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Nitrates Directive requires limited inputs of manure and mineral fertilizer in dairy farming systems

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Abstract

Properly managed manures have a high fertilizer value and are thus a valuable source of nutrients in forage production systems. An efficient utilization of these nutrients, however, is limited by the crop's demand for nitrogen (N) and phosphorus (P). Moreover, environmental goals implied by the EU Nitrates Directive impose constraints on the use of manure and mineral fertilizer. In the present study a simulation model is used to explore limits on the use of cattle slurry and mineral fertilizer in grass and silage maize production in the Netherlands. The study indicates that grasslands can utilize cattle slurry rates ranging from 260 to 300 kg N (90-110 kg P_2O_5) per ha per year without exceeding a target value of 11.3 mg N per litre in nearby surface water (peat and clay soils) or the upper groundwater (sandy soils) or accumulating P in the soil, provided that i) appropriate amounts of mineral fertilizer N are supplemented, and ii) growing conditions are good and the grassland is well-managed. Lowest manure N rates apply to sandy soils and a mixed use of cutting and grazing, highest rates to clay soils under a 'cutting only' regime. Not more than 180-190 kg slurry-N (65-70 kg P_2O_5) per ha per year should be applied to silage maize in general. When grown on dry soils susceptible to leaching, however, slurry rates on maize land need a further reduction to 160 kg N per ha per year (= 60 kg P_2O_5). Growing conditions and crop management are not always perfect and this negatively affects the environmental performance. Under those circumstances manure rates should be reduced by 40 and 10 kg N per ha on grassland and on maize land, respectively, compared to good growing conditions and management. Adjustments of the diet and manure separation can reduce the amounts of P_2O_5 per unit manure N and thus create additional room to fertilize crops with manure instead of mineral fertilizer N. When grass and maize are grown in rotation, cattle slurry and fertilizer applications to maize and grass should be strongly adjusted to account for the changed mineralization and immobilization patterns in the various phases of the rotation. The present study concludes that, from the point of view of N leaching and P accumulation, manure rates should be determined by the share of different crop types, their position in the rotation, the hydrological situation and soil type, the harvest regime, growing conditions, the P_2O_5 to N ratio of both manures and crops, and the management skills of growers.

Keywords: dairy farming, leaching, management, manure, modeling, nitrogen, Nitrates Directive, phosphorus

1. Introduction

The use of manure and fertilizers is inevitably associated with losses of nitrogen (N) and phosphorus (P) to the environment. These losses can compromise the quality of groundwater and surface water. It may hence be necessary to limit the use of manures and fertilizers (Carton & Jarvis, 2001).

Policies on nutrients use often prioritize the regulation of manure rates (e.g. Nitrates Directive (Anonymous, 1991)). One of the reasons for this is that these rates are linked to animal densities which, at the scale of Europe as a whole, show a negative relationship with the quality of air and water due to N and P emissions from manures (Schröder, 2005; Oenema *et al.,* 2007). Controlling animal densities via permissible manure rates could thus reduce the pressure to use land too intensively and alleviate the environmental consequences of high inputs of nutrients. Moreover, manures have features that make them exert pressure on the environment in a more direct way. Manures, slurries in particular, contain ammonium-N which, upon volatilization as ammonia, can have a detrimental effect on the quality of terrestrial and aquatic ecosystems once deposited. Manures also contain organically bound N. This N mainly mineralizes during the growing season and can be taken up by crops then. However, mineralization partly takes place beyond the period during which crops take up nutrient as a result of which N can be lost to groundwater or surface water. Wherever there is excess manure, farmers will be inclined to cover crop N demands with manure as much as possible. P accumulation will then be the inevitable consequence, as manures commonly contain too little N per unit P. Restrained inputs of manure combined with balanced additions of N-fertilizer (or biologically fixed N) are hence needed to fully exploit the P in manures (Schröder, 2005) and avoid the saturation of soils with P. Limiting P inputs to the amounts of P exported in harvests is thus a necessary step to prevent the eventual loss of P to surface water. From this perspective manure and mineral fertilizer N rates should be combined in such a way that N losses stay below levels needed for the targeted N concentration in water, whilst avoiding the accumulation or depletion of P (Schröder *et al.*, 2007a). Manure management on grassland and maize deserves special scrutiny in the Netherlands as they are the only crops grown on most livestock farms, occupying about two third of the agricultural area. Characterics of Dutch agriculture are addressed in greater detail in Schröder *et al.* (2005a) and Aarts *et al.* (2008).

Losses of N and P to water bodies are, inter alia, determined by the gap between inputs and outputs. Outputs, in turn, are determined by the availability of N and P from manures and fertilizers, the ability of a crop to intercept these nutrients, and the extent to which intercepted nutrients are invested in harvested plant fractions instead of residues. The availability of N and P from manures and fertilizers is determined by the manuring history, the composition of the manure and factors affecting the conversion of nutrients, viz. mineralization, immobilization/ fixation, (de)nitrification and volatilization. The ability of a crop to intercept the available nutrients is determined by the application time and application method of manures and fertilizers, by crop characteristics, and by yield reducing factors and yield limiting factors other than N and P.

In the past decades numerous field experiments investigating the relationships between N and P inputs, outputs and surpluses, have been carried out (e.g. Schröder *et al.*, 1998; Vellinga & André, 1999). These experiments, usually consisting of series of randomized plots, encompass a wide range of crop types, soil types, weather, combinations of manures and fertilizers, and other management aspects. These experiments allow calculation of the N surplus (input - output) which is an indicator of N losses (Schröder *et al.*, 2004). Establishing relationships between nutrient surpluses and water quality under or on agricultural land is, however, much more complicated and has thus been determined in relatively few field experiments. Soil type and crop type specific relationships between N surplus and water quality have yet become available from the national Monitoring Program established on commercial farms in the Netherlands (Fraters *et al.*, 2007). Results from field experiments and this national Monitoring Program have been combined in a model. This model helps to identify combinations of manure and fertilizer-N that could lead to predefined N and P surpluses. The system boundary of the model is the field, not the farm. Consequently, the model does not simulate e.g. the permissible livestock density or the achievable milk production. The structure of the model and results obtained with it, have been described in detail by Schröder *et al.* (2005a, 2007a). The present paper reports on a re-run of the model with updated parameter values and on testing the model with updated independent data.

The aim of the present simulation study is to assess how much cattle slurry and mineral fertilizer N inputs can be applied to grassland and maize land in the Netherlands, with limited or no accumulation of P in the soil and without exceeding a value of 11.3 mg nitrate-N per litre in the upper 1 meter of groundwater or 11.3 mg total-N in nearby surface water. These conditions were instigated by the Ministry of Agriculture, Nature and Food security and based on its interpretation of the EU Nitrates Directive (Anonymous, 1991).

2. Materials and methods

2.1 General

Water quality under and along agricultural land is determined, inter alia, by the discrepancy between N and P inputs and outputs to and from that land (i.e. the surplus per unit area) and the loss pathways of this surplus. In order to model the relationship between (allowable) inputs and (required) water quality and vice versa, inputs and outputs as well as the fate of their difference should be accurately defined.

2.2 Input

In our model we define N input as the sum of applied and excreted manure-N (so, minus the gaseous N losses from housing and storage), mineral fertilizer N, soil mineral N at the onset of the growing season (SMN_{spring}), deposition of atmospheric N, biologically fixed N and N mineralized from soil organic matter. Sources of this mineralization are crop residues (including roots, stubbles, harvest losses and winter cover crops), and manure applied in previous years. Of these inputs manure-N, mineral fertilizer N and atmospheric N are the external inputs, the others represent internal fluxes (Figure 1).

We assume a SMN_{spring} input of 30 kg N per ha (Schröder *et al.*, 1998) and an annual atmospheric deposition of 31 kg N per ha (Anonymous, 2004). We estimate that on an annual basis 75 kg N per ha is mineralized from grass roots and stubbles (Velthof & Oenema, 2001), 25 kg N per ha from maize roots and stubbles (Schröder, 1991) and 40 kg N per ha from winter cover crops grown after maize (Schröder *et al.*, 1996). These contributions to mineralization can only be sustained through similar annual inputs into the soil organic N pool. Likewise, the N mineralization from manure inputs in previous years is also accounted for. The long term residual N mineralization from cattle slurry (i.e. beyond the first 12 months after its application) amounts to around 75% of the organic N input with manure (Schröder *et al.*, 2005b, 2007b). Assuming an equilibrium situation, we balance this mineralization via a similar annual investment into the soil organic N pool. Biologically fixed N is assumed to be zero as clover is hardly present in Dutch grasslands but in the discussion section we address situations in which it would be present.

Our calculations are restricted to cattle slurry which is by far the dominant manure type on farms growing grass and maize in the Netherlands (Menzi, 2002). As slurry composition can be changed via adjustments of the diet,, we explored the consequences of diets poor in P or protein, next to the common diet. Slurry treatment can also change the composition of manure. For instance, slurry separation can result in two fractions with quite different amounts of P and organically bound N per kg total N. Effects of these measures on slurry composition are summarized in Table 1.

Table 1. Ratios of ammoniacal N and total N in manures and of total N and P_2O_5 in manures and crops

Product		Kg NH_4-N per kg total N	Kg P_2O_5 per kg total N	References
Manures	Dung & Urine, grass dominated	0.50	0.31	Aarts *et al.*, 2008
	Slurry, common diet, untreated	0.50	0.36	Van Dijk, 2003; Aarts *et al.*, 2008
	Slurry, diet poor in P, untreated	0.50	0.31	unpublished data from the Cows and Opportunities project
	Slurry, diet poor in protein, untreated	0.35	0.36	Schröder *et al.*, 2005c; Reijs, 2007
	Liquid fraction after separation, common diet	0.71	0.21	Schröder *et al.*, 2007c
	(Solid fraction after separation, common diet)*	(0.22)	(4.0)	Schröder *et al.*, 2007c
Crops	Grassland, cut	-	0.30	Aarts *et al.*, 2008
	Grassland, grazed	-	0.27	Aarts *et al.*, 2008
	Silage maize	-	0.37	Aarts *et al.*, 2008

* *Included for the sake of completeness but not used in dairy scenarios.*

On dairy farms where grass is partly harvested by grazing animals (i.e. a mixed use of cutting and grazing) the composition of urine and dung excreted during grazing is, by nature, largely determined by the composition of young grass which has a slightly higher N content. In this situation we adopted a weighted average amount of 0.31 kg P_2O_5 per kg total N in urine and dung instead of the 0.36 of slurry which is dominated by the composition of the winter diet (Aarts *et al.*, 2008).

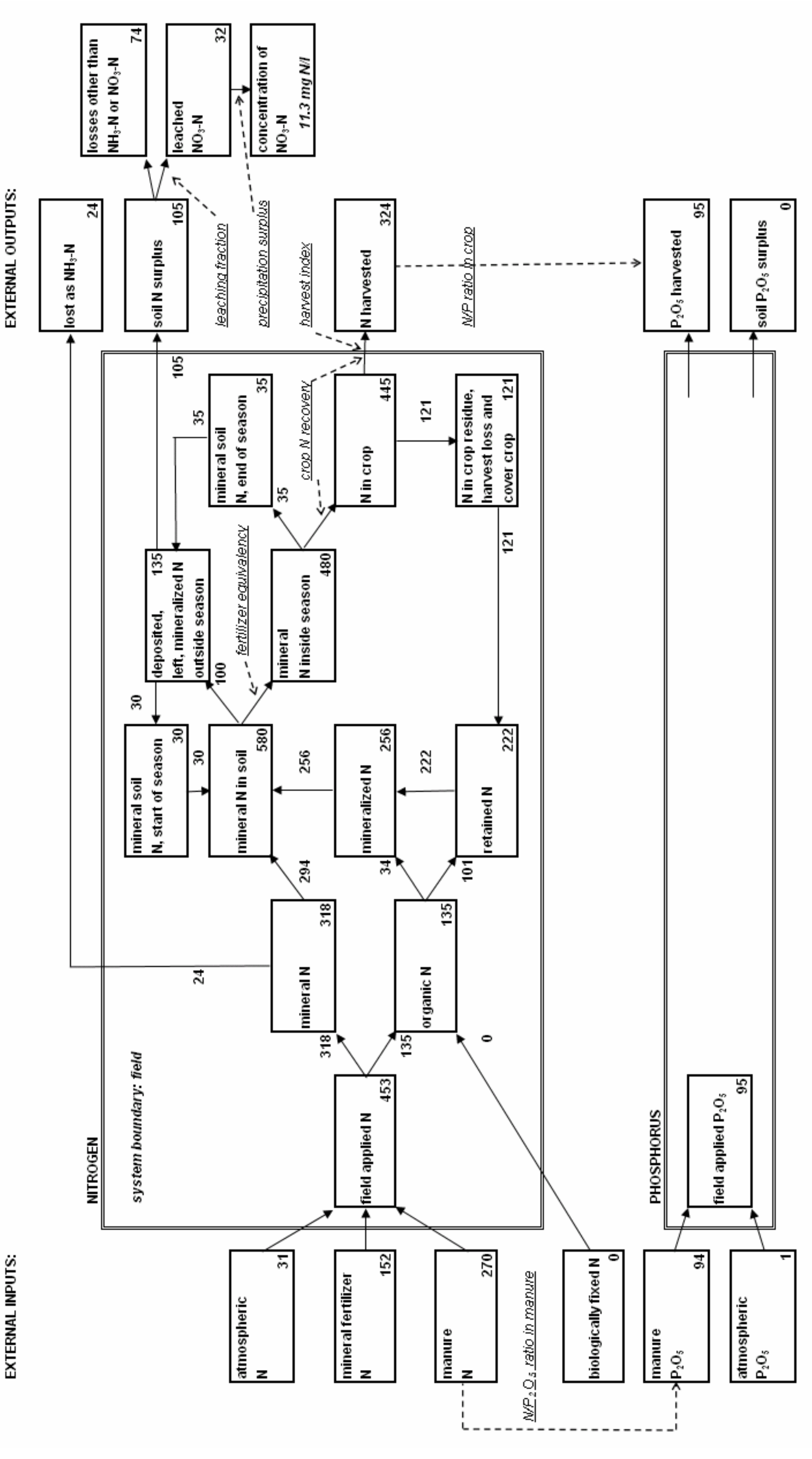

Figure 1. Flow diagram of external N inputs and outputs and internal N fluxes in the present model, including a numerical example (Table 6) referring to grassland under good growing conditions and management with a mixed use of cutting and grazing, grown on a sandy soil with a mean highest groundwater table between 0.40 and 0.80 m below the soil surface.

2.3 Output

In order to assess the soil N surplus, all outputs must be subtracted from the inputs. We define these outputs as the sum of crop N which is removed by either grazing or cuttings (see below), N investments in (new) crop residues, and N stored in the organic N fraction of manure in as much as it is not mineralized in the first 12 months after application. In an equilibrium situation, defined here as a situation in which there is no change in total N content of the soil, the annual N input from mineralizing crop residues and formerly applied manure, equals the N invested in these pools. In other words: to sustain a system several inputs require annual renewal. This may not hold on an annual basis in regularly renovated grassland or in all phases of a crop rotation. We address this situation in more detail in our scenarios to explore the consequences (see below).

Ammonia losses, too, must be subtracted for a correct assessment of the soil N surplus. For arable land we estimate these losses to amount to, on average, 12% of the applied ammoniacal N (Velthof *et al.*, 2008), assuming that slurry is either injected (2% loss) or incorporated with a spreader-mounted rotavator (22% loss). For grassland we have adopted ammonia losses of 19% (sandy and clay soils, sod injector-applied) to 26% (peat soils, trailing shoe-applied) of the ammoniacal manure N input and 2.2% of the total manure N when excreted during grazing (Velthof *et al.*, 2008)). Ammonia volatilization from fertilizers is set at 2% of the mineral fertilizer N input, bearing in mind that calcium ammonium nitrate and not urea is by far the dominant fertilizer type in the Netherlands (Harrison & Webb, 2001). Harvested N, ammonia losses and the soil N surplus are the outputs crossing the system boundary, whereas the other outputs represent internal fluxes becoming inputs again (Figure 1).

The harvested N output is determined by i) the fertilizer equivalency i.e. the availability to plants of N from various sources including manure and crop residues relative to mineral fertilizer N (Table 2, including references), ii) the uptake efficiency i.e. the fraction of the available N taken up by the crop whilst accounting for the reduction in uptake efficiency at higher input levels (Table 3, including references) and iii) the harvest efficiency i.e. 1 minus the fraction of crop N which is lost before it is either eaten or removed via harvests (Table 4, including references).
In accordance with present legislation in the Netherlands, we assume that manure ex storage is applied in spring (grassland, maize) and early summer (grassland), that manure is injected into the sod (sandy and clay soils) or applied with a trailing shoe (peat soils) on grassland, and injected or instantaneously incorporated into a bare soil and that maize is followed by a cover crop.

Table 2. Fertilizer-N equivalency of various N sources for grass and maize.

Source	Grass	Maize	Reference
Soil mineral N in spring	100%	100%	By definition
Applied cattle slurry N*	50%	52%	Van Dijk et al., 2004; Schröder et al., 2005b, 2007b & 2008
Excreted urine and dung during grazing*	21%	-	Vellinga et al., 2001; Van Dijk et al., 2004
Atmospheric deposition	75%	75%	After Schröder & Van Keulen, 1997
Mineralization of soil N, including crop residues and the resistant organic N fraction of manure	75%	60%	Lammers, 1983; after Schröder & Van Keulen, 1997

* *In the first 12 months after application/excretion.*

Table 3. N uptake efficiency of fertilizer N equivalents for grass and maize (derived from: Alberda (1968); Prins (1980); Sibma & Ennik (1988); Middelkoop & Aarts (1991); Schröder et al. (1998, 2005b, 2007b); Vellinga & André (1999); Ten Berge et al. (2002); Nevens & Reheul (2002); Nevens & Reheul (2003); Nevens (2003); Schils & Kok (2003)).

	Grass	Maize
Initial efficiency at low input rates	85%	75%
Indicative mineral fertilizer N rate (kg N per ha) at which efficiency commences to diminish ('deflection point')	270	80
Efficiency reduction (% (absolute) per 100 kg additional mineral N per ha) beyond deflection point	10%	10%
N uptake plateau (kg N per ha) at which marginal N efficiency becomes 0%	510 and 460 for fully cut swards and swards with mixed use, respectively	330, 190 and 130 for clay, sandy soils with MHG < 0.80 and sandy soils with MHG > 0.80 m, respectively*

* *MHG = mean highest groundwater table.*

Table 4. Fraction (%) of crop not taken in or exported from the field due to mechanical damage to sward by animals and due to lost crop material during wilting and mechanical harvesting (Beuving et al., 1989; Corporaal, 1993).

Regime	Soil type*	Grass	Maize
Cutting only	All	4%	5%
Mixed use of cutting and grazing	Peat	20%	-
	Clay	15%	-
	Sand with MHG < 0.80 m	15%	-
	Sand with MHG > 0.80 m	10%	-

* *MHG = mean highest groundwater table.*

2.4 Apparent fate of the soil N surplus

In the previous sections the calculation of the soil N surplus in a steady state situation has been explained. Soil organic N pools do not change then and the soil N surplus (i.e. corrected for ammonia volatilization) is either denitrified or leached. We have calculated the effect of the N soil surplus on N concentrations in groundwater (sandy soils) and surface water (clay and peat soils) by multiplying the N surplus by crop and soil specific leaching fractions and dividing the product by crop and soil specific precipitation surpluses (Table 5). The combined effects of these two factors have been derived from the national Minerals Policy Monitoring Programme (LMM) established in the early nineties. In this programme, the soil N surpluses of commercial farms are related to their observed nitrate-N concentrations in the upper 1 meter groundwater in sandy soils, or their observed total-N concentrations in ditch water (peat soils) or in drainage water or the upper 1 meter groundwater (clay soils).

In view of ecological targets in surface water (mainly to be found in areas with clay and peat soils) policy makers in the Netherlands consider the total N concentration more relevant an indicator than just nitrate N. Moreover, the share of non-nitrate-N (i.e. ammonium-N, dissolved organic N) in water increases from on average 13 to18% on sandy soils to 12 to 20% on clay soils and more than 80% on peat soils (Zwart *et al*, 2008).

Table 5. Net leaching fractions (kg N leached per kg soil N surplus; s.d.'s based on yearly variation in brackets), the median precipitation surplus (mm; 10% and 90% percentiles in brackets), and the soil N surplus (kg N per ha; in brackets the values of this surplus based on a combination of the lower value of the leaching fraction (mean - 2 x s.d. / √n) and the 90% percentile of the precipitation surplus, and the upper value of the leaching fraction (mean + 2 x s.d. / √n) and the 10% percentile of the precipitation surplus), associated with a N concentration of 11.3 mg nitrate-N (sandy soils) or total N (clay and peat soils) per litre, as affected by land use, soil type and mean highest groundwater level (MHG) (National Monitoring Program 1992-2005 (Fraters et al., 2007)).

Land use	Soil type*	Net leaching fraction (kg/kg)	Precipitation surplus (mm)	Allowable soil N surplus (kg N/ha)
Arable land	Clay	0.36 (0.17)	353 (294-420)	112 (70-196)
	Sand, MHG < 0.40 meter	0.38 (0.16)	358 (304-405)	106 (72-160)
	Sand, 0.80 < MHG < 0.40 meter	0.58 (0.17)	332 (297-387)	65 (50-92)
	Sand, MHG > 0.80 meter	0.73 (0.16)	332 (295-392)	51 (40-69)
Grassland	Peat	0.04 (0.01)	320 (264-379)	>300
	Clay	0.12 (0.03)	311 (247-375)	296 (197-442)
	Sand, MHG < 0.40 meter	0.20 (0.11)	274 (221-319)	156 (96-259)
	Sand, 0.80 < MHG < 0.40 meter	0.30 (0.10)	280 (226-346)	105 (72-159)
	Sand, MHG > 0.80 meter	0.38 (0.11)	298 (245-362)	88 (62-126)

* *MHG = mean highest groundwater table.*

Groundwater quality on sandy soils in this ongoing monitoring programme is annually measured once during March-September. On most farms only 16 samples are taken, compared to 48 on semi-experimental pilot farms. The whole farm area is sampled, taking the grassland : maize ratio into account (Fraters *et al.*, 1998, 2005). On farms situated on clay soils, the water from 16 drains per farm is sampled with a maximum of four times per drainage season (October to April). If drains are absent the upper meter of groundwater is sampled twice per drainage season (Fraters *et al.*, 2008, 2001). Water quality of farms on peat soils refers to ditches which are sampled in the winter season (Fraters *et al.*, 2002). At each farm 8 ditches are sampled downstream, 4 ditches originating from the fields belonging to the farm itself and 4 that discharges water from upstream farms as well. For analyses the data are restricted to ditches which originate from fields belonging to the farm itself in order to minimize influence of adjacent farms and other nutrient sources such as waste water. Ditches are sampled once per winter.

During the 1992-2005 period the LMM consisted of, on average, 60 (16-115) dairy farms, 27 (0-58) arable farms, and 14 (0-40) mixed farms and/or pig/poultry farms each year (Zwart *et al.*, 2008). Of the monitored arable farms approximately 51% and 49% are located on clay and sandy soils (including loess soils), respectively. Of the dairy farms approximately 9%, 24% and 67% are located on peat, clay and sandy soils (including loess soils), respectively. Other farms are almost all (about 80%) located on sandy soils.

According to measurements collected in the LMM, 12% and 36% of the soil N surplus on clay soils was recovered in the water of ditches on grassland and on arable land, respectively. For grassland on peat soils this apparent leaching fraction amounts to 4%. The leaching fractions on sandy soils with a deep ground water (Mean Highest Groundwater level (MHG) deeper than 0.80 meter) are greater. On grassland 38% appears to leach to groundwater.

Much higher leaching fractions are indicated by the LMM for arable land. On sandy soils with deep groundwater, the calculated leaching fraction averages 73%. The observed nitrate-N concentrations in sandy soils become lower with higher groundwater levels. On wet sandy soils (MHG above a depth of 0.40 m) leaching fractions amount to 20% and 38% on grassland and arable land, respectively. The derivation of these leaching fractions is explained in greater detail in Fraters *et al.* (2007). Note that the LMM based leaching fractions for arable crops originate from farms that grow little maize if any. We yet assume that these fractions apply to any arable crop including maize.

The positive relationship between the MHG depth and the value of the leaching fraction has been attributed to denitrification in the layer between the root zone and 1 meter below the groundwater table in situations with shallow groundwater, although denitrification was not measured in the LMM. Under those conditions groundwater is in direct contact with soil layers containing degradable carbon, by which denitrification is enhanced (Munch & Velthof, 2006). In the discussion section we address this matter in greater detail.

2.5 Phosphorus balance

An integrated approach towards nutrient emission from agriculture requires attention to P, as manure P is inevitably added with manure N. For that purpose we have adopted a soil surface P-balance (Figure 1). The P input is the sum of atmospheric P (1 kg P_2O_5 (= 0.4366 P) per ha per year (Richards & Dawson, 2008)) and excreted or applied manure-P, which is deduced from the manure-N input following the P_2O_5 to N ratios. We assumed that no other P inputs are being used than atmospheric P and manure P. The P output comprises the P removed by either grazing animals or cuttings. Outputs are calculated as the product of N outputs and the P_2O_5 to N ratio in crops (Table 1). We have explored the sensitivity of our calculations by running the model with P_2O_5 to N ratios of crops that were 20% larger or smaller. This analysis has been restricted to a dairy farm with a mixed use of cutting and grazing on a sandy soil with a MHG depth between 0.40 and 0.80 meter.

For the calculations of P concentrations in water, site-specific information on the P status of the soil, the hydrology and chemical and biological transformations of inorganic and organic P is required (Schoumans & Chardon, 2003). Contrary to N, where experiments show that N leaching rapidly changes when the N-input changes (e.g. Garret *et al.*, 1992; Aarts *et al.*, 2001), the situation for P is thus more complicated. We therefore did not attempt to predict P concentrations in water from P surpluses.

2.6 Numerical example

We have included a numerical example of the relationship between inputs, outputs, the soil surpluses of N and P and the N concentration in groundwater, to show how the previous reasoning works (Table 6). This illustration refers to well-managed grassland with a mixed use of cutting and grazing, for a farm situated on a sandy soil with MHG at depths between 0.80 and 0.40 meter, under growing conditions to which the coefficients of Tables 2 to 4 refer. The corresponding fluxes are illustrated in Figure 1.

Table 6. Calculation of the N concentration in groundwater under grassland with a mixed use of cutting and grazing on sandy soils with a mean highest groundwater depth between 0.40 and 0.80 meter in combination with good growing conditions and management (see text for explanations and assumptions), as related to the inputs and outputs at the field level (consult Figure 1 for a flow diagram).

				Total N	Fertilizer N equivalents ***	Total P$_2$O$_5$
Inputs	Manure		kg/ha	270	111	94
	Fertilizer		kg/ha	152	149	
	Clover		kg/ha	0		
	Deposition		kg/ha	31	23	1
	SMN$_{spring}$		kg/ha	30	30	
	Mineralization	Roots	kg/ha	75	56	
		Harvest losses	kg/ha	46	35	
		Manure*	kg/ha	101	76	
		Cover crop	kg/ha	0		
	TOTAL		kg/ha	705	480	95
Outputs	Crop		kg/ha	324		95
	Ammonia		kg/ha	24		
	Investments	SMN$_{spring}$	kg/ha	30		
		Roots	kg/ha	75		
		Harvest losses	kg/ha	46		
		Manure**	kg/ha	101		
		Cover crop	kg/ha	0		
	TOTAL		kg/ha	600		95
Soil surplus			kg/ha	105		0
Leaching fraction			kg/kg	0.30		
Precipitation surplus			mm	280		
Nitrate-N concentration			mg/l	11.3		

* *N mineralized from manure applied in previous years (residual N).*

** *Residual manure N invested (residual N).*

*** *See Table 2.*

2.7 Validation of the model

Before applying the model we have tested its assumptions. Parallel to the present study, Aarts *et al.* (2008) estimated the net N yield of grasslands in the Netherlands by analysing the annual records of commercial dairy farms from eight recent years (1998-2006). The analysis comprised, on average, 36 (range 28-53 per year) farms on peat soils, 57 farms (range 39-91) on clay soils, 61 (range 51-84) on wet sandy soils and 34 farms (range 23-64) on dry sandy soils. The point of departure of the analysis was the energy requirement of the herd on each individual farm and the estimated energy and N contents of forages and concentrates. By combining these data with registered purchases of feed and estimates of the on-farm N yield of silage maize (other crops were not grown) and the N losses from forages during conservation and feeding, Aarts *et al.* (2008) made an estimate of the apparent N yield from grassland. Their data base also comprised data on the allocation of manure N and mineral fertilizer N to either grazed or cut grassland and to maize land on each farm. This allowed us to compare the use efficiency of N (NUE, i.e. the product of fertilizer equivalency, uptake efficiency and harvest efficiency; Tables 2-4) achieved on these farms, to the NUE of comparable inputs with the present model. Moreover, the coefficients in Table 5 were tested against a recent independent dataset of soil N surpluses and nitrate N concentrations in the upper groundwater (average 2000-2005) from pilot farms on sandy soils participating in the Cows & Opportunities project (Oenema *et al.*, 2001).

2.8 Exploration of manure-fertilizer combinations

We subsequently used the MS Excel ™ Solver Tool to determine which combinations of manure N and fertilizer N ('variable cells') would maximize the harvestable N yield ('target cell'). This was done under the constraints that i) the N concentration in groundwater is 11.3 mg nitrate-N per litre (sandy soils) or 11.3 mg total N per litre (clay and peat soil) (or lower concentrations when no further yield increase was brought about by additional N inputs), and ii) the P surplus is 0 kg per ha i.e. soil P pools are depleted nor augmented unless stated otherwise ('constraints cells'). The algorithms are given in Appendix I. The Solver Tool has the unfortunate property that it prematurely stops optimizations whenever too low starting values of the variables have been chosen, regardless the defined maximum number of iterations. The program then suffices with a message that a solution was not found or that variable cell values have converged to certain values instead of arriving at a real optimum. This phenomenon could be successfully avoided by choosing larger starting values, visually 200 kg slurry N and 200 kg mineral fertilizer N per ha. In addition we tested various rate combinations around the recommended optimum for each scenario, to check whether the optimum in terms of target and constraints had really been achieved.

Separate calculations were made for grasslands with a 'cutting only' regime, for grasslands with the common mixed use, i.e. in which about one third of the production is harvested via grazing, and for silage maize. For mixed grassland use we assumed that an average of 65 kg N per ha per year is excreted outdoors in the form of urine and dung (Aarts *et al.,* 2008).

The previous scenarios were run with the coefficients presented in Tables 2-4. These coefficients were derived from field experiments and applicable to good growing conditions (i.e. irrigation and drainage, soil fertility status, exclusion of field borders, perfect pest control) and good management (i.e. the timing of operations). Evaluations based on these data are not necessarily representative for all commercial forage production systems. For instance, the timing of operations cannot always be optimized on each individual field, or the utilization of N and P on a whole field basis may be somewhat lower than on experimental plots in the same field. To mimic these effects we also ran the model for a situation in which we arbitrarily reduced the assumed crop uptake efficiency by 10% (e.g. 67.5% instead of 75%) and simultaneously reduced the harvest efficiency by 5 percent points (e.g. 9% losses instead of 4%). We called this parameter set 'fair growing conditions and management', as opposed to the previous 'good growing conditions and management'.

The leaching fractions derived from the LMM vary from year to year, as indicated by the standard deviations (Table 5). Therefore the allowable N rates vary as well. The lower and upper boundaries of the 95% confidence interval for N rates can be approximated by running the MS Excel ™ Solver Tool again with imposed leaching fractions equal to 'mean - 2 x s.d./√n' and 'mean + 2 x s.d./√n', respectively. Precipitation surpluses also vary, as indicated by the 90% and 10% percentile values (Table 5). We can not retrieve to what extent precipitation surpluses determine the value of the leaching fraction. In order to get yet an idea of the consequences of variation of both factors, we have simulated 'worse case' and 'best case' scenarios (i.e. worse and better than average) by combining the upper value of leaching fraction with the precipitation surplus belonging to the 10% percentile value and the lower value of the leaching fraction with the precipitation surplus belonging to the 90% percentile value, respectively.

On most dairy farms in the Netherlands both grass and maize are grown. Therefore, we have also explored the room for the application of manure and N fertilizer when grass is being substituted by maize. This exploration was restricted to the average leaching fractions. Peat soils were excluded from this exploration because arable crops, including maize, are hardly grown on this soil type. Consequently, the leaching fraction for arable crops could not be derived from the LMM monitoring programme.

When both crops are present on a farm, they are often rotated because crops generally perform better when grown at a lower frequency. Rotation implies that grassland is regularly ploughed out. This ploughing strongly stimulates mineralization and this augments the available supply of mineral N (Velthof & Oenema, 2001; Velthof et al., 2002). If ignored as an input of N to subsequent crops, most of the mineralized N will be lost to the environment. Conversely, young grassland can temporarily immobilize N, thus reducing immediate losses to the environment (Velthof & Oenema, 2001; Velthof et al., 2002). We accounted for these turnover processes by running the model once more while taking the N dynamics in a rotation into consideration. We restricted these calculations to a sandy soil with 0.80 < MHG < 0.40 meter, a mixed use of grassland, and the average soil-specific leaching fractions and precipitation surpluses. Further, we assumed avoidance of P accumulation at the whole farm level. We adopted a rotation comprising four years of temporary grassland followed by two years maize ('66,6% grassland and 33.3% maize'). We surmised an additional annual 150 kg N mineralization per ha from the ploughed grassland (2 years x 150 = 300 kg N per ha) and an additional annual N build up of 75 kg N per ha under grassland (4 years x 75 = 300 kg N per ha). In reality, however, mineralization and immobilization are generally larger during the first year(s) of each crop phase. It is unclear at which spatial scale the nitrate target in the Nitrates Directive should be achieved (Anonymous, 1991), so we distinguished two situations: one in which nitrate stays below the target under each individual crop (C) and another in which nitrate stays below the target at the whole farm level (F). The outcomes were compared with our initial approach where we ignored the N dynamics of the rotation (I). The simulation was restricted to situations with good growing conditions and crop management.

3. Results

3.1 Validation

The estimated use efficiency of N (NUE) applied to grasslands on commercial farms (Aarts *et al.* 2008), found itself in between the NUE values simulated by parameter settings of the model assuming ‘good growing conditions and management’ and ‘fair growing conditions and management’. The NUE of maize, however, was more close to ‘good growing conditions and management’. The NUE at the whole farm level, reflecting weighted contributions from both crops in terms of hectares and the amounts of N involved, held an intermediate position between ‘good’ and ‘ fair’ again (Table 7).

Table 7. Comparison of the N use efficiency (NUE (kg N per kg N) = net N yield of crops / (manure-N applied or excreted during grazing + mineral fertilizer N + atmospheric N deposition + N mineralization)) of registered N inputs and estimated N yields on commercial dairy farms on sandy soils (Aarts et al., 2008), and the calculated N use efficiency of similar N inputs by the model (‘mixed use of grassland’) used in the present study.

Soil type	Crop	Model		Farm data ‘estimates from practice 1998-2006’
		‘good growing conditions and management’	‘fair growing conditions and management’	
Peat	Grassland	50	42	46
Clay	Grassland	61	52	58
	Maize	59	50	58
	Whole farm	61	52	58
Sandy, MHG* < 0.40 meter	Grassland	63	54	59
	Maize	61	52	61
	Whole farm	63	53	59
Sandy, MHG* > 0.80 meter	Grassland	63	54	59
	Maize	60	51	59
	Whole farm	63	53	59

* *MHG = mean highest groundwater table.*

The average daily temperature during the growing season in the years investigated by Aarts *et al.* (2008) was slightly higher than the average of the last 30 years, a common phenomenon in the last decade. Accumulated rainfall in all years but 2003 and 2006 was above the long term average. Estimated NUE’s were lowest in these two dry years. The observed average NUE of commercial farms based on the approximated grassland N yields, suggests that the assumptions in our model concerning the integral effect of the fertilizer equivalency, uptake efficiency and harvest efficiency, are reasonable.

Applying our average leaching fractions and precipitation surpluses (Table 5) to the observed soil N surpluses of pilot farms on sandy soils slightly overestimated the nitrate-N concentrations compared to the observed concentrations on the whole farm level (Figure 2). It is beyond the scope of this paper to examine this moderate discrepancy in detail. Local rainfall may have differed from the long term average. Besides, immobilization may have exceeded mineralization whereas the model supposes a permanent equilibrium between both. Moreover, leaching fractions may not be exactly constant over the whole range of N surpluses. They may be lower at the slightly lower N surplus level of the pilot farms involved. However, the available literature on this aspect is not univocal (Schröder & Van Keulen, 1997; Van Beek *et al.*, 2003; Fraters *et al.*, 2007). In general, we yet dare to conclude that this part of the validation also shows a reasonable fit between simulated and observed data.

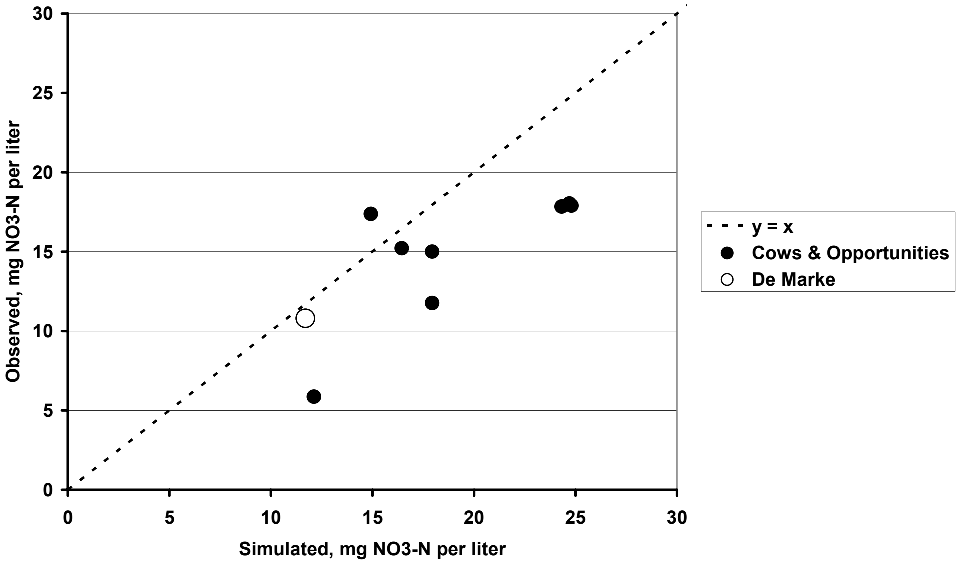

Figure 2. *Observed (average 2000-2005) versus simulated nitrate-N concentration in the upper 1 m of groundwater of dairy farms on sandy soils participating in the Cows and Opportunities project (experimental farm De Marke indicated by* ***O****).*

3.2 Manure and fertilizer N rates at the crop and farm level

3.2.1 Standard slurry composition

If grass is harvested via the estimated shares of cutting and grazing and growing conditions and management are ‘good’, 260-280 kg manure-N (= 90-100 P_2O_5) per ha can be applied annually without exceeding a value of 11.3 mg N per litre groundwater or surface water and without accumulation of P. Under ‘fair’ conditions manure application rates must be limited to 220-240 (80-90 kg P_2O_5) kg N per ha. Under a ‘cutting only’ regime, the corresponding annual rates would be 290-300 (‘good’, Figure 3A, Appendix 1A) and 240-260 (‘fair’, Figure 3B, Appendix 1B) kg N per ha. Soil type, growing conditions and management have a relatively strong effect on the rates on maize land. Under good growing conditions and management, simulated rates on maize land range from 180-190 kg manure-N (65-70 kg P_2O_5) per ha on clay soils and wet sandy soils to 160 kg manure-N (60 kg P_2O_5) per ha on dry sandy soils. Under fair conditions the corresponding rates would drop to 170-180 (60-65 kg P_2O_5) and 150 kg N (55 kg P_2O_5) per ha of maize land, respectively.

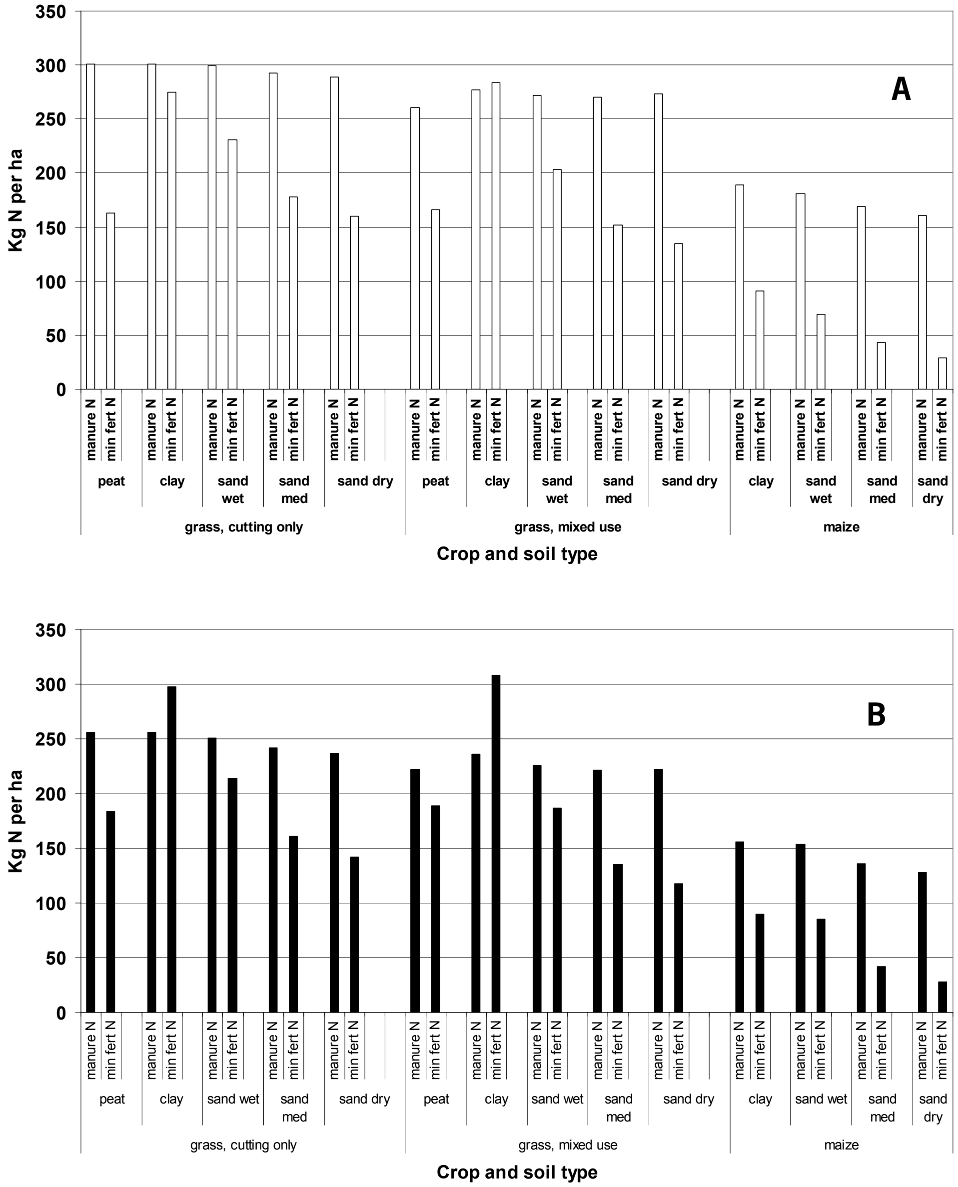

Figure 3. Simulated manure and mineral fertilizer ('min fert N') rates (kg N per ha), as affected by crop type (grass 'cutting only regime', grass mixed use of cutting and grazing, silage maize), soil type (peat, clay, wet sandy soil (mean highest groundwater table = MHG<0.40 m), moderately dry sandy soil ('sand med' = 0.80 m<MHG<0.40 m) or dry sandy soil (MHG>0.8 m), and the growing conditions and management (A = 'good growing conditions and crop management' , B = ' fair growing conditions and crop management'; consult text for explanation).

Changing the permitted annual P surplus by 10 kg P_2O_5 per ha has an effect of approximately 25 kg on the simulated rate of manure-N per ha. This logically follows from the surmised N to P_2O_5 ratio of the manure and underlines that permitted P surpluses determine to what extent the N demand of crops can be met with manure instead of mineral fertilizer N. Note that the utilization of manure-P fully depends on the availability of sufficient N. The calculated manure N-rates are thus inevitably associated with the calculated mineral N supplements (Figure 3A & B, Appendices 1A & B).

Our calculations indicated that under 'worse case' circumstances (i.e. when a relatively large fraction of the N surplus is leached in a relatively small volume of surplus precipitation, as defined in section 2.8), manure rates on grassland with a mixed use should be limited to 260-280 and 190-230 kg N per ha for 'good growing conditions and crop management' and for 'fair growing conditions and crop management', respectively. Corresponding rates for grassland with a 'cutting only regime' would be 280-300 and 230-260 kg N per ha. Simulated rates on maize land in this 'worse case' scenario would be 170-180 on clay soils and wet sandy soils and 150 on dry sandy soils, when growing conditions and management are 'good'. Corresponding rates would be 160-170 kg N per ha on clay soils and wet sandy soils and 140 kg N per ha on dry sandy soils, when growing conditions and management were 'fair' (Figure 4 for a moderately dry soil, Appendix II for all other soil types). Again, the calculated manure N-rates are inevitably associated with the calculated mineral N supplements. Lower N supplements would result in lower N concentrations in water but would at the same time increase the P surpluses.

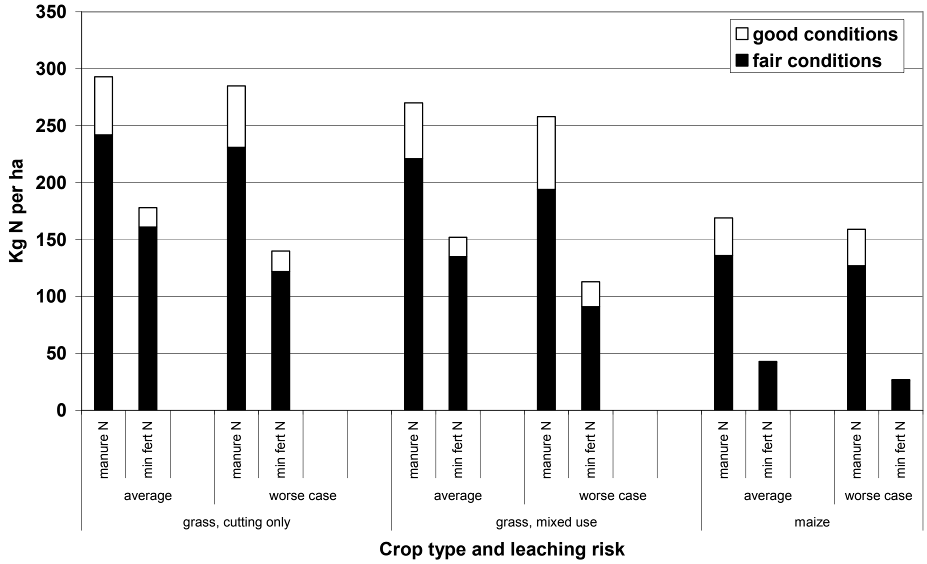

Figure 4. *Simulated manure and mineral fertilizer ('min fert N') rates (kg N per ha) on a moderately dry soil (0.80 m<mean highest groundwater table<0.40 m), as affected by crop type (grass 'cutting only regime', grass mixed use of cutting and grazing, silage maize), and the growing conditions and management when exposed to average leaching risks and under a 'worse case' situation (consult text for explanation).*

A sensitivity analysis indicated that if crops would contain 20% more P_2O_5 per unit N, manure rates on grassland could be augmented by approximately 60 kg N per ha at the expense of comparable amounts of mineral fertilizer N. The corresponding effect on maize land was approximately 40 kg manure-N per ha. Conversely, a 20% decrease of the P_2O_5 to N ratio of crops required to reduce the manure rate on grassland by approximately 40 kg N per in favour of comparable amounts of mineral fertilizer N. The corresponding effect on maize land was approximately 25 kg manure-N per ha.

Whatever the adopted P_2O_5 to N ratio in the crop, simulated rates of manure N and mineral fertilizer N are much lower on maize land than on grassland (Figure 3A & B, Appendices 1A & B). Consequently, the share of maize land determines which rates of both N sources are simulated at the whole farm level (Table 8).

Table 8. Simulated manure and mineral N fertilizer rates at a whole farm level under average leaching risks whilst aiming at a P_2O_5 surplus of 0 kg per ha and a N-concentration of 11.3 mg N per litre (or less when no further yield increase is brought about), as affected by growing conditions and management, harvest regime of grassland, soil type and the share of maize land in the total farm area

Soil type	Maize share	Good growing conditions and management				Suboptimal growing conditions and management			
		Mixed use		Cutting only		Mixed use		Cutting only	
		Manure-N	Mineral fertilizer-N	Manure-N	Mineral fertilizer-N	Manure-N	Mineral fertilizer-N	Manure-N	Mineral fertilizer-N
	(%)	(kg N/ha)	(kg N/ha)	(kg N/ha)	(kg N/ha)	(kg N/ha)	(kg N/ha)	(kg N/ha)	(kg N/ha)
clay	15	264	255	284	247	224	275	241	267
	30	251	226	267	220	212	243	226	236
	45	237	197	251	192	200	210	211	204
sand, MHG < 0.40 m*	15	258	183	281	207	215	172	236	195
	30	245	163	264	182	204	156	222	175
	45	231	143	246	158	194	141	207	156
sand, 0.80 m > MHG > 0.40 m	15	255	136	274	158	208	121	226	143
	30	240	119	256	138	196	107	210	125
	45	225	103	237	117	183	93	194	107
sand, MHG > 0.80 m	15	256	119	270	140	208	105	221	125
	30	239	103	251	121	194	91	204	108
	45	223	87	231	101	180	78	188	91

* *MHG (mean highest groundwater table during winter).*

3.2.2 Deviating slurry composition

Diets poor in P could allow an increase of simulated manure rates of 30 kg N per ha on grassland (mixed use of cutting and grazing) and 25 kg N per ha on maize land, under ‘good’ growing conditions and management. Corresponding values under ‘fair’ conditions would be 25 and 20 kg N per ha (Figure 5, Appendices 3A & B). On sandy soils in particular, these upward adjustments of the manure rates must go hand in hand with similar downward adjustments of the mineral fertilizer N rates, in order to keep the nitrate-N concentration in groundwater below the target of 11.3 mg N per litre.

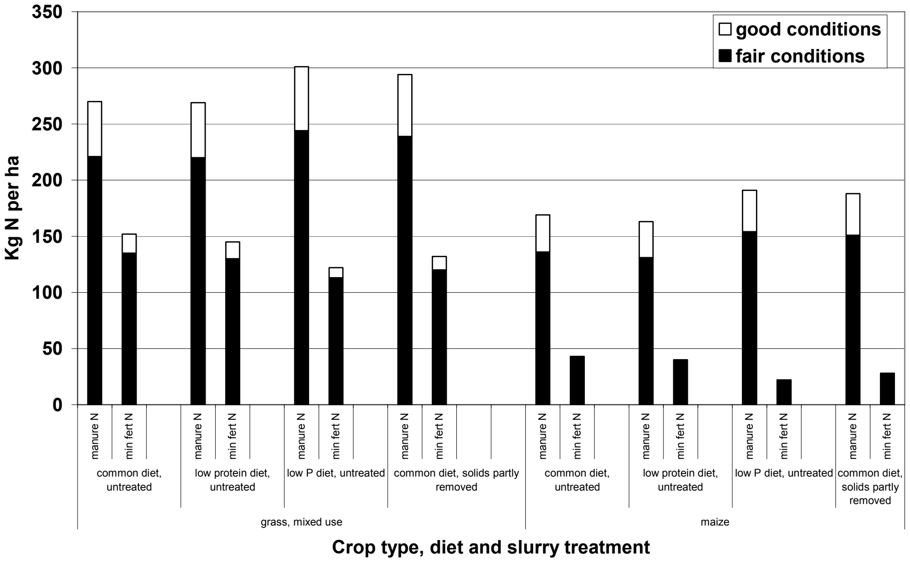

Figure 5. Simulated manure and mineral fertilizer ('min fert N') rates (kg N per ha) on a moderately dry soil (0.80 m<mean highest groundwater table<0.40 m), as affected by crop type (grass mixed use of cutting and grazing, silage maize), and measures to change the composition of manure (consult Table 1 for these changes), and the growing conditions and management (consult text for explanation).

Low protein diets hardly affect the room for the application of manure N (Figure 5, Appendices 3A & B). The slightly lower risks for ammonia volatilization losses of slurries originating from low protein diets, allow a reduction of mineral fertilizer N supplements, however.

If untreated slurry and the liquid fraction resulting from slurry separation would be mixed in a 3 to 1 ratio on the basis of total N contents, this blend would contain 0.55 instead 0.50 ammoniacal N per kg total N and 3.09 instead of 2.77 kg N per kg P_2O_5. Consequently, 20 kg N (fair growing conditions and management) to 25 kg N (good growing conditions and management) more manure-N could be applied on grassland with a mixed use of cutting and grazing, provided that mineral fertilizer N inputs would be reduced by almost similar amounts of N. Corresponding adjustments of manure rates on maize land would be 15 and 20 kg manure N per ha (Figure 5, Appendices 4A & B). The larger the share of the liquid fraction in the blend, the lower the simulated mineral fertilizer N supplement.
The above calculations once more show that the P_2O_5 to N ratio of manure determines to what extent the N requirements of crops can be met with manure instead of mineral fertilizer N. In other words: manure use is limited by the amount of P_2O_5 taken up by crops.

3.2.3 Adjustments of rates in a crop rotation

Considerable adjustments of N inputs are necessary in individual crops, particularly when the nitrate target is to be achieved for each individual crop (scenario C). The allowable application rates of manure on maize in our initial approach (169 kg N per ha per year) should be reduced to nil. Conversely, the allowable application rate of manure on grassland could be increased from an initial annual rate of 270 kg manure N per ha to approximately 350 kg N per ha (Table 9). The calculated differences between the three scenarios in terms of the simulated rates at the whole farm level, are insignificant, in particular because the model does not account for potentially better N uptake efficiencies when crops are grown in rotation.

Table 9. Manure and mineral fertilizer N inputs simulated in individual crops to achieve nitrate targets at the level of individual crops (C) or at the farm level (F) when grassland (mixed use) and silage maize are grown in a 66.6% / 33.3% rotation, as compared with the results of calculations where the N dynamics of mineralization and build-up associated with a rotation are ignored (I) (consult text for further assumptions).

Scenario	Scale	N (kg per ha per year)					Nitrate-N (mg per litre water)	P_2O_5 surplus, kg per ha per year
		Mineralized N	Manure-N	Mineral fertilizer N	Immobilized N	N yield		
I	Grassland	0	270	152	0	324	11.3	0
	Maize	0	169	43	0	167	11.3	0
	Whole farm	0	240	119	0	277	11.3	0
C	Grassland	0	347	161	75	327	11.3	25
	Maize	150	0	32	0	148	11.3	-50
	Whole farm	50	231	118	50	267	11.3	0
F	Grassland	0	351	131	75	320	9.3	30
	Maize	150	0	73	0	165	15.3	-60
	Whole farm	50	234	112	50	268	11.3	0

4. Discussion

4.1 How much manure from a nitrate perspective?

The present study indicates that N concentrations in surface water and groundwater are not only determined by the inputs of manure but rather by the combination of manure and mineral fertilizer N. Moreover, on grassland with a 'cutting only regime', up to 290 to 300 kg manure N per ha can be applied annually without exceeding a concentration of 11.3 mg N per litre, and without applying more P than the amount removed via crops. Simulated rates of manure-N would increase substantially if the amount of P_2O_5 per unit manure N would become lower as a result of adjustments of the diet or slurry separation; the extent to which crop N requirements can be met with manure instead of mineral fertilizer N is indeed determined by the P taken up by crops and not by N. If manure with a common P_2O_5 to N ratio would be used, the simulated rates are higher than the 170 kg manure N per ha stipulated by the Nitrates Directive. A similar conclusion was drawn by Ten Berge *et al.* (2002). The ability of grass to utilize substantial amounts of manure without increased leaching risks, can be attributed to its large N uptake capacity, to favourable growing conditions and to the long growing season in the Netherlands (Peeters & Kopec, 1996), as well as to the empirical evidence that only a fraction of the soil N surplus is recovered in nearby surface water (peat and clay soils) or the upper 1 meter of the groundwater (sandy soils). This applies in particular to situations with shallow groundwater. Theoretically, the latter can be explained by either denitrification or by temporary accumulation of organic N in the soil. Gradual changes of the amount of N in soil organic matter are hard to measure. Still we do not think that accumulation is a likely explanation because land use has not recently been changed towards grasslands which would favour accumulation (Figure 6), and because soil N surpluses have decreased during the last decade (Aarts *et al.*, 2008; Zwart *et al.*, 2008). This leaves denitrification as the most probable explanation of why only a fraction of the soil N surpluses ends up in groundwater. This apparent denitrification is much larger than what is commonly measured with the acetylene inhibition technique. However, this technique underestimates denitrification, especially in wet soils where gas diffusion is hampered (Bollman & Conrad, 1997; Seitzinger *et al.*, 1993). Moreover, in most studies denitrification is only measured in the top soil (Barton *et al.*, 1999). The combination of shallow groundwater tables and the presence of fresh organic matter in the upper soil layers may create conditions favouring denitrification, resulting in relatively low nitrate-N concentrations in the upper groundwater. Additional indications for the possible underestimation of denitrification is provided by farm balance calculations showing a considerable 'not accounted for' term, especially in grassland (Van der Meer, 1991; Garrett *et al.*, 1992; Jarvis, 2000; Van der Salm *et al.*, 2007). In line with this, Wachendorf *et al.* (2004) found a leaching fraction of 30-40% on grassland, which is comparable with our observation (39%) on a similar soil type.
The present study also shows that growing conditions and crop management, the harvest regime of grasslands and the share of crops other than grasslands (i.e. silage maize) in the rotation of dairy farms, all determine to what extent N rates should be limited from the perspective of N leaching and P accumulation. Even with mixed grassland use (i.e. one third of the production harvested via grazing) and a maize share ranging from the common 15 to 30% of the farm area (http://statline.cbs.nl), the annual use of approximately 190-260 kg manure N per ha can be reconciled with a N concentration of 11.3 mg per litre and a P-surplus of 0 kg per ha under growing conditions and management that appear to be applicable to commercial dairy farms in the Netherlands. (Tables 7 & 8).

The present application rates of manures to meet the targets for the N concentration and P accumulation are somewhat lower than the ones calculated in Schröder *et al.* (2005a, 2007b). This is due to a combination of factors. First, the adopted values of the ratio of leaching fractions and precipitation surpluses (which determines to what extent a soil N surplus contributes to the ultimate N concentration in water) are slightly lower, in particular in the case of grassland on sandy soils. This adjustment of the model was based on updated data from the monitoring network (Fraters *et al.*, 2007). Second, we have used a lower P_2O_5 to N ratio of grass as indicated by an extended data set (Aarts *et al.*, 2008), implying that less manure (P) was needed to balance the removal of P in harvests. This effect was slightly compensated, however, in case of a mixed use of grassland, as we have accounted now for the lower amounts of P_2O_5 per unit N ratio in the dung and urine excreted during grazing, contrary to Schröder *et al.* (2005a, 2007a) who did not discriminate between slurry ex storage on the one hand and dung and urine on the other. Third, the most recent survey of commercial dairy farms by Aarts *et al.* (2008) has indicated that in reality the utilization of N is, on average, lower than the utilization simulated by the model following the parameter set 'good growing conditions and crop management', whereas an earlier survey (Aarts *et al.*, 2005) made Schröder *et al.* (2005a, 2007a) conclude that commercial farms performed according to the parameter set 'good'. Note, however, that the recent survey of Aarts *et al.* (2008) indicates that supervision as provided by the Cows and Opportunities project, could enable dairy farmers to utilize N inputs as good as in our scenario 'good growing conditions and management'.

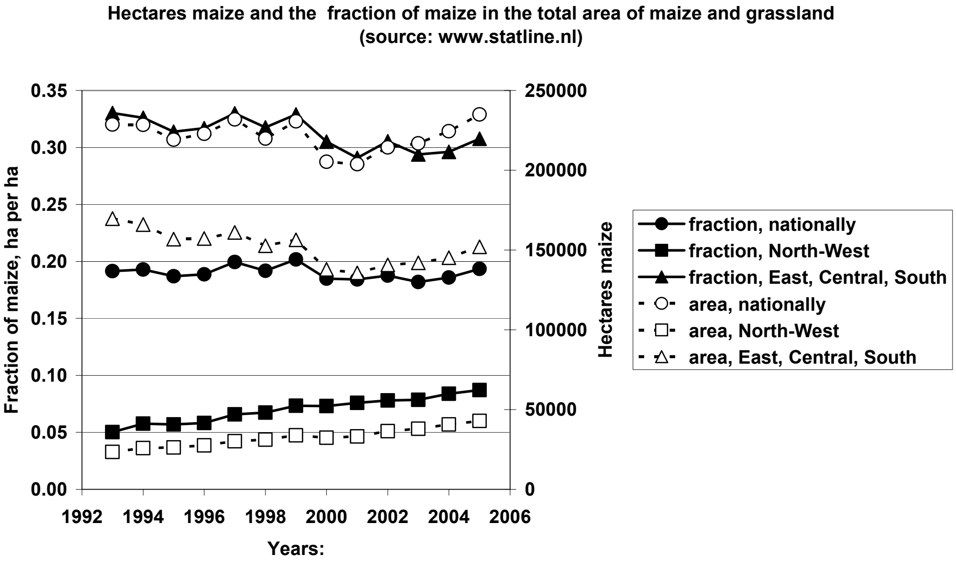

Figure 6. *Time course of the total area in the Netherlands (nationally, north-west region, east-central-south region) devoted to silage maize production (hectares) and its share (hectares per hectare) in the total area of grassland and maize.*

The N concentrations resulting from the manure - fertilizer N combinations as calculated in the present study can, unfortunately, not yet be validated with data of the N concentration in water as observed in the existing monitoring network. The available data of sandy soils in particular pertain to 2005 and earlier years during which permitted manure and fertilizer rates were higher than the ones simulated in the present study. In those years most dairy farms on sandy soils were allowed to apply slightly more than 250 kg manure per ha, supplemented with around 150 kg mineral fertilizer N per ha, and so they did (Aarts *et al.*, 2008). Fraters *et al.* (2008) reported that the median nitrate concentration in the upper groundwater under dairy farms on sandy soils participating in the monitoring network, amounted to 14.2 mg N per litre, implying that N applications at that time were indeed too high to comply with the target of the Nitrates Directive. Even the currently (2009) permitted rates (250 kg manure-N, 42-44 kg (manure-) P, and 100-150 kg mineral fertilizer N per ha) may still be higher than needed to comply with environmental targets.

Note that our calculations show a trade-off between the extent to which manure can be safely used and the room for grazing, because manure excreted during grazing results in greater leaching losses than mechanically applied manure ex storage (Vellinga *et al.*, 2001; Nevens & Reheul, 2003; Wachendorf *et al.*, 2004).

4.2 How to avoid incorrect estimates of inputs?

4.2.1 Actual inputs of manure N and P

The applicability of our calculations to the general practice strongly relies on a precise determination of all relevant N inputs. This refers to e.g. a correct assessment of the N and P excretion per animal category present on the farm, per production level and per type of diet (Kebreab *et al.*, 2001; Schröder *et al.*, 2005c; Reijs, 2007). Estimates of excretion should be consistent with estimates and observations of the amounts of N and P removed in crops, milk and meat and inputs from feed (Tamminga *et al.*, 2004). Subsequently, accurate estimates of the gaseous N losses from housing and manure storages are needed to assess how much manure-N will eventually be applied to the fields (e.g. Bussink & Oenema, 1998). Moreover, reliable accounts of the manure imported to or exported from the farm are necessary. Special attention is also required for the P_2O_5 to N ratio of manures, because for instance pig and poultry slurries as well as solid manures from cattle contain much more P per kg N than the cattle slurry used in the present study (Schröder, 2005). Obviously this is also true for the solid fraction resulting from cattle slurry separation. Consequently, in all cases in which these types of manures would be used, less manure N can be applied if P inputs into the soil have to be balanced with P outputs. Conversely, the relative substitution of mineral fertilizer N by manure could increase without accumulating P, if crops would contain less P_2O_5 per unit N due to restricted N inputs to land, as illustrated in our sensitivity analysis. Hence, the composition of manures and crops, including concentrates, deserves constant monitoring.

Note that our calculations are based on the assumption that the application of cattle slurry is associated with low ammonia volatilization losses as a result of legislation demanding injection or the immediate incorporation of manure. If this were not the case, more mineral fertilizer N would have to be applied to either maximize the yield or could have been applied without exceeding the permitted soil N surplus, be it at the expense of the air quality.
We emphasize that we adopted fixed values for several crop residue related characteristics, which result in negative soil N surpluses at low input levels. However, reduced input levels can have a negative feedback on the quantity of N invested in crop residues and SMN_{spring} and thus on the assumed contribution to available N. Reduced inputs can also affect the fertilizer equivalency of these organic N sources and, on a regional scale, will sooner or later indirectly affect the amounts of N deposited via the atmosphere.

4.2.2 N Input via biological fixation

N inputs via biological fixation need to be taken into account as well even though, at present, mixed stands of grass and white clover are relatively rare in the Netherlands. The area of grassland with white clover ranges between 50 and 100 thousand hectares, i.e. 5%-10% of the grassland area in the Netherlands, as suggested by seed sales (Corré, pers. comm.). Mixed stands with a visual cover of, for instance, 30% clover, can annually fix as much as 130-160 kg N per ha (Elgersma & Hassink, 1997; Schils, 2002). If the area of mixed stands increases, this input will thus deserve more attention as N losses could be higher than expected on the basis of manure and fertilizer inputs only.

4.2.3 N input from ploughed swards

Ploughing grassland leads to an enhanced mineralization of accumulated plant material and soil organic matter. The quantity and fate of mineralised N is related to the history of the old sward, to the time of ploughing, to the type of subsequent crop and to weather conditions. Adjustment of the applied rates of manure and fertilizer N to the N mineralization from ploughed grassland is a prerequisite to minimize N leaching. The present study suggested that application rates of manure on maize following grass should be reduced to nil, in agreement with the experimental results of Nevens & Reheul (2002). Conversely, the allowable application rate of manure on grassland following maize could be increased by roundabout 80 kg N per ha. Clearly, crop rotations involving the regular ploughing of grassland and the associated re-establishment of new leys, require considerable adjustments of N inputs. *Mutatis* *mutandis*, similar implications apply to situations where grassland is ploughed down and followed by new grassland (i.e. plain grassland renovation).

4.3 How to avoid incorrect estimates of outputs?

The applicability of our calculations does not only depend on a correct assessment of inputs (see previous section), but also on the anticipated level of outputs. Output levels are determined by assumptions concerning the extent to which inputs are properly utilized by crops and net production potentials are exploited as much as possible. The study of Aarts *et al.* (2008) suggested that the utilization of N on commercial farms is, on average, not as good as in most field experiments (Table 7). We have anticipated this shortcoming by running our calculations for fair conditions as well (Figures 3-5). Such fair conditions may pertain to many aspects such as an incorrect timing of tillage, manuring, the establishment or destruction of swards and cover crops, and harvests including those via grazing. Proper attention should also be paid to growth factors other than N and P such as soil supplies of Ca, Mg and K, the physical soil fertility, pest control, and appropriate drainage and irrigation strategies. If such 'best practices' are not enforced by law via incentives and fees, the message to farmers should at least be that high inputs can only be justified by high crop outputs. Aarts *et al.* (2008) observed a considerable variation in the utilization of N across farms, suggesting that there is room for improvement. Participants in the Cows and Opportunities project, for instance, demonstrated that the utilization of N can be strongly improved.

4.4 Annotations to the relationships between soil N surpluses and N concentrations in water

The leaching coefficients are derived from a monitoring programme (LMM) and not based on a full mechanistic understanding of the underlying processes. The network consists of a population of farms that may gradually change in terms of hydrology, land use and input levels of N and P. Nevertheless, we have applied the coefficients to our supposedly steady state situations. As denitrification is promoted by the presence of nitrate and degradable carbon (Munch & Velthof, 2006), the leached fraction of the N surplus could be lower at reduced input levels. This would lead to higher nitrate-N concentrations. Such a negative relationship between soil N surpluses and leaching fractions was reported by Schröder & Van Keulen (1997) and Fraters *et al.* (2007). Conversely, Van Beek *et al.* (2003) concluded that the leaching fraction is positively related to the soil N surplus which would reduce the leaching fraction at lower input levels. These uncertainties added to the complex effects of climate change on crop performance and soil processes, may affect coefficients and thus leaching. Still, the validation of the relationship against an independent, recent data set representing farms with reduced inputs rates (Figure 2) does provide us with some confidence. It is also encouraging that Wachendorf *et al.* (2004) found a leaching fraction of 30-40% is grassland experiments on a soil type where we arrived at a leaching fraction of 38%. Similarly, De Ruijter *et al.* (2006) found a leaching fraction of 79% for arable crops on dry sandy soils where we applied a value of 73%.

4.5 Ecological targets

In our study we evaluated the room for manure and fertilizer use in view of a N concentration of 11.3 mg total N (clay and peat soils) or nitrate-N (sandy soils) per litre, the latter in agreement with the Nitrates Directive. However, according to the Water Framework Directive (WFD; Anonymous, 2000), practices must be directed at ecological targets in surface waters which, depending on their eventual definition, may require lower total N concentrations than 11.3 mg per litre, let alone nitrate-N per litre (Rabalais, 2002; Camargo & Alonso, 2006). In addition, N (and P) originating from the sub soil may contribute to the eutrophication of surface water in peat regions in particular, in addition to the emissions directly linked to the use of manure and fertilizers, as accounted for in our calculations. Therefore, our conclusions will not necessarily mean that the calculated N rates will comply with the requirements of the WFD when fully implemented.

The present study suggests that denitrification plays an important role in the relationship between N input and N concentrations in groundwater. This also deserves attention as denitrification is associated with nitrous oxide production, which is a very potent greenhouse gas. However, when designing policies and measures directed at global effects, it is sensible to evaluate impacts per litre milk rather than per hectare. From that perspective, extensification as such does not necessarily reduce the emission at the global scale (e.g. Schröder *et al.*, 2004). So far, it is uncertain which measures dairy farmers should take for the benefit of the global climate (e.g. Velthof & Oenema, 1997). Final decisions on this issue may also affect the conclusions of the present study. An aspect of denitrification which is to be evaluated and addressed locally, however, pertains to the negative effect of denitrification on heavy metal and sulphate concentrations in deeper groundwater (Cremer *et al.*, 2003), especially in calcareous soils rich in sulphides (i.e. through pyrite oxidation). Moreover, denitrification resulting from the oxidation of pyrite supplies and organic matter in deeper soil layers has a finite character. Hence, extensive monitoring is required for timely adjustments, if only because the aforementioned chemical compounds need to be addressed to achieve compliance with the EU Groundwater Directive (Anonymous, 2006).

5. Conclusions

Cut grasslands in the Netherlands can utilize cattle manure with a common P_2O_5 to N ratio up to rates of 290-300 kg manure N (105-110 kg P_2O_5) per ha per year without exceeding a target value of 11.3 mg nitrate-N per litre or accumulating P in the soil. It can be realized provided that i) appropriate amounts of mineral fertilizer N are supplemented, and ii) growing conditions are good and the grassland is well managed. Under similar conditions, cattle manure rates on grasslands with a mixed use of cutting and grazing, should be reduced to 260-280 kg manure-N (90-100 kg P_2O_5) per ha per year, including the N excreted during grazing. Rates on silage maize should not exceed 160-190 kg manure N (= 60-70 kg P_2O_5) per ha per year, the lower values referring to sandy soils with groundwater tables deeper than 0.80 meter. Fair growing conditions and crop management, as encountered on a certain proportion of farms and in some years, reduce the room for manure applications by roundabout 40 and 10 kg manure N per ha on grassland and maize land, respectively. Adjustments of the diet and manure separation can reduce the amount of P_2O_5 per unit manure N and thus create additional room to fertilize crops with manure instead of mineral fertilizer N.

Manure rates should therefore be determined by the share of the different crop types, the hydrological situation and soil type, the harvest regime, growing conditions, the P_2O_5 to N ratio of both manures and crops, and management skills of the growers.

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Appendix I.

Appendix 1A. Simulated manure and mineral N fertilizer rates, resulting N and P2O5 yields and associated N-concentration in water and P2O5 surplus under average leaching risks and good growing conditions and management, whilst aiming at a N-concentration of 11.3 mg N per liter (or less when no further yield increase is brought about) and a P2O5 surplus of -10, 0 or +10 kg per ha, as affected by crop type, harvest regime, soil type, and manure type (when applicable)

Crop type	Harvest regime	Growing conditions & management	Soil type	Manure type:		Environment:		Harvested crop yield:		Permissible N:	
				Nm/Ntot	Ntot/P_2O_5	NO_3-N or Ntot* water (mg/l)	P_2O_5 surplus (kg/ha)	N (kg/ha)	P_2O_5 (kg/ha)	manure (kg/ha)	fertilizer (kg/ha)
grass	cutting only	good	peat	0.50	2.77	2.9	-10	375	110	273	184
						3.0	0	375	110	301	163
						3.0	10	375	110	329	142
			clay			7.5	-10	375	110	273	297
						7.6	0	375	110	301	275
						7.8	10	375	110	329	252
			sand, MHG < 0.4**			11.3	-10	373	109	272	256
						11.3	0	373	109	299	231
						11.3	10	373	109	327	205
			sand, 0.8 > MHG > 0.4			11.3	-10	366	107	266	204
						11.3	0	365	107	293	178
						11.3	10	364	107	320	152
			sand, MHG > 0.8			11.3	-10	362	106	262	185
						11.3	0	361	105	289	160
						11.3	10	360	105	316	134
grass	mixed use	good	peat	0.50	2.77	3.4	-10	313	91	234	187
						3.4	0	313	91	261	166
						3.5	10	313	91	289	145
			clay			8.9	-10	332	97	249	306
						9.0	0	332	97	277	284
						9.1	10	332	97	305	262
			sand, MHG < 0.4**			11.3	-10	327	95	245	229
						11.3	0	326	95	272	203
						11.3	10	325	95	299	177
			sand, 0.8 > MHG > 0.4			11.3	-10	325	95	243	178
						11.3	0	324	95	270	152
						11.3	10	322	94	297	126
			sand, MHG > 0.8			11.3	-10	328	96	246	161
						11.3	0	327	96	273	135
						11.3	10	325	95	299	109
maize	cutting	good	clay	0.50	2.77	11.3	-10	189	70	163	118
						11.3	0	187	69	189	91
						11.3	10	186	69	215	64
			sand, MHG < 0.4**			8.9	-10	180	66	154	110
						9.5	0	180	66	181	69
						11.0	10	180	66	209	57
			sand, 0.8 > MHG > 0.4			11.3	-10	170	63	144	70
						11.3	0	167	62	169	43
						11.3	10	164	61	193	17
			sand, MHG > 0.8			11.3	-10	163	60	136	56
						11.3	0	159	59	161	29
						11.3	10	156	58	185	3

*NO_3-N (nitrate-N) on sandy soils, Ntot (total N) on peat and clay soils

**MHG (mean highest groundwater table during winter)

Appendix 1B Simulated manure and mineral N fertilizer rates, resulting N and P2O5 yields and associated N-concentration in water and P2O5 surplus under average leaching risks and fair growing conditions and management, whilst aiming at a N-concentration of 11.3 mg N per liter (or less when no further yield increase is brought about) and a P2O5 surplus of -10, 0 or +10 kg per ha, as affected by crop type, harvest regime, soil type, and manure type (when applicable)

Crop type	Harvest regime	Growing conditions & management	Soil type	Manure type:		Environment:		Harvested crop yield:		Permissible N:	
				Nm/Ntot	Ntot/P_2O_5	NO_3-N or Ntot* water (mg/l)	P_2O_5 surplus (kg/ha)	N (kg/ha)	P_2O_5 (kg/ha)	manure (kg/ha)	fertilizer (kg/ha)
grass	cutting only	fair	peat	0.50	2.77	3.4	-10	320	94	229	206
						3.4	0	320	94	256	184
						3.5	10	320	94	284	163
			clay			8.9	-10	320	94	229	320
						9.1	0	320	94	256	298
						9.2	10	320	94	284	276
			sand, MHG < 0.4**			11.3	-10	314	92	224	240
						11.3	0	314	92	251	214
						11.3	10	313	92	279	189
			sand, 0.8 > MHG > 0.4			11.3	-10	303	89	215	187
						11.3	0	302	88	242	161
						11.3	10	301	88	269	135
			sand, MHG > 0.8			11.3	-10	298	87	211	168
						11.3	0	297	87	237	142
						11.3	10	295	86	264	116
grass	mixed use	fair	peat	0.50	2.77	3.9	-10	264	77	194	210
						3.9	0	264	77	222	189
						3.9	10	264	77	249	168
			clay			10.3	-10	281	82	208	330
						10.4	0	281	82	236	308
						10.5	10	281	82	264	286
			sand, MHG < 0.4**			11.3	-10	270	79	199	213
						11.3	0	270	79	226	187
						11.3	10	269	79	253	162
			sand, 0.8 > MHG > 0.4			11.3	-10	264	77	194	161
						11.3	0	263	77	221	135
						11.3	10	261	76	247	109
			sand, MHG > 0.8			11.3	-10	265	78	195	144
						11.3	0	263	77	222	118
						11.3	10	262	77	248	92
maize	cutting	fair	clay	0.50	2.77	11.3	-10	156	58	130	117
						11.3	0	155	57	156	90
						11.3	10	153	57	181	63
			sand, MHG < 0.4**			10.7	-10	153	57	126	107
						11.3	0	153	57	154	85
						11.3	10	151	56	180	59
			sand, 0.8 > MHG > 0.4			11.3	-10	138	51	111	69
						11.3	0	135	50	136	42
						11.3	10	132	49	160	15
			sand, MHG > 0.8			11.3	-10	131	48	104	55
						11.3	0	128	47	128	28
						11.1	10	124	46	152	1

*NO_3-N (nitrate-N) on sandy soils, Ntot (total N) on peat and clay soils

**MHG (mean highest groundwater table during winter)

Appendix II.

Appendix 2 Simulated manure and mineral N fertilizer rates, resulting N and P2O5 yields and associated N-concentration in water and P2O5 surplus under pessimistic (lowest value) and optimistic (highest value) assumptions concerning the leaching fraction and precipitation surplus, whilst aiming at a N-concentration of 11.3 mg N per liter (or less when no further yield increase is brought about) and a P2O5 surplus of 0 kg per ha, as affected by crop type, harvest regime, growing conditions and management, soil type, manure type (when applicable) or legal constraints (when applicable)

Crop type	Harvest regime	Growing conditions & management	Soil type	Manure type: Nm/Ntot	Manure type: Ntot/P2O5	Environment: NO3-N or Ntot* water (mg/l)	Environment: P2O5 surplus (kg/ha)	Harvested crop yield: N (kg/ha)	Harvested crop yield: P2O5 (kg/ha)	Permissible N: manure (kg/ha)	Permissible N: fertilizer (kg/ha)
grass	cutting only	good	peat	0.5	2.77	4.5 - 1.9	0	375	110	301	163
			clay			11.2 - 5.3	0	375	110	301	275
			sand, MHG < 0.4**			11.3 - 8.7	0	363 - 375	106 - 110	291 - 301	168 - 275
			sand, 0.8 > MHG > 0.4			11.3	0	355 - 373	104 - 109	285 - 300	140 - 232
			sand, MHG > 0.8			11.3	0	352 - 370	103 - 108	282 - 297	131 - 202
grass	mixed use		peat			5.2 - 2.2	0	312	91	261	166
			clay			11.3 - 6.2	0	331 - 332	97	276 - 277	250 - 284
			sand, MHG < 0.4**			11.3 - 10.2	0	311 - 332	91 - 97	260 - 277	139 - 284
			sand, 0.8 > MHG > 0.4			11.3	0	309 - 336	90 - 98	258 - 280	113 - 207
			sand, MHG > 0.8			11.3	0	314 - 340	92 - 99	263 - 284	106 - 179
maize	cutting		clay			11.3	0	171 - 204	63 - 76	172 - 206	50 - 180
			sand, MHG < 0.4**			11.3 - 6.4	0	171 - 180	63 - 66	172 - 181	50 - 69
			sand, 0.8 > MHG > 0.4			11.3 - 11.1	0	158 - 180	58 - 66	159 - 181	27 - 69
			sand, MHG > 0.8			11.3	0	152 - 170	56 - 63	153 - 171	18 - 48
0 grass	cutting only	fair	peat	0.5	2.77	5.2 - 2.2	0	320	94	256	184
			clay			11.3 - 6.3	0	319 - 320	93 - 94	255 - 256	261 - 298
			sand, MHG < 0.4**			11.3 - 10.3	0	299 - 320	87 - 94	240 - 256	150 - 298
			sand, 0.8 > MHG > 0.4			11.3	0	289 - 314	85 - 92	231 - 252	122 - 216
			sand, MHG > 0.8			11.3	0	285 - 308	83 - 90	228 - 247	113 - 185
grass	mixed use		peat			5.9 - 2.5	0	264	77	222	189
			clay			11.3 - 7.2	0	277 - 281	81 - 82	233 - 236	235 - 308
			sand, MHG < 0.4**			11.3	0	250 - 281	73 - 82	211 - 236	122 - 295
			sand, 0.8 > MHG > 0.4			11.3	0	229 - 279	67 - 81	194 - 234	91 - 191
			sand, MHG > 0.8			11.3	0	222 - 279	65 - 82	188 - 234	81 - 163
maize	cutting		clay			11.3	0	138 - 173	51 - 64	139 - 174	48 - 179
			sand, MHG < 0.4**			11.3 - 7.7	0	139 - 153	51 - 57	139 - 154	49 - 86
			sand, 0.8 > MHG > 0.4			11.3	0	127 - 147	47 - 55	127 - 148	26 - 70
			sand, MHG > 0.8			11.3	0	121 - 138	45 - 51	121 - 138	17 - 47

*NO3-N (nitrate-N) on sandy soils, Ntot (total N) on peat and clay soils

**MHG (mean highest groundwater table during winter)

Appendix III.

Appendix 3A — Simulated manure and mineral N fertilizer rates, resulting N and P2O5 yields and associated N-concentration in water and P2O5 surplus under average leaching risks and good growing conditions and management, whilst aiming at a N-concentration of 11.3 mg N per liter (or less when no further yield increase is brought about) and a P2O5 surplus of 0 kg per ha, as affected by manure composition through dietary manipulation, crop type, harvest regime, and soil type

Crop type	Harvest regime	Growing conditions & management	Soil type	Manure type:		Environment:		Harvested crop yield:		Permissible N:	
				Nm/Ntot	Ntot/P_2O_5	NO_3-N or Ntot* water (mg/l)	P_2O_5 surplus (kg/ha)	N (kg/ha)	P_2O_5 (kg/ha)	manure (kg/ha)	fertilizer (kg/ha)
grass	mixed use	good	peat	0.50	2.77 ***	3.4	0	313	91	261	166
				0.50	3.20 ***	3.5	0	313	91	292	143
				0.35	2.77 ***	3.5	0	313	91	261	162
			clay	0.50	2.77	9.0	0	332	97	277	284
				0.50	3.20	9.1	0	332	97	310	258
				0.35	2.77	9.2	0	332	97	277	282
			sand, MHG < 0.4**	0.50	2.77	11.3	0	326	95	272	203
				0.50	3.20	11.3	0	325	95	304	173
				0.35	2.77	11.3	0	325	95	272	197
			sand, 0.8 > MHG > 0.4	0.50	2.77	11.3	0	324	95	270	152
				0.50	3.20	11.3	0	322	94	301	122
				0.35	2.77	11.3	0	322	94	269	145
			sand, MHG > 0.8	0.50	2.77	11.3	0	327	96	273	135
				0.50	3.20	11.3	0	325	95	304	105
				0.35	2.77	11.3	0	325	95	271	129
maize	cutting	good	clay	0.50	2.77	11.3	0	187	69	189	91
				0.50	3.20	11.3	0	185	69	216	63
				0.35	2.77	11.3	0	184	68	185	88
			sand, MHG < 0.4**	0.50	2.77	9.5	0	180	66	181	85
				0.50	3.20	11.2	0	180	66	209	58
				0.35	2.77	11.2	0	180	66	181	82
			sand, 0.8 > MHG > 0.4	0.50	2.77	11.3	0	167	62	169	43
				0.50	3.20	11.3	0	164	61	191	19
				0.35	2.77	11.3	0	162	60	163	40
			sand, MHG > 0.8	0.50	2.77	11.3	0	159	59	161	29
				0.50	3.20	11.3	0	156	58	182	6
				0.35	2.77	11.3	0	153	57	154	26

*NO_3-N (nitrate-N) on sandy soils, Ntot (total N) on peat and clay soils

**MHG (mean highest groundwater table during winter)

*** standard manure 0.50 and 2.77, low P diets 0.50 and 3.20, low protein diets 0.35 and 2.77

Appendix 3B. Simulated manure and mineral N fertilizer rates, resulting N and P2O5 yields and associated N-concentration in water and P2O5 surplus under avereage leaching risks and fair growing conditions and management, whilst aiming at a N-concentration of 11.3 mg N per liter (or less when no further yield increase is brought about) and a P2O5 surplus of 0 kg per ha, as affected by manure composition through dietary manipulation, crop type, harvest regime, and soil type

Crop type	Harvest regime	Growing conditions & management	Soil type	Manure type:		Environment:		Harvested crop yield:		Permissible N:	
				Nm/Ntot	Ntot/P_2O_5	NO_3-N or Ntot* water (mg/l)	P_2O_5 surplus (kg/ha)	N (kg/ha)	P_2O_5 (kg/ha)	manure (kg/ha)	fertilizer (kg/ha)
grass	mixed use	fair	peat	0.50	2.77 ***	3.9	0	264	77	222	189
				0.50	3.20 ***	3.9	0	264	77	246	170
				0.35	2.77 ***	3.9	0	264	77	221	185
			clay	0.50	2.77	10.4	0	281	82	236	308
				0.50	3.20	10.5	0	281	82	262	287
				0.35	2.77	10.5	0	281	82	236	306
			sand, MHG < 0.4**	0.50	2.77	11.3	0	270	79	226	187
				0.50	3.20	11.3	0	269	79	251	164
				0.35	2.77	11.3	0	269	79	226	183
			sand, 0.8 > MHG > 0.4	0.50	2.77	11.3	0	263	77	221	135
				0.50	3.20	11.3	0	261	77	244	113
				0.35	2.77	11.3	0	262	76	220	130
			sand, MHG > 0.8	0.50	2.77	11.3	0	263	77	222	118
				0.50	3.20	11.3	0	262	77	244	96
				0.35	2.77	11.3	0	262	77	221	113
maize	cutting	fair	clay	0.50	2.77	11.3	0	155	57	156	90
				0.50	3.20	11.3	0	153	57	178	67
				0.35	2.77	11.3	0	151	56	152	87
			sand, MHG < 0.4**	0.50	2.77	11.3	0	153	57	154	85
				0.50	3.20	11.3	0	151	56	176	63
				0.35	2.77	11.3	0	150	55	151	82
			sand, 0.8 > MHG > 0.4	0.50	2.77	11.3	0	135	50	136	42
				0.50	3.20	11.3	0	133	49	154	22
				0.35	2.77	11.3	0	131	48	131	40
			sand, MHG > 0.8	0.50	2.77	11.3	0	128	47	128	28
				0.50	3.20	11.3	0	126	46	145	9
				0.35	2.77	11.3	0	123	46	124	26

*NO_3-N (nitrate-N) on sandy soils, Ntot (total N) on peat and clay soils

**MHG (mean highest groundwater table during winter)

*** standard manure 0.50 and 2.77, low P diets 0.50 and 3.20, low protein diets 0.35 and 2.77

Appendix IV.

Appendix 4A

Simulated manure and mineral N fertilizer rates, resulting N and P2O5 yields and associated N-concentration in water and P2O5 surplus under average leaching risks and good growing conditions and management and a mixed use of cutting and grazing, whilst aiming at a N-concentration of 11.3 mg N per liter (or less when no further yield increase is brought about) and a P2O5 surplus of 0 kg per ha, as affected by crop type, soil type, and manure type (when applicable)

Crop type	Harvest regime	Growing conditions & management	Soil type	Manure type:		Environment:		Harvested crop yield:		Permissible N:	
				Nm/Ntot	Ntot/P_2O_5	NO_3-N or Ntot* water (mg/l)	P_2O_5 surplus (kg/ha)	N (kg/ha)	P_2O_5 (kg/ha)	manure (kg/ha)	fertilizer (kg/ha)
grass	mixed use	good	peat	0.50	2.77	3.4	0	313	91	261	166
				0.55	3.09	3.4	0	312	91	284	149
				0.61	3.49	3.4	0	313	91	312	128
				0.66	4.01	3.4	0	313	91	349	100
				0.71	4.72	3.4	0	313	91	399	62
			clay	0.50	2.77	9.0	0	332	97	277	284
				0.55	3.09	9.0	0	332	97	302	264
				0.61	3.49	9.0	0	332	97	332	238
				0.66	4.01	9.0	0	332	97	372	206
				0.71	4.72	9.0	0	332	97	426	161
			sand, MHG < 0.4**	0.50	2.77	11.3	0	326	95	272	203
				0.55	3.09	11.3	0	326	95	296	183
				0.61	3.49	11.3	0	326	95	326	159
				0.66	4.01	11.3	0	326	95	365	126
				0.71	4.72	11.3	0	326	95	418	82
			sand, 0.8 > MHG > 0.4	0.50	2.77	11.3	0	324	95	270	152
				0.55	3.09	11.3	0	324	95	294	132
				0.61	3.49	11.3	0	324	95	324	108
				0.66	4.01	11.3	0	324	95	362	76
				0.71	4.72	11.3	0	324	95	415	33
			sand, MHG > 0.8	0.50	2.77	11.3	0	327	96	273	135
				0.55	3.09	11.3	0	327	96	297	116
				0.61	3.49	11.3	0	327	96	327	91
				0.66	4.01	11.3	0	327	96	366	59
				0.71	4.72	11.3	0	327	96	419	15
maize	cutting	good	clay	0.50	2.77	11.3	0	187	69	189	91
				0.55	3.09	11.3	0	187	69	211	71
				0.61	3.49	11.3	0	188	69	239	47
				0.66	4.01	11.3	0	188	69	274	15
				0.71	4.72	11.3	-7	189	70	294	0
			sand, MHG < 0.4**	0.50	2.77	9.5	0	180	66	181	69
				0.55	3.09	11.3	0	180	66	202	66
				0.61	3.49	11.3	0	180	66	228	44
				0.66	4.01	11.3	0	180	66	264	11
				0.71	4.72	11.3	-6	180	66	279	0
			sand, 0.8 > MHG > 0.4	0.50	2.77	11.3	0	167	62	169	43
				0.55	3.09	11.3	0	167	62	188	26
				0.61	3.49	11.3	0	168	62	213	4
				0.66	4.01	11.3	-7	170	63	221	0
				0.71	4.72	11.3	-15	172	64	225	0
			sand, MHG > 0.8	0.50	2.77	11.3	0	159	59	161	29
				0.55	3.09	11.3	0	159	59	179	13
				0.61	3.49	11.3	-2	161	59	195	0
				0.66	4.01	11.3	-10	163	60	199	0
				0.71	4.72	11.3	-17	165	61	203	0

*NO_3-N (nitrate-N) on sandy soils, Ntot (total N) on peat and clay soils

**MHG (mean highest groundwater table during winter)

Appendix 4B Simulated manure and mineral N fertilizer rates, resulting N and P2O5 yields and associated N-concentration in water and P2O5 surplus under average leaching risks and fair growing conditions and management and a mixed use of cutting and grazing, whilst aiming at a N-concentration of 11.3 mg N per liter (or less when no further yield increase is brought about) and a P2O5 surplus of 0 kg per ha, as affected by crop type, soil type, and manure type (when applicable)

Crop type	Harvest regime	Growing conditions & management	Soil type	Manure type:		Environment:		Harvested crop yield:		Permissible N:	
				Nm/Ntot	Ntot/P_2O_5	NO_3-N or Ntot* water (mg/l)	P_2O_5 surplus (kg/ha)	N (kg/ha)	P_2O_5 (kg/ha)	manure (kg/ha)	fertilizer (kg/ha)
grass	mixed use	fair	peat	0.50	2.77	3.9	0	264	77	222	189
				0.55	3.09	3.9	0	264	77	240	175
				0.61	3.49	3.9	0	264	77	262	158
				0.66	4.01	3.9	0	264	77	292	136
				0.71	4.72	3.9	0	264	77	332	106
			clay	0.50	2.77	10.4	0	281	82	236	308
				0.55	3.09	10.4	0	281	82	256	292
				0.61	3.49	10.4	0	281	82	280	272
				0.66	4.01	10.4	0	281	82	312	245
				0.71	4.72	10.4	0	281	82	356	208
			sand, MHG < 0.4**	0.50	2.77	11.3	0	270	79	226	187
				0.55	3.09	11.3	0	269	79	245	172
				0.61	3.49	11.3	0	270	79	268	153
				0.66	4.01	11.3	0	270	79	299	128
				0.71	4.72	11.3	0	270	79	340	94
			sand, 0.8 > MHG > 0.4	0.50	2.77	11.3	0	263	77	221	135
				0.55	3.09	11.3	0	263	77	239	120
				0.61	3.49	11.3	0	263	77	262	102
				0.66	4.01	11.3	0	263	77	291	78
				0.71	4.72	11.3	0	263	77	331	45
			sand, MHG > 0.8	0.50	2.77	11.3	0	263	77	222	118
				0.55	3.09	11.3	0	263	77	240	103
				0.61	3.49	11.3	0	264	77	262	85
				0.66	4.01	11.3	0	264	77	292	61
				0.71	4.72	11.3	0	264	77	332	27
maize	cutting	fair	clay	0.50	2.77	11.3	0	155	57	156	90
				0.55	3.09	11.3	0	155	57	174	74
				0.61	3.49	11.3	0	155	57	196	54
				0.66	4.01	11.3	0	155	57	226	27
				0.71	4.72	11.3	-2	155	57	257	0
			sand, MHG < 0.4**	0.50	2.77	11.2	0	153	57	154	85
				0.55	3.09	11.3	0	153	57	172	69
				0.61	3.49	11.2	0	153	57	194	49
				0.66	4.01	11.2	0	153	57	223	23
				0.71	4.72	11.3	-3	153	57	250	0
			sand, 0.8 > MHG > 0.4	0.50	2.77	11.3	0	135	50	136	42
				0.55	3.09	11.3	0	135	50	151	28
				0.61	3.49	11.3	0	135	50	171	10
				0.66	4.01	11.3	-3	136	50	185	0
				0.71	4.72	11.3	-10	138	51	188	0
			sand, MHG > 0.8	0.50	2.77	11.3	0	128	47	128	28
				0.55	3.09	11.3	0	128	47	143	15
				0.61	3.49	11.3	0	128	47	160	0
				0.66	4.01	11.3	-6	130	48	163	0
				0.71	4.72	11.3	-13	132	49	167	0

*NO_3-N (nitrate-N) on sandy soils, Ntot (total N) on peat and clay soils

**MHG (mean highest groundwater table during winter)