NPo-forskning
fra Miljøstyrelsen

Nr. A20 1991

Simulation of Nitrogen Losses Using the SOILN Model

Miljøministeriet **Miljøstyrelsen**

Danish Research Programme on Nitrogen, Phosphorus and Organic Matter (NPO)

The aim of the NPO Research Programme is to gather knowledge on the decomposition of Nitrogen (N), Phosporus (P) and organic matter (O) in the soil, and on their impact on lakes, watercourses, inlets, groundwater and the sea.

This report is one of a total of about 50 reports to be issued in connection with the implementation of the NPO Research Programme. The National Agency of Environmental Protection (NAEP) is responsible for the programme, under which about 70 NPO projects have been launched, carried out at 25-30 institutions.

In the 1970's and the beginning of the 1980's there was a growing awareness of the threats to life in watercourses etc. presented by discharges of nutrients – and of the risk of nitrate contamination of groundwater. In 1984 a report was prepared, synthesising existing knowledge in this field. The report, known by the name of NPO Report, was published by the NAEP.

To follow up this report the Dansih Parliament took the first steps in 1985 to reduce pollution with nutrients – laying down requirements for storage and application of farm yard manure in the agricultural sector.

For the purpose of improving our knowledge on the impact of nutrients in nature, the Danish Parliament also reserved 50 million DKK for the research programme, running from 1985 to the end of 1990.

The significance of the NPO Research Programme was further underlined with the Danish Parliament's adoption of the Action Plan on the Aquatic Environment in 1987. The results of the NPO Research Programme will play a vital role in the evaluation of the effects of the Action Plan.

To safeguard the technical and economic interests relating to the research activities a steering group was set up, having the overall responsibility for the implementation of the NPO Research Programme. Furthermore, three coordination groups were formed, each of them responsible for one of the three fields: soil and air, groundwater, and surface water.

The reports are published in the series »NPo-forskning fra Miljøstyrelsen« (NPO Research in the NAEP), divided into three sections:

A: reports on soil and air
B: reports on groundwater
C: reports on watercourses, lakes and marine waters.

The NAEP has been secretariat for the research programme. The reports published in this series are edited by the Agency with the assistance of the coordination groups.

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Sammanfattning

Simulering av kväveförluster med hjälp av SOILN modellen

En markkvävemodel (SOILN) användes tillsammans med en modell för vatten och värmeflöden i mark (SOIL) för att simulera kväveförluster från fyra fält i Danmark. Fälten odlades enligt konventionell praksis vilket bl a inkluderade spridning av stallgödsel. Två av fälten var belägna i ett område på Jylland (Rabis) med sandjord medans de två andra fälten var belägna i ett område på Själland (Syv) med sandig lättlera. Parameteriseringen av modellen baserades på treåriga dataset (1987-1990) från de olika fälten och på tidigare tillämpningar med modellen. Simulerade nitratkoncentrationer i markvätskan jämfördes med motsvarande mätvärden. Medelvärdet av simulerad nitratutlakning från de olika fälten varierade mellan 49 och 91 kg N ha^{-1} år^{-1}.

Ett flertal olika odlingsåtgärder för att reducera kväveutlakningen simulerades. Kriteriet för dessa åtgärder var att växtens tillväxt (N-upptag) ej skulle förändras jämfört med de ursprungliga simuleringarna. Om mängden handelsgödsel reducerades och tidpunkten för stallgödselspridning ändrades kunde nitratutlakningen för de olika fälten reducerades med respektive 11%, 31%, 42% och 70%. Genom att också ändra från vår till höstgrödor kunde nitratutlakningen reduceras med 32%, 47%, 53% och 70%. Om fånggrödor odlades och handelssgödslingen reducerades kunde nitratutlakningen reduceras med 64%, 65%, 70% och 70%. Motsvarande mängder nitratutlakning i detta fall var då 30, 17, 27 och 20 kg N ha^{-1} år^{-1}. Användandet av fånggrödor i dessa odlingssystem medförde en ökad uppbyggnad av det organiska kvävet i marken. Nedplöjning av halm och byte från flytgödsel till fastgödsel simulerades också men dessa åtgärder hade en mindre uttalad effekt på nitratutlakningen.

Summary

A soil nitrogen model (SOILN) coupled to a soil water and heat model (SOIL) was used to simulate nitrogen losses from four arable fields in Denmark. The fields were cropped and managed according to conventional farming practices including the application of manure. Two of the fields were located in the middle of Jylland on sandy soils (Rabis), whereas the other two were located in Sjaelland on sandy loam soils (Syv). Model parameterization was based on 3-years of data (1987-90) from the field sites and on previous applications of the model. Simulated nitrate concentrations in the soil solution were compared with corresponding measured values. Mean simulated nitrate leaching from the different fields varied between 49 and 91 kg N ha^{-1} $year^{-1}$.

Various measures to reduce nitrate leaching, involving changes in management practices, were also simulated. A major criterium for these measures was that they should not lead to any changes in crop production levels (N-uptake). Nitrate leaching was reduced by 11%, 31%, 42% and 70% in the four fields by reducing the amount of commercial fertilizer applied and by altering the timing of manure application. Changing from spring crops to winter crops resulted in a reduction in nitrate leaching by 32%, 47%, 53% and 70% respectively. By introducing catch crops, in combination with a reduction in commercial fertilizer rates and a change in the timing of manure application, leaching was reduced by 64%, 65%, 70% and 70%. Corresponding nitrate leaching values in this case were 30, 17, 27 and 20 kg N ha^{-1} $year^{-1}$. Introducing a catch crop in these cropping systems resulted in an increased buildup of soil organic nitrogen. Incorporation of straw and changing from liquid to solid manure were also simulated, but had less pronounced effects on nitrate leaching.

1. Introduction

SOILN model

Nitrogen leaching from arable soil is a highly dynamic process showing considerable temporal variability due to variation in weather conditions, cropping systems and management practices. To understand how the various biological and physical processes operate with regard to soil mineral N dynamics and nitrogen losses, mathematical models can be used. From 1984 to 1986 such a model was developed with the main purpose of describing soil mineral N dynamics and nitrogen losses from soil (SOILN model, Johnsson et al., 1987). The model was coupled to a soil water and heat model (SOIL; Jansson & Halldin, 1979). Since then, the model has been thoroughly applied and tested in various field experiments (Johnsson et al., 1987; Bergström & Johnsson, 1988; Jansson et al., 1987; Jansson & Andersson, 1988; Gustafson, 1988; Jansson et al., 1989b; Borg et al, 1990; Bergström et al 1990; Eckersten & Jansson, 1990; Bergström & Jarvis, 1990; Torstensson, 1990). These studies have shown that the model can estimate nitrogen leaching with good precision if soil mineral nitrogen dynamics can be well described (Johnsson, 1990). Thus, in the case of an application for which the data set for parameterization is limited, the SOILN model could be used based on the parameterizations made during the previous applications and tests of the model. Within the NPO-programme, a model describing nitrogen flows in the soil-plant system has also been developed (DAISY; Hansen et al., 1990). It is similar to the SOILN and SOIL models in terms of its one-dimensional structure and its intended areal scale for application. However, thus far the DAISY model has only been tested to a limited extent.

Objectives

The main purpose of this study was to use the SOIL and SOILN models 1) to estimate nitrogen losses from fields subjected to ordinary farming practise and 2) to simulate the effect of various kinds of measures, involving changes in management practices, aimed at reducing nitrate leaching. The model was applied to four arable fields where only a limited amount of data were available (Hansen 1990). Thus, model parameterization was partly based on previous applications of the model. The fields were located within two of the experimental areas established by the Danish NPO-programme (Syv and Rabis).

2. Model description

Model structure

The modelling approach consists of a coupling in series of a soil nitrogen model (SOILN; Johnsson et al., 1987) and a soil water and heat model. The soil water and heat model (SOIL; Jansson & Halldin, 1979) provides driving variables for the SOILN model, i.e., infiltration, water flow between layers and to drainage tiles, unfrozen soil water content and soil temperature. The model has a one-dimensional vertical structure, with the profile divided into layers which may vary, depending on required accuracy as well as physical and biological characteristics of the soil.

2.1 Soil water and heat model

SOIL model

The water and heat model is based on two coupled differential equations describing heat and water transport (derived from Fourier's and Darcy's laws, respectively) in a soil profile. Snow dynamics, frost, evapotranspiration, infiltration and surface runoff and drainage flows are included. The model uses standard daily meteorological data as input to predict soil water and heat conditions at any level in the soil profile.

Soil water flow

The flow of water in both partially frozen and unfrozen soil is calculated by combining Darcy's law and the law of mass balance (Richards, 1931):

$$\frac{\partial \theta}{\partial t} = - \frac{\partial}{\partial z}\left(K \left(\frac{\partial \psi}{\partial z} + 1 \right)\right) - S \qquad (1)$$

where θ is the soil water content, ψ is the water tension, K is the unsaturated hydraulic conductivity, z is the soil depth, and S is a sink term (root water uptake, drainage, etc.). The water retention curve and the hydraulic conductivity function are given by expressions based on earlier work by Brooks & Corey (1964) and Mualem (1976).

Tile drainage

Water flow to drainage tiles occurs when the simulated groundwater level is above the level of the tiles. Calculation of potential evapotranspiration is based on the Penman combination equation as given by Monteith (1965). Actual water uptake by roots from each layer is calculated according to a time-dependent depth distribution of roots and an empirical reduction function accounting for soil water availability.

Soil heat flow

The heat flow equation includes both the freezing-thawing of water and the convective effect of water flow:

$$\frac{\partial(CT)}{\partial t} - L_f \rho_i \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z}\left(K_h \frac{\partial T}{\partial z}\right) - C_w \frac{\partial(T q_w)}{\partial z} \quad (2)$$

where C denotes the volumetric heat capacity of the soil, T the temperature, L_f the latent heat of freezing, ρ_i the density of ice, θ_i the ice content, K_h the thermal conductivity, C_w the volumetric heat capacity of water, and q_w the vertical flow rate of water. In frozen soils, the water and heat equations are coupled using a freezing point depression function.

2.2 Soil nitrogen model

SOILN model

The soil nitrogen model (Johnsson et al., 1987) includes the major processes determining inputs, transformations and outputs of nitrogen in arable soils (Fig. 1). Inputs of nitrogen can be in the form of commercial fertilizer or manure or both, added to the topsoil, and atmospheric deposition to the soil surface; harvest, leaching and denitrification constitute the output. Litter, faeces and humus comprise the organic-N fractions. The litter fraction represents undecomposed material (e.g., crop residues, dead roots), microbial biomass and metabolites. The faeces component represents the digested fraction in manure, i.e., excluding bedding material. The humus component represents stabilized organic material derived from litter decomposition. Organic carbon pools are included for litter and faeces in order to regulate nitrogen mineralization and decomposition.

Humus

Mineralization of humus nitrogen is calculated as a first-order rate process:

$$N_{h \to NH_4} = k_h\, e_t\, e_m\, N_h \quad (3)$$

where N_h is the nitrogen humus mass, k_h is the specific mineralization constant and e_t and e_m are response functions for soil temperature and moisture.

Litter and faeces

Similarly, decomposition of the litter carbon pool, $C_{l(d)}$, is calculated as a first-order rate process:

$$C_{l(d)} = k_l\, e_t\, e_m\, C_l \quad (4)$$

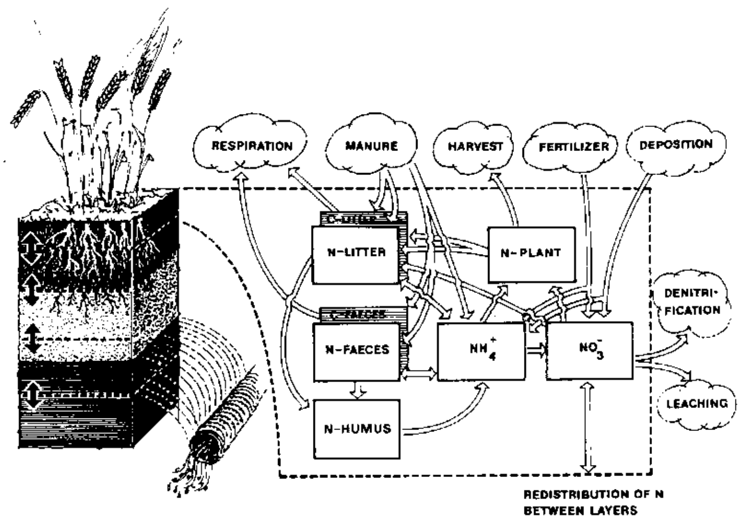

Figure 1. Structure of the soil nitrogen model, showing state variables (boxes) and flows (arrows) included in the model. The model structure is replicated for each soil layer (From Johnsson et al., 1987).

where k_l is the specific mineralization constant and C_l is the carbon litter mass. Decomposition of the faeces carbon pool is calculated in the same way.

Decomposition products are partitioned into three fractions according to a microbial synthesis efficiency (f_e) and a humification fraction (f_h). One fraction is lost as carbon dioxide (CO_2), a second fraction is assimilated and recycled within the pool, and the remainder is stabilized as humus. Corresponding nitrogen flows are calculated assuming a constant carbon-nitrogen ratio (r_0) of decomposer biomass and humification products.

The net mineralization of litter nitrogen is determined by the balance between the release of nitrogen during decomposition and the nitrogen immobilized during microbial synthesis and humification:

$$N_{l \leftrightarrow NH_4} = \left(\frac{N_l}{C_l} - \frac{f_e}{r_o} \right) C_{l(d)} \qquad (5)$$

where N_l is the nitrogen litter mass. Negative values for $N_{l \leftrightarrow NH4}$ in eq. (5) indicate net immobilization (i.e., $N_l/C_l < f_e/r_0$), so that mineral-N is transferred to the litter-N pool. Mineralization from faeces is handled in the same fashion.

Abiotic response functions A Q_{10} expression (e.g. Bunnel et al., 1977) is used for the soil temperature response function, e_t, regulating all biological processes in the model. The effect of soil moisture, e_m, on biological activity (all processes except denitrification) is calculated based on the assumption that the activity decreases on either side of an optimum soil moisture content range (Johnsson et al., 1987).

Plant N uptake

Plant uptake of nitrogen is treated using a time-dependent empirical function requiring parameter values specific for the crop and site concerned. A logistic growth curve (cf. Greenwood et al., 1974) is used to define a potential uptake demand during the growing season, which is distributed in the soil profile according to an assumed root distribution. Nitrogen uptake is reduced when the demand exceeds the available mineral-N in the soil (given as a fraction of the total mineral-N in soil). At harvest and ploughing the roots and harvest residues are incorporated into the soil litter pool.

Denitrification

Denitrification rates are calculated as follows:

$$N_{NO_3 \rightarrow N_2O + N_2} = k_d \, e_{md} \, e_t \, e_{NO_3} \qquad (6)$$

where k_d is a potential rate and e_t, e_{md} and e_{NO3} are response functions accounting for the effects of soil temperature, soil oxygen status and soil nitrate content, respectively. The effect of oxygen status is indirectly expressed as a function of soil moisture content, which increases from zero at a threshold water content and reaches a maximum of 1.0 at saturation. The effect of nitrate is given as a Michaelis-Menton type expression, i.e. a hyperbolic function controlled by a half-saturation constant.

Nitrate transport

Nitrate transport is calculated as the product of water flow and nitrate concentration in the soil layer from which the water flow originates. Ammonium is considered to be immobile in the soil profile.

3. Site descriptions

Syv and Rabis

Four fields, on which both manure and commercial fertilizer had been regularly applied (see Appendices 1-4), were chosen arbitrarily from a list of fields presented in a report by Hansen (1990). The fields were located in two experimental areas connected with the NPO-programme in Denmark: Syv baek, located in Ramsö municipality in the middle of Sjaelland, and Rabis baek, located in Karup municipality in the middle of Jylland. The fields chosen at Syv are denoted as L1 and L4, while those at Rabis are designated as S2 and S6, in accordance with the notations used by Hansen (1990).

Sand and sandy loams

The area at Syv consists of till, and the soils at the chosen sites are sandy loams. The area at Rabis consists of glacifluvial deposits, and the soils at the chosen sites are sand. Organic N contents of the soils are given in Table 1. The field sites are described in detail by Hansen (1990). Additional information, concerning harvest yields, management practices, soil organic N contents, and soil water contents were kindly provided by B. Hansen (pers. comm. 1990). The meteorological measurements at Rabis and Syv are described in Olesen (1990).

Table 1. *Initial values of organic nitrogen in the soil layers (kg N ha^{-1}) at the different field sites at 1 April 1987.*

	Field							
Soil layer	L1 humus	L1 litter	L4 humus	L4 litter	S2 humus	S2 litter	S6 humus	S6 litter
0-20 cm	4860	40	5470	40	3450	20	2760	20
20-40 cm	3840	20	2750	20	2250	10	910	10
40-70 cm	2500	10	2290	10	1350	0	910	0
70-100 cm	830	0	1370	0	1840	0	930	0
0-100 cm	12100		11950		8920		5540	

4. Model parameterization

4.1 Water and heat simulations

Previous application

Parameterization of the SOIL water and heat model was based on an application of the model by Johnsson & Jansson (1990) and on measurements of the soil physical properties made at the field sites.

Soil profile

The soil profiles were divided into four layers down to 1 m depth: 0-20 cm, 20-40 cm, 40-70 cm, and 70-100 cm. Free drainage was assumed at 1 m depth. Measurements were made of soil texture, water retention characteristics and saturated hydraulic conductivity in one profile at each field site (Hansen, 1990). Functions for hydraulic conductivity and water retention were adapted to these measured values.

Meteorological data

Meteorological data, which were obtained from measurements made at the experimental areas, were kindly provided by J.E. Olesen (pers. comm. 1990).

Evapotranspiration

Parameters related to evapotranspiration were based on the parameter setting by Johnsson & Jansson (1990). The surface resistance parameter in the Penman-Monteith equation was adjusted to obtain a reasonable degree of agreement between simulated and measured soil water contents in the different layers. Water contents were measured on some occasions in the soil cores in connection with soil sampling for mineral-N analyses. Some of the parameter values used in the simulations are given in Appendix 5.

4.2 Nitrogen simulations

Procedure

The parameterization of the SOILN model was based on previous applications to various sites in Sweden, as mentioned above (Johnsson et al., 1987; Bergström and Johnsson et al., 1988; Jansson et al., 1987; Borg et al., 1990; Gustafson, 1988). Information about the soil, management, crops, and harvest, etc., were obtained from the field sites (Hansen et al., 1990). The model was adapted to the field site by changing site-specific parameters, such as the amount of organic-N in the soil and potential crop uptake. The model was not calibrated by changing rate constants controlling mineralization, etc. The values of these parameters were used the same as the values in the previous applications, where calibrations had been made.

Simulations were made in two steps: Firstly, nitrogen losses and N-turnover in the four fields were simulated according to the actual crops and management practices. Plant N-uptake estimates were used as target values for simulated uptake, and measured nitrogen concentrations in soil solution were compared with simulated concentrations. Secondly, various alterations in management practices were simulated to evaluate their effect on simulated nitrogen losses.

Various parameters common to the different applications are given in Appendix 6. Parameters related to crops and management during each of the years are given in Appendices 1-4.

Soil nitrogen

Values for the initial amounts of humus-N in the soil were based on measurements of total organic N made at the different field sites (Tab. 1). Initial amounts of litter-N in the topsoil were 40 kg N ha^{-1}in fields at Syv and 20 kg N ha^{-1} in the fields at Rabis. Initial values of mineral N content in the soil was roughly estimated so that the simulated and measured nitrate concentrations in the soil solution agreed at the first measurement occasion.

N mineralization

Parameter values related to mineralization of soil litter nitrogen were the same as those used in the application by Johnsson et al. (1987). Corresponding faeces-N parameters were identical to those used by Borg et al. (1990). The value of the rate constant for humus mineralization was set equal to the value obtained by Torstensson (1990) when applying the model to a sandy loam soil in southwest Sweden. This soil was assumed to be very similar to the soils in the present study. In addition, the cropping history of that field, including manure application, was similar to those of the fields being treated here. The soil moisture response function was the same as that used in Johnsson et al. (1990), whereas the soil temperature response function corresponded to that used by Bergström and Johnsson (1988).

Denitrification

The value for the potential denitrification rate was based on the value used by Johnsson et al. (1990) for a barley crop when testing the denitrification part of the model. Their value for the potential rate in the grass ley treatment of the same experiment was about 5-fold higher. However, it was assumed that the cropping systems in the present investigation, based mainly of annual grains, were more similar to the barley treatment in the study above than to the ley treatment.

Fertilization

Measurements of organic N and ammonia N contents in applied manure were available for all fields. It was assumed that 15% of the ammonia in the manure was lost during spreading as a result of ammonia volatilization. When manure was spread on a growing crop, 30% of the ammonia in the manure was assumed to be lost. These reductions were made prior to the simulations, since the model does not treat ammonia volatilization. The C:N ratio of the manure was set to 22 in all treatments.

4.3 Estimation of crop N uptake

Available field crop data were limited to grain and straw yields. To estimate total plant N uptake and the relative amounts of N in harvested material, harvest residues and roots, the following assumptions were made:

- The grain N-content was 2.2% (dry matter).
- The nitrogen content of harvest residues from grain crops was 0.9% (dry matter).
- The nitrogen content of rape seed was 4.1% (dry matter).
- The nitrogen content of harvest residues from rape crops was 1.1% (dry matter).
- 50% of the above-ground residue-N of grain crops was left on the field, and 50% was exported as straw.
- 20% of the total plant-N uptake was located in roots (Hansson et al., 1989). Due to the very low production of the barley on field S6, the root-N fraction there was assumed to be 30% (Hansson et al., 1989).
- The above-ground residues:crop yield ratio for rape (dry matter) was assumed to be 2.5.

These assumptions are mainly based on data from field experiments in Sweden (E. Haak, unpublished). Potential plant N uptake was parameterized so that simulated actual uptake was similar to an estimate based on the above described assumptions. Similarly, the harvested fraction of plant N and the plant residue fraction (App. 6) were based on these assumptions. Crop uptake was assumed to begin about 2 weeks after sowing. A compensatory vertical redistribution of potential root uptake was made in all applications (Johnsson et al., 1987).

4.4 Measures to reduce N losses

Criteria

A major criterium used when simulating changes in the original management practices was to keep plant-N uptake (i.e., production and yield) reasonably unchanged. Changes of 5% or less per year were considered acceptable. Thus, changes were made to achieve as great a reduction in N losses as possible without exceeding the - 5% limit.

Changes in management

The following alterations in the original management practices were simulated:

1. The amount of manure applied was reduced, and, if necessary, the timing of the manure application was changed. The application rate of commercial fertilizer was not changed.

2. The application rate of commercial fertilizer was reduced and the timing of the manure application was altered. The total amount of manure applied during the period was kept unchanged.
3. Winter crops were cultivated instead of spring crops. Crop growth was assumed to start after sowing in autumn (App. 1-4), cease at the end of November and resume after winter, at the end of March. The application rate of commercial fertilizer was reduced and the timing of the manure application was changed as described under point 2 above.
4. Straw was left at harvest and incorporated into the topsoil at ploughing instead of being removed. The application rate of commercial fertilizer was reduced and the timing of the manure application was changed as described under point 2 above.
5. A catch crop was added to the main crop. The catch crop continued to grow after harvest of the main crop up until the end of November. The soil was not ploughed until the following spring. At ploughing, the whole catch crop was worked into the soil. It was assumed that the main crop was not negatively influenced by the catch crop. The application rate of commercial fertilizer was reduced and the timing of the manure application was changed as described under point 2 above.
6. Solid manure was substituted for liquid manure. 65% of total N was assumed to be in the organic form (this was the approximate relation for the solid manure applied on field S2). The timing of the manure application was changed as described under point 2 above. Since solid manure contains a relatively larger fraction of organic-N, which is not immediately available for crop uptake, the switch from liquid to solid manure made it necessary to somewhat increase the application rates of commercial fertilizer compared to the application rates as described under point 2 above.

Note that the management practices described under points 3 to 6 involved reductions in commercial fertilizer rates as described under point 2, i.e., reduced amounts of commercial fertilizer. The various alterations in parameter settings, made to study the effect of the different management practices, are shown in Appendices 1-4.

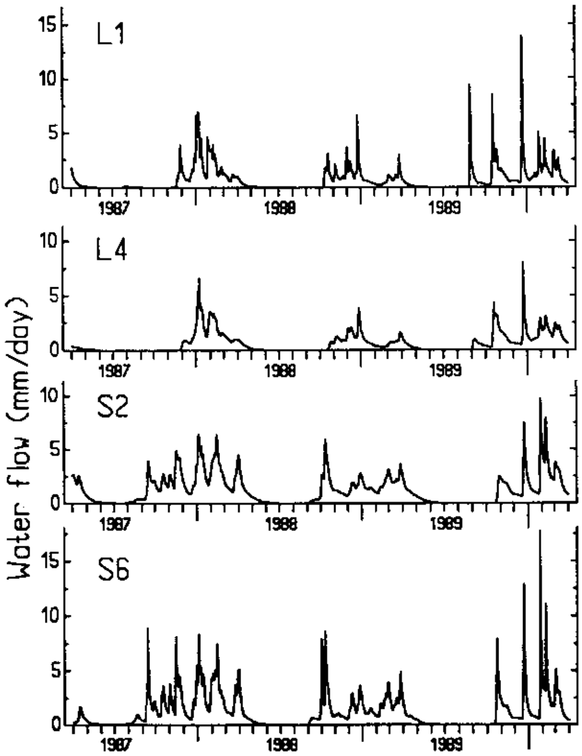

Figure 2. Simulated drainage flows at 1 m depth in the different fields.

5. Results

5.1 Water balance

Simulated drainage for the various fields is given in Table 2. Drainage volumes from the Rabis fields were about twice those of the Syv fields, reflecting the higher precipitation rates at Rabis. Drainage during the winter season occurred for 5-6 months at Syv and about 6-8 months at the Rabis fields (Fig. 2).

Table 2. Precipitation (corrected for wind losses) and drainage flow at 1m depth. Annual sums for the periods 1 April to 31 Mars the following year and 3-year total for the period 1 April 1987 to 31 Mars 1990.

Field	Precipitation (mm) 87/88	88/89	89/90	Total	Drainage (mm) 87/88	88/89	89/90	Total
L1	615	578	692	1885	275	201	234	710
L4	615	578	692	1885	242	178	317	737
S2	938	740	775	2453	608	401	416	1425
S6	938	740	775	2453	594	408	424	1426

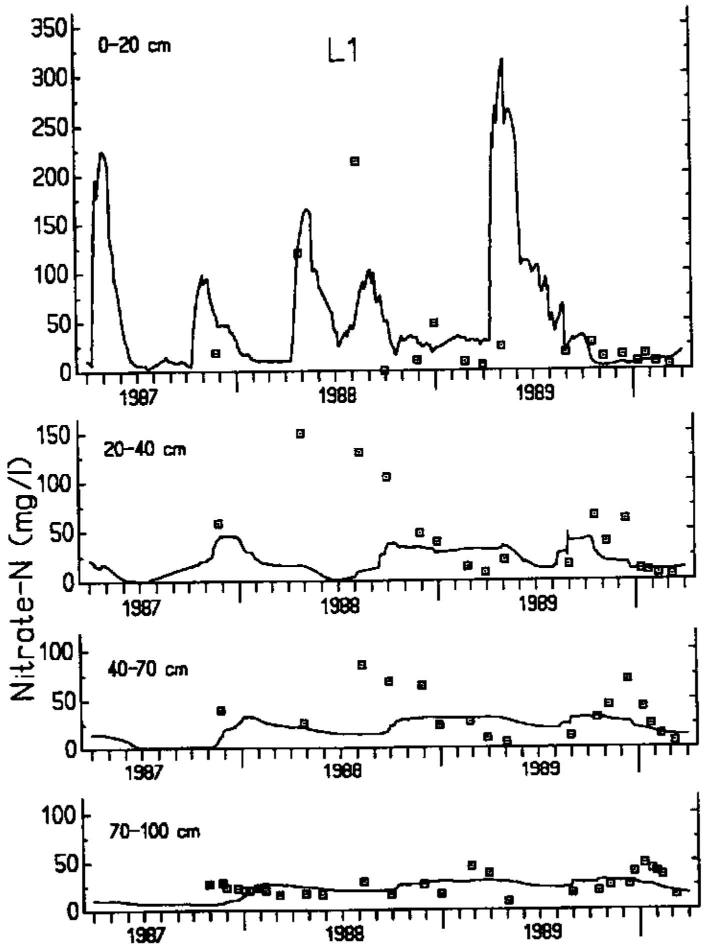

Figure 3. Simulated and measured (□) nitrate-N concentrations in soil solution at different depths in the soil profile at field L1.

5.2 Nitrate concentrations

Simulated and measured nitrate concentrations in the soil solution in the different treatments are given in Figures 3 to 6. A generally good agreement was obtained, considering the limited amount of data available for adapting the model to the different sites. It should be noted that differences between simulated and measured concentrations

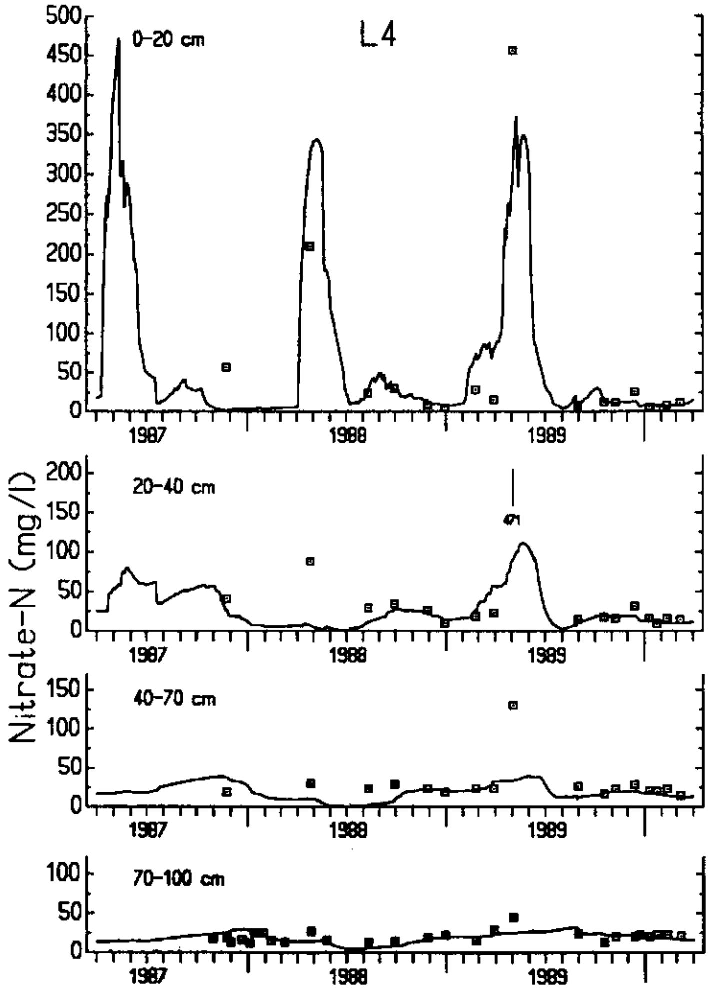

Figure 4. Simulated and measured (□) nitrate-N concentrations in soil solution at different depths in the soil profile at field L4.

can be due either to a deviation between simulated and measured water contents or simulated and measured soil nitrate contents. Deviations between simulated and measured nitrate concentrations occurred mainly in the upper layers of the sandy loam soils at Syv. However, the concentration of nitrate in the soil solution of the bottom layer determines the concentration of the leachate.

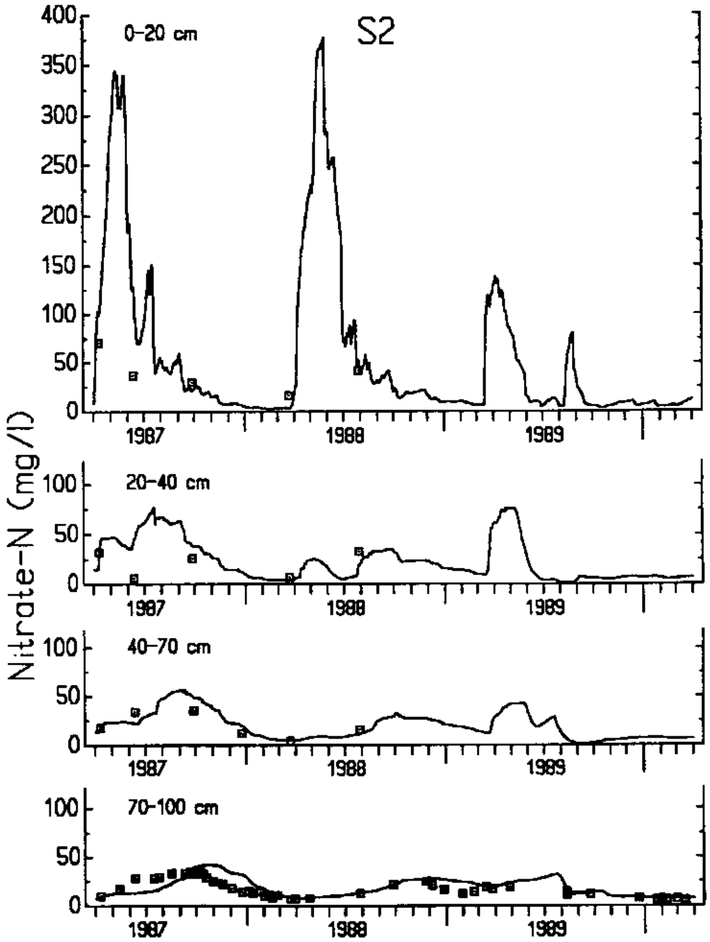

Figure 5. Simulated and measured (□) nitrate-N concentrations in soil solution at different depths in the soil profile at field S2.

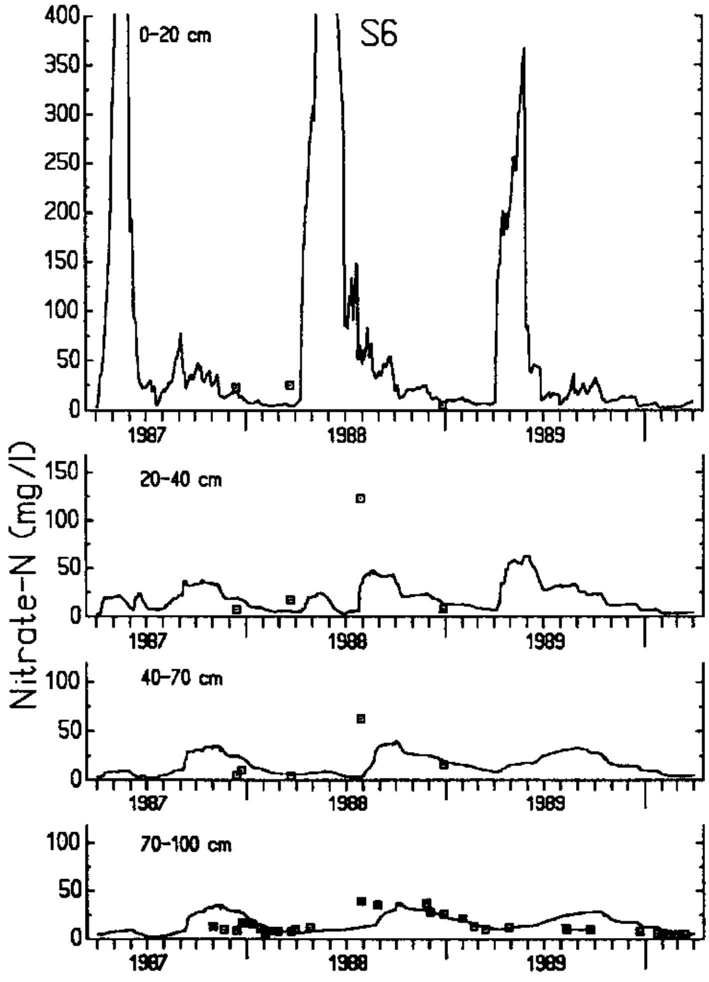

Figure 6. Simulated and measured (□) nitrate-N concentrations in soil solution at different depths in the soil profile at field S6.

5.3 Nitrogen losses

Reducing the total amount of applied manure or commercial fertilizer resulted in a considerable reduction in leaching (Tab. 3-7). These fertilization reductions were made without reducing the total plant N uptake (i.e., ± 5% change was tolerated). Losses of N due to harvest export were considerably higher in the Syv (L1 and L4) treatments than in the Rabis (S2 and S6) treatments (Tab. 3-7). Grain yields at Syv ranged between 5300 and 7000 kg dry matter ha^{-1} $year^{-1}$, while yields at Rabis ranged between 2000 and 3100 kg dry matter ha^{-1} $year^{-1}$ (App. 1-4). As mentioned above, prior to the simulation, N-losses due to ammonia volatilization were subtracted from the total amount of ammonium nitrogen in applied manure.

Table 3. Harvest export (including both grain and straw), leaching and denitrification losses. Annual sums for the periods 1 April to 31 Mars the following year and 3-year total for the period 1 April 1987 to 31 Mars 1990. All values in kg N ha^{-1}.

	Harvest export				Leaching				Denitrifikation			
	87	88	89	Total	87/88	88/89	89/90	Total	87/88	88/89	89/90	Total
L1												
Normal	161	103	202	466	55	56	86	197	6	7	8	21
Reduced manure	161	97	195	453	19	15	19	53	4	5	5	14
Reduced commercial fert.	**157**	**104**	**198**	**459**	**17**	**19**	**23**	**59**	**4**	**6**	**6**	**16**
Solid manure	157	101	196	454	27	28	35	90	5	6	7	19
L4												
Normal	85	156	160	400	52	32	65	148	2	3	4	9
Reduced manure	85	156	154	395	52	32	46	129	2	2	4	9
Reduced commercial fert.	**84**	**149**	**155**	**388**	**26**	**29**	**46**	**102**	**1**	**3**	**4**	**8**
Winter crops	84	149	166	399	26	20	32	78	1	2	3	6
Catch crop	84	149	149	382	26	8	17	51	1	2	3	6
S2												
Normal	84	91	76	251	146	86	41	273	0	0	0	0
Reduced manure	84	88	74	246	77	48	32	157	0	0	0	0
Reduced commercial fert.	**83**	**90**	**73**	**246**	**71**	**59**	**29**	**159**	**0**	**0**	**0**	**0**
Straw incorporation	66	70	72	209	66	60	32	157	0	0	0	0
Winter crops	83	101	82	266	56	46	27	128	0	0	0	0
Catch crop	83	89	75	247	26	18	37	81	0	0	0	0
Solid manure	83	90	73	246	89	71	31	191	0	0	0	0
S6												
Normal	81	62	65	208	112	91	49	253	0	0	0	0
Reduced manure	79	62	65	206	107	88	49	244	0	0	0	0
Reduced commercial fert.	**81**	**61**	**62**	**204**	**112**	**73**	**40**	**225**	**0**	**0**	**0**	**0**
Straw incorporation	62	45	48	155	105	73	43	221	0	0	0	0
Winter crops	81	76	76	232	89	57	24	170	0	0	0	0
Catch crop	81	60	65	206	39	26	27	92	0	0	0	0

Field L1

The L1 treatment was characterized by high inputs of N, mainly as liquid manure, and a large harvest export of N (Tab. 4). Leaching losses were considerable. Denitrification losses were significant, but

Table 4. Annual means of simulated nitrogen flows (kg N ha^{-1} year^{-1}) at field L1 for the period 1 April 1987 - 30 Mars 1990. Partial flows are given in italics. The total applied amount of NH4-N in manure is given within parentheses. The amount remaining after ammonia volatilization was subtracted from this total is used in the balance calculations.

Flow	Cropping system			
	Original application	Reduced manure	Reduced commercial fertilizer	Solid manure
Inputs				
Commercial fertilizer	97	97	45	69
Manure organic-N	61	30	59	127
Manure NH_4-N (NH_3 volatil. subtracted)	98	50	96	48
Total applied manure NH_4-N	(140)	(71)	(137)	(69)
Deposition	16	16	16	16
Sum of inputs	**272**	**194**	**216**	**261**
Internal flows				
Net mineralization	105	87	103	141
Net litter mineralization	*30*	*30*	*30*	*30*
Net faceces mineralization	*35*	*18*	*34*	*72*
Humus mineralization	*40*	*39*	*40*	*40*
Humification	69	57	70	92
Humification of litter	*48*	*47*	*48*	*47*
Humification of faeces	*21*	*11*	*21*	*45*
Plant uptake	241	231	237	236
Outputs				
Harvest (including straw export)	155	151	153	151
Leaching	66	18	20	30
Denitrification	7	5	5	6
Sum of outputs	**228**	**174**	**178**	**188**
Change in litter-N	+8	+7	+8	+8
Change in faeces-N	+4	+2	+5	+10
Change in humus-N	+34	+18	+29	+52
Change in living plant-N	0	-3	-2	0
Total change in organic-N	**+42**	**+24**	**+40**	**+70**
Change in mineral-N	+2	-3	-2	+3
Total change in N	**+44**	**+20**	**+38**	**+73**

had no major influence on the soil N balance. Organic-N in the system increased by 42 kg N ha^{-1} year^{-1} (Tab. 4).

L1: fertilizer reduction

A total reduction of 79 kg N ha^{-1} year^{-1} (31 kg org-N ha^{-1} year^{-1} + 48 kg NH_4-N ha^{-1} year^{-1}) in manure applied to the L1 field resulted in a 73% reduction in leaching (48 kg N ha^{-1} year^{-1}) without changing the total plant N uptake (Tab. 4). When the amount of commercial fertilizer was reduced by 53 kg N ha^{-1} year^{-1}, and the timing of the manure application was altered, leaching was reduced by 70% (46 kg N ha^{-1} year^{-1}). Losses due to denitrification were somewhat reduced. When reducing the amount of applied manure, the soil organic-N

Table 5. Annual means of simulated nitrogen flows (kg N ha^{-1} $year^{-1}$) at field L4 for the period 1 April 1987 - 30 Mars 1990. Partial flows are given in italics. The total applied amount of NH4-N in manure is given within parentheses. The amount remaining after ammonia volatilization was subtracted from this total is used in the balance calculations.

Flow	Cropping system				
	Original application	Reduced manure fertilizer	Reduced commercial	Winter crop	Catch crop_4
Inputs					
Commercial fertilizer	126	126	104	104	1043
Manure organic-N	6	4	6	6	6
Manure NH_4-N (NH_3 volatil. subtracted)	30	21	30	30	30
Total applied manure NH_4-N	(35)	(24)	(35)	(35)	(35)
Deposition	16	16	16	16	16
Sum of inputs	**178**	**167**	**156**	**156**	**156**
Internal flows					
Total net mineralization	87	86	86	87	92
Net litter mineralization	*31*	*31*	*30*	*31*	*36*
Net faceces mineralization	*3*	*2*	*3*	*3*	*3*
Humus mineralization	*53*	*53*	*53*	*53*	*53*
Total humification	45	44	44	46	35
Humification of litter	*43*	*43*	*42*	*44*	*33*
Humification of faeces	*2*	*1*	*2*	*2*	*2*
Plant uptake	207	204	201	212	226
Outputs					
Harvest (including straw export)	134	132	129	133	127
Leaching	49	43	34	26	17
Denitrification	3	3	3	2	2
Sum of outputs	**186**	**178**	**166**	**161**	**146**
Change in litter-N	0	-1	-1	-2	+30
Change in faeces-N	+1	+1	+2	+2	+2
Change in humus-N	-8	-9	-9	-8	-18
Change in living plant-N	0	0	0	+6	0
Total change in organic-N	**-7**	**-9**	**-8**	**-2**	**+14**
Change in mineral-N	-1	-2	-2	-3	-4
Total change in N	**-8**	**-11**	**-10**	**-5**	**+10**

buildup was reduced, while the reduction in commercial fertilizer resulted in an increase in organic-N similar to that observed in the original application.

L1: solid manure

The use of solid manure and a reduction in commercial fertilizer resulted in 10 kg N ha^{-1} $year^{-1}$ more leaching compared with the use of liquid manure and a reduction in commercial fertilizer. The extent of the increase in soil organic N was also considerably greater.

Field L4

The L4 treatment was characterized by considerable inputs of commercial fertilizer, while manure N inputs were low and did not occur until the end of the simulated period (App. 2). Harvest export of N was considerable (Tab. 5) as were leaching losses. Denitrification losses were significant, but lower than in the L1 treatment and did not have any major influence on the soil N balance. A small decrease in soil organic-N of 7 kg N ha^{-1} $year^{-1}$ was observed. This was mainly due to the low input of manure and the high harvest export.

L4: fertilizer reduction

The degree that fertilization could be reduced without reducing harvest yield was smaller in L4 than in L1 (Tab. 5). Reducing manure application by 11 kg N ha^{-1} $year^{-1}$ (2 kg org-N ha^{-1} $year^{-1}$ + 9 kg NH_4-N ha^{-1} $year^{-1}$) resulted in a leaching decrease of about 12% (6 kg N ha^{-1} $year^{-1}$). It was possible to reduce the commercial fertilizer rate by 22 kg N ha^{-1} $year^{-1}$, which resulted in a leaching reduction of 31% (15 kg N ha^{-1} $year^{-1}$). Reducing fertilization did not enhance the decline in soil organic-N.

L4: winter and catch crops

An additional reduction in leaching, assuming that the rate of commercial fertilizer had already bee reduced, was obtainable by either changing from spring crops to winter crops or by using catch crops. Using winter crops reduced leaching by an additional 8 kg N ha^{-1} $year^{-1}$, resulting in a total reduction of 47% compared with the original application. Simulated crop N uptake in autumn varied between 17 and 20 kg N ha^{-1} (App. 2). The introduction of catch crops resulted in an additional leaching reduction of about 17 kg N ha^{-1} $year^{-1}$, resulting in a total reduction of 65% compared with the original application. Simulated N-uptake by the catch crop varied between 39 and 47 kg N ha^{-1} (App. 2). The use of winter crops reduced the decrease in soil organic N. Using a catch crop slightly increased soil organic N, since the whole catch crop was incorporated into the soil at harvest.

Field S2

The S2 treatment was characterized by considerable inputs of both commercial fertilizer and liquid manure N (App. 3). Harvest export of N was low (Tab. 6), while leaching losses were very high. Denitrification losses were negligible in this soil because soil water contents were low. Soil organic N increased by 23 kg N ha^{-1} $year^{-1}$.

S2: fertilizer reduction

It was possible to decrease leaching by 43% (39 kg N ha^{-1} $year^{-1}$) by reducing the manure application by 50 kg N ha^{-1} $year^{-1}$ (20 kg org-N ha^{-1} $year^{-1}$ + 30 kg NH_4-N ha^{-1} $year^{-1}$). Reducing commercial fertilizer by 50 kg N ha^{-1} $year^{-1}$ resulted in a 42% (38 kg N ha^{-1} $year^{-1}$) reduction in leaching. Reducing fertilization led to a decrease in the soil organic-N buildup.

Table 6. *Annual means of simulated nitrogen flows (kg N ha^{-1} $year^{-1}$) at field S2 for the period 1 April 1987 - 30 Mars 1990. Partial flows are given in italics. The total applied amount of NH4-N in manure is given within parentheses. The amount remaining after ammonia volatilization was subtracted from this total is used in the balance calculations.*

Flow	Cropping system						
	Original application	Reduced manure	Reduced commercial fertilizer	Winter crop	Catch crop_4	Solid manure	Straw incorporation
Inputs							
Commercial fertilizer	93	93	43	43	43	61	43
Manure organic-N	33	13	33	33	33	60	33
Manure NH_4-N (NH_3 volatil. subtracted)	50	20	50	50	50	27	50
Total applied manure NH_4-N	(58)	(24)	(58)	(58)	(58)	(32)	(68)
Deposition	20	20	20	20	20	20	20
Sum of inputs	**195**	**145**	**146**	**146**	**146**	**168**	**146**
Internal flows							
Total net mineralization	75	63	76	76	96	91	74
Net litter mineralization	*15*	*15*	*15*	*16*	*36*	*15*	*15*
Net faceces mineralization	*20*	*8*	*20*	*20*	*20*	*36*	*20*
Humus mineralization	*39*	*39*	*39*	*39*	*39*	*39*	*39*
Total humification	35	28	35	37	47	45	44
Humification of litter	*23*	*23*	*23*	*24*	*35*	*23*	*31*
Humification of faeces	*12*	*5*	*12*	*12*	*12*	*22*	*12*
Plant uptake	148	145	137	148	181	138	136
Outputs							
Harvest (including straw export)	84	82	82	89	82	82	70
Leaching	91	52	53	43	27	64	52
Denitrification	0	0	0	0	0	0	0
Sum of outputs	**175**	**134**	**135**	**132**	**109**	**146**	**122**
Change in litter-N	+2	+1	+1	+2	+9	+1	+4
Change in faeces-N	+1	+0	+1	+1	+1	+1	+1
Change in humus-N	-4	-12	-4	-3	+7	+6	+4
Change in living plant-N	+25	+24	+16	+17	+19	+17	+17
Total change in organic-N	**+23**	**+14**	**+14**	**+17**	**+36**	**+25**	**26**
Change in mineral-N	-3	-3	-3	-3	+1	-3	-2
Total change in N	**+20**	**+11**	**+11**	**+14**	**+37**	**+22**	**24**

S2: winter and catch crops

An additional reduction in leaching, assuming that the application of commercial fertilizer had already been reduced, was possible by either changing from spring crops to winter crops or by using catch crops. A change over to winter crops reduced leaching by an additional 10 kg N ha^{-1} $year^{-1}$, resulting in a total reduction of 53% compared with the original application. Simulated N-uptake in autumn varied between 15 and 17 kg N ha^{-1} (App. 3). Alternatively, the introduction of catch crops led to an additional reduction in leaching of about 26 kg N ha^{-1} $year^{-1}$, resulting in a total reduction of 70% compared with the original application. Simulated N-uptake by the catch crop varied between 54 and 67 kg N ha^{-1} (App. 3). Examples assuming lower rates of N uptake by the catch crops are given in Table 3. Converting to winter crops slightly increased the soil organic N buildup. Using a catch crop increased the buildup of soil organic N considerably, since the whole catch crop was incorporated into the soil at harvest.

S2: solid manure

Using solid manure and reducing the rate of commercial fertilizer increased leaching by 11 kg N ha^{-1} $year^{-1}$ and enhanced soil organic-N buildup compared with the use of liquid manure and a reduction in commercial fertilizer rate.

Incorporating straw at ploughing and reducing the rate of commercial fertilizer only slightly decreased leaching (1 kg N ha^{-1} $year^{-1}$), the decrease being due to immobilization the immobilization of soil mineral N in autumn. The reduction was larger during the first year of incorporation than during subsequent years. The enhanced buildup of soil organic N resulted in larger N mineralization levels, leading to a slightly increase in leaching during the two following years (Tab. 3).

Field S6

The S6 treatment was characterized by a large input of solid manure the first spring, while commercial fertilizer was applied during the following two springs (App. 4). Harvest export of N was low (Tab. 7), whereas leaching losses were very high. As for S2, denitrification losses were negligible in this soil owing to low soil water contents. Despite large leaching losses, soil organic N increased by about 28 kg N ha^{-1} $year^{-1}$, mainly owing to the high input of manure.

S6: fertilizer reduction

It was possible to decrease leaching slightly by reducing fertilization (Tab. 3, 7). The large amounts of manure applied in the spring of 1987 (332 kg N ha^{-1} $year^{-1}$) could not be reduced to any great extent, since most of the nitrogen was in organic form and thus not immediately available to the crop. Reducing the manure application by 6 kg N ha^{-1} $year^{-1}$ (4 kg org-N ha^{-1} $year^{-1}$ + 2 kg NH_4-N ha^{-1} $year^{-1}$) decreased leaching by about 4% (3 kg N ha^{-1} $year^{-1}$). It was possible to reduce the commercial fertilizer rate by 11 kg N ha^{-1} $year^{-1}$, which reduced leaching by 11% (9 kg N ha^{-1} $year^{-1}$). The buildup of soil organic N was not changed much by these small reductions in fertilization.

S6: winter and catch crops

An additional reduction in leaching, assuming that the application of commercial fertilizer had already been reduced, was possible by either changing from spring crops to winter crops or by using catch crops. Using winter crops reduced leaching by an additional 18 kg N ha^{-1} $year^{-1}$, resulting in a total reduction of 32% compared with the original application. Simulated N-uptake in autumn varied between 13

Table 7. Annual means of simulated nitrogen flows (kg N ha^{-1} $year^{-1}$) at field S6 for the period 1 April 1987 - 30 Mars 1990. Partial flows are given in italics. The total applied amount of NH4-N in manure is given within parentheses. The amount remaining after ammonia volatilization was subtracted from this total is used in the balance calculations.

Flow	Cropping system					
	Original application	Reduced manure	Reduced commercial fertilizer	Winter crop	Catch crop_4	Straw incorporation
Inputs						
Commercial fertilizer	53	53	42	42	42	42
Manure organic-N	76	72	76	76	76	76
Manure NH_4-N (NH_3 volatil. subtracted)	35	33	35	35	35	35
Total applied manure NH_4-N	(41)	(39)	(41)	(41)	(41)	(41)
Deposition	20	20	20	20	20	20
Sum of inputs	**183**	**178**	**172**	**172**	**172**	**172**
Internal flows						
Total net mineralization	85	82	85	86	111	81
Net litter mineralization	*16*	*16*	*16*	*17*	*42*	*13*
Net faceces mineralization	*47*	*45*	*47*	*47*	*47*	*47*
Humus mineralization	*21*	*21*	*21*	*21*	*21*	*21*
Total humification	48	47	48	51	63	58
Humification of litter	*20*	*20*	*20*	*23*	*35*	*30*
Humification of faeces	*28*	*26*	*28*	*28*	*28*	*28*
Plant uptake	107	106	105	123	172	104
Outputs						
Harvest (including straw export)	69	69	68	77	69	52
Leaching	84	81	75	57	30	74
Denitrification	+0	0	0	0	0	0
Sum of outputs	**154**	**150**	**143**	**134**	**99**	**126**
Change in litter-N	+1	+1	+0	+1	+26	+9
Change in faeces-N	+1	+1	+1	+1	+1	+1
Change in humus-N	+27	+25	+27	+30	+42	+36
Change in living plant-N	0	0	0	+4	0	0
Total change in organic-N	**+28**	**+27**	**+28**	**+36**	**+69**	**+46**
Change in mineral-N	+1	+1	+1	+2	+4	+0
Total change in N	**+29**	**+28**	**+29**	**+38**	**+73**	**+46**

and 22 kg N ha^{-1} (App. 4). Alternatively, introducing catch crops reduced leaching by an additional 45 kg N ha^{-1} $year^{-1}$, resulting in a total reduction of 64% compared with the original application. Simulated N-uptake by the catch crop varied between 46 and 80 kg N ha^{-1} (App. 4). Examples assuming lower rates of N uptake by the catch crops are given in Table 3. Using winter crops only slightly increased the soil organic N buildup, whereas using a catch crop increased the buildup of soil organic N considerably.

S6: straw incorporation

Incorporating straw at ploughing and reducing the rate of commercial fertilizer only slightly decreased leaching (1 kg N ha^{-1} $year^{-1}$), the decrease being due to immobilization of soil mineral N in the autumn. The reduction was larger during the first year of incorporation, but the enhanced buildup in soil organic-N resulted in larger N mineralization levels and thus slightly higher leaching levels during the two following years, which reduced the total effect (Tab. 3).

6. Conclusions

Input data

The strength of the data used for the present application lies in the fact that they represent typical kinds of conventional farming practices. It is important to stress that the model has been tested for several years with many different applications, resulting in a considerable buildup of experience concerning the behaviour, parameterization and validity of the model. Thus, knowledge from previous applications form the basis for this application, for which only a limited amount of data have been available for calibration, while also increasing the reliability of the results achieved. In addition, the agreement found between simulated and measured nitrate concentrations in deeper layers increase our confidence in the leaching estimates.

The most sensitive parts of the present simulations were the plant uptake estimations. Harvest export is normally (assuming a system with reasonable leaching losses) the largest output of nitrogen from the soil. However, errors in the measurements and estimations of harvest export would not have affected our estimates of other kinds of nitrogen losses. Instead, such errors would affect our estimates of the humus mineralization rate and thus the change in soil organic nitrogen over time.

Leaching

Simulated mean annual nitrate leaching for the different fields during the 3-year period varied between 49 and 91 kg N ha^{-1} $year^{-1}$. The reliability of these estimates was strengthened by the general agreement between simulated and measured nitrate concentrations in the bottom layer of the soil profiles. The largest amounts of N-leaching occurred from the sandy fields at Rabis where higher precipitation compared with the Syv site resulted in larger drainage volumes.

Denitrification

Denitrification losses varied between 3 and 7 kg N ha^{-1} $year^{-1}$ from the sandy loam soils at Syv. Denitrification losses from the sandy soils at Rabis were negligible owing to low soil water contents.

Soil organic-N

Soil organic N increased in all fields except in L4 at Syv, which is notable since leaching losses were high, especially in the sandy fields at Rabis. The increases varied in size between 28 and 42 kg N ha^{-1} $year^{-1}$ among the fields. In L4 a small decline occurred, which resulted from the low input of manure combined with large harvest exports. Remarkably high amounts of soil organic nitrogen at the start of the period were also measured, especially in the Syv soils but also in the S2 field at Rabis. This indicates that a buildup of organic nitrogen have occurred previously.

Changes in management

By introducing various changes in management practices, it was possible to reduce nitrogen leaching by more than 50% at all sites without reducing harvest yields. The highest redcution in leaching attainable was 73%.

Reduced fertilization

At the L1 field at Syv, a 70% reduction was achieved by merely reducing the amount of commercial fertilizer applied and changing the timing of the manure application. The corresponding reduction at the other fields varied between 11 and 42%.

Winter crops

By changing from spring to winter crops at these sites, leaching was additionally reduced. Total reductions varied between 32 and 53% for the L4 and Rabis fields.

Catch crops

An additional decrease in leaching was also achievable by growing catch crops when the main crop was spring sown. Combining the use of catch crops together with a reduction in the rate of commercial fertilizer, a decrease, varying between 64 and 70%, was achieved. However, this simulation assumed considerable N-uptake by the catch crop (total N-uptake varied between 39 and 80 kg N ha^{-1} $year^{-1}$). Since knowledge about the development and N uptake potential of catch crops are still lacking, several N-uptake rates by catch crops were assumed in the simulations to demonstrate potential variations in nitrate leaching. It should also be noted that the model only considers the effect of catch crops on nitrogen cycling and nitrogen availability. Thus other considerations related to the use of catch crops, such as competition, weed control, etc., are not included.

Introducing a catch crop enhanced the buildup of soil organic nitrogen. In the long term such a buildup leads to increased N mineralization rates. Thus, fertilization levels should be continually reduced to maintain low leaching rates.

The denitrification potential used in these applications was based on a calibration of the denitrification function for a loam soil in Sweden cropped with barley. However, a considerably higher denitrification potential was obtained for a grass ley system at the same site. Thus, combining the main crops with catch crops or insown leys might enhance the denitrification potential, resulting in higher denitrification losses.

Straw incorporation

The incorporation of straw at ploughing (instead of removing straw at harvest), together with a reduction in the commercial fertilizer rate, led to only a slight decrease in nitrate leaching. Although the reduction was larger during the first year of incorporation, the increased buildup of soil organic-N led to an increase in N mineralization rates, thereby slightly enhancing nitrogen leaching during the following two years, which reduced the overall effect.

Solid fertilizer

Using solid instead of liquid manure resulted in an increase in leaching, since N mineralization increased and a supplementary application of commercial fertilizer had to be made. Because N mineralization also occurs during parts of the year when there are no growing crops, mineralized N is relatively more exposed to leaching than mineral-N in fertilizers, which are usually applied in the beginning of the growing season.

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Appendices

Appendix 1. Crops and management practices used at field L1 during the simulated 3-year period from 1 April 1987 to 31 Mars 1990. Amounts of NH_4-N in applied manure, before reduction for ammonia losses, are given within parentheses. Where original management practices have been changed the value or date is presented in bold text. All amounts in kg ha^{-1}.

	1987		1988		1989	(1990)
Original application:						
Crop	Winter barley		Winter rape		Winter wheat	Winter barley
Sowing date	15 Sep 1986		10 Sep 1987		20 Sep 1988	15 Sep 1989
Harvest date	3 Aug		7 Aug		10 Aug	
Grain yield (dw)	5500		2350		7000	
Straw export (dw)	3300		0		4500	
Sim. tot. plant-N at harvest	229		206		288	
Sim. N-uptake in autumn	28		31		29	
Fertilization date	10 Apr	17 Oct	7 Apr	18 Oct	10 Apr	12 Apr
Manure org-N (liquid)	-	58	80	22	22	-
Manure NH_4-N (liquid)	-	85 (122)	130 (185)	39 (56)	39 (56)	-
Commercial fert.-N	146	-	-	-	-	146
Application rates of manure reduced:						
Fertilization date	10 Apr	17 Oct	**1 Apr**	18 Oct	**1 Apr**	12 Apr
manure org-N (liquid)	-	**0**	80	**0**	**11**	-
manure NH_4-N (liquid)	-	**0**	130 (185)	**0**	**20 (29)**	-
commercial fert.-N	146	-	-	-	-	146
Application rates of commercial fertilizer reduced and dates for manure application changed:						
Fertilization date	10 Apr	**1 Apr**	**1 Apr**	18 Oct	**1 Apr**	12 Apr
Manure org-N (liquid)	-	58	80	**0**	**44**	-
Manure NH_4-N (liquid)	-	85 (122)	130 (185)	**0**	**78 (111)**	-
Commercial fert.-N	**54**	-	-	-	-	146
Solid manure substituted for liquid manure and application rates of commercial fertilizer reduced:						
Fertilization date	10 Apr	**1 Apr**	**1 Apr**	18 Oct	**1 Apr**	12 Apr
Manure org-N (liqui)	-	**117**	172	**0**	**101**	-
Manure NH_4-N (liquid)	-	**44 (63)**	**65 (93)**	**0**	**38 (54)**	-
Commercial fert.-N	**90**	-	-	**36**	-	**82**

Appendix 2. Crops and management practices used at field L4 during the simulated 3-year period from 1 April 1987 to 31 Mars 1990. Amounts of NH_4-N in applied manure, before reduction for ammonia losses, are given within parentheses. Where original management practices have been changed the value or date is presented in bold text. All amounts in kg ha^{-1}.

	1897	1988	1989		(1990)
Original application:					
Crop	Spring rape	Winter wheat	Spring barley		
Sowing date	14 Apr	17 Sep 1987	14 Apr		
Harvest date	25 Aug	19 Aug	8 Aug		
Grain yield (dw)	1950	5300	5500		
Straw export (dw)	0	3500	3400		
Sim. tot. plant-N at harvest	170	223	228		
Sim. N-uptake in autumn	20	-	-		
Fertilization date	10 Apr	3 Apr	2 Feb	14 Apr	
Manure org-N (liquid)	-	-	19	-	
Manure NH_4-N (liquid)	-	-	89 (105)	-	
Commercial fert.-N	146	148	-	84	
Application rates of manure reduced:					
Fertilization date	10 Apr	3 Apr	2 Feb	14 Apr	
Manure org-N (liquid)			**13**		
Manure NH_4-N (liquid)			**62 (73)**		
Commercial fert.-N	146	148		84	
Application rates of commercial fertilizer reduced and dates for manure application changed:					
Fertilization date	10 Apr	3 Apr	2 Feb	14 Apr	
Manure org-N (liquid)			19		
Manure NH_4-N (liquid)			89 (105)		
Commercial fert.-N	**105**	148		**60**	
Winter crops substituted for spring crops and commercial fertilizer reduced:					
Crop	Spring rape	Winter wheat	**Winter barley**		**Winter crop**
Sowing date	14 Apr	17 Sep 1987	**11 Sep 1988**		**11 Sep 1989**
Harvest date	25 Aug	19 Aug	8 Aug		
Sim. N-uptake in autumn	20	17	17		
Catch crops (cc) included and commercial fertilizer reduced:					
Crop	Spring rape	Winter wheat **+ cc**	Spring barley **+ cc**		
Sowing date	14 Apr	17 Sep 1987	14 Apr		
Harvest date	25 Aug	19 Aug	8 Aug		
Sim. N-uptake in catch crop		47	39		

Appendix 3. *Crops and management practices used at field S2 during the simulated 3-year period from 1 April 1987 to 31 Mars 1990. Amounts of NH_4-N in applied manure, before reduction for ammonia losses, are given within parentheses. Where original management practices have been changed the value or date is presented in bold text. All amounts in kg ha^{-1}.*

	1897		1988		1989	
Original application:						
Crop	Spring barley		Spring barley		Spring barley + insown ley	
Sowing date	5 Apr		8 Apr		28 Mar	
Harvest date	13 Aug		7 Aug		10 Aug	
Grain yield (dw)	2900		3100		2900	
Straw export (dw)	1800		1900		1900	
Sim. tot. plant-N at harvest	120		130		120	
Sim. N-uptake in insown ley	-		-		73	
Fertilization date	1 Apr	2 Apr	25 Mar	4 Apr	15 Mar	10 Aug
Manure org-N (liquid)	60	-	40	-	-	-
Manure NH_4-N (liquid)	89 (105)	-	60 (70)	-	-	-
Commercial fert.-N	-	68	-	68	110	32
Application rates of manure reduced:						
Fertilization date	1 Apr	2 Apr	25 Mar	4 Apr	15 Mar	10 Aug
Manure org-N (liquid)	**20**	-	**20**	-	-	-
Manure NH_4-N (liquid)	**30 (35)**	-	**30 (35)**	-	-	-
Commercial fert.-N	-	68	-	68	110	32
Application rates of commercial fertilizer reduced and dates for manure application changed:						
Fertilization date	1 Apr	2 Apr	25 Mar	4 Apr	15 Mar	10 Aug
Manure org-N (liquid)	**54**	-	**46**	-	-	-
Manure NH_4-N (liquid)	**80 (94)**	-	**69 (81)**	-	-	-
Commercial fert.-N	-	**0**	-	**30**	**100**	**0**
Winter crops substituted for spring crops and commercial fertilizer reduced:						
Crop	Spring barley		**winter barley**		**winter barley** + insown ley	
Sowing date	5 Apr		**11 Sep 1987**		**11 Sep 1988**	
Harvest date	13 Aug		7 Aug		10 Aug	
Sim. N-uptake in autumn	15		17		51 (insown ley)	
Catch crops (cc) included and commercial fertilizer reduced:						
Crop	Spring barley + cc		Spring barley + cc		Spring barley + insown ley	
Sowing date	5 Apr		8 Apr		28 Mar	
Harvest date	13 Aug		7 Aug		10 Aug	
Sim. N-uptake by catch crop	54		67		56 (insown ley)	
Solid manure substituted for liquid manure and commercial fertilizer reduced:						
Fertilization date	1 Apr	2 Apr	25 Mar	4 Apr	15 Mar	10 Aug
Manure org-N (solid)	**107**	-	**72**	-	-	-
Manure NH_4-N (solid)	**42 (49)**	-	**32 (38)**	-	-	-
Commercial fert.-N	-	**32**	-	**60**	**92**	**0**

Appendix 4. Crops and management practices used at field S6 during the simulated 3-year period from 1 April 1987 to 31 Mars 1990. Amounts of NH_4-N in applied manure, before reduction for ammonia losses, are given within parentheses. Where original management practices have been changed the value or date is presented in bold text. All amounts in kg ha^{-1}.

	1897	1988	1989	(1990)
Original application:				
Crop	Spring barley	Spring barley	Spring barley	
Sowing date	18 Apr	16 Apr	10 Apr	
Harvest date	18 Aug	18 Aug	14 Aug	
Grain yield (dw)	2500	2000	2100	
Straw export (dw)	1500	1100	1200	
Sim. tot. plant-N at harvest	125	95	100	
Fertilization date	15 Apr	10 Apr	4 Apr	
Manure org-N (solid)	228	-	-	
Manure NH_4-N (solid)	104 (122)	-	-	
Commercial fert.-N	-	80	80	
Application rates of manure reduced:				
Fertilization date	15 Apr	10 Apr	4 Apr	
Manure org-N (solid)	**217**	-	-	
Manure NH_4-N (solid)	**99 (116)**	-	-	
Commercial fert.	-	80	80	
Application rates of commercial fertilizer reduced and dates for manure application changed:				
Fertilization date	15 Apr	10 Apr	4 Apr	
Manure org-N (solid)	228	-	-	
Manure NH_4-N (solid)	104 (122)	-	-	
Commercial fert.-N	-	**60**	**65**	
Winter crops substituted for spring crops and commercial fertilizer reduced:				
Crop	Spring barley	**Winter barley**	**Winter barley**	**Winter crop**
Sowing date	18 Apr	**11 Sep 1987**	**11 Sep 1988**	**11 Sep 1989**
Harvest date	18 Aug	18 Aug	14 Aug	
Sim. N-uptake in autumn	22	17	13	
Catch crops (cc) included and commercial fertilizer reduced:				
Crop	Spring barley + cc	Spring barley + cc	Spring barley + cc	
Sowing date	18 Apr	16 Apr	10 Apr	
Harvest date	18 Aug	18 Aug	14 Aug	
Sim- N-uptake by catch crop	80	73	46	

Appendix 5. Parameter values used in the water balance simulations for the fields at Rabis and Syv. Symbols are defined in Johnsson & Jansson (1990).

Parameter	Symbol	Unit	Parameter values
Penetration of net radiation through canopy			
Extinction factor	k	-	0.5
Root water uptake reduction			
Constant	a	day mm^{-1}	0.35
Constant	b	mm	0
Critical tension	y_c	cm	800
Evaporation of intercepted water			
Leaf area index - minimum		m	0
Leaf area index - maximum		m	4
Surface resistance	r_{si}	s m^{-1}	5
Interception storage	i_{LAI}	mm LAI^{-1}	0.5
Soil evaporation			
Increased aerodynamic resistance	r_{LAI}	s m^{-1}	50
Constant in surface resistance function	r_y	s m^{-1}	150
Snowmelt			
Density of newly fallen snow		kg m^{-3}	150
Coefficient in thermal conductivity func.	S_k	W m^4 kg^{-2}	4
Heat sum coefficient	m_T	kg °C^{-1} m^{-2}	3
Global radiation function	m_R	kg MJ^{-1}	0.2-0.5[a]
Transpiration			
Surface resistance - minimum		s m^{-1}	30
Surface resistance - maximum		s m^{-1}	120
Aerodynamic resistance			
Roughness length - minimum	z_0	m	0.01
Roughness length - maximum	z_0	m	0.08
Displacement height - minimum	d	m	0.07
Displacement height - maximum	d	m	0.56

[a] Depends on snow age

Appendix 6. Parameter values used in the soil nitrogen simulations.

Parameter	Value
Dry deposition	7.3 kg N ha^{-1} $year^{-1}$
Wet deposition, concentration in rain water	1.6 mg N l^{-1}
C:N-ratio of above ground residues	50 (grain crops), 40 (rape)
C:N-ratio of roots	25
Harvested fraction of plant-N uptake	
(incl straw removal of grain crops)	0.7 (grain crops), 0.5 (rape)
Above-ground residue fraction of plant-N uptake	0.1 (grain crops), 0.3 (rape)
Ploughing depth	0.2 m
Litter mineralization and immobilization	see Johnsson et al., 1987
Faeces mineralization and immobilization	see Borg et al., 1990
Rate constant for humus mineralization	0.5×10^{-4}
Soil temperature response function	see Bergtrsöm and Johnsson 1988
Soil moisture response function (except denit)	see Johnsson et al., 1987
Denitrification response to soil moisture	
Activity range (below saturation)	20%
Coefficient *d*	2
Potential denitrification rate 0-20 cm	0.054 g N m^{-2} day^{-1}
Potential denitrification rate 20-40 cm	0.027 g N m^{-2} day^{-1}
Half saturation constant	10 mg l^{-1}
Fraction of roots in layer 1/2/3/4 at max depth	0.85/0.10/0.03/0.02
Time at which max root depth is established	16 May (winter crops), 4 June (spring crops)

Data Sheet

Publisher: Ministry of the Environment, National Agency of Environmental Protection, Strandgade 29, DK-1401 København K.

Serial title and no.: NPo-forskning fra Miljøstyrelsen, A20

Year of publication: 1991

Title:
Simulation of Nitrogen Losses Using the SOILN Model

Subtitle:

Author(s):
Johnsson, Holger

Performing organization(s):
Swedish University of Agricultural Sciences,
Box 7070, 750 07 Uppsala

Abstract:
SoilN losses were simulated in 4 arable fields cropped and managed according to conventional farming practices. Simulated nitrate leaching varied between 49 and 91 kg N ha^{-1} $year^{-1}$. Various measures to reduce nitrate leaching were also simulated. Nitrate leaching was reduced by between 11% and 70% when the amount af commercial fertilizer was reduced and the timing of manure application altered. Nitrate leaching was reduced by between 64% and 70% if catch crops also were included.

Terms:
agriculture; field experiments; leaching; fertilization; manure application; soil types; mathematical models; nitrogen CAS 7727-37-9

ISBN: 87-503-9039-2

ISSN:

Price: (incl. 22 % VAT): 55 DKr

Format: AS5

Number of pages: 44 p.

Edition closed (month/year): March 1991

Circulation: 500

Supplementary notes:
Report from coordination group A for soil and air

Printed by: Luna-Tryk ApS, Copenhagen

Registreringsblad

Udgiver: Miljøstyrelsen, Strandgade 29, 1401 København K.

Serietitel, nr.: NPo-forskning fra Miljøstyrelsen, A20

Udgivelsesår: 1991

Titel:
Simulation of Nitrogen Losses Using the SOILN Model

Undertitel:

Forfatter(e):
Johnsson, Holger

Udførende institution(er):
Sveriges Lantbruksuniversitet

Resumè:
N-tab blev simuleret fra 4 opdyrkede marker, hvor afgrødevalg og landbrugspraksis svarer til konventionelt landbrug. Den simulerede nitratudvaskning varierede fra 49 til 91 kg. N ha/år. Forskellige tiltag, der skulle reducere udvaskning blev også simuleret. Hvis kunstgødningtilførslen blev reduceret og husdyrgødningstilførslen blev timet, faldt nitratudvaskningen fra 11 til 70%. Derudover faldt nitratudvaskningen fra 64 til 70%, hvis efterafgrøder blev inkluderet.

Emneord:
landbrug; dyrkningsforsøg; udvaskning; gødskning; jordbundstyper; matematiske modeller; nitrogen CAS 7727-37-9

ISBN: 87-503-9039-2

ISSN:

Pris: 55,- **(inkl. 22 % moms)**

Format: AS5

Sideantal: 44 s.

Md./år for redaktionens afslutning: marts 1991

Oplag: 500

Andre oplysninger:
Rapport fra koordinationsgruppe A for jord og luft

Tryk: Luna-Tryk ApS, København

NPo-forskning fra Miljøstyrelsen

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Nr. A 4 : Ammoniakafsætning omkring et landbrug med malkekvæg
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Nr. A11 : Bestemmelse af NH_3-fordampning med passive fluxmålere
Nr. A12 : NH_3-fordampning fra gyllebeholdere
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Nr. A19 : N-transformation in Soil, Amended with Digested Pig Slurry
Nr. A20 : Simulation of Nitrogen Losses Using the SOILN Model
Nr. A21 : Landbrugets gødnings- og arealanvendelse i 1983 og 1989

Den med * mærkede titel er ikke trykt på udgivelsesdagen for denne rapport, men forventes trykt i løbet af 1991.

Nr. A19 er tidligere annonceret med titlen:
Afgasset gylles indflydelse på N-omsætning i jorden.

Nr. A20 er tidligere annonceret med titlen:
Simulering af kvælstoftab med SOIL-N-modellen

Simulation of Nitrogen Losses Using the SOILN Model

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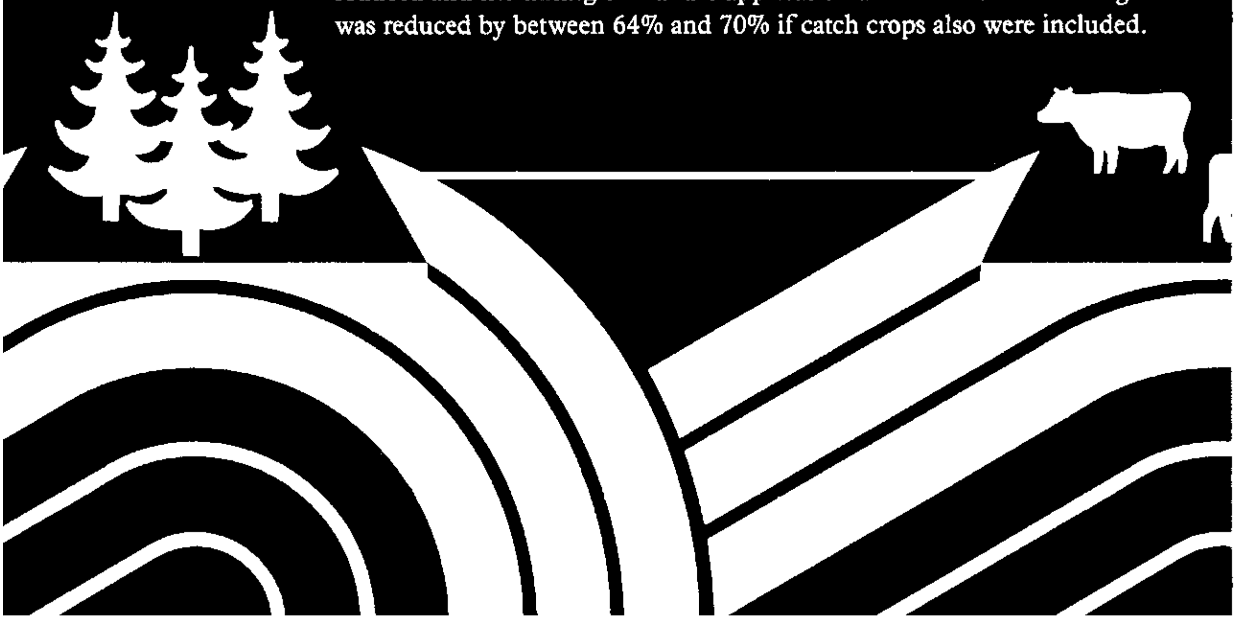

Miljøministeriet **Miljøstyrelsen**

Strandgade 29, 1401 København K, tlf. 31 57 83 10

Pris kr. 55.- inkl. 22% moms

ISBN nr. 87-503-9039-2

-forskning nr. A20 1991

Miljøstyrelsen