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Efficient resource management in dairy farming on peat and heavy clay soils

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Abstract

Peat and heavy clay soils in the Netherlands are mainly used for permanent grassland to support dairy farming. As a result of intensification in dairy farming during the last decades, environmental quality is threatened by high emissions of N and P. Increased drainage of the wet soils has induced high mineralization rates, with associated losses of organic matter and nutrients. Improved utilization of N and P sources and new grazing and feeding strategies are proposed to reach environmental targets without loss of production. A sustainable prototype-system is designed by stepwise theoretical improvements of the current dairy farm. Although groundwater levels are kept high to limit breakdown of soil organic matter, the high availability of N and P from unavoidable peat mineralization offers the possibility to drastically reduce fertilizer inputs, which will directly reduce nutrient losses to the environment. Reduction of protein content in the ration reduces ammonia emission by approximately 20%, while milk production levels of 14,000 kg ha^{-1} per year can be maintained. The change from full to restricted grazing effectively reduces N losses from soil, but ammonia emission reductions are only significant with an improved slurry-application technique. A reduction in young stock reduces the roughage requirements but contributes little to the reduction of the nutrient surplus. Reduction of N imports trades off with the restoration of the soil-N stock, which is depleted by mineralization and unavoidable losses. Optimization of the utilization of nutrient resources is an effective first step to realize a sustainable farming system.

Keywords: dairy farming, nutrient use efficiency, nitrogen, sustainability.

Introduction

Recent studies have shown that current dairy farming systems in the Netherlands, with high external inputs, import large quantities of nitrogen (N) and phosphorus (P) relative to export in dairy products (Boons-Prins *et al.*, 1996; Van Bruchem *et al.*, 1999; Aarts *et al.*, 1999; 2000a; 2000b). These low outputs in products relative to the high inputs are associated with low nutrient utilization efficiencies and high emissions to the environment. Groen & Van Bruchem (1996) and Aarts *et al.* (1999) have shown that inputs of N and P in fertilizer and concentrates can be reduced considerably without reducing milk production per hectare.

Our study focuses on the peat and heavy clay soils, which in the western part of the Netherlands are the major soil types that are predominantly used as grassland for dairy farming. This traditional land use has resulted in an open landscape with important cultural-historical features, and Dutch society aims at preserving this land use. However, current land and crop management practices lead to emission of large quantities of N and P, which results in eutrophication of surface- and groundwater and in air pollution, with a negative environmental impact. So current dairy farming systems should be modified to attain national and regional environmental goals.

During the last two centuries, surface water level has been lowered artificially by drainage to facilitate and stimulate agricultural production. The enhanced drainage of a peat soil increases its carrying capacity for heavy machinery and livestock, and accelerates warming up of the soil in spring. However, the lower water tables result in increased soil compaction and accelerated oxidation of the peat layer, with the associated subsidence of the soil surface (Schothorst, 1977). Current policy regulations only allow a decrease in water level equal to the observed subsidence, maintaining the difference between the water level and the soil surface.

A number of valuable wetland ecosystems associated with the high groundwater levels are vulnerable to excessive nutrient inputs and drainage measures. The most important source (about 50%) of N and P for surface waters and wetlands is the nutrient loss from fertilized grasslands (Hendriks *et al.*, 1994). The magnitude of these losses depends on nutrient management and groundwater level. To identify the scope for reduction of these losses, and its consequences for the dairy farming system, options for more efficient nutrient management should be formulated and examined.

During the last five years, the average annual milk production on peat and clay soils was about 11,000 kg ha^{-1}, which is associated with nutrient surpluses averaging 323 kg N and 46 kg P_2O_5 ha^{-1} per year, excluding natural inputs (Beldman & Prins, 1999). In the near future this production system will be faced with stricter environmental constraints as – according to current Dutch legislation – the surpluses should be reduced to 180 kg N and 20 kg P_2O_5 ha^{-1} by the year 2003 (Henkens & Van Keulen, 2001). In this paper we will present various options for a prototype system that – in theory – in the long run is environmentally sustainable. The prototype system should meet the target values for nutrient surpluses, and consider the health (Waltner-Toews, 1997) of the soil-plant-animal system. The Dutch government aims at a target level of ammonia volatilization from agricultural sources that is 70% below the level of 1980. Emission of N_2O should be reduced according to the regulations for greenhouse gases. Nitrate concentration in the groundwater below 2 m depth should not exceed the EU drinking water standard of 50 mg l^{-1} (Anon., 1991). Surface water quality should be guaranteed by restricted nutrient inputs from lateral flow and run-off. Total P application in inorganic fertilizer and manure should not exceed output in products, to avoid P accumulation in the soil. Realization of these goals will require more efficient nutrient utilization, for instance by reducing input levels. In addition, the well being of men and animals should be improved as much as possible, and a reasonable farmers' income should be guaranteed.

This paper aims at contributing to the discussion on sustainable dairy farming in north-west Europe by focusing on environmental aspects of dairy farming on peat and heavy clay soils.

Nutrient flows in current dairy farming

This study focuses on the so-called 'Green Heart' region of the Netherlands, where the major part of the peat and clay soils are located. This region covers a large part of the province of Zuid Holland and the western part of the province of Utrecht. The total area is 150,000 ha, comprising 100,000 ha of agricultural land of which 90% is used as permanent grassland for dairy farming. In some parts arable farming is practised, i.e., mainly close to the rivers where the peat is covered by a layer of clay.

The majority of dairy farms in the Green Heart region are situated on pure peat soil. The water level in the ditches is maintained at 40 cm below ground level. Average N flows per farm (Figure 1) were derived from information obtained in 1996/97 from 5048 dairy farms on peat soil (Beldman & Prins, 1999). On the average specialized dairy farm, the annual milk production is 10,670 kg FPCM (fat and protein corrected milk) ha^{-1}, at an annual milk production level per cow of 7020 kg. Home-grown forage supplies 60% of the energy requirements of the stock, which is further supplemented by concentrates (about 30%) and roughage (10%) (Beldman & Prins, 1999). Average fertilizer level (248 kg N ha^{-1}) is in excess of the requirements, taking into account the high N supply from natural sources (mineralization, deposition and fixation) and the cattle slurry applications. Average stocking density is 1.6 adult cows ha^{-1} and 8 young animals per 10 cows. N surplus at farm level is predominantly lost to the environment (Figure 1) by ammonia volatilization (16%), leaching and denitrification (combined 75%). Estimates of ammonia volatilization from excreta and N losses from the soil are based on Steenvoorden *et al.* (1999) and Oenema & Roest (1998), respectively. Slurry is applied by a 'sleepvoet' machine (a set of pipes hauled over the soil surface). N accumulation in the soil is the rest-term of the N balance.

Maize comprises about 5% of the forage produced. Maize production on peat soils indirectly results in soil degradation caused by ploughing and drainage, which enhance organic matter mineralization and negatively affect soil structure. Moreover, maize production is associated with risks of high N losses to the environment and is in conflict with the aim to preserve the historical landscape.

Due to erratic precipitation and concomitant soil wetting, mineralization in organic soils strongly fluctuates. So N availability may occasionally exceed crop demand, irrespective of fertilizer regime. This leads to high crude protein (CP) concentrations in consumed fresh grass in the course of summer, which leads to high urea concentrations in milk, and to considerable losses of mineralized N to ground- and surface water.

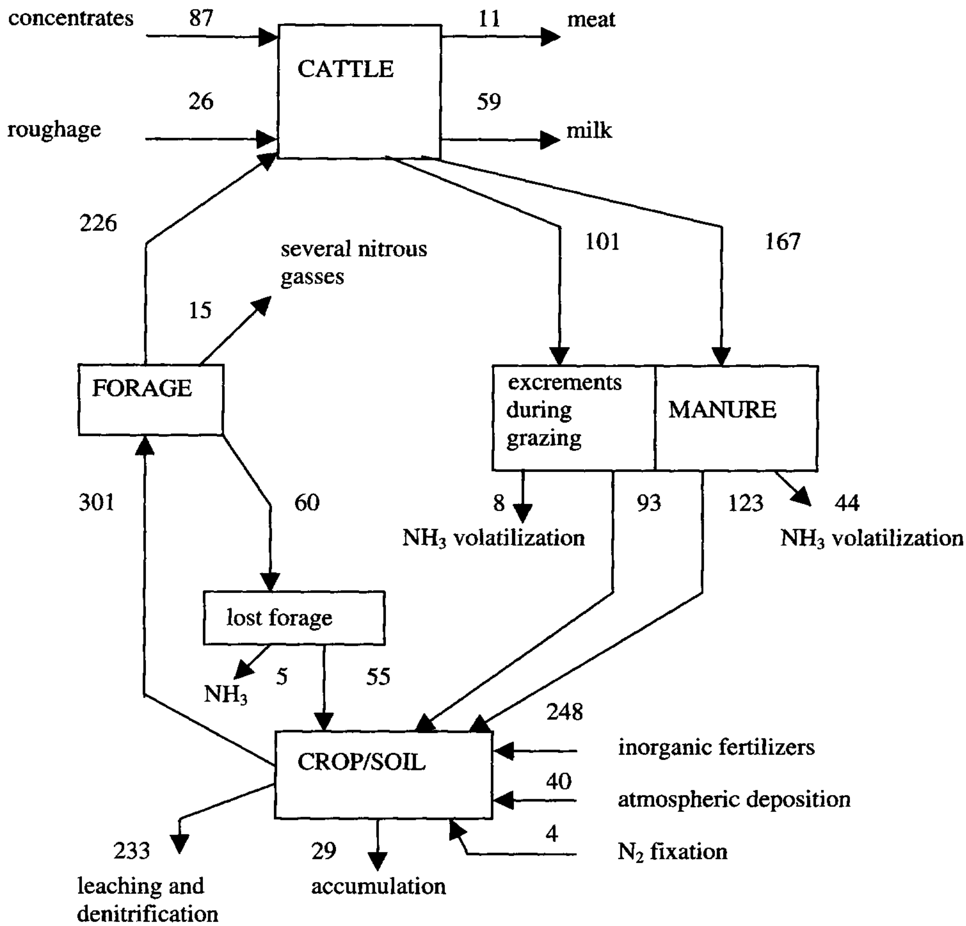

Figure 1. Main N flows (kg ha^{-1} per year) in an average dairy farming system on peat soil in 1996/1997.

At farm level, the ratio between N in product output and external N inputs is 0.19, which means a very low N utilization efficiency. The annual surplus of imported N (361 kg) over N in product output (70 kg) is 291 kg ha^{-1} (365 kg including natural sources). The ratio output/input for P is 0.36, suggesting that large quantities of imported P accumulate in the soil, as its limited mobility restricts emission to surface- and groundwater.

In the soil-plant system, the internal flows of N are quite large. Gross mineralization is about 400 kg N ha^{-1} (Schothorst, 1977) whereas in these peat soils only 60% of inorganic N from mineralization and fertilizer is taken up by the grass (Vellinga *et al.*, 1993). Part of the N lost in lateral flow and run-off is captured in ditch debris that mainly consists of soil eroded from the ditch border. The debris is returned to the soil by regular ditch cleaning, resulting in an input of around 100 kg organic N in the surrounding land (Hendriks *et al.*, 1994). All in- and output fluxes result in a positive N balance, i.e., the soil-plant subsystem accumulates about 84 kg N ha^{-1} per year.

Perspectives for more efficient nutrient management

A strategy aiming at minimization of nutrient losses to the environment should take into account the components of the system and their interactions. Below, possible strategies for the main components of the farming system are proposed.

Water and soil management

In the Green Heart region of the Netherlands, water bodies like lakes, canals and small ditches occupy 10% of the area. To realize an acceptable quality of the surface water, emissions from agriculture should be minimized. In practice, a border zone of 0.5 m between agricultural land and water is not fertilized or cultivated. Extending this border zone considerably reduces nutrient losses to surface water. A border zone of 2 m between land and water should therefore be excluded from fertilization.

The ditches in the region are generally cleaned every two years, and the nutrient-rich debris is distributed over the adjacent land. This cleaning, which is required to restore the drainage capabilities of the ditches, results in a strong reduction in the P content of the surface water. For N, the net cleaning effect is insignificant. The removal of N-rich organic material is counteracted by reduced denitrification capacity of the ditch's sapropelium layer (Hendriks *et al.*, 1994). Proper ditch cleaning may result in restoration of the water-soldier (*Stratiotes aloides)* vegetation.

To stop further oxidation and compaction of the peat parent material, environmental policy stipulates that maximum ditch water levels should not exceed –20 cm in nature areas or –60 cm in agricultural areas. These water levels are maintained by importing river water, with the associated import of N (about 48 kg ha^{-1} per year) and P (3.5 kg ha^{-1} per year), which contributes to eutrophication of the ditch water. However, the most important source (about 50%) of N and P in the ditch water is nutrient loss from fertilized grasslands (Hendriks *et al.*, 1994). Apart from the applied fertilizing techniques, soil hydrology also influences nutrient losses. Efficient nutrient management has to take into account the hydrology-specific characteristics.

Animal manure

To control ammonia losses, the time animal excrements are in contact with the air should be as short as possible. Indoors, excrements have to be transported to a closed, anaerobic storage tank as quickly as possible. Frequent stable floor cleaning and a closed storage, even during slurry mixing, is recommended. According to Dutch legislation, slurry has to be applied to the soil by injection, but on peat soils the 'sleepvoet' technique is allowed to avoid damage to the topsoil by the injectors. The 'sproeiboom' ('spraying rod' with perforations) is an alternative technique that optimally preserves the peat soil and efficiently distributes the slurry with the aid of rather large amounts of water. This considerably decreases ammonia losses too. However, the required large amounts of water may be prohibitive.

A reduction of the quantities and concentrations of urea excretion will restrict ammonia losses at the source. New feeding strategies that are based on low-protein diets have already shown to be effective in reducing urea excretion (Smits *et al.*, 1995) and mineral N in slurry (Van Bruchem *et al.*, 1999).

Considerable N losses, mainly from urine, occur during grazing. Part of the urea in urine volatilizes as ammonia (about 13%, see e.g. Bussink (1996)), the remainder is predominantly nitrified and largely lost by denitrification and leaching. Restricting grazing to daytime only and a short grazing period in summer reduce these losses (Hilhorst *et al.*, 2001). Longer periods indoors in summer also enable the farmer to offer a balanced ration instead of a diet of mainly protein-rich grass during day-and-night grazing.

Cattle

Utilization of dietary N by the high-productive cattle should be maximized, avoiding any excessive N intake. Especially a surplus of rumen-degradable protein relative to fermentable carbohydrates (characterized as a positive value of 'OEB[1]', indicating an excess of unstable proteins in feed) should be avoided. This surplus is excreted in urine, and at grazing is largely lost to the environment. Variation in intake of OEB determines most of the variation in urea concentration in urine (Valk *et al.*, 1990; Van Vuuren *et al.*, 1996). Based on data from 60 dairy farms (De Visser & Verhoeven, 2000) the ratio of inorganic and organic N in cattle slurry has been computed from OEB intake rates. This relationship will be used in the further design. With respect to animal health, excessive protein intake may result in reduced fertility, sickness and high urea concentrations in milk.

In addition to improving nutrient utilization efficiency at animal level, the aim is to also increase efficiency at herd level by minimizing the number of young stock, the latter being far less efficient than adult cows. If cows are kept for 4 lactation cycles on average, only 25% young stock is required for replacement.

Soil and roughage

If feed rations of about 6.0 MJ per kg DM NEL (Net Energy for Lactation; in Dutch nomenclature equivalent to 875 VEM, i.e., feed units for milk; see Table 2) are sufficient for cows to sustain high levels of milk production (Van Bruchem *et al.*, 1999), roughage may be included in the ration from pastures that receive only small amounts of fertilizer. In peat soils the natural supply of N mineralized from organic matter is high, and supplementary fertilizer is required only at the onset of the growing season when mineralization rate is low due to low soil temperatures and anaerobic conditions.

Grazing strategy should focus on the reduction of grazing losses. Short grazing

[1] Dutch acronym for 'degradable protein balance'.

periods combined with rotational grazing increase grazing efficiency compared with the frequently used 4-day grazing interval. Restricted grazing (about 10 hours per day) instead of continuous grazing results in reduced N emissions from excreta, and limits sward growth retardation in urine and dung patches.

Methodology

Research approach

When designing farming systems, whole-farm analysis is required to take into account the interactions between the various system components. It nearly is impossible to test the multitude of systems that would arise from single measures and their combinations. Therefore, information from innovative experiments in the subsystems soil, animals, housing and storage, yield a number of technical options that are integrated at farm level to yield a number of sustainable farm designs. The options in the subsystems are associated with minor or strong effects on the environmental goals, and are categorized as *improved* and *further improved.* The best system design should lead to maximum realization of system objectives.

System objectives

Ammonia losses from the dairy farming system that is environmentally sustainable should be reduced to 70% of the level in 1980, which means a target level of 30 kg N ha^{-1}. Emission of N_2O from manure and fertilizer N should be reduced by about 50% (3% per year during 20 years as agreed in the Rio de Janeiro conference on Global Warming) to 34 kg N ha^{-1}, including the 'unavoidable' losses from the peat soil (i.e., 26 kg N). To keep nitrate concentrations in the upper groundwater below 50 mg l^{-1} – the EU Drinking Water Quality Directive – leaching of nitrate should not exceed 34 kg N ha^{-1}. Concentrations of N and P in lateral water flow to ditches should not exceed the target levels for surface water quality (2.2 mg N l^{-1} and 0.15 mg P l^{-1}, respectively).

N and P surplus per hectare should not exceed the legally permitted 180 kg N and 20 kg P_2O_5. Since the natural N supply from peat soils is far above that of the average Dutch soil, the environmentally acceptable surplus of N may well be much lower, depending on the environmental constraints mentioned earlier.

System design

Principles

System design is based on four principles: (i) reducing N and P inputs through reductions in fertilization level, (ii) optimizing nutrient use from cattle excreta, (iii) reducing feed import by feeding mainly home-grown roughage, and (iv) feed rations that are balanced with respect to energy and protein supply.

To conserve the unique peat soils, high ditch- and groundwater levels are maintained and soils are not ploughed. At animal level, three strategies are selected to increase nutrient use efficiency: (i) low protein diets are offered that do not exceed the protein requirements, resulting in an OEB intake of approximately zero, (ii) cows are kept on average for 4 instead of the usual 3 lactation cycles, reducing the number of young stock required for replacement, and (iii) restricted grazing to control daily feed quality, and reduce urine excretion and associated nutrient losses at pasture.

At pasture level, low-protein concentrations in the roughage and reduced fertilizer losses are aimed at. N fertilizer levels are restricted to avoid luxury consumption by the vegetation. Cutting grass in a late growth stage increases biomass production per kg applied N, while the roughage is low in protein and rich in structural compounds. The relation between N supply and net harvested biomass measured at farm level is based on a compilation of literature data, recent experimental results (K.M. Van Houwelingen, pers. comm.) and data from innovative dairy farms in the region (Smit, 1999).

To reduce ammonia volatilization, innovations like frequent stable floor cleaning and *improved* slurry application techniques based on recent findings at experimental farm 'De Marke' (Van Miltenburg *et al.*, 1999), are introduced in manure management.

Nutrient inputs and outputs are quantified for three components of the dairy farm, i.e., production of milk, manure and roughage. A number of options (mainly for engineering techniques; see Table 1) and combinations of options result in specific inputs and outputs at farm level. To realize the system objectives, the options will be changed to arrive at an acceptable prototype system.

Table 1. Available options in the design process.

Attribute	Engineering criterion	Options
Environment		
	1 Soil type	Peat, clay on peat
	2 Water table	–40 cm, –60 cm
Plant type		
	3 Crop type	Indigenous, sown perennial ryegrass
Techniques		
	4 Stable floor cleaning	Standard, dung scraper
	5 Slurry application	Sod injection, 'sleepvoet' on short/tall grass
	6 Grass protein content	Range: 125 – 250 g per kg DM
	7 Roughage supplement	Maize, beet pulp
	8 Concentrates per kg milk	0.10, 0.25, 0.30 kg
	9 Type of concentrate	Standard, low CP, beet pulp
	10 Replacement rate (%)	25, 33
	11 Grazing in summer	Day and night, restricted
	12 Milk production per cow	4500 to 9000 kg per cow per year
	13 Herbicide use	Yes, no
	14 Unfertilized border zone	0.5 m, 2 m
	15 Manure treatment	None, dung composting, dilution

Energy requirements of the cattle

Energy requirements of the animals are calculated using the relations from Hijink & Meijer (1987). A 'standard' cow of 600 kg live weight daily requires 34.6 + 3.2 * (kg of daily milk production) MJ Net Energy for maintenance and milk production. A correction factor of 1.1 is used to adjust for the higher metabolism of current cows compared with those on which the regression is based (cf. Van Deurzen *et al.*, 1996). Requirements increase during grazing (10%), during pregnancy (from 3.1 to 15.2 MJ per day at the end) and during the juvenile stage, and are quantified according to Dutch criteria (Anon., 1998).

Energy requirements have been calculated for single lactating cows for a range of annual milk production levels and two grazing strategies, i.e., conventional grazing and restricted grazing. The *conventional grazing* management is more or less similar to the strategy at experimental station ROC Zegveld. In winter, i.e., from October to March (49% of the year), cattle are indoors. In spring (about 13 days) and autumn (about 52 days) the animals are outdoors for 15 hours per day, while in summer (121 days, i.e., 33% of the year) they are indoors for 4 hours per day. The *restricted grazing* strategy is defined as: milking cows are indoors from October until April (winter) and for 10 hours per day during summer to limit N losses during grazing. Total energy requirements slightly differ (Table 2) due to energy required for grazing.

At herd level, daily energy requirements for maintenance, growth and grazing of young stock are on average 34 MJ per animal for the first year and 41 MJ for the second. In the design the replacement rate has been set to 25%, i.e., 1 calf + 1 yearling per 4 adult cows.

Required feed quality

To realize a sufficient feed and thus energy intake by the high-productive cows, a minimum energy and protein content is required (Ketelaars & Tolkamp, 1991) that strongly depends on production level. Minimum contents of 5.5 MJ NEL per kg DM (800 VEM) and 120 g CP per kg DM are selected (to protect the animals' health). Based on maximum permitted urea concentrations in the milk, CP content and OEB

Table 2. Daily and annual energy requirements (MJ NEL[1]) per lactating cow, including average requirements for grazing and pregnancy.

	Conventional grazing			Restricted grazing		
kg milk y^{-1}	Winter d^{-1}	Summer d^{-1}	Total $10^3 y^{-1}$	Winter d^{-1}	Summer d^{-1}	Total $10^3 y^{-1}$
4500	97	106	30	97	99	29
6000	114	123	35	114	116	34
7500	131	140	40	131	131	39
9000	150	158	45	150	152	44

[1] Net Energy for Lactation; in Dutch nomenclature equivalent to 875 Voeder Eenheden Melk (VEM, i.e., feed units for milk). For further explanation see Tamminga *et al.*, 1994.

intake should not exceed 250 g per kg DM and 250 g per cow per day, respectively. Indirectly, i.e., based on the N balance of the whole farming system, limitations to protein intake of the cattle may be imposed by environmental constraints related to N loss treated in the design process of the prototype.

In the design process, the chemical composition of the grass and silage on offer varies in energy, CP and OEB contents. In the first cut, a heavy, long growing sward realizes the lowest CP contents (120 g per kg DM). Table 3 shows the nutritional characteristics of grass in current practice and in two situations with lower N supplies (*improved* situations), based on data from farmers (Smit, 1999) and fertilizer experiments.

Required feed compounds

Energy is predominantly supplied by home-grown fodder. In the first instance, three feeding strategies are considered: 0.10, 0.25 and 0.30 kg concentrates per kg produced milk. In all three strategies, 20% of the energy requirement in winter is supplied by low-protein, fibre-rich hay. The remainder is supplied by a 50/50 mixture of low- and high-protein grass silage from early and late summer cuts, respectively. In the *further improved* situation this results in a silage mix of first cut low-protein silage of 125 g CP and CP-rich silage of 200 g per kg DM. In addition to similar quantities of concentrate offered in winter, 2–3 kg hay (about 10% of the energy requirements) and low-protein silage are given in summer in the stable at restricted grazing, and 2 kg maize or beet pulp at full grazing. In Table 4 three options are illustrated: (i) full grazing, *improved* roughage quality and a high concentrate supply,

Table 3. Feed composition in the design.

Feed component	Net Energy Lactation[1]		CP g kg^{-1}	N % DM	OEB g kg^{-1}
	MJ kg^{-1}	VEM kg^{-1}			
	Current				
Silage	6.2	900	180–200	3	50–80
Fresh grass	6.9	1000	235	3.8	100
	Improved				
Silage (1st–later cuts)	5.9–6	850–870	150–200	2.5–3	25–75
Fresh grass	6.7	975	210	3.4	50
	Further improved				
Silage (1st-later cuts)	5.5–6	800–880	125–200	2–3	0–50
Fresh grass	6.6	950	180	3	25
Hay at low N supply	5.4	789	145	2.5	–11

[1] See Table 2.

Table 4. Calculated daily dry matter intake (kg per cow) during lactation at a number of annual milk production levels (kg milk per cow) for three systems.

Milk production level	All year	Winter		Summer		
	Concentrates	Silage	Total	Silage	Fresh grass	Total
	Full grazing; 0.30 kg concentrates kg^{-1} milk (+ 2 kg pulp per cow)					
4500	4.5	11.3	15.8	2[p]	11.4	17.9
6000	6.0	12.5	18.5	2[p]	12.5	20.5
7500	7.5	13.8	21.3	2[p]	11.7	21.2
9000	9.0	15.0	24.0	2[p]	12.9	23.9
	Restricted grazing; 0.25 kg concentrates kg^{-1} milk					
4500	3.7	11.1	16.5	9.1	7	16.1
6000	4.9	11.5	19.4	10.8	8	18.8
7500	6.1	12.2	22.2	12.5	9	22.5
9000	7.5	12.9	25.5	14.5	10	24.5
	Restricted grazing; 0.10 kg concentrates kg^{-1} milk					
4500	1.5	15.2	16.7	8.9	7	16.4
6000	2.0	17.7	19.7	10.3	8	19.3
7500	2.5	20.1	22.6	11.6	9	22.1
9000	3.0	22.9	25.9	12.3	10	25.3

[p] Contribution of pulp (kg) in the ration.

(ii) restricted grazing, *further improved* roughage and medium concentrate supply, and (iii) restricted grazing, *further improved* roughage and low concentrate supply. At restricted grazing, feeding of low-protein silage is possible, both in winter and in summer (during the daily indoor period). The intake of fresh grass is derived from a relationship between grass intake, milk yield and length of the grazing period (Anon., 1998). *Ad libitum* intake depends on the energy contents of the silage and the fresh grass (Ketelaars & Tolkamp, 1991).

Protein requirements are covered, as advised (Anon., 1998), for 110% on average in winter to 125% in summer. The options 0.25 and 0.10 kg concentrates per kg milk at full grazing are not feasible without low-protein supplements, because of an unacceptably high OEB intake. Daily OEB intake can be reduced to 400 g per cow by daily (indoor) supplementation with 2 kg beet pulp (OEB of –55 g per kg DM). At restricted grazing, daily OEB intake will not exceed 200 g per cow.

At herd level, the type of herd management determines the feed requirements. In this case the options for replacement rate are relevant. Table 5, showing the effects of replacement rate, concentrate supply and milk yield, illustrates that some combinations require more home-grown roughage than available. Production of 14,000 kg milk ha^{-1}, using cows of 4500 kg milk (<0.30 kg concentrates kg^{-1} milk) (Table 5) or cows of 9000 kg milk at 0.10 kg concentrates kg^{-1} milk (data not shown), requires additional roughage from external sources. With current grassland management

Table 5. Feed requirements (10^3 kg DM ha^{-1} per year) at an annual milk yield of 14,000 kg ha^{-1} for different strategies of milk yield per cow, replacement rate (RR, in % of adult cows), concentrate supply (CO; kg concentrates kg^{-1} milk) and grazing (F, full grazing; R, restricted grazing). N_{in} total N intake (kg ha^{-1} per year).

System		Herbage/silage		Grazed	Hay	Total	Concen-trates	Fodder	Total	N_{in}
RR	CO	CP low	CP high							
	4500 kg cow^{-1} y^{-1}									
25	0.25 F	3.6	2.8	6.8	0.5	13.8	3.6	2.7	20.0	519
25	0.25 R	6.8	4.5	2.1	4.1	17.4	3.6	0.0	21.0	387
	9000 kg cow^{-1} y^{-1}									
33	0.30 F	2.0	1.6	4.3	0.3	8.1	4.3	1.9	14.3	248
25	0.30 F	1.9	1.5	4.0	0.3	7.7	4.3	1.8	13.8	236
25	0.25 F	2.0	1.7	4.4	0.3	8.3	3.6	2.0	13.9	255
25	0.25 R	4.1	2.8	1.4	2.8	11.1	3.6	0.0	14.7	307

maximum net yields of 12,000 kg milk have been reported (Figure 2). At this production level, a reduction in CP and OEB contents in feed supplements is necessary, to avoid excess OEB intake by the lactating cows.

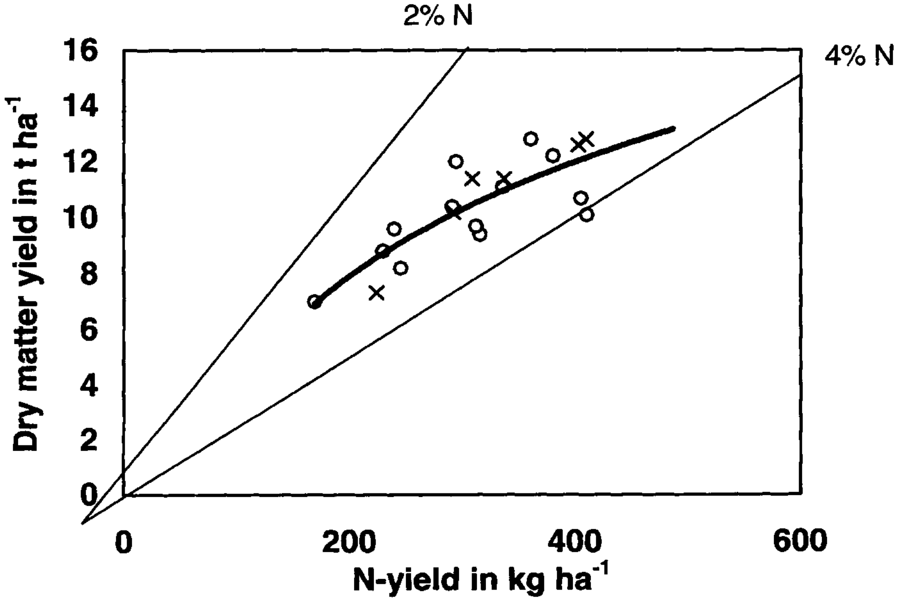

Figure 2. Relationship between net N yield (kg ha^{-1} per year) and net DM yield, derived from current farms (circles) and the experimental farm (crosses) in the region of Zegveld. The fitted line is used in yield calculations under current conditions.

In the design process, the herbage qualities of Table 3 will be used, adapting harvest and fertilizer regime to attain these qualities.

Home-grown forage: grass production and quality

At the physical conditions of peat soils in the Green Heart region, DM yield of grass is determined by availability of N and by cutting or grazing strategy. Data from grassland with a rather similar defoliation strategy were used, i.e., data for full grazing in summer by 2 dairy cows per hectare and a cutting percentage of 200 (a farm average of two silage harvests per unit area per year). The relations between N yield and net DM production and between N fertilizer level and net N yield (Figure 2) were quantified on the basis of experiments at ROC Zegveld (K.M. Van Houwelingen, pers. comm.) and production data from 6 commercial dairy farms (Smit, 1999). The relation between N yield and DM yield is similar to other observations at similar cutting strategies (Bussink, 1996; Prins *et al.*, 1981; Van Steenbergen, 1977). Production and N yield were determined at farm level and refer to net annual amounts of roughage from full grazing and harvested silage. The relations are valid for grassland on peat soils with a ditch water level of –40 to –60 cm. Maximum annual net herbage yields are about 12,000 kg per ha (Figure 2).

Since the relation in Figure 2 is based on about 50% mowing and 50% day-and-night grazing, the *improved* system, with an identical defoliation regime, is located on the curve at the target N content of the biomass. Annual average N content is

Table 6. Net grass silage production in relation to N contents at moderate (improved system) and low (further improved system) N fertilization rates. In the right-hand column calculated net N requirements from fertilizer are given.

Cutting Period	Net DM yield	N content at harvest	Net N yield	N from natural sources[1]	Gross N from inorganic fertilizer and manure
	10^3 kg ha^{-1}	% of DM	---------- kg N ha^{-1}	----------	----------
	Improved				
May	3.5	2.5	88	44	90
June	2.5	3.0	75	38	77
> 1 July	2.0 per cut	3.5	70	46	52
Annual total	12 (5 cuts)		373	220	323
	Further improved				
1 June	5.0	2.0	100	63	98
July	3.5	2.5	88	79	35
Sept	3.0	3.0	90	78	30
Annual total	11.5 (3 cuts)		278	220	163

[1] Source: Noij, 1992.

about 3% (see Table 3). This is associated with a net harvested biomass of 10,700 kg ha^{-1}. It is assumed that at Best Technical Means (BTM), i.e., 'good agricultural practice' (Anon., 1998), and realizing lower harvest losses, 12,000 kg can be attained. Allocation of the biomass over the successive cuts is shown in Table 6.

For the *further improved* system, the biomass at an annual N content of 2.5% cannot be found on the empirical curve in Figure 2, because in current practice cutting intervals were too short. For the *further improved* system the first cut is harvested at a late growth stage to produce silage with a low protein content and a high content of structural components. On the basis of experiments with long cutting intervals (Lantinga & Groot, 1996; Prins *et al.*, 1981) 5000–6000 kg silage ha^{-1} with a N content of 2% can be harvested on 1 June. Its energy content will be about 5.5 MJ (800 VEM) per kg DM, and OEB will be zero or negative. A yield of about 5000 kg per ha at 2% N represents a data point above and left of the line in Figure 2. However, final annual DM and N yields will be higher, depending on the strategy followed. After 1 June another 6000 kg DM ha^{-1} can be harvested in two cuts, with about 2% N, from mown-only pastures, realizing an annual N yield of 240 kg. Less dry matter is produced per kg N when the grass is grazed instead of mown, because with grazing less biomass is removed whereas more N is lost. Grazed pastures may produce 4000–5000 kg DM ha^{-1} with about 3% N in two to three cuts of 1800–2000 kg ha^{-1} or a similar amount by rotational grazing. These mown and grazed pastures take up 288 kg N at most. So required fertilizer levels can be calculated if fertilizer efficiency and supply from natural N sources are known.

Natural N sources

Annual N supply from natural sources on peat soils at a groundwater level of –40 cm (± 10 cm) amounts to about 240 kg ha^{-1}, 220 kg of which during the growing season. This N originates from soil organic matter decomposition, atmospheric deposition, microbial N fixation and surface water inputs. N from atmospheric deposition currently is about 40 kg ha^{-1}, but will probably decrease to about 30 kg in the coming years, because of environmental policy measures. Uptake of natural N is about 40 and 50 kg ha^{-1} per month in the periods May-June and July-September, respectively (Noij, 1992).

Fertilizer requirements

Gross fertilizer-N requirements can be estimated on the basis of DM and net N yields per cut, taking into account supply from natural sources, N in harvest losses (about 10% of gross yield at BTM) and losses of not recovered fertilizer. Fertilizer trials on poorly drained peat soils (Vellinga *et al.*, 1993) showed a N recovery of 60%, resulting in a fertilizer requirement in the *improved* system of 323 kg ha^{-1}, resembling the advised strategy 'maximum' (Anon., 1998) for this type of soils. For the *further improved* system the gross requirement amounts to 163 kg N, enabling 3 cuts of roughage.

Nutrients from manure: pathways

Annual outputs of N and P in manure and urine are calculated from intake minus product output (weight gain and milk). The excreted N and P at herd level and their utilization vary as a result of the diet, stable hygiene, grazing time and number of young stock. Slurry management in the stable is limited to two alternatives: 'current' stable with slatted floor, or 'improved' stable with sloping floor and dung scraper. Inorganic N (N_i) in the excreta is estimated from daily OEB intake (De Visser & Verhoeven, 2000). Ammonia volatilization rates are calculated from N_i. For current and improved stables, ammonia volatilization is 5 and 14% of N_i (Biewinga, 1999), respectively. For slurry application by 'sleepvoet' on short and tall grass, these percentages are 10 and 30, respectively (Mulder & Huijsmans, 1994), and for grazing on pastures receiving 50–200 kg fertilizer N it is 8–13% of N_i (Bussink, 1996).

At 'full grazing', 62.3% of the annual amount of manure is produced outdoors, and 37.7% at grazing (for details, see Hendriks *et al.*, 1994, p. 142). The same values are used for young stock. At 'restricted grazing', total excretion indoors is 83%.

Combinations of feeding, replacement rate and grazing strategy lead to variable environmental losses (Table 7). A change in concentrate type from (low-protein) standard to beet pulp (composition changing from 18 to 14 g N and from 4.5 to 0.8 g P per kg DM) strongly reduces P excretion. N excretion is reduced to some extent. A reduction in concentrate supply per kg milk increases P and N excretion and N losses, due to the higher fraction roughage in the ration. The transition from full to restricted grazing reduces N excretion and total ammonia volatilization. However, ammonia losses from the stable (longer indoor periods) and slurry applications slightly increase. The *further improved* grass quality decreases N excretion effectively, but ammonia volatilization only slightly. The volatilization is strongly reduced if the lowest emission rates are valid at BTM.

Table 7. Calculated N and P excretion and fate of excreted N (kg ha^{-1} per year) at two concentrate supplies, two types of concentrate feed (c, standard, low protein concentrates; p, dry beet pulp), full (F) or restricted (R) grazing and improved (I) or further improved (FI) ration. Calculations refer to cows producing 9000 kg milk, replacement rate of 25% and milk production of 14,000 kg ha^{-1} per year. BTM (Best Technical Means) of slurry management using loss fractions reported for 'De Marke' (Biewinga, 1999).

System	Excretion		NH_3 emission					N to soil
	P	N	Stable	Breath	Application	Grazing	Total	
0.25c F I	34	264	12	3	25	7	47	217
0.25p F I	21	254	11	3	23	6	43	211
0.20p F I	23	264	12	3	24	7	46	218
0.20p R I	20	241	14	3	29	3	49	192
0.20p R FI	20	219	12	3	24	2	41	178
0.20p R FI BTM	20	219	4	3	8	2	17	202

Design of a sustainable system

Starting point in the design is the target of the production system. The aim is to realize an annual milk yield of 14,000 kg milk (FPCM) ha^{-1}. From this level, feed requirements of the herd are calculated on the basis of the coefficients quantified earlier. Only the most probable combinations (from a total of 55,296, see Table 1) are selected for this study. Inputs and outputs have to match the system objectives. If not, other options for the production technique are selected.

The results shown above limit the number of options. Concentrate supply has to exceed 0.10 kg per kg milk to cover energy requirements. Given a physiological maximum to voluntary intake of 25 kg DM per cow per day, a supply of 0.20 is sufficient. A low, yet realistic replacement rate is advisable to reduce nutrient losses per kg milk produced. A rate of 25% is selected. A relatively high annual milk yield per cow is recommendable, while safeguarding animal health, i.e., at least 7500 (current level), but preferably 9000 kg. Lowering protein and OEB levels in the feed reduces urea excretion (Van Vuuren *et al.*, 1996) and claimed negative effects of N excess on animal fertility (Van Bruchem *et al.*, 1999). This is realized by decreasing fertilization level and extending the cutting interval. The difference in ammonia volatilization between full and restricted grazing depends on the loss fractions in stable and field. This should be examined in models.

Feed requirements strongly vary for herds differing in milk yield per cow (Table 4). Total maintenance requirements per hectare are directly proportional to the number of cows at the fixed milk quotum. A change in grazing strategy results in only small differences in feed requirements. The extra energy required for longer grazing is covered by the higher energy content of the ration that includes a higher fraction of fresh grass. Yet, more N is recycled by the herd and therefore lost to the environment at full grazing. So a stepwise improvement of the system is selected, including the following steps: (i) reducing nutrient surplus by reducing fertilizer use, (ii) improving animal health and reducing ammonia losses by reducing CP content and increasing fibrous material in the ration, (iii) using increased nutrient utilization efficiency (from measures 1 and 2) to increase production per hectare, (iv) increasing milk production per cow, (v) reducing number of young stock, (vi) restricting grazing, and (vii) further improving grass quality.

Total feed requirements for the *improved* system following the first 5 steps, and *the further improved* system (following all 7 steps) are summarized in Table 8. All required herbage and part of the fodder can be produced on-farm – even at the highest milk yield – in combination with 0.20 kg concentrates per kg milk. The drastic changes in ration composition result in lower N intake and lower N excretion rates.

The stepwise decrease in external inputs results in increased roughage requirements (Table 9, steps 2–6). But increasing milk yield per animal, reducing replacement rate and restricting grazing (steps 8–10), reverses this. Reduced concentrate use (steps 4 and 16) and increasing milk yield (step 7) increase ammonia and leaching losses, yet this is counterbalanced by an increased milk yield per animal, a decreasing replacement rate and a lower grass protein content. Reducing fertilizer use strongly reduces nutrient surplus and loss of inorganic N. Ammonia emission is only

Table 8. Feed requirements (10^3 kg ha^{-1} per year) to obtain an annual milk yield of 14,000 kg ha^{-1} from a dairy system on peat soil for the designed systems 'improved' and 'further improved', compared with the current system at an annual milk yield of 10,670 and extrapolated to 14,000 kg ha^{-1}, and the total N intake by each of these systems.

System	Herbage/Silage		Grazed	Total	Concen-trates	Fodder	Total feed	Total N intake
	CP low	CP high						
Current 10,670	1.7	1.4	3.9	7.0	3.2	2.2	12.4	352
Current 14,000	2.2	1.8	5.2	9.2	4.2	2.9	16.4	463
Improved	2.0	1.7	4.4	8.1	3.6	2.2	13.9	348
Further improved	4.6	3.0	1.4	9.0	2.8	2.8	14.7	335

effectively reduced if slurry management is improved. The other measures reduce inorganic N excretion rates to some extent only, yet do result in lower OEB contents (Table 9) and a lower fraction of inorganic N in slurry (data not shown). The use of pressed beet pulp as concentrate reduces OEB and protein intake below requirements, which should be somewhat corrected with other concentrate types (step 12). The more extensive nutrient management could well restrict fertilizer N losses and thus increase the N recovery (step 15). In theory, import of hay and concentrates can be further replaced by home-grown feed (steps 14 and 16) but this slightly increases environmental N losses. From step 13 onwards, the designed system meets all environmental targets, offering a number of designs of a sustainable prototype of which one is selected below.

The loss of inorganic N is assumed equal to the inorganic N not recovered from fertilizer and manure. So the threefold reduction in fertilizer use, as shown in step 11 and beyond (Table 9), results in a similar reduction in environmental losses. The various output fluxes of N are hard to quantify. Nitrogen may (i) run-off and be transported to surface water, (ii) be denitrified in ditch debris and lost as N_2O, (iii) be immobilized by soil micro-organisms, (iv) be taken up by water vegetation, or (v) be leached as nitrate. Most of the nitrate will denitrify in subsoil or ditch and not affect groundwater quality. As a result, a considerable quantity of the greenhouse gas N_2O is formed, yet much less than in the original situation.

Lay out of a system with optimized resource use

Characteristics of the optimized system as depicted in step 15 of Table 9 are summarized in Table 10. Width of the non-fertilized border zone along the ditch is 2 m to restrict nutrient losses to surface water (Hendriks *et al.*, 1994). The ditch is cleaned at least once every two years, and the nutrient-rich debris is distributed over the adjacent land. Rotational grazing is practised on pastures near the farm house to facilitate diurnal stable visits and to promote formation of a firm grass sod with high tiller density, which contributes to increased grassland nutrient use efficiency (Lantinga *et al.*, 1999). Remote pastures are cut only and receive chemical fertilizer at an annual

Table 9. Stepwise improvement of resource efficiency, illustrated by calculated roughage amounts (10^3 kg ha^{-1} per year) and characteristics of N and P economy for a herd at an annual milk production intensity of 10,670 (current) and 14,000 kg ha^{-1} (target) on peat and heavy clay soil. Steps 9 and 11 reflect feed ration, replacement and grazing strategy of the improved ('I') and the further improved system ('FI'), respectively. N_i, inorganic N; Fertilizer and N level refer to chemical fertilizer; CO, concentrates.

Step No.	Changed option	Old	New	Required roughage		OEB		NH_3	N surplus	P surplus	N_i lost from soil
				Home-grown	Imported	Summer	Winter				
				10^3 kg ha^{-1} per year		g d^{-1} per cow		kg ha^{-1}			
1	Current situation	10,670 kg milk ha^{-1}		6.8	2.1	935	555	69	296	27	181
2	Fertilizer level[1]	248 N; 20 P	184 N; 0 P	6.8	2.1	935	555	68	232	7	155
3	Grass quality	Current	Improved	7.0	2.1	580	340	54	206	7	135
4	CO kg milk^{-1}	0.33	0.25 kg	7.8	2.3	705	430	57	193	3	139
5	CO type	Standard	Beet pulp	7.8	2.3	505	230	54	185	−7	135
6	Fodder	Maize	Beet pulp	7.8	2.2	430	15	53	186	−7	133
7	Kg milk ha^{-1}	10,670	14,000	10.2	2.9	430	15	70	189	−9	152
8	Kg milk cow^{-1}	7000	9000	8.7	2.4	430	−40	59	182	−9	137
9 'I'	Replacement	40%	25%	8.0	2.3	345	−60	54	180	−9	130
10	Grazing	Full	Restricted	7.4	2.8	330	−60	59	188	−9	105
11 'FI'	N level & grass quality	184; Improved	70; Furth. improved	8.1	2.9	−190	−118	54	75	−3	58
12	CO type	Pulp	Mixed	8.1	2.9	−35	−110	62	105	1	64
13	Slurry management	Standard	Improved (BTM)	8.1	2.9	−35	−110	28	105	1	75
14	Hay & N level	Import; 70	Home-grown; 100	10.9	1.8	−35	−110	28	68	−5	87
15	N recovery; N level	60%; 100 N	70%; 80 N	10.9	1.8	−35	−110	28	49	−5	62
16	CO kg milk^{-1}; N level	0.25; 80 N	0.20; 110 N	11.8	1.4	70	−45	30	68	−8	72

[1] Grass quality unchanged in this step (follows later if appropriate).

Table 10. Characteristics of the optimized dairy farming system.

Mineralization	240	kg N ha^{-1} per year
Milk production	14,000	kg FPCM ha^{-1}
%CP in milk	3.47	%
Dairy cows	1.56	cows ha^{-1}
Milk production per cow	9000	kg FCPM per year
Concentrates	25	kg $(100\ kg)^{-1}$ milk
%N in concentrates	1.8	%
Cattle breed	HF	–
Replacement rate	0.25	
Grazing	14 hours per day from 1 May to 1October	
N slurry stable period	83% of annual total	
N slurry grazing period	17%	
N from chemical fertilizer	80	kg N ha^{-1} per year
P_2O_5 from chemical fertilizer	0	kg P_2O_5 ha^{-1} per year
Water level	–40	cm
Other roughage	beet pulp, hay	
Stables	improved floor, dung scraper	

rate of 70 kg ha^{-1}, in addition to slurry. Breakdown and N depletion of soil organic matter (about 5000–10,000 kg DM ha^{-1} per year) by mineralization is largely unavoidable, but is to a large extent replenished by annual inputs of animal manure (about 4000 kg DM ha^{-1}) and harvest losses.

An annual milk production level of 14,000 kg ha^{-1} will generate sufficient income for one family on an average Dutch farm (35 ha). Milk production per cow is 9000 kg, i.e., a stocking rate of 1.56 cows per ha of Holstein-Friesian breed. The replacement rate is 0.25.

Restricted grazing (14 hours per day) is practised from 1 May to 30 September. Slurry application technique is 'sleepvoet' on short grass. To preserve the peat soil as much as possible without limiting field access by cattle and machinery, the ditch water level is 40 cm below ground level, which is about 20 cm above the regional average. Mixing protein-poor and protein-rich silage, and supplementing only small amounts of concentrates, controls the quality of the ration. Additional roughage consists of home-grown hay and low-protein and energy-rich beet pulp that partly replaces the concentrates used in the original situation.

The resulting inputs and outputs of the farming system show a dramatic increase in nutrient utilization efficiency. The N surplus at farm level decreases from 291 (current) to 47 kg ha^{-1} per year, and the P surplus of 17 kg ha^{-1} per year is reversed to a net loss of 10 kg. The level of the nutrient surplus satisfies the Dutch regulations. The significant net loss of P from the system (see also Table 9) goes at the expense of the large and formerly built-up soil nutrient stock, which in the long run may have to be corrected. N losses, however, are fully replenished by 'unavoidable' inputs from atmospheric deposition and welling up groundwater. Ammonia emission satisfies the aim of 30 kg N at maximum. Because of denitrification, the nitrate concentration in the upper groundwater is below the EU limit. Reduction of N_2O meets the target (–50%), because a reduction proportional to a threefold fertilizer reduction is expected. Inorganic N losses (62 kg, see Table 9) to ground- and surface water will largely be transformed to N_2O, of which in turn about two-thirds is transformed to harmless N_2 (Koops *et al.*, 1996).

Discussion and conclusions

In the proposed prototype for a sustainable dairy farming system a relatively high groundwater table (–40 cm) is maintained for long-term conservation of the peat material. In practice, this measure does not appear to result in loss of biomass production and field accessibility (Smit, 1999). The low N fertilizer rate in the *improved* system does not compensate for the unavoidably lower amount of mineralized organic N, and as the organic-matter fluxes from manure increase compared with the current system, they somewhat replenish the loss of soil organic matter.

The consequence of the strong reduction in external nutrient inputs is a reduction in nutrient surpluses and environmental loss in agreement with the targets aimed at. However, unavoidable losses by denitrification and lateral flow remain a point of concern for agriculture on peat and heavy clay soils due to high soil organic matter content in combination with high water levels. Surface water in this region will always be polluted due to breakdown of peat. Estimating the 'background pollution' from lateral water flow that contained about 5 mg N and 0.6 mg P, Hendriks *et al.* (1994) calculated an annual supply to nature reserves of about 23 kg N and 2.5 kg P ha^{-1}. The farmer cannot be blamed for these emissions. So agricultural emissions to surface water – which can never be zero – should be As Low As Reasonably Attainable (ALARA principle).

Restricted grazing will reduce leaching losses from urine N. On the other hand, ammonia volatilization seems to increase at longer indoor periods, due to losses in the stable and during application. Total ammonia losses, however, are reduced because of lower protein intake resulting from better control over the feed quality during longer periods indoors. The increased fraction of ensiled roughage in the ration results in more labour for mowing and ensiling. If these extra costs are to be limited, this work should not be carried out by external labour (Van Miltenburg *et al.*, 1999).

Improvements in resource efficiency strongly focus on higher N utilization efficiency by a combination of cutting heavy swards, more silage and less grazing, and low-protein by-products. Promising results at the experimental farm ROC Zegveld on peat soil and with low fertilization levels (K.M. Van Houwelingen, pers. comm.) and at APMinderhoudhoeve on low-protein rations for high-productive cows (Van Bruchem *et al.*, 1999), formed the basis for the suggested options. Such systems can realize the suggested milk production only if carefully managed. Similar intensity levels in terms of milk production per unit area have been reported for the region (Reijneveld *et al.*, 2000). The suggested annual milk production level of 9000 kg per cow does entail risks in terms of animal health and reproduction. It will be necessary, therefore, to carefully examine the relation between milk production level and replacement rate. Moreover, silage production involves risks like the vulnerability of heavy swards to unfavourable weather conditions, the low digestibility of older grass or the competitiveness of low-quality plant species present on peat soils. Also, the low OEB content aimed for can strongly vary due to occasionally high mineralization rates of peat material. This effect should be counterbalanced by a controlled ration during the indoor periods.

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