccuracies in measured N fluxes, leading to underestimation of outputs (losses) and/or overestimation of inputs.

Intensively managed grasslands in The Netherlands usually receive 2 or 3 cattle slurry dressings of 20-30 m^3 per ha each, and in addition 2-5 N-fertilizer dressings per growing season. Ideally, dung and urine patches should be excluded from manuring and fertilization and attempts have been made to identify these patches, using precision techniques (Van der Putten and Hack-ten Broeke 1997). However, such techniques are not yet operational. Hence, dung and urine patches do receive additional nutrients via cattle-slurry and fertilizer applications.

Over the last 25 years, 19 PhD theses at Wageningen (Agricultural) University have addressed N management of intensively managed pastures in The Netherlands, covering N supply for rapid herbage growth, optimization of N utilization by dairy cows and minimizing N losses to the wider environment (e.g. Meijs 1981; Korevaar 1986; Lantinga 1985; Van Vuuren 1993; Van Loo 1993; Deenen 1994; Van de Ven 1996; Bussink 1996; Velthof 1997; Van den Pol-van Dasselaar 1998; Hack-ten Broeke 2000; Aarts 2000; Valk 2002; Schils 2002; Huijsmans 2003; Taweel 2004; Tas 2005; Smit 2005; Vellinga 2006). Three of these theses also address P (Aarts 2000; Valk 2002; Schils 2002), and none K or other plant nutrients elements. It may be concluded thus that managing N in pastures is key to economically viable and environmentally sound dairy production, and that improving N management involves optimizing grassland and grazing management, animal feeding and the genetic potential of the dairy herd, and manure and fertilizer management from a whole-farm perspective.

In the prototype system for dairy farming and the environment 'De Marke' (Aarts 2000; Hilhorst et al. 2001), where the major objective is the realization of very strict environmental standards, a choice has been made for strongly restricted grazing time. In this farming system, so-called 'siesta-grazing' has been introduced, i.e., grazing for a restricted number of hours early in the morning and in the evening, alternated with periods in the stable for supplementation with energy-rich maize forage to compensate for the protein-rich grass at pasture. This grazing system restricts the fraction of urine and dung voided at pasture and thus reduces field heterogeneity. It also contributes to effective re-utilization of the nutrients in dung and urine collected in the stable, through appropriate application technology of the slurry, i.e., at the right time and in the right amount.

There has been some discussion about the advantages of permanent pastures and continuous forage maize (silage maize) compared to leys in rotation with forage maize (Aarts 2000; Vellinga 2006). Evidently, in permanent pastures soil fertility accumulates as they are supplied with nutrients according to the requirements of the urine- and dung-unaffected areas. Rotations with temporary leys restrict the build-up of soil fertility, while soil cultivation contributes to homogenization of the soil. Moreover, silage maize in rotation minimizes soil-borne diseases, while reseeding of pastures has the additional advantage of introducing new high-yielding grass species. However, other side-effects of leys in rotation make the optimum ratio of permanent grassland and temporary leys in the grassland area highly farm-specific.

Micronutrients as well as Na, Mg and P are increasingly supplied via concentrate feeding, instead of via fertilizer application to grassland soil. Eventually, this leads to mineral-enriched dung and ultimately to enrichment of the grassland soils with the consequence of increased uptake of these (micro-)nutrients in herbage, reducing the need for supplementation of minerals. However, farmers usually do not know the input of nutrients other than N and P to grassland soil via urine, dung and slurries; soil analyses for micronutrient contents in grassland soil are seldom performed, and changes in soil micronutrient status are often obscured by the high spatial variability. Yet, agricultural soils in The Netherlands are steadily enriched with, for example, Cu and Zn at mean rates of 0.5 to 1 kg per ha per year (Moolenaar 1998; CBS 2003), contributing to non-sustainability of the system because of increased metal contents in crops and increased leaching to ground and surface waters (e.g. Römkens et al. 2003). Input–output (micro-)nutrient balances play a crucial role in analysing changes in (micro-)nutrient contents in the soil, as a basis for improving nutrient management decisions, especially in pastures.

MANAGING HERBAGE N IN PASTURES

Nitrogen is the key element in determining pasture productivity. Farmers have known this for decades and N fertilizers have been used abundantly in the second half of the 20th century (Van Burg et al. 1980; Aarts et al. 1992). Increasing N availability increases grass growth rates and reduces the length of the growth period for a harvestable cut (Sibma and Alberda 1980; Prins 1983). The length of the (re-)growing period strongly affects dry-matter yield, herbage N concentration, non-recovered N (N not taken up by the vegetation) and marginal dry-matter response (Figure 2). The 'characteristic' picture is that marginal response increases with length of the growing period, while herbage N concentration and non-recovered N decrease (Vellinga 2006). These effects have important consequences for improving N use efficiency and grassland management.

Consequences of grazing at a later stage

In general, herbage digestibility decreases with extension of the growing period by about 1.5-2.5 % per week (Korevaar 1986), suggesting that grazing at later growth stages results in lower energy intake from herbage. However, positive effects of standing herbage mass and sward height on herbage intake have also been recorded (Tharmaraj et al. 2003).

Grazing at later growth stages and thus higher standing dry-matter (DM) yield, leads to higher herbage allowances and to longer grazing periods per paddock. Daily herbage allowance (in kg DM per cow) is an important management factor in herbage intake and in grazing efficiency (Meijs 1981), and can be managed by either varying the length of the re-growth period, i.e. leading to variable biomass density or by adjusting paddock size. Short grazing periods per paddock per cut lead to more stable herbage intake and to lower grazing losses, and are associated with stable and on average higher milk production. Also 'leader–follower' grazing systems, with specific production groups or with young stock as followers, i.e. grazing after the main dairy herd, have proven successful in maintaining high milk production levels (Mayne et al. 1988). Hence, grazing at later growth stages is possible without negative effects on herbage intake, milk production and grazing efficiency.

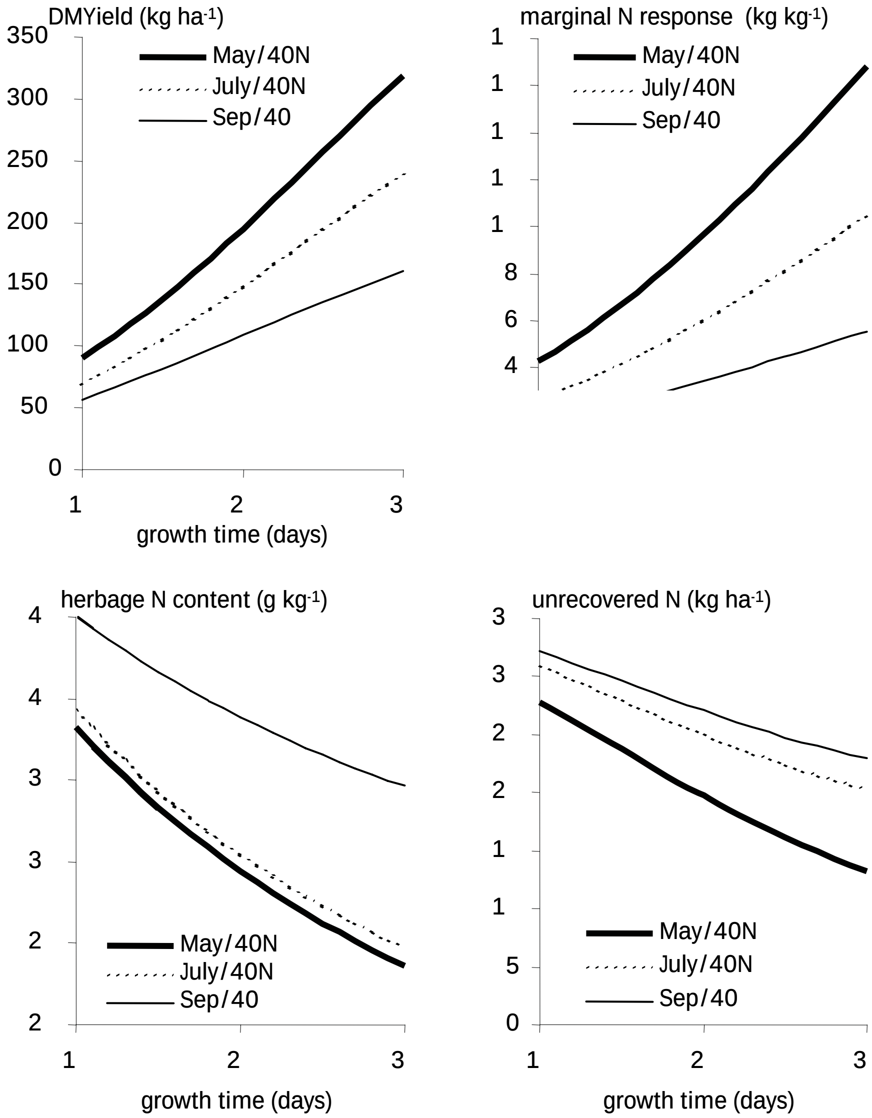

Figure 2. *Relationships between growth time (X-axis) and mean dry-matter yield (kg.ha^{-1}) (upper left), the mean marginal response (kg DM.kg^{-1}N) (upper right), the mean herbage N content (g N.kg^{-1} DM) (lower left) and the mean amount of unrecovered N (kg.ha^{-1}) (lower right) in the second, fourth and sixth cut, starting at May 1, July 1 and September 1, with a nitrogen (N) application rate of 40 kg.ha^{-1} (and preceding applications of 80 kg N.ha^{-1}). The marginal response in the upper right panel literally depicts the increase in DM following an increase in N application from 39 to 40 kg.ha^{-1} (From: Vellinga 2006)*

Extending the length of the growing period by 10 days, relative to common practice, results in lower herbage N content (approximately 8 g per kg) and, for a 100 % grass diet, in a reduction in animal N intake by 60-120 g per cow per day. As a consequence, N excretion via urine is about 50-100 g per cow day lower and herbage N utilization via milk about 5 % higher (Vellinga 2006). At a stocking rate of 2 cows per ha, nitrate concentrations in the groundwater can be reduced by 7-14 mg per l. Moreover, it results in an increase in herbage yield of 300-600 kg DM per ha per year (Vellinga 2006).

The relatively short growing times per cut and the relatively high herbage N contents of pastures on commercial dairy farms (Holshof 1997a; 1997b) are in contrast with the suggested ‘optimal’ growing period of 25-35 days (Vink and Wolbers 1997), to produce herbage with appropriate digestibility, N content, N use efficiency and a satisfactory marginal response. Tamminga et al. (2004) reported for the year 2003 an average herbage N content for grazing of 35.8 g per kg. Results of Stienezen et al. (2005) show that 41 % of the farmers grazed at DM yields below 1700 kg per ha and 16 % at DM yields exceeding 1700 kg per ha. The other respondents used criteria such as ‘two fists high’. Grazing at a relatively young stage is usually practiced because of the presumed tasty herbage with high energy content, and the perceived decrease in herbage digestibility with a decrease in fertilizer N input and increase in growing time (Ondersteijn 2002). Farmers prefer short grazing periods because of the more regular intake and low grazing losses (Stienezen et al. 2005). Farmers want to avoid the risk of decreases in milk production, associated with the perceived lower herbage energy content, lower palatability, increased number of stems and irregular herbage intake when switching to grazing (and cutting) at later growth stages.

Role of information in supporting operational N management under grazing

In a recent review of available tools for supporting operational and tactical grassland management, Stienezen et al. (2005) concluded that as yet no easy and reliable methods for determining herbage availability and quality at operational management level are available for dairy farmers. This contrasts with dairy-herd management, where, for example, milk yield per cow is recorded twice daily and milk quality at herd level once per two days to once per fortnight. Quantitative data that can be collected are herbage yield and quality, and soil information. Imaging spectroscopy appears a promising new technique for the rapid and non-destructive determination of herbage yield and quality for the near future (Schut and Ketelaars 2003; Stienezen et al. 2005).

Measurements of soil nutrient availability and available soil water provide indirect information on grassland productivity. For nutrient availability, a distinction is made between intensity and capacity determinants (Van Erp 2002). Soil mineral N is an intensity determinant and the usefulness of its determination throughout the growing season for N management decisions have been explored in various research projects (Titchen et al. 1993; Vellinga 2006). The results obtained so far are rather disappointing, and as a consequence, soil tests for mineral N have not yet been incorporated in nutrient management decisions in practice. The disappointing results are mainly related to the huge spatial heterogeneity in pastures, the laborious sampling procedures, and also because of the rather non-responsive character of soil mineral N (Vellinga 2006). For other nutrients, mostly empirical (correlative) capacity tests are used, requiring a sampling frequency of once in two to four years, though mechanistic multi-nutrient intensity tests (0.01 M $CaCl_2$) show promising results (Van Erp 2002) and allow guidance in the course of the growing season. However, all soil tests require taking representative soil samples, and this remains a time-consuming procedure in pastures.

CONCLUDING REMARKS

During the second half of the 20th century, nutrient management under grazing has evolved from optimizing manure and fertilizer applications for high herbage yield, using the economic marginal-response criterion, towards improving nutrient use efficiency at farm level, while maintaining productivity, using economic, environmental and social criteria. This change in scope has tremendously increased its complexity. At the same time, continuously changing economic, environmental and social criteria, through changes in agricultural and environmental policies and public perceptions, have greatly increased nutrient management dynamics. Farmers in The Netherlands are confronted with changes in manure policy every 1 to 4 years (Oenema and Berentsen 2005), which forces them to frequently adjust N and P management at farm level.

In the course of time, absolute and relative fertilizer costs in commercial dairy farming have declined, but the time and costs associated with nutrient management have strongly increased as a result of the necessity to comply with changing manure policies. Dairy farmers switch to restricted grazing or zero-grazing, in part because it contributes to higher nutrient use efficiency at farm level, albeit at increased costs (Van den Pol-van Dasselaar et al. 2002).

Introduction of nutrient balance sheets and the MINeral Accounting System (MINAS) in the 1980s and 1990s, respectively, has greatly contributed to the understanding of nutrient cycling and nutrient management at farm level, especially in dairy farming. Nutrient balances are easy to handle and understand, and provide guidance to improving nutrient use efficiency. Switching to a manure policy based on N and P application standards instead of balances from 2006 onwards, is a step backwards in this respect.

Emphasis in nutrient management under grazing in research and practice has been on N and to a much lesser extent on P, K and Mg, because of its impact on productivity (economy-driven) and the environment (policy-driven). Nitrogen appears in multiple forms, especially in animal excrements, and many of these forms are mobile and volatile and contribute to a wide range of ecological effects (Galloway et al. 2002). Excess N accumulates in groundwater and surface waters, but hardly in grassland soil. In contrast, P and heavy metals such as Cu and Zn are immobile and tend to accumulate in soils. The associated increased availability of P, Cu and Zn may contribute to increased herbage productivity and more balanced animal nutrition, but continuing accumulation may ultimately lead to increased leaching losses to surface waters and to toxic metal levels in herbage. Accumulation of P and metals ultimately sets limits to livestock density in intensively managed dairy farming. Inputs via purchased animal feed and fertilizers should balance outputs via animal products and 'acceptable' losses. Increasingly, intensive dairy farms will have to export nutrients via animal manure in addition to dairy and beef products. Manure processing, i.e., manure separation in a solid fraction containing most of the P, metals and organically bound N, and a liquid fraction containing soluble salts (e.g. K, Cl, NH_4), may provide a solution, as it offers the possibility of exporting the solid fraction only, without the voluminous liquid fraction.

NOTES

[1] Nutrient use efficiency is used frequently and is often poorly defined; in this chapter we will use the ratio between the quantity of a nutrient element leaving a system (paddock, farm, region) in desired product and external inputs (fertilizer, animal manure, concentrates) into that system.
[2] Potassium is also a so-called 'macro-element', i.e. needed in relatively large quantities for crop production, and essential for animal health, but it has received far less attention in recent years because of its limited environmental impact.
[3] Pig numbers started to decline from the end of the 1990s as a result of swine fever and subsequent buy-out of pig quota by the government. Poultry continued to increase until poultry quota were established in 2002, followed by buy-out of poultry quota by the government.

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