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Nitrogen leaching from conventional versus organic farming systems — a systems modelling approach

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Abstract

The level of nitrogen leaching from organic compared to conventional farming was evaluated by using a systems modelling approach. Two different methods were used for estimating and evaluating nitrate leaching. A simple function was used in which nitrate leaching is dependent on percolation, soil clay content, average nitrogen input and crop sequence. A nitrogen balance model was used to estimate the long-term potential for nitrate leaching. These methods were applied to models of both current conventional farming systems in Denmark in 1996 and of well-managed organic farming systems. On average, the total estimated nitrogen input to the organic systems was lower (104–216 kg N ha^{-1} year^{-1}) than to the conventional farming systems (146–311 kg N ha^{-1} year^{-1}). The N-balances in the organic fields showed a surplus of nitrogen (net input of nitrogen) in to the root zone of 60–143 kg N ha^{-1} year^{-1}. In the conventional systems the surplus varied from 25 to 155 kg N ha^{-1} year^{-1}. The modelled nitrogen leaching from the organic systems varied from 19 to 30 kg N ha^{-1} year^{-1} on loamy soils to 36–65 kg N ha^{-1} year^{-1} on sandy soils. The modelled nitrogen leaching from the organic systems was always lower than from the comparable conventional agricultural systems due to: (I) the lower total input of nitrogen to the organic systems; and (II) the composition of the organic crop rotations including extensive use of catch crops. However, the modelling of nitrogen leaching has many uncertainties, principally due to difficulties in predicting the nitrogen leaching from different types of grass fields. Comparison of the results from two methods: (i) modelling of nitrogen leaching; and (ii) N-balances for the root zones, showed that organic arable crop production and dairy/beef farming on sandy soils are farming systems with a clear potential for lower nitrogen leaching than from the selected conventional systems. It is still uncertain whether the nitrogen leaching is lower or higher from organic arable crop production systems on loamy soil and organic pig production on loamy and sandy soil than from the same conventional systems in Denmark. The results point to the need for future research in the following areas: (i) the ability to build up soil organic nitrogen in organic farming systems and the consequences for both the level of crop production and nitrogen

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leaching in the long term; (ii) the effects of catch crops in organic crop rotations; and (iii) a better operational understanding of nitrogen leaching from different types of organically managed grass and grass-clover fields.

Keywords: Nitrate leaching; System approach; Symbiotic N_2 fixation; Catch crop

1. Introduction

Agricultural production in intensively managed systems in Europe has increased over the last 50 years, partly due to the increased use of nitrogen fertilisers. This intensification of agriculture and the ploughing up of old grassland (Addiscott, 1992) are the main causes of the high nitrate losses to ground- and surface waters. In Denmark the average nitrate leaching from sandy catchments during 1989–1996 amounted to 123 kg N ha^{-1} $year^{-1}$ and from loamy catchments it was 72 kg N ha^{-1} $year^{-1}$ (Grant et al., 1997). The nitrogen load in watercourses was 12 kg N ha^{-1} $year^{-1}$ in sandy catchments and 27 kg N ha^{-1} $year^{-1}$ in loamy catchments. The average nitrate concentration in the upper groundwater was 53 mg NO_3 l^{-1} in sandy catchments and 19 mg NO_3 l^{-1} in loamy catchments. During the same period agriculture accounted for approximately 81% of the nitrogen load in Danish watercourses (Windolf et al., 1997) and about 70% of the nitrogen inputs to the sea (the Kattegat) via water courses and atmospheric deposition (Iversen, 1997). Denmark is designated as vulnerable and sensitive to nitrate pollution of surface and groundwater by the European Union. The Danish implementation of the EU nitrate directive is approved by the European Union although a derogation on dairy grassland farming is currently undergoing negotiation (Torben Bonde, personal communication).

During recent decades the political target, as formulated in the Aquatic Environment Action Plan No. I of 1987, has been to reduce leaching losses of nitrogen from Danish agriculture by 50%. As a result of the regulations the consumption of artificial nitrogen fertiliser in Denmark has dropped from 392 millions kg N in 1985 to 285 millions kg N in 1996 on the approximately 2.5×10^6 ha agricultural land. However, it has not yet been possible directly to demonstrate any reductions in nitrogen leaching from the root zone of agricultural fields, partly because of the relatively short measuring period and partly because of the large fluctuations in leaching caused by variation in the annual rainfall. Model simulations, on the other hand, show that the leaching of nitrate during 1989–1996 was reduced by 17% (Grant et al., 1997). Recently, the Action Plan No. II has been initiated in order to meet the original objectives from 1987. The plan includes additional restrictions on the use of nitrogen fertiliser in Denmark and new land use objectives favouring wet meadows, organic farming, etc.

At the same time as there has been an increased focus on reducing the leaching of nitrate from the agriculture there has been an increasing interest in organic farming in Denmark. From 1988 to 1999 organic farming is expected to increased from 0.2 to about 5% of the total agricultural area in Denmark (Action plan II, 1999). Furthermore, market analyses currently show a market increase in the consumer demand for organic products. Consequently there is a need to evaluate the environmental effect of organic farming, and especially the level of nitrate leaching from the soil. In the new Action Plan, organic farming is one of the proposed means for reducing the losses of nitrogen from Danish agriculture.

The Danish authorities define organic farming as a farming practice aiming to establish stable production systems with a high concern for nature and the environment. As far as possible it is aimed to have animals on the farms. In addition, it is forbidden to use industrial N fertilisers, synthetic pesticides and growth-promoting chemicals as well as industrially produced feed additives. The input of nutrients to the fields is based on organic fertilisers, manure, green manure, crop residues, etc., and N_2 fixation from leguminous plants. Plant diseases, weeds, and pests are controlled through crop rotations, mechanical soil cultivation and an appropriate choice of crop varieties.

There are only few published results from actual field investigations of nitrogen leaching from organic farming and they do not give a realistic picture of the level of nitrate leaching from different organic farming systems. Therefore we have chosen a modelling approach which makes use of current knowledge on the effects of farming practices on nitrate leaching in Denmark.

This paper applies a systems approach (Kristensen and Halberg, 1997) to the estimation and evaluation of nitrate leaching from conventional and organic farming systems in Denmark. Two different model types were used: an empirical nitrogen leaching model and a nitrogen balance model. The two methods were chosen to assess the effect of the modelling approach on the estimates of nitrogen leaching. The models were applied to six different conventional and organic farm types.

2. Methods

2.1. The general model

Agriculture, since it is an open dissipate system, always involves the loss of nutrients, and especially mobile nitrate, with the percolating water. Nitrate leaching occurs when there is a large amount of soluble inorganic nitrogen in the soil at times of the year when low evapotranspiration and/or high precipitation lead to percolation from the root zone. In order to minimise the risk of nitrogen leaching it is essential to synchronise nitrogen mineralisation and the demand of the plants for nitrogen (Thomsen et al., 1993). The level of nitrogen leaching is influenced by soil and weather conditions, and by the management decisions such as:

1. choice of crop rotation (including crop types and catch crops);
2. type, timing and amount of nitrogen fertiliser application;
3. type and timing of cultivation

In order to reduce the loss of nitrogen from agricultural fields it is essential to understand how different farming practises influence nitrate leaching from the soil. The choice of crop rotation, crop types and catch crops plays a major role. The timing of soil cultivation is often dictated by the crop rotation. If, for example, winter cereals are part of the crop rotation, then it is necessary to cultivate the soil in autumn, and this promotes the leaching of nitrate from preceding grass-clover crops (Francis et al., 1992; Djurhuus and Olsen, 1997). Catch crops significantly reduce the content of inorganic nitrogen in the soil in autumn and thus the risk of nitrate leaching. Aronsson and Torstensson (1998) found a 40–50% reduction in nitrogen leaching in a catch crop treatment compared to the control during years when the establishment of the catch crop succeeded. Thorup-Kristensen (1994) found that catch crops reduced the soil mineral nitrogen content (N_{min}) in the autumn with quantities between 65 and 144 kg N ha^{-1} as compared to bare soil. The amount of fertiliser or/and manure application and these time of application also have significant effects on the leaching of nitrate, particularly if the application raises the level of inorganic nitrogen in the soil when there is percolation from the root zone.

The nitrogen flows on the farm and in the soil are complex and involve various nitrogen compounds and biogeochemical processes. Fig. 1 shows the general model for the nitrogen cycle used in this study. The nitrogen inputs to the cropping system are in the form of artificial fertiliser, animal manure, atmospheric deposition and N_2 fixation, whereas the nitrogen outputs are leaching, volatilisation of ammonia, denitrification and crop removal. The system is not necessarily in equilibrium and the term ΔN_{soil} describes possible changes in the content of soil nitrogen.

The general model (Fig. 1) was chosen because it is simple and includes the interaction of those factors in the nitrogen cycle that will be changed when converting to organic farming. Therefore, when estimating the potential for nitrogen leaching the focus is on:

1. choice of crop rotation (including crop types and catch crops);
2. type and amount of nitrogen fertiliser application;

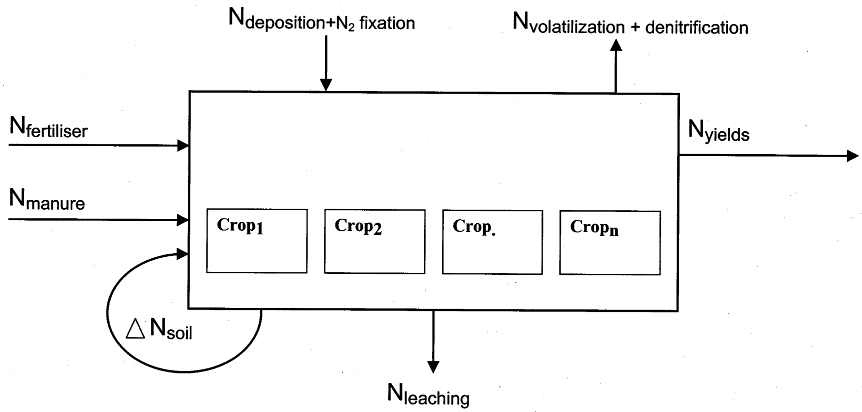

Fig. 1. The general nitrogen cycle model used in the study. The nitrogen inputs are in the form of artificial fertiliser ($N_{fertiliser}$), animal manure (N_{manure}), atmospheric deposition and N_2 fixation ($N_{deposition+N_2\ fixation}$) while the nitrogen outputs are leaching ($N_{leaching}$), volatilisation of ammonia and denitrifiction ($N_{volatilization+denitrification}$) and crop removal ($N_{yields}$). The system is not necessarily in equilibrium and ΔN_{soil} describes possible changes in the content of soil organic nitrogen.

3. type and amount of animal manure application

In the model, the type and amount of manure application is determined by the stocking rate of animals per hectare and the amount of imported feed and animal manure.

2.2. N-balance sheet for the root zone

The N-balance for the root zone of a cropping system can be used to evaluate the long term potential for nitrogen leaching. The net input of nitrogen to the root zone is defined as:

$$N_{net\ input} = N_{manure} + N_{fertiliser} + N_{fixation} + N_{deposition} - N_{yields} \quad (1)$$

Thus the calculated net input of nitrogen is derived from estimates of nitrogen inputs and assessments of nitrogen in crop yields. All the uncertainties of the various parameters are thus included in the estimate of net nitrogen input. The net input of nitrogen can also be expressed as the sum of nitrogen leaching, ammonia volatilisation, denitrification and the change in soil organic nitrogen (immobilisation or mineralisation):

$$N_{net\ input} = N_{leaching} + N_{volatilization} + N_{denitrification} + \Delta N_{soil} \quad (2)$$

It is difficult to isolate $N_{leaching}$ from the equation because it is difficult to quantify the other entries: $N_{volatilization} + N_{denitrification} + \Delta N_{soil}$. Petersen (1996) found that 5–35% of the ammonia-nitrogen in the manure can be lost by volatilisation depending on the application method. Denitrification is more important on clay compared to sandy soils. Five to thirty percent of the nitrogen from the manure from cattle can be lost by denitrification (Petersen, 1996). Changes in the soil organic nitrogen (ΔN_{soil}) are also difficult to quantify because the net changes are small compared to the total pool of about 4–10 t N ha^{-1}. Constant agricultural practice will in the long term (more than 100 years) result in a system in balance, with equilibrium in the soil organic matter content (Christensen and Johnston, 1997). A comparison of the net input of nitrogen to the root zones of different agricultural systems can be used to evaluate the long term potential for nitrogen leaching assuming that $N_{volatilisation} + N_{denitrification}$ are largely unaffected by the agricultural system.

2.3. The N-leaching-model

The leaching of nitrogen (L) was estimated with the empirical model (Simmelsgaard, 1998):

$$L = \exp(1.136 - 0.0628 \cdot \text{clay} + 0.00565 \cdot N + \text{crop}) \cdot P^{0.416} \quad (3)$$

where clay is the clay content in percent in the 0–25 cm depth, N is the average nitrogen input ($N_{manure} + N_{fertiliser} + N_{fixation}$) to the field in kg ha^{-1} year^{-1}, P is the percolation in mm year^{-1} and crop is a parameter estimate related to the summer crop and the following winter crop. In Simmelsgaard (1998) original equation the $N_{fixation}$ was not part of the N input. We decided to include the N_2 fixation because it is a principal nitrogen input to organic farming systems.

Model parameters were estimated from two data series of nitrogen leaching from conventionally farmed fields, and the model described 54% of the total variation of nitrogen leaching in the data series (Simmelsgaard, 1998). The rest of the variation could be due to uncertainties in measuring the nitrogen leaching and characterising the soil, intensity and timing of soil cultivation or the prehistory of the soil before the measurements started.

It was decided to use average values for the clay content and the percolation obtained from the sandy and the loamy catchments in the Agricultural Catchment Monitoring from 1989–1996. The clay content in the top soil was 5.1% on sandy soil with and annual percolation of 465 mm year^{-1}. The corresponding values for the loamy soil were 14.2% and 345 mm year^{-1}.

2.4. The N_2- fixation-model

Symbiotic N_2 fixation in leguminous plants make use of the inexhaustible atmospheric source of nitrogen, and can be a very important nitrogen input in organic farming systems. The N_2 fixation is mainly influenced by the inorganic nitrogen content in the soil, the soil water content, the soil temperature all of them abiotic factors, and the legume species (biotic factor). A general N_2 fixation model (kg N ha^{-1} year^{-1}) depending on dry matter yields (DM_{legume}, kg ha^{-1} year^{-1}) of leguminous plants was formulated by Høgh-Jensen et al. (1998):

$$N_{fixation} = DM_{legume} \cdot N\% \cdot N_{leaves} \cdot (1 + N_{root+stubble} + N_{trans-soil} + N_{trans-animal} + N_{immobile}) \quad (4)$$

where N% is the concentration of nitrogen in the leguminous plant, N_{leaves} is the proportion of fixed nitrogen in the leaves, $N_{root+stubble}$ is the proportion of fixed nitrogen in the roots and stubbles, $N_{trans-soil}$ is the proportion of fixed nitrogen transferred from the legumes to non-legumes in the soil, $N_{trans-animal}$ is the proportion of fixed nitrogen transfer from the legumes to non-legumes via grazing animals, and $N_{immobile}$ is the proportion of fixed nitrogen, originating from the legumes, which is immobilised in the soil.

2.5. Models for the conventional farming systems

The chosen level of detail for the comparison of conventional and organic arable and livestock systems is shown in Fig. 2. Three different types were chosen: arable crop-; pig-; and dairy/beef production systems on both loamy and sandy soils (Table 1). Current conventional farming in Denmark is described by data from the programme called Agricultural Catchment Monitoring. Fig. 2 also has the proportion of the total area in the Agricultural Catchment Monitoring programme occupied by each group. It varies from 6% for conventional dairy/beef production systems on loamy soil to 38% for conventional dairy/beef production systems on sandy soil. These percentages of cultivated land in the different production systems in the Agricultural Catchment Monitoring (see Fig. 2) correspond roughly to the national average.

The Agricultural Catchment Monitoring (Grant et al., 1997) is conducted in six agricultural catchments in Denmark. Three are on sandy soils and the other three are located on loamy soils. Each catchment has an area of about 5–10 km^2. The average livestock density in the Agricultural Catchment Monitoring was 1.00 LU ha^{-1} in 1996[1] which was slightly higher than in the whole country (0.95 LU ha^{-1}).

[1] LU, livestock unit, the manure from a large milking cow.

2.6. Models for the organic farming systems

Fig. 2 shows that conventional livestock systems are compared to organic systems which have a lower livestock density. The organic systems are designed based on the criteria for organic systems in Denmark laid down by the Plant Directorate and the National Association for Organic Farming. These regulations restrict the import of manure from outside the farm (25% of the nitrogen demand of the crops must be imported as conventional manure) as well as the total input of manure to the fields (maximum livestock density is 1.4 LU ha^{-1} at the farm). However, the designed organic systems also follow the less severe manure regulations for organic farming in the European Union, saying that the total application of manure should be below 170 kg N ha^{-1} $year^{-1}$ (EU-regulation 1804/1999). In addition, the organic livestock farming systems are designed to achieve 75% self-sufficiency for feed in the pig systems and 85% in the dairy/beef production systems.

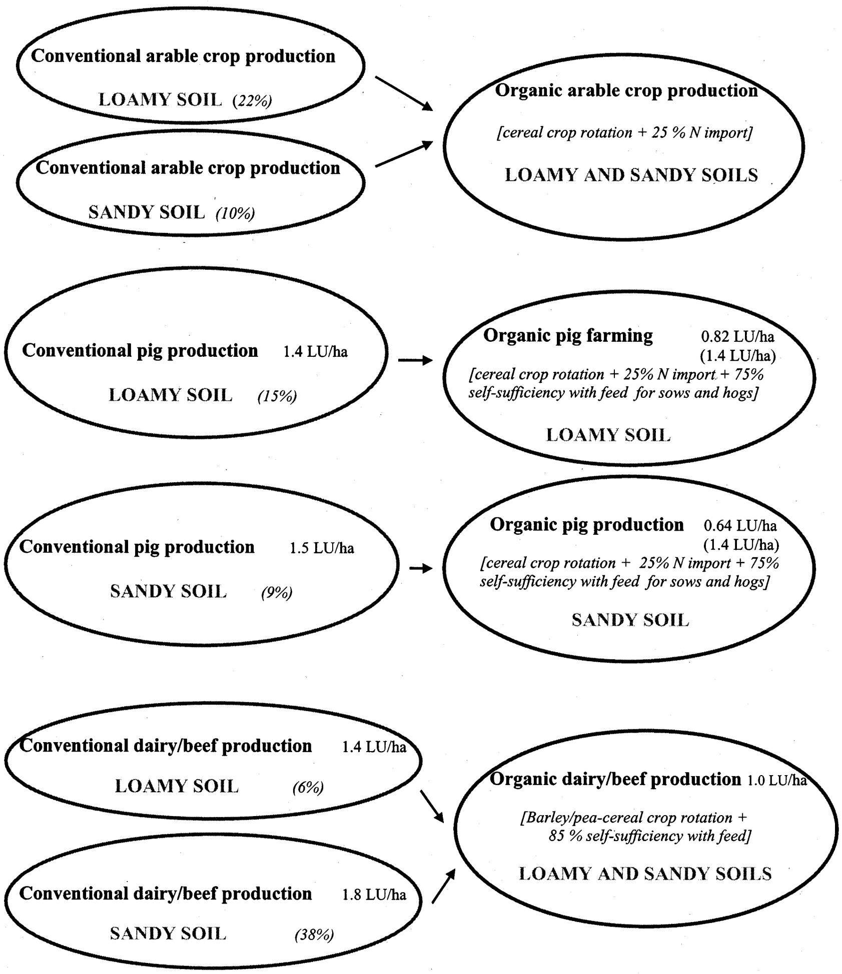

Fig. 2. Comparison of conventional and organic arable and livestock systems in the study. Three different types were chosen: arable crop-, pig-, and dairy/beef production systems on both loamy and sandy soils. The percentages show the part of the different conventional farming systems of the total area of approximately 5000 ha. The LU values show the total livestock density including the import of animal manure.

Table 1
Crop yields and nitrogen fixation for conventional farming systems from the Agricultural Catchment Monitoring

Loamy soils			Sandy soils		
Crop rotation	Yields[a] FU ha^{-1}	N-fixation[b] kg N ha^{-1} $year^{-1}$	Crop rotation	Yields[a] FU ha^{-1}	N-fixation[b] kg N ha^{-1} $year^{-1}$
Conv. Arable					
Winter wheat	8400	2	Winter wheat	5900	2
Spring barley	6000	2	Spring barley	3900	2
Root crops	11600	2	Root crops	–	2
Legumes	6000	188	Legumes	5300	168
Oil-seed rape	4500	2	Oil-seed rape	–	–
Grass	–		Grass	–	–
Conv. pig framing					
Winter wheat	8100	2	Winter wheat	6800	2
Spring barley	5800	2	Spring barley	5000	2
Root crops	12200	2	Root crops	–	–
Legumes	–	–	Legumes	4200	131
Oil-seed rape	3800	2	Oil-seed rape	4400	2
Grass	–	–	Grass	–	–
Conv. dairy/beef farming					
Winter wheat	7850	2	Winter wheat	7200	2
Spring barley	5200	2	Spring barley	4500	2
Root crops	12000	2	Root crops	10000	1
Legumes	5200	164	Legumes	3600	112
Oil-seed rape	2600	1	Oil-seed rape	1800	2
Grass	6700	38	Grass	6400	37

[a] Crop yield in main crop+catch crop. All yields are shown in Scandinavian feed units (FU). One FU corresponds to 1 kg of barley.
[b] N-fixation is calculated according to Kyllingsbæk (1995).

A number of different organic arable and livestock farms were designed (Simmelsgaard et al., 1998). The crop yields were estimated from data from organic farms in Denmark from 1987 to 1996. Organic dairy farming is the best investigated system, whereas organic arable farming systems and especially organic pig production systems are less well known. Five course crop rotations were assumed and the fields were assumed to be ploughed in the autumn for weed control in one year out of five. A mixture of ryegrass and grass-clover is undersown in the cereals to function as catch crops and green manure. The number of animals at the livestock farms is adjusted to match the available feed.

The organic arable crop farms mainly rely on cereals (Table 2). Manure is imported corresponding to 25% of the nitrogen demand of the crops as defined by the Danish regulations.

The organic pig farms are designed with a self-sufficiency for feed of 75% and an import of manure equalling 25% of the crop nitrogen demand (Table 2). On sandy soils there are 65 breeding sows and an annual production of 1255 pigs per 100 ha (0.64 LU ha^{-1}) and on loamy soils there are 84 sows and 1621 pigs per 100 ha (0.82 LU ha^{-1}). In total, the density of animals (sows and pigs) is 1.4 LU ha^{-1} on both soil types when the imported manure is included. For grazing the sows use 6 ha on loamy soils and 4.6 ha on sandy soils.

The organic dairy/beef farms are 85% self-sufficient in feed and have no additional import of manure (Table 2). The cows are assumed to be grazing 185 days a year except 6 hours a day when they are kept indoors. On loamy soils there are 76 cows and 78 heifers per 100 ha and 75 cows

Table 2
Crop yields and nitrogen fixation in organic arable crop, and in pig and dairy/beef production systems based on Simmelsgaard et al. (1998)[a]

Loamy soils				Sandy soils			
Crop rotation	Yields[a] FU ha^{-1}	Clover- yields[b] hkg ha^{-1}	N_2-fixation kg N ha^{-1} $year^{-1}$	Crop rotation	Yields[a] FU ha^{-1}	Clover-yields[b] hkg ha^{-1}	N_2-fixation kg N ha^{-1} $year^{-1}$
Organic arable crop farm				*Organic arable crop farm*			
Spring barley with undersown grass-clover	3770	8	36	Spring barley with undersown grass-clover	2720	7	31
Grass-clover (50%)	0	36	166	Grass-clover (50%)	0	30	139
Winter wheat with catch crop	5020	4	22	Oats with catch crop	3930	3	19
Spring barley with catch crop	4460	4	22	Winter rye with catch crop	2740	3	19
Oats	3650			Spring barley	3060		
Organic pig farm				*Organic pig farm (irrigated soil)*			
Spring cereal with undersown grass-clover	4028	7	43	Spring cereal with undersown grass-clover	2849	6	37
Grass-clover (38%)	3518	30	186	Grass-clover (38%)	3315	28	174
Spring cereal with catch crop	4735	3	19	Spring cereal with catch crop	3667	2	12
Spring barley with catch crop	4017	3	19	Spring barley with catch crop	2849	2	12
Spring cereal	3982	0	0	Spring cereal	2849	0	0
Organic dairy/beef farm				*Organic dairy/beef farm (irrigated soil)*			
Barley/pea with undersown grass-clover (15% pea)	3900+390	6	54	Barley/pea with undersown grass-clover (30% pea)	3500+390	5	68
Grass-clover (26%)	6100	25	143	Grass-clover (26%)	5900	24	137
Grass-clover (26%)	6100	25	143	Grass-clover (26%)	5900	24	137
Spring cereal with catch crop	3300+390			Spring cereal with catch crop	3300+390		
Spring cereal with catch crop	3300+390			Spring cereal with catch crop	3300+390		

[a] Crop yields are based on registrations from organic farms in Denmark from 1987 to 1996. Crop yield in main crop+catch crop. All yields are shown in Scandinavian feed units (FU). One FU corresponds to 1 kg of barley.

[b] Dry matter-production in clover-grass is assumed to be 7.1 t ha^{-1} (6100 FU/ha with 1.16 kg dry matter per FU) on loamy soil, 6.0 t ha^{-1} (5200 FU ha^{-1} with 1.16 kg dry matter per FU) on non-irrigated sandy soil, and 6.8 t ha^{-1} (5900 FU ha^{-1} with 1.16 kg dry matter per FU) on irrigated sandy soil. Yields are from Halberg and Kristensen (1997) and the nitrogen concentration from Strudsholm et al. (1995).

and 77 heifers per 100 ha on sandy soils. The density of animals is 1 LU ha^{-1} for both soil types.

3. Evaluation of the N-leaching model

3.1. A conventional example — the Agricultural Catchment Monitoring

In the Agricultural Catchment Monitoring of conventional farms the actual nitrogen leaching was measured at 32 permanent stations from 1990. The 32 stations were selected to characterise current Danish conventional farming in this study. At each station, soil water was collected weekly from ten suction cups placed at 1 m, representing an area of approximately 100 m^2. On loamy soil, with a ground water table close to the surface, the DAISY model (Hansen et al., 1990) was used to estimate the percolation from the root zone, while the EVACROP model (Olesen and Heidmann, 1990) was used at the other more sandy soil sites.

The model from Simmelsgaard (1998) is used to calculate the nitrogen leaching. As an average

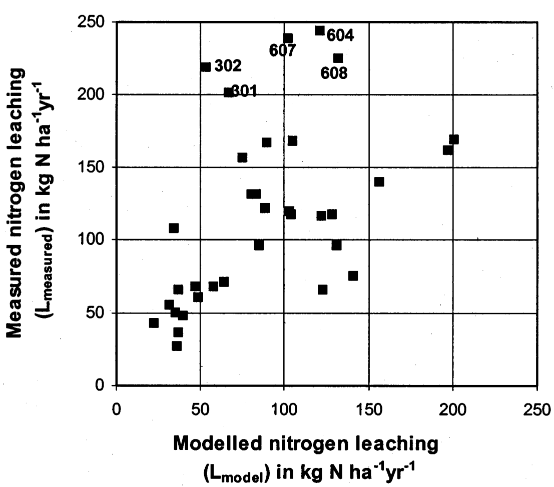

Fig. 3. Comparison of measured ($L_{measured}$) and modelled (L_{model}) nitrogen leaching (kg N ha^{-1} year^{-1}) for 32 field stations in the Agricultural Catchment Monitoring as average values for 1990 to 1994. The model is from Simmelsgaard (1998). Regression Eq. (5) includes the five extreme values, whereas they are excluded from Eq. (6).

(1990–1994) the measured ($L_{measured}$) and modelled (L_{model}) nitrogen leaching (kg ha^{-1} year^{-1}) for the 32 stations has the following relation ($P < 0.05$):

$$L_{model} = 0.38\ L_{measured} + 44.2,\quad r^2 = 0.24 \text{ and } n = 32 \tag{5}$$

There are five stations where the modelled nitrogen leaching is very different (absolute values) from the measured nitrogen leaching (Fig. 3, no. 301, 302, 604, 607 and 608). Excluding the five stations gave the following relation between the modelled and measured nitrogen leaching ($P < 0.05$):

$$L_{model} = 0.89\ L_{measured},\ r^2 = 0.45 \text{ and } n = 27 \tag{6}$$

The five strongly divergent stations are all located on dairy farms with a moderate to high livestock density (1.1–1.6 LU ha^{-1}) and a rather high percolation from the root zone (532–665 mm year^{-1}). Stations 604, 607 and 608 are located on a sandy outwash plain. Stations 301 and 302 are located in a very undulating landscape with loamy soils where complicated hydrogeological conditions may explain the great absolute deviation between the measured and modelled nitrate leaching. These uncertainties do not apply at any of the other stations.

The model (Simmelsgaard, 1998) strongly underestimated the leaching of nitrate for the crop combinations: 'grass, grass' and 'grass, winter cereal', but also for 'cereals, winter cereal', and 'cereals, catch crop' (Fig. 4). On the other hand the model overestimated the nitrogen leaching from 'cereals, animal manure'. The crop combinations with grass received a high input of nitrogen (357–467 kg N ha^{-1} year^{-1}) and mainly occur in the crop rotations at the dairy farms on the sandy soils. Leaching of nitrogen can show a high degree of variation between different grass fields depending on the management practice (age, amount of manure application, amount of nitrogen fixation, grazing, etc.). Thus, the high proportion of grass in the crop rotations at the divergent stations (604, 607 and 608) located on the sandy outwash plains may explain why the measured nitrogen leaching is higher than the modelled (Fig. 4).

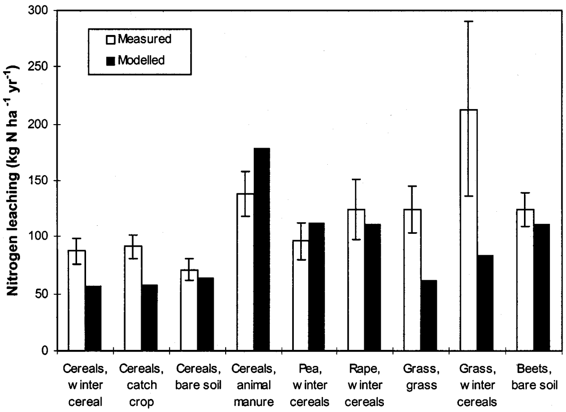

Fig. 4. Comparison of measured and modelled nitrogen leaching (kg N ha^{-1} year^{-1}) for the crops (previous crop, winter crop) in the Agricultural Catchment Monitoring from 1990 to 1996.

3.2. An organic example — an organic crop rotation trial

There are very few data on nitrogen leaching from organic farming systems. Tentatively, the nitrogen leaching model will be evaluated on 3 years' data from an organic six-course dairy rotation at the Research Centre Foulum in Denmark. The crop rotation consists of barley with undersown grass–clover, grass–clover, grass–clover, pea/barley whole crop, winter wheat, and beets (Askegaard and Eriksen, 1997). The soil type is a loamy sand (7.7% clay) and the organic trial has been conducted since 1987. Various experiments have been carried out since 1994 including two levels of application of manure. The suction cell-method (16 cups in each field and weekly collections) was used to collect soil water samples and the water balance model EVACROP (Olesen and Heidmann, 1990) was used to calculate percolation.

The nitrogen balance at the field level was estimated from crop yields in the experiment and the N_2 fixation model. Nitrogen inputs from grazing cows were estimated at 25 kg N ha^{-1} year^{-1} as an average for the crop rotation (the two grass-clover fields out of the total of six fields are receiving 75 kg N ha^{-1} year^{-1} from grazing cows). The N_2 fixation was calculated as 69 kg N ha^{-1} year^{-1} on average during the crop rotation. The total input of nitrogen varied from 199 (0.9 LU ha^{-1}) to 240 kg N ha^{-1} year^{-1} (1.4 LU ha^{-1}), and the net input of nitrogen was 82 and 116 kg N ha^{-1} year^{-1} with the two stocking densities (Table 3).

Generally, the modelled nitrogen leaching is higher than the measured, on average 11 kg N ha^{-1} year^{-1}(Table 3). The main reason for the annual variation of nitrogen leaching is the large variation in percolation between the 3 years (64–578 mm year^{-1}).

4. Results of the modelling

4.1. Comparison of N-balances

On average, the total nitrogen input to the organic systems (104–216 kg N ha^{-1} year^{-1}) is lower than to the conventional agricultural systems (146–311 kg N ha^{-1} year^{-1}) (Table 4). Part of the nitrogen from artificial fertilisers in the conventional systems has been replaced in the organic systems by symbiotically fixed N_2. The average crop N-yields (shown as N_{yield} in Table 3) are lower for the organic than the conventional systems, with the greatest difference in the arable crop farms and smallest difference in the dairy/beef farms. This is due to the fact that the crop rotation is not radically changed when converting from conventional to organic dairy farming since grass–clover is also a principal crop in the conventional system. The lower N-yields in the organic farming systems are also a consequence of incorporating straw, which is less usual in the conventional systems. The conventional farming practice typically implies removing the straw from the fields, and both the straw and grain are included in the yields. Traditionally, in organic farming practice, straw is incorporated in the soil, in order to obtain a high soil organic matter content, and only grains are included in the yields.

The N-balance sheets (Table 4) show a surplus of nitrogen (net input of nitrogen) in the organic fields between 60 and 143 kg N ha^{-1} year^{-1}. In the conventional systems the surplus varied from 25 to 155 kg N ha^{-1} year^{-1}. In the arable crop

Table 3
Nitrogen balances, measured and modelled nitrogen leaching for the organic six-course dairy rotation at the Research Centre Foulum, Denmark from 1994 to1997[a]

	LU (ha^{-1})	Total N (kg N ha^{-1} $year^{-1}$)	N_{yield} (kg N ha^{-1} $year^{-1}$)	N_{net} (kg N ha^{-1} $year^{-1}$)	Measured $N_{leaching}$ (kg N ha^{-1} $year^{-1}$)	Modelled $N_{leaching}$ (kg N ha^{-1} $year^{-1}$)
1994/95	0.9	199	113	86	54	55
(578 mm $year^{-1}$)	1.4	240	119	121	59	69
1995/96	0.9	199	112	87	4	22
(64 mm $year^{-1}$)	1.4	240	121	119	5	28
1996/97	0.9	199	127	72	23	36
(208 mm $year^{-1}$)	1.4	240	133	107	31	45
Average	0.9	199	117	82	27	38
Average	1.4	240	124	116	32	47
Average	1.2	220	121	99	29	43

[a] The experiment included two levels of application of manure equal to 0.9 and 1.4 LU ha^{-1}. The total nitrogen input to the rotation (Total N), the nitrogen content of the yields (N_{yield}) and the net input of nitrogen (N_{net}) are shown as calculated from the nitrogen balances. Figures in brackets are calculated percolation amounts.

farms on loamy soil and the pig farms on both loamy and sandy soils there was a greater net input of nitrogen to the organic than to the conventional systems. The N-balances show the opposite for arable crop production and dairy/beef farms on sandy soil where the net input of nitrogen to the crop rotations are lower for the organic compared to the conventional systems. This is a consequence of a high import of animal manure in the conventional arable crop production system due to economical reasons. A high livestock density in the conventional dairy/beef farming system on sandy soils explains the relative low net input of nitrogen for the organic dairy/beef farming system. For loamy soil the dairy/beef farm has the same net input of nitrogen in the organic and the conventional system.

4.2. Comparison of the N-leaching

Differences in the modelled nitrogen leaching between the conventional and organic systems are entirely due to: (i) differences in the total nitrogen input (Table 4); and (ii) the choice of crops in the rotations (Tables 5 and 6) since the clay content and the percolation is kept constant for the same soil type (see Eq. (3)).

The crop types in the conventional and organic farming systems were classified according to the nine combinations used in the nitrogen leaching model (Tables 5 and 6). For the conventional farms, the nine types each represent averages of somewhat diverse practices and no conventional practice correspond exactly to the individual types in Tables 5 and 6. In the organic pig farms, sows graze 6 ha (loamy soil) or 5 ha (sandy soil) of grass per 100 ha. These grazed fields may be prone to high nitrate leaching, and it was decided to regard such fields as crop type no. 9 (Table 6, 'cereals, animal manure'). The extensive use of grass as a winter crop without application of animal manure in the winter (except for fields with grazing sows) in the organic systems reduces the modelled nitrate leaching losses from the organic compared to the conventional systems. This effect is, for example, seen for pig farming on loamy soil where the input of nitrogen to conventional and organic farming is almost equal (212:214 kg N ha^{-1} $year^{-1}$). Here the modelled nitrogen leaching is 46 kg N ha^{-1} $year^{-1}$ for conventional pig farming and 30 kg N ha^{-1} $year^{-1}$ for organic pig farming (see Tables 5 and 6) because of the extensive use of grass as a winter crop in the organic system. In comparison, the

Table 4
N-balances and modelled N-leaching for conventional (conv.) and organic (org.) agricultural production systems (kg N ha^{-1} $year^{-1}$)[a]

			LU ha^{-1}[a]	Total N	$N_{atmosphere}$[b]	N_{manure}	$N_{fertiliser}$	N_{yield}	N_{net}	$N_{leaching}$[c]
Arable crop farm	Loam	Conv.		146	22	4	120	121	25	32
		Org.		116	69	47	0	56	60	19 (29)
	Sand	Conv.		212	31	96	85	105	107	90
		Org.		104	61	43	0	44	60	36 (46)
Pig farm	Loam	Conv.	1.4	212	25	102	86	115	97	46
		Org.	0.8 (1.2)	214	73	141	0	87	126	30 (49)
	Sand	Conv.	1.5	227	31	126	70	106	122	111
		Org.	0.6 (1.3)	211	67	144	0	68	143	61 (95)
Dairy/beef farm	Loam	Conv.	1.4	241	25	130	87	150	91	48
		Org.	1.0	215	90	126	0	120	95	28 (49)
	Sand	Conv.	1.8	311	41	160	111	156	155	103
		Org.	1.0	216	91	124	0	117	99	65 (104)

[a] Values in parentheses include imported animal manure.
[b] N_2-fixation plus atmospheric deposition (the latter set at 20 kg N ha^{-1} $year^{-1}$).
[c] values in parentheses are modelled nitrogen leaching for organic agricultural systems without catch crops.

Table 5
Agricultural area (%) with different crop types in the conventional agricultural systems classified according to the nine crop combinations in the nitrogen leaching model

No.	Previous crop	Winter crop	Arable crop farm loam	Arable crop farm sand	Pig farm 1.4 LU ha^{-1} loam	Pig farm 1.5 LU ha^{-1} sand	Dairy/beef farm 1.4 LU ha^{-1} loam	Dairy/beef farm 1.8 LU ha^{-1} sand
1	Grass	Grass	10	23	17	10	22	55
2	Barley	Grass			3	2	9	10
3	Grass	Winter cereals	3		6		4	
4	Beets	Bare soil	18	16	4		10	12
5	Cereals	Winter cereals	31	23	29	39	27	7
6	Cereals	Catch crop	2		4	8	3	
7	Rape or pea	Winter cereals	3	4	17	20	3	3
8	Cereals	Bare soil	32	22	9	10	8	2
9	Cereals	Animal manure		11	11	11	14	10

Table 6
Agricultural area (%) with different crop types in the organic agricultural systems classified according to the nine crop combinations in the nitrogen leaching model. The values in parentheses are for organic systems without catch crops.

No.	Previous crop	Winter crop	Arable crop farm loam	Arable crop farm sand	Pig farm 1.4 LU ha^{-1} loam	Pig farm 1.4 LU ha^{-1} sand	Dairy/beef farm 1.0 LU ha^{-1} loam	Dairy/beef farm 1.0 LU ha^{-1} sand
1	Grass	Grass		20 (20)	14 (14)	15 (15)	40 (40)	40 (40)
2	Barley	Grass	60 (20)	40 (20)	60 (20)	60 (20)	40 (20)	40 (20)
3	Grass	Winter cereals	20 (20)					
4	Beets	Bare soil						
5	Cereals	Winter cereals		20 (20)				
6	Cereals	Catch crop						
7	Rape or pea	Winter cereals						
8	Cereals	Bare soil	20 (60)	20 (40)	20 (60)	20 (60)	20 (40)	20 (40)
9	Cereals	Animal manure			6 (6)	5 (5)		

conventional systems are using winter cereals (wheat) to a great extent (Table 5).

The modelled nitrate leaching from the organic systems varies from 19–30 kg ha^{-1} year^{-1} on loamy soils to 36–65 kg ha^{-1} year^{-1} on sandy soils (Table 4). The modelled nitrogen leaching from the organic systems is in all cases lower than from the selected conventional agricultural systems. In particular, the modelled nitrogen leaching is reduced on sandy soils when converting to organic farming.

Typically, the organic farming systems have 20–40% of the fields in the rotation covered with grass during winter and 20% have bare soil during winter in order to control weeds. Nitrogen leaching in the organic systems has also been calculated for the situation with no grass during winter (parentheses in Tables 4 and 6). It appears that the modelled nitrogen leaching from the organic systems with no grass during winter is increased, reaching approximately the same level as in conventional farming (Table 4).

5. Discussion

5.1. The nitrogen leaching model

The nitrogen leaching model (Simmelsgaard, 1998) was evaluated for both conventional and organic farming systems. It is known that the leaching of nitrogen from grass fields depends on many factors such as the amount of applied animal manure (Scholefield et al., 1993), grazing intensity of animals (Ryden et al., 1984), and the time of soil cultivation (Addiscott, 1992; Djurhuus and Olsen, 1997). In the data set used to estimate the model parameters for the nitrogen leaching model there were 33 grass fields. Seventeen of the fields were grass-clover and 16 rye grass. Of the 16 rye grass fields, seven were used for seed and only few of the grass fields were grazed. The nitrogen leaching model was therefore unable to estimate the exact nitrogen leaching from all types of managed grass fields. The crop combination 'grass, winter cereal' occurs only in very few (3%) of the fields in the organic and conventional systems which were compared. The crop combination 'grass, grass' occurs in 23% (8–59%) of the conventional fields and in 22% (0–40%) of the corresponding organic fields. Especially, the crop combination 'grass, grass' and thereby different management practices of the grass fields in both the conventional and organic farming systems introduces an uncertainty in the modelled nitrogen leaching. We assume that this uncertainty will have the same order of magnitude for the compared conventional and organic systems, so that relative differences between the nitrogen leaching from the conventional and organic systems are unaffected.

5.2. Nitrogen leaching and net input of nitrogen

There are only few published field investigations of nitrogen leaching from organic farming practices both. These results do not give a realistic picture of the level of nitrogen leaching from different types of organic farming since: (i) the years and duration of the investigations varied; (ii) the methods used were not directly comparable; (iii) soil types and climatic conditions differed; and (iv) most of the studies concerned dairy farms. In general, the results show that the leaching of nitrate from organic farming was very low, from 8 to 34 kg N ha^{-1} year^{-1}, outside Denmark (Brandhuber and Hege, 1992; Granstedt, 1992; Stopes and Philipps, 1992; Younie and Watson, 1992; Watson et al., 1993; Nolte and Werner, 1994; Philipps et al., 1995; Eltun, 1995; van der Werff et al., 1995) and from 27 to 40 kg N ha^{-1} year^{-1} in Denmark (Kristensen et al., 1994; Magid and Kølster, 1995; Askegaard and Eriksen, 1997). Some of the investigations directly compared conventional and organic farming. The investigations from Scotland, Germany and Norway showed a higher leaching potential from conventional compared to organic farming (Younie and Watson, 1992; Brandhuber and Hege, 1992; Eltun, 1995) while one Danish analysis (Kristensen et al., 1994) showed no significant difference in the nitrate leaching potential.

In the present paper two different methods were used to estimated the leaching of nitrogen from the conventional and organic systems: (I) modelling of nitrogen leaching; and (II) N-balances for the root zone. A high net input of nitrogen to the fields indicates a high long-term nitrogen leaching potential or a potential for higher yields. In the cases where the two methods indicate the same tendency, the difference in modelled nitrate leaching between the organic and conventional systems can be treated with greater confidence. However, it is necessary to explain the results where a high net input of nitrogen to the field coincides with low modelled nitrate leaching.

Net input of nitrogen is the surplus of the nitrogen in the soil root zone. It is not possible to deduce the nature of this nitrogen surplus because net input of nitrogen will go to: (I) nitrogen leaching; (II) the build-up of the pool of soil organic nitrogen; (III) ammonia volatilisation and denitrification; or (IV) higher crop yields than estimated. Long-term field experiments on sandy soils have shown that generally there has been a decline in the pool of soil organic matter and nitrogen during the last 100–150 years (Christensen and Johnston, 1997). On the other hand, investigations on clayey soils show that it is possible to increase the pool of soil organic matter by application of animal manure (Christensen and Johnston, 1997). But in sandy soil types it is difficult to build-up organic matter in the soil as long as the soil is being cultivated annually. A cool climate and a heavy annual precipitation are conductive to increases in the total carbon content in the soils. Thus, organic dairy farming in Norway was able to significant increase the content of carbon from 1989 to 1995 in soils with a low original organic matter content (Løes and Øgaard, 1997). Long term experiments have also shown that ley-arable rotations, typically used in organic farming, are capable of increasing the soil organic carbon content by 13–28% compared to arable farming (Smith et al., 1997). It might be possible to build-up organic matter in agricultural soils by use of perennial grass fields or by application of large amounts of organic matter in the form of crop residues or animal manure (Johnston et al., 1994).

The organic agricultural practice with the use of perennial grass fields, catch crops, re-circulation of crop residues to the soil, and the use of organic instead of artificial fertilisers, can be assumed to result in a higher level of soil organic nitrogen. In the long run, this nitrogen will be mineralised again and results in either higher crop yields or higher nitrogen leaching.

It should be noted that crop rotations for the conventional systems were taken from observed practices in 1996, whereas the rotations for the organic systems were the estimated best practices. For the conventional farms it is therefore necessary to remember that it is the political target to reduce the leaching of N as observed in 1996 and as used in this study. As far as the organic farms are concerned the 'best practice' is not necessary the same as current practice. Thus the yields for the organic farming systems are based on measurements from actual farms where less than optimal crop rotations may have been used. This suggests that some of the estimated high net nitrogen inputs may be due to underestimated yields for these organic crop rotations.

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