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Limits to intensity of milk production in sandy areas in The Netherlands

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Abstract

Agricultural land in sandy areas is mainly in use by dairy farms. As a result of intensive fertilisation and irrigation, environmental quality is threatened by lost nutrients and lowered groundwater levels. Therefore, Dutch government put decreasing limits to losses of nutrients, with lowest values for well-drained sandy soils. Besides, use of groundwater for irrigation will be restricted. Reducing milk production per hectare can be effective to reduce nutrient losses but is costly, as is the increase of output of nutrients by exporting manure. Improved resource management, leading to reduced inputs per kg milk, might be a more attractive option to realise both environmental and economic goals. This paper describes a procedure to quantify the impact of management on the limits of milk production per hectare on well-drained sandy soils, at defined maximum levels of permitted nutrient losses. The procedure has been applied to a range of farming systems, in order of increasing complexity of nutrient management. It is concluded that current average milk production intensity (12,400 kg ha^{-1} yr^{-1}) has to be reduced drastically if farm management is not successful in increasing the conversion of dietary N (into milk and body weight) and the re-use of N in manure. On the other hand, results suggest that an intensity of almost 15,000 kg ha^{-1} yr^{-1} should be attainable by best farmers.

Key words: resources, management, nutrients, nitrogen, N, nitrate, dairy farming, milk production, systems research, limits, environment, sandy soils, groundwater.

Introduction

The sandy soils in the Netherlands are mainly used for forage production for dairy cattle, with 520,000 ha permanent grassland (mainly perennial ryegrass, *Lolium perenne* L.), and 180,000 ha silage maize (*Zea mays* L.) as main crops, representing 82% of the cultivated area. The sandy regions are also important for collecting groundwater, as a source of drinking water for human consumption. Moreover, many valuable nature reserves are located in the sandy areas and recreation has become an important source of income. From the 1960's onwards, farms strongly intensified milk production per hectare by increasing inputs of fertilisers, concentrates and (irrigation) water. Current average milk production in sandy areas is 12,400 kg ha^{-1} yr^{-1}, 500 kg above the national average (Beldman & Prins, 1999).

This intensification has negatively affected environmental quality, through emissions of nitrogen (N) and phosphorus (P) and lowered groundwater levels. Farm nutrient outputs, in milk and meat, represent on average only 16 (N) and 27% (P) of inputs, mainly in purchased feeds and fertilisers (Aarts *et al.*, 1999b). As a consequence, nitrate concentrations in the upper groundwater of the sandy regions exceed the standard (50 mg l^{-1}) of the 1980 EU Drinking Water Quality Directive by a factor of up to five (Fraters *et al.*, 1998). As supply from extractable groundwater for human consumption became limiting, additional water from the rivers Rhine and Meuse has to be purified, at high costs.

To be sustainable, dairy farming systems must be acceptable to society. Therefore, in 1997 legislation was introduced, defining gradually decreasing maximum permitted surpluses of N and P for the period 1998–2008. In 1999 it was decided that the final norms should be realised in 2003. Calculated surpluses are based on the balance between farm nutrient inputs in feeds and fertilisers and outputs in milk, animals and manure. Hence, deposition and N fixation by leguminous crops are not included as inputs in this 'farm gate balance' approach of the MINeral Accounting System (MINAS; Van den Brand & Smit, 1998). Permitted surpluses for N are lowest for well-drained sandy soils, because of a supposedly low denitrification rate in the subsoil and their importance for the supply of drinking water. For these soils, the final maximum surplus is 60 kg N ha^{-1} yr^{-1} for silage maize, and 140 kg for grassland. For maize, undersown with Italian ryegrass to prevent nitrate leaching in the period from maize harvest until next spring, maximum surplus is 100 kg N ha^{-1} yr^{-1}. For intensive farms the acceptable surplus is increased by 15 kg N ha^{-1} yr^{-1}. P surplus for all crops is limited to 9 kg ha^{-1} yr^{-1}. As current average surpluses are 340 kg ha^{-1} yr^{-1} for N and 39 for P (Beldman & Prins, 1999), considerable reductions have to be realised. Moreover, it is expected that in the near future irrigation of crops will only be permitted to prevent death by drought, as reseeding grassland after a drought period may lead to excessive leaching of nitrate, as a result of mineralisation of the accumulated organic N in the upper soil layers (Whitehead, 1990).

Dairy farms can probably meet the environmental standards through reducing milk production per hectare, by expanding farm size, because input in fertilisers and feeds per hectare will decrease more than output in milk and cattle. However, agricultural land is very expensive and such developments therefore supposedly not economically sustainable. Moreover, a societal demand exists for alternative use of available land, such as expanding nature reserves. Export of manure, to increase farm output of nutrients, is also expensive, and may lead to off-site environmental problems. Improved resource management, resulting in reduced farm inputs of fertilisers, water and feed per kg milk, appears the most attractive option to realise both environmental and economic goals (Jarvis *et al.*, 1996). A considerable amount of information is available on the scope for reducing nutrient surpluses at a fixed level of milk production per hectare through improved management (Jarvis & Aarts, 2000; Kuipers & Mandersloot, 1999; Whitehead, 1995). However, the impact of improved management on attainable milk production per hectare at fixed nutrient surpluses, such as those defined in Dutch legislation, appears not to have been quantified. This paper describes a procedure to quantify such impact for well-drained sandy soils. A range of management options is presented, in the form of farming systems, in order of increasing complexity of management and efficiency in N utilisation. Maximum milk production for each of these systems is quantified, demonstrating the potential benefits of improving management.

A procedure to determine limits to milk production intensity

General description

Characteristic for dairy farming is the combination of plant and animal production in one system. Nutrients cycle through the system, by exchanging manure and forage between the plant and animal components. Mass and nutrient flows can, to a certain extent, be controlled by management. The procedure to estimate maximum milk production intensity comprises six steps, describing plant and animal production and the associated mass and nutrient flows through the system (Figure 1). In the first step, maximum attainable net crop yields of the plant component of the system are quantified, as dictated by soil and crop characteristics, environmental restrictions and management decisions, such as intensity of grazing. In the next step, minimum feed requirements of the animal component are quantified on the basis of characteristics of the herd. Maximum crop yields and minimum feed requirements are combined in step 3, resulting in equations to calculate maximum milk production per hectare in an environmentally acceptable way on the basis of soil, crop and herd characteristics. A number of parameters in these equations can be affected by management. In step 4 a range of farming systems is formulated, in order of increasing complexity of management. The equations, derived in step 3, are used to estimate limits to milk production per hectare for each of the farming systems, for two levels of maximum permitted nutrient surpluses and four levels of water supplying capacity of the soil (step 5). As maximum permitted N surplus is considered the major en-

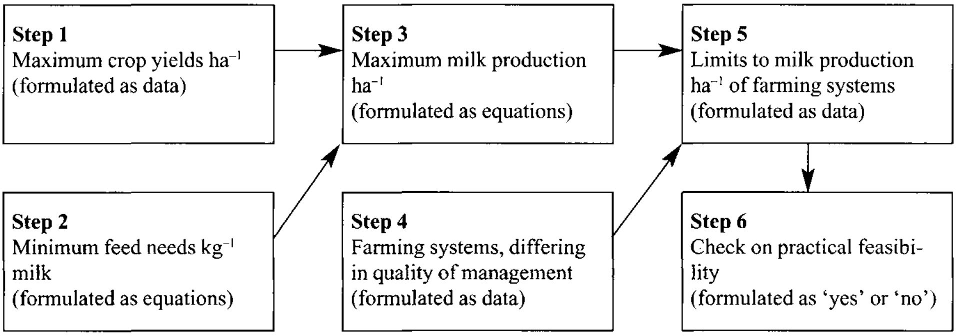

Figure 1. Successive steps in the procedure to determine limits to milk production per hectare of farming systems (⟶ flow of information).

vironmental constraint for farming system intensity (Aarts *et al.,* 1999a), P-supply to the herd and P-surpluses of the farming systems are assessed ex post, as part of the check on the practical feasibility of the farming systems (step 6). Steps 4 to 6 are described in the section 'Application'.

Quantitative relations and data, used in the procedure, were derived from literature and experimental research and can easily be adapted. The procedure has been applied in the design of dairy farming systems for well-drained sandy soils with strict environmental goals. Since 1992, such a farming system, called 'De Marke', has been tested as a prototype at farm scale, providing an opportunity for validation and improvement of the procedure, including basic data and causal relations (Aarts *et al.,* 1999b; Aarts *et al.*, 1992).

Maximum crop yields, in dependence of soil and management characteristics and environmental restrictions (step 1)

On well-drained sandy soils in the Netherlands, availability of *water* is in general the major growth-limiting factor (Aarts *et al.,* 1999a). Uptake of carbon dioxide in the photosynthetic process takes place through the stomata, openings in the epidermis of the leaves, and concurrently water vapour diffuses to the outside air. When stomata close because of drought, to reduce transpiration, uptake of carbon dioxide also decreases. Hence, a proportional relation exists between water transpired and total dry matter produced (De Wit, 1958). Water consumption per unit harvestable dry matter, in a given environment, is a plant species characteristic. It is influenced to a limited extent by fertilisation (Bürcky, 1993; Van der Schans & Stienezen, 1998), mainly as a result of a change in the partitioning of dry matter produced between harvestable and non-harvestable parts (roots and stubble). During the growing season in the Netherlands, average consumption amounts to 350 and 175 kg water per kg harvestable dry matter for grass and maize, respectively (Aarts *et al.,* 1999a). The low value for maize can be partly attributed to a more water-efficient photosynthetic mechanism (van Keulen & Van Laar, 1986), and partly to a smaller proportion of dry matter invested in stubble and roots. Available water during the growing season is determined by rainfall and soil water supplying capacity (sum of soil water storage capacity in the rooted zone and maximum capillary rise during the growing season).

As a result of application of excessive doses of slurry in the past, the P status of most sandy soils is so high, that crops hardly respond to *P fertilisation* (Habekotté *et al.*, 1998), in contrast to *N fertilisation.* Grass under a cutting regime, generally takes up 85% of the mineral N present in the rooted layers of the soil, to a level of about 300 kg ha^{-1} (Middelkoop & Aarts, 1991; Prins, 1983). Beyond that level, the uptake fraction slowly decreases. Under grazing, mineral N from urine and faeces also contributes to available N. As a relatively large proportion of that N is concentrated in 'hot spots', utilisation efficiency is low. The number of such spots can be reduced considerably by adapting the grazing regime, for instance from day-and-night grazing to daytime grazing only. Maize takes up about 75% of the available N to a level of 100 kg ha^{-1}, but beyond that level the uptake fraction sharply decreases. As N uptake ceases rather early in the growing season, only a small proportion of the N min-

Table 1. Model-calculated average net yields for grass and maize, if nitrate content in the upper groundwater has to be restricted to 50 mg l^{-1} and irrigation is only allowed to prevent death by drought.

	Water-supplying capacity soil			
	25 mm (very dry)	75 mm (dry)	125 mm (rather humid)	175 mm (humid)
Dry matter (kg ha^{-1})				
Grass, cut for silage	8263	9077	9888	11119
Grass, day-and-night grazing, cut twice	7574	8159	8742	9432
Grass, day-and-night grazing, cut once	6989	7578	8122	8700
Grass, day-and-night grazing, no cut	6437	7003	7560	8053
Grass, day grazing, cut twice	7879	8573	9240	10039
Grass, day grazing, cut once	7552	8226	8888	9581
Grass, day grazing, no cut	7255	7940	8593	9230
Maize, without catch crop	8722	9701	10502	10680
Maize, with catch crop	9576	10965	12371	12709
N (kg ha^{-1})				
Grass, cut for silage	289	310	330	351
Grass, day-and-night grazing, cut twice	246	254	264	274
Grass, day-and-night grazing, cut once	221	235	244	253
Grass, day-and-night grazing, no cut	202	214	226	234
Grass, day grazing, cut twice	273	287	298	309
Grass, day grazing, cut once	259	274	286	297
Grass, day grazing, no cut	254	271	284	297
Maize, without catch crop	119	127	132	134
Maize, with catch crop	130	144	156	159
*Energy (kVEM ha^{-1})**				
Grass, cut for silage	7205	7915	8622	9695
Grass, day-and-night grazing, cut twice	6918	7510	8100	8799
Grass, day-and-night grazing, cut once	6701	7298	7849	8434
Grass, day-and-night grazing, no cut	6360	6919	7469	7956
Grass, day grazing, cut twice	7193	7862	8506	9277
Grass, day grazing, cut once	7167	7825	8472	9148
Grass, day grazing, no cut	7168	7845	8490	9119
Maize, without catch crop	8295	9226	9987	10157
Maize, with catch crop	9107	10428	11765	12086

* 1 kVEM = Dutch feeding standard for energy, comparable to 6.9 MJ Net Energy for Lactation.

eralised from late summer onwards, can be taken up. A catch crop, such as undersown Italian ryegrass, growing after maize harvest, can prevent leaching of excess mineral N until next spring (Schröder, 1998).

To estimate *harvestable yields* of grass and maize at limited availability of N and water, simple crop growth models have been developed (Aarts & Middelkoop, 1990; Middelkoop & Aarts, 1991). Yield reductions, associated with economically sub-optimal fertiliser application rates, that restrict nitrate concentrations in the upper groundwater to the standard of 50 mg l^{-1}, have been shown to depend on soil water supplying capacity, with the largest reductions on soils with the highest capacity. On average, dry matter yield of grass is reduced by 7% under daytime grazing, compared to 12% for day-and-night grazing (higher fertilisation levels permitted because of reduced quantities of N in urine patches). For maize, yield reduction is 17%, but only 4% when combined with a catch crop. Reductions in N-yield are about twice as high, because of reduced N contents in the dry matter at the lower fertiliser application rates.

Considerable *losses of yields* may occur during grazing, harvesting, conserving and feeding. For maize, losses of dry matter have been estimated at 11%, for grass 17% when cut, 20% when grazed day-and-night and 14% when grazed during daytime only. These assumptions are similar to generally accepted Dutch standards for 'good agricultural practice' (Anonymous, 1997), but adapted slightly because of the specific characteristics of well-drained soils.

Final estimated *net yields* (harvestable yields minus sum of losses), presented in Table 1, correspond well with results of field experiments on sandy soils (Aarts *et al.*, 1999a) and with the results of 'De Marke'. On that farm, largely consisting of very dry soils and measured nitrate contents in the upper groundwater of 50 mg l^{-1}, net dry matter yield of grass (daytime grazing, cut twice and 40 mm irrigation) for the period 1992–1997 was 8,600 kg ha^{-1} on average, N yield 268 kg. Dry matter and N yield of maize (with Italian ryegrass as catch crop and 5 mm irrigation) was 9,600 and 120 kg ha^{-1}, respectively.

Minimum feed requirements, in dependence of herd characteristics (step 2)

Simple equations have been formulated for energy, P and protein requirements at herd level. However, these equations can easily be sub-divided or otherwise detailed, if desired. Dairy cows *require energy* for maintenance, growth, pregnancy, physical activity and milk production. According to Dutch feeding standards (Anonymous, 1997), annual energy requirements of a mature dairy cow with a (standard) weight of 600 kg are 2,013 kVEM (1 kVEM = 6.9 MJ Net Energy for Lactation; Van Es, 1978), plus 0.46 kVEM per kg milk produced (standardised at 3.32% protein and 4.00% fat). For pregnancy, 105 kVEM is needed annually. To rear a calf until its first lactation 3,975 kVEM is needed and during the first two lactations, an additional 329 kVEM is needed for body growth. Therefore, replacing a milking cow requires an 'investment' of 4,304 kVEM. The required number of calves to rear depends on the replacement rate of the cows, defined as the percentage of the number of milking cows annually sold. Hence, energy requirements per kg milk produced (Ereq) depend on milk production per cow and replacement rate, and can be approximated by equation 1, including the energy needs of both cows and calves.

$$\mathrm{Ereq} = (2118+0.46*M+4304*R/100)/M \qquad (1)$$

with,

M: annual milk production per cow (kg, standardised at 3.32% protein and 4.00% fat).

R: annual replacement rate of cows (%)

Results at 'De Marke' indicate that the energy requirements of the herd, based on equation 1, are underestimated by approximately 5%. That is in agreement with the results of recent feeding experiments (Valk, 1999, Institute for Animal Science and Health, pers. comm.). This might be associated with higher maintenance requirements for the current, high yielding cows with higher body weights, since requirements were formulated some 15 years ago. To arrive at a more realistic estimate, the results of equation 1 are multiplied by 1.05.

Dietary *requirements for P* with safety margins to account for variation among individual animals, are estimated at 3.5 g kg^{-1} dry matter intake, or nearly 4.0 g P $kVEM^{-1}$ (Lynch & Caffrey, 1997; Van der Schans, 1998).

Protein-N in the diet of herd is converted into milk and body weight or excreted in urine and faeces. In Dutch dairy farming systems, the conversion efficiency from feed into milk and body weight is often only 16% (Aarts *et al.*, 2000). Theoretically, lactating cows might reach 43%, but under practical conditions that value is not attainable (Van Vuuren, 1994; Van Vuuren & Meijs, 1987; Whitehead, 1995), because of variation in N requirements among individual cows. Within the herd, the possibilities for individual feeding are limited. Hence, most animals consume more N than strictly needed, to prevent N deficiency of some individuals. Moreover, the N content of the ration may vary in the course of time, for instance because of grazing at daytime (high N content grass) and ingesting silage maize indoors at night (low N content). Cows can only partly buffer such fluctuations. Conversion of N into milk is more efficient than into body weight and young stock and non-lactating cows are also part of the herd. Consequently, a conversion efficiency of dietary N at farm level exceeding 25% will hardly be attainable under practical farming conditions, as indicated by results at 'De Marke' (Aarts *et al.*, 2000).

The required N-content in feed depends on the conversion efficiency of dietary N and the N-content of milk and body, i.e. 5.3 and 25.0 g kg^{-1}, respectively (Ketelaars & Van der Meer, 1999). Body weight production is a function of the replacement rate of the cows. Assuming (PR, 1997) that the weight of a mature cow is 600 kg, male calves (50%) are sold directly after birth at a weight of 40 kg, and surplus female calves (50% – replacement rate cows) at an average weight of 215 kg (50% directly after birth, 25% at one year of age and 25% at 22 months), N sales in milk and body weight can be calculated by equation 2. Subsequently, N requirement follows from total N sales and from N conversion efficiency from feed into milk and body weight (equation 3).

$$No = [5.3+(600*25*R/100+50/100*40*25+(50-R)/100*215*25)/M]/1000$$
$$No = (5.3+(96R+3188)/M)/1000 \quad (2)$$

$$Nreq = (5.3+(96R+3188)/M)/(10*Nut) \quad (3)$$

with,
No: sales of N per kg milk, including sales of body weight (kg)
Nreq: N requirements per kg milk (kg)
Nut: N conversion efficiency from feed into milk and body weight (%)

Maximum milk production intensity in dependence of soil, crop and herd characteristics and environmental restrictions (step 3)

Total energy and N requirements of a dairy farm follow from the energy and N requirements per kg milk (equations 1 and 3, respectively) and total milk production. Part of the requirements is covered by net yields of home-grown grass and maize. Average net feed yields of a farm are dictated by soil moisture supplying capacity, share of the different crops in total farm area, whether or not maize is followed by a catch crop and the grazing system, and can be derived from the data presented in Table 1. The gap between feed requirements and net feed yields has to be filled by purchased feeds. In the Netherlands, a variety of commercial feeds is available. The ratio between N (kg) and energy (kVEM) in common commercial feeds varies from 0.010 – 0.072, with 0.026 for the concentrate most commonly used (PR, 1997). That permits an intensive farmer to optimise the diet of the herd.

$$Ei = Y^*Ereq - Ep \qquad (4)$$
$$Ni = Y^*Nreq - Np \qquad (5)$$

with,
Ei and Ni: purchased energy and N, respectively (kVEM $ha^{-1}$and kg ha^{-1})
Y: milk production of the farm (kg ha^{-1})
Ereq and Nreq: energy and N requirements per kg milk, respectively (kVEM and kg)
Ep and Np: net energy and N yields of the farm, respectively (kVEM ha^{-1} and kg ha^{-1})

The quantity of N in purchased fertilisers and feeds, minus the sales in milk and body weight, should not exceed the maximum permitted 'farm gate surplus', unless manure is exported.

$$Ni + Nfer - Y^*No < Nsurplus$$
$$Ni < Y^*No + Nsurplus - Nfer \qquad (6)$$

with,
Nfer: input of N in purchased fertilisers (kg ha^{-1})
Nsurplus: maximum permitted 'farm gate N surplus' (kg ha^{-1})

Equations 5 and 6 can be combined:

$$Y < (Nsurplus - Nfer + Np)/(Nreq - No) \qquad (7)$$

Input of N in purchased feed should not exceed output in sold products plus the permitted surplus, minus that in purchased fertilisers:

$$n^*Ei < Y^*No + Nsurplus - Nfer \qquad (8)$$

with,
n: content of N in purchased feed (kg $kVEM^{-1}$)
Ei: purchased energy (kVEM ha^{-1})

Combining equations 4 and 8 yields:

$$Y < (Nsurplus - Nfer + n*Ep)/(n*Ereq - No) \quad (9)$$

Maximum milk production per ha, as dictated by energy and N requirements and maximum N surpluses, follows from either equation 7 or 9. In a comparable way, equations have been developed for maximum milk production intensity as a function of herd P requirements and permitted P surplus. However, on well-drained sandy soils the N-restrictions are in general most constraining. Whether equation 7 or equation 9 yields the lowest value, and the value itself, partly depends on factors beyond control of the farmer, such as maximum permitted 'farm gate N surplus' and soil moisture supplying capacity. However, also management decisions play a role, as they can influence parameters directly (the replacement rate of cows or the choice of purchased feed, for instance) or indirectly.

Manure management indirectly affects mineral fertiliser N requirements, as illustrated in a slightly simplified example. On a soil with a water supplying capacity of 75 mm, annual net N yield of grass (day grazing, cut twice) is 287 kg ha^{-1} (Table 1) and maximum permitted N surplus 140 kg ha^{-1}. Hence, maximum input in manure (volatilisation of ammonia included) and purchased mineral fertilisers is 287+140 = 427 kg N ha^{-1}. That implies that 287/427, i.e. 67% of the N, 'applied' in manure (excretion during grazing included) and mineral fertilisers, has to be recovered in the long term (including re-use of N returned to the soil in grazing and harvesting losses or after temporary storage in stubble and roots). Such a utilisation efficiency can easily be realised, if only purchased mineral N is used. In that case, unfortunately, no milk production is possible, because manure cannot be applied. Because of high losses (mainly through ammonia volatilisation and denitrification), recovery from manure N will be below 67%, so some mineral N is needed to realise the average of 67%. Reducing losses from manure, for instance by 'low emission' housing or careful storage and application of manure, increases the recovery of N and reduces the need for mineral fertilisers. As a consequence, more manure can be applied, allowing higher milk production.

Effects of management decisions on the parameters of the equations can be determined by 'best professional judgement' or derived by modelling the effects of individual and combinations of measures. In general, farm management, aiming at maximising milk production per hectare in an environmentally acceptable way without exporting manure, should focus on minimising the use of purchased mineral fertilisers through improved utilisation of nitrogen from manure and on a reduced area of crops with relatively high fertiliser demands, like grass. Moreover, feed requirements should be minimised and the proportion of these requirements covered by home-grown crops maximised (to reduce the needs for purchased feeds).

Application

Farming systems, varying in quality of management (step 4)

In Table 2, a range of management options is presented in the form of farming systems, in order of increasing complexity of management and increasing utilisation efficiency of N. The purpose of this range is to examine to what extent quality of management does influence maximum possible milk production per hectare. Other systems could be designed, but they would fall somewhere within the range defined here. For ease of calculation, a computer-based programm, 'Irene 5', has been applied.

The last system in Table 2 (number 10) represents experimental farm 'De Marke', and requires high quality management (Aarts *et al.*, 1999a). A recent survey of the Dutch dairy farming sector has indicated the capability among innovative Dutch farmers to manage their farms at this level (Oenema, 2000). Therefore, the formulated systems can be regarded practically feasible. System 1 resembles an 'average' present-day farming system, with minor adaptations to realise the environmental goals. Grazing is restricted to daytime, as practiced already on 50% of the farms, to increase the proportion of manure excretion indoors, and therefore reducing purchases of mineral fertiliser. Moreover, net grass yield is higher if grazing time is restricted, reducing purchases of feeds. Comparable to common practice, grass is cut twice and grazed three or four times, providing equal amounts of grass products in the diet during summer (fresh grass) and winter (grass silage). N-fertilisation levels are about 250 and 100 kg plant available N ha^{-1} for grass and maize, respectively, 40% below current practice. Levels increase slightly with water supplying capacity

Table 2. Characteristics of dairy farming systems on well-drained sandy soil, in order of increasing complexity of resource management to improve N utilization efficiency. System 1 resembles a slightly modified present-day commercial system, system 10 represents experimental farming system 'De Marke'.

	Farming system									
System characteristic	1	2	3	4	5	6	7	8	9	10
Milk per cow* (kg yr^{-1})	7625	7625	7625	7625	8000	8000	8250	8250	8500	8773
Replacement cows (% yr^{-1})	47	40	35	30	30	30	30	30	30	28
Conversion dietary N (%)	17	18	19	20	20	21	21	22	23	24
Farm area in grassland (%)	80	80	75	70	70	70	65	65	60	55
Purchased mineral N on grass (kg ha^{-1})	200	175	175	175	150	150	125	125	125	125

* fat (4.00%) and protein (3.32%) corrected; in the Netherlands about 6% above real production.

of the soil, because of increasing potential yield of N. In addition to cattle manure, grassland is fertilised with 200 kg purchased mineral N ha^{-1}, about 85 kg below the current level at commercial farms. In contrast with current practice, maize in system 1 is only fertilised with cattle manure, and Italian ryegrass is grown directly after maize harvest, as catch crop. The reduced fertilisation levels of the crops result in 10% lower N contents in the dry matter, which supposedly increases conversion of dietary N slightly from 16 to 17%. As in current practice, almost all female calves are reared for replacement, resulting in a replacement rate of 47% (most of the cows are sold already at an age of 4 years, after two lactation periods). In system 1, milk production per cow and the ratio between the areas of grass and maize are equal to current practice. Farmers should be able to manage system 1 without effort.

Going from system 1 to system 10, improved management increases N utilisation. The number of calves to be reared is reduced, because of a lower annual replacement rate of cows (from 47 to 28%), mainly as a result of improved health care and housing of the milking cows, increasing productive lifetime. Maize area increases, from 20 to 45%, to allow formulation of more balanced diets (ratio between energy and protein), resulting in improved conversion of dietary N up to 24%. Milk production per cow increases by 1,150 kg over the range of systems, mainly through genetic improvement and optimal health care and feeding. Daily grazing time, for instance, is split in two periods of 4 hours each, one in the morning and one in the evening. In the afternoon, cows stay indoors and are fed maize, to compensate for the high N uptake with grass. Moreover, this 'siesta-grazing system' (developed at 'De Marke') protects the cows from high mid-day temperatures outdoors, in summer. Overall fertilisation levels of grass and maize do not change from system 1 to 10. Nevertheless, input of purchased mineral N on grassland decreases from 200 to 125 kg ha^{-1}, as a result of improved recycling of N in animal manure and a reduction in grassland area. Ammonia volatilisation from urine and faeces is lower, as a result of 'low emission' housing of cattle (excrements are transported fast to a closed slurry storage). In addition, method and timing of manure application have been improved.

Maximum milk production intensity per hectare for each of the farming systems was calculated, for very dry soil (25 mm water supplying capacity), medium dry soil (75 mm), medium humid soil (125 mm) and humid soil (175 mm). Two levels of permitted maximum farm gate N surplus were considered: one equal to the realised surplus of experimental farm 'De Marke' (95 kg ha^{-1}), the other calculated according to the final standards from Dutch legislation (MINAS; 137–147 kg ha^{-1}, depending on farm area in grassland, as maximum surplus of grassland differs from that of maize).

Results and discussion (steps 5 and 6)

Maximum milk production intensities of the various farming systems clearly show the decisive impact of quality of management in dealing with environmental restrictions (Table 3). Improving management, from that in system 1 to that in system 10, roughly doubles attainable milk production per hectare. In poorly managed systems, maximum attainable milk production is so low, that such systems probably will not be sustainable from an economic point of view, considering the high costs of land

Table 3. Maximum attainable milk production (t ha^{-1}, corrected to 4.00% fat and 3.32% protein) of farming systems, varying in management, water supplying capacity of the soil and maximum farm gate N-surplus. MINAS-surplus depends on the percentage grassland and varies between 147 (system 1) and 137 kg ha^{-1} (system 10); 95 kg ha^{-1} is the average surplus of experimental farm 'De Marke' (1993–1998).

Soil	Very dry (25 mm)		Dry (75 mm)		Medium humid (125 mm)		Humid (175 mm)	
Surplus	95 kg	MINAS	95 kg	MINAS	95 kg	MINAS	95 kg	MINAS
System								
1	5.8	7.5	6.1	7.8	6.7	8.3	7.0	8.7
2	7.1	8.9	7.3	9.1	7.9	9.8	8.3	10.1
3	7.7	9.6	8.0	9.9	8.6	10.6	9.0	10.9
4	8.3	10.3	8.6	10.6	9.4	11.3	9.7	11.7
5	9.1	11.1	9.4	11.4	10.2	12.1	10.5	12.5
6	9.7	11.8	10.0	12.1	10.8	12.9	11.1	13.3
7	10.5	12.5	10.8	12.8	11.6	13.6	11.9	14.0
8	11.1	13.2	11.5	13.6	12.3	14.4	12.7	14.8
9	11.7	13.9	12.2	14.4	13.0	15.2	13.4	15.6
10	12.5	14.7	12.9	15.2	13.8	16.0	14.2	16.4

per kg milk. For none of the systems, the calculated maximum was unrealistic in terms of the maximum permitted P surplus (9 kg ha^{-1}) or of the P requirement in the diet.

Water supplying capacity of the soil, influencing crop yields, has an impact of 1,200–1,700 kg ha^{-1}, rather low compared to the impact of management. That can be illustrated, using system 7 as an example, assuming a MINAS-surplus (141 kg N ha^{-1}). Crops on a 175 mm soil yield on average 2,939 kVEM and 34 kg N ha^{-1} higher than on a 25 mm soil (data from Table 1). To produce one kg of milk in system 7, 0.92 kVEM and 0.029 kg N is needed (results of equations 1 and 3; based on total feed requirements of the herd).Hence, an additional 1,172 kg milk ha^{-1} can be produced (34/0.029), increasing output in milk and body weight with 8.3 kg N ha^{-1}. This allows increased input in purchased feed. However, additional output can only partly be compensated by additional input of feed, because of losses from additional manure. Additional purchased feed will lead to higher milk production, increasing feed purchases again. Hence, finally milk production is 1,482 kg ha^{-1} higher for the humid soil. Because of higher N yields of the crops on a soil with a high water supplying capacity, fertilization requirements are higher too. These higher requirements can be met by the additional manure produced, and a slightly better performance of fertilizers on humid soils, so the mineral fertilizer requirement does not really change. For the additional milk production 1,263 kVEM is needed (0.92*1,482), while 2,939 kVEM is additionally available. Therefore, the farm can reduce inputs of energy in purchased feed, leading to an increase in the ratio between N (kg) and kVEM from 0.033 (25 mm) to 0.057 (175 mm).

There is no absolute guarantee that, under all conditions, realisation of the MINAS-surplus of 137–147 kg N ha^{-1} will indeed restrict the nitrate content in the upper groundwater to 50 mg l^{-1}. At 'De Marke', on soils very dry and sensitive to leaching, this target level is realised at a surplus of only 95 kg N ha^{-1} (Aarts *et al.*, 1999a). A reduction in the MINAS-surplus of on average 47 kg, to a value similar to the actual surplus of 'De Marke', reduces maximum attainable milk production by 1,700–2,200 kg ha^{-1}. Nevertheless, levels of 12,500–14,200 kg ha^{-1} can be attained, i.e. almost equal to or above the current average on sandy soils. Fat and protein corrected milk production at 'De Marke' is 12,487 kg ha^{-1} (real milk production 11,890 kg ha^{-1}), which agrees well with the calculated results of system 10 on comparable soil.

Quality of management, as assumed in systems 9 and 10, seems feasible in the near future for well-educated and motivated farmers. Therefore, a milk production of nearly 15,000 kg ha^{-1}, substantially above the current average, should be attainable on most soils at the maximum farm gate N surpluses defined in Dutch legislation (MINAS).

For actual milk quota of the farm above the calculated maximum attainable level, additional measures are needed, which may require fundamental changes in the farming system. A possibility could be to rear young stock off-farm. Rearing a calf until first lactation requires about 120 kg dietary N, used at an efficiency of less than 10%, as determined at 'De Marke' (Van Der Schans, 1998). Disregarding the contribution of young stock, utilisation efficiency of dietary N at 'De Marke' would be 27%, instead of the actual 24%. Moreover, utilisation efficiency of N in the manure of young stock is low, because most is excreted during grazing (day-and-night). If, in farming system 10, young stock would be reared off-farm, maximum attainable milk production would increase considerably to 16,000–18,200 kg ha^{-1} (surplus 95 kg N ha^{-1}; water supplying capacity of the soil 25–175 mm) or 18,800–21,100 kg ha^{-1} (surplus according to MINAS). Economic analyses indicate low benefits of rearing young stock on intensive farms. Hence, rearing young stock might be more profitably on less intensive farms, for instance on clay or peat soils with higher permitted farm gate N surpluses. However, this practice increases the risk of spreading of animal diseases.

Further reducing grazing time (more urine and faeces collected indoors) and technical improvements in manure handling (creating different types of organic fertilisers) and application (lower losses by volatilisation of ammonia, improved spreading) can reduce the need for purchased mineral fertilisers considerably. Conversion efficiency of dietary N may be further increased through improved techniques to optimise rations, reducing the need for purchased dietary N. An example of such a technique, implemented at 'De Marke', is separate harvesting of cobs and stover of maize. Stover provides excellent fodder for non-lactating cows and young stock, cobs can replace purchased concentrates for high-yielding cows. If conversion of dietary N by cows could be increased from 27 (at 'De Marke') to 30% and the use of purchased mineral N on grassland reduced from 125 to 50 kg N ha^{-1}, maximum milk production could be 21,800–24,300 kg ha^{-1}, assuming off-farm rearing of young stock and a maximum surplus of 95 kg N ha^{-1}. Still higher milk production levels are only possible if manure is exported from the farm.

Conclusions and perspectives

The procedure presented in this paper appears useful in quantifying the effects of farm specific conditions and farm management on limits to milk production at exogenously defined maximum N surpluses. Data and quantitative relations can be adapted easily to reflect improved knowledge, as a result of research. Results indicate that in sandy areas, with rather deep groundwater levels, milk production levels above the current average of 12,400 kg ha^{-1} are in principle technically attainable through improved resource management, even at a maximum farm gate surplus of 95 kg N ha^{-1}, 47 kg below the maximum defined in Dutch legislation. On the other hand, poor management will restrict milk production to levels far below current average. Water supplying capacity of the soil, influencing crop yields, has an impact of 1,200-1,700 kg ha^{-1}, rather low compared to the impact of management. Therefore, improving farmers' skills in efficient nutrient management should have high priority. Tools to identify the most suitable farming system, taking into account both economic and environmental goals, farm-specific conditions and farmer's skills, have to be further developed. Moreover, research has to focus on improved recycling of nutrients in urine and faeces, to reduce the need for purchased mineral N, and on increasing the conversion efficiency of dietary N into milk and body weight, to reduce the need for purchased feed N.

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