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Beretning nr. 2214

N-transformation and N-transport in a sandy loam and a coarse sandy soil cropped with spring barley

II. Nitrate leaching

N- omsætning og N-transport i en sandblandet lerjord og en grovsandet jord bevokset med vårbyg

II. Nitratudvaskning

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Summary

Nitrate leaching was studied in two field experiments grown with spring barley on a sandy loam and a coarse sandy soil located at the experimental stations Askov and Jyndevad, respectively. The studies were carried out from spring 1987 to spring 1990. At Askov the treatments were: unfertilized, 100 kg NH_4^+-N/ha in pig slurry applied in the spring and 133 kg N/ha in N-fertilizer. At Jyndevad the treatments were: unfertilized, 50 kg NH_4^+-N/ha in pig slurry applied in spring, 100 kg NH_4^+-N/ha in pig slurry applied in spring, 100 kg NH_4^+-N/ha in pig slurry applied in late autumn, 100 kg NH_4^+-N/ha in pig slurry applied in spring with ryegrass as an undersown catch crop and 120 kg N/ha in N-fertilizer. Nitrate concentrations in the percolate from the root zone were obtained by use of porous ceramic cups placed at a depth of 100 and 80 cm at Askov and Jyndevad, respectively. The soil water samples were taken weekly or biweekly. Percolation from the root zone was in the winter period calculated by use of measured values of precipitation and simulated potential evapotranspiration. During the growth period and autumn also soil water contents measured by means of neutron scattering were used for the calculations. The three years were characterized by high precipitation and relatively warm winter periods.

The mean annual nitrate leaching in the N-fertilized treatments was 62 kg N/ha at Askov and 65 kg N/ha at Jyndevad. At Jyndevad, ryegrass as an undersown catch crop reduced the leaching significantly. Application of pig slurry in late autumn on the coarse sandy soil caused an significant increase in the nitrate leaching. Thus the nitrate leaching during the following winter period and spring/summer was equivalent or higher than the amount of NH_4^+-N in the slurry. Furthermore, the results stress the significance of both the amount of N-fertilizer and slurry and also of nitrogen mineralization. Thus the last year the nitrate leaching in the unfertilized treatments was 71 and 80 kg N/ha for Askov and Jyndevad, respectively, which was at the same level as the other treatments except for the treatments with the catch crop and autumn applied slurry.

Key words: Nitrate leaching, pig slurry, catch crop, spring barley.

Resumé

Udvaskning af nitrat er blevet målt i markforsøg med vårbyg på en grov sandblandet lerjord og grovsandet jord på henholdsvis Askov og Jyndevad forsøgsstationer. Undersøgelserne forløb fra foråret 1987 til foråret 1990. I Askov var forsøgsbehandlingerne: ugødet, tilførsel af 100 kg NH_4^+-N/ha i svinegylle om foråret og tilførsel af 133 kg N/ha i handelsgødning. I Jyndevad var forsøgsbehandlingerne: ugødet, tilførsel af 50 kg NH_4^+-N/ha i svinegylle om foråret, tilførsel af 100 kg NH_4^+-N/ha i svinegylle om foråret, tilførsel af 100 kg NH_4^+-N/ha i svinegylle omkring 1. december, tilførsel af 100 kg NH_4^+-N i svinegylle om foråret og med udlæg af alm. rajgræs og tilførsel af 120 kg N/ha i handelsgødning. Jordvand til bestemmelse af nitratkoncentration i percolatet fra rodzonen blev udtaget med keramiske sugekopper placeret i 100 og 80 cm dybde i henholdsvis Askov og Jyndevad. Udtag af jordvand blev foretaget ugentlig eller hver anden uge.

Afstrømning fra rodzonen blev beregnet ud fra målte værdier af nedbør og beregnede værdier af potentiel fordampning, og i sommerhalvåret og efteråret tillige på basis af målinger af jordens vandindhold målt ved neutronspredningsmetoden.

De 3 forsøgsår var karakteriseret af store nedbørsmængder og relativt varme vintre. Den gennemsnitlige årlige nitratudvaskning i de handelsgødede led var 62 kg N/ha i Askov og 65 kg N/ha i Jyndevad. I Jyndevad var udlæg af alm. rajgræs i stand til at reducere nitratudvaskningen betydeligt. Tilførsel af svinegylle i efteråret på den grovsandede jord medførte en kraftig forøget nitratudvaskning. Nitratudvaskningen i den efterfølgende vinterperiode og forår/sommer var således af samme størrelsesorden eller større end indholdet af NH_4^+-N i den tilførte gylle.

Herudover understreger resultaterne betydningen af mængde og type af gødning, men også af N-mineraliseringen. Således var nitratudvaskningen i 1989/90 i de ugødede behandlinger 71 og 80 kg N/ha i henholdsvis Askov og Jyndevad, hvilket var på samme niveau som de andre behandlinger bortset fra forsøgsleddene med efterafgrøde og efterårsudbragt svinegylle.

Nøgleord: Nitratudvaskning, svinegylle, efterafgrøde, vårbyg.

Introduction

This paper deals with nitrate leaching in a N-balance project described by *Djurhuus and Lind* (5), which ran for a three year period from spring 1987 to spring 1990, on a sandy loam and a coarse sandy soil.

The purpose of the project was to estimate nitrate leaching, denitrification and net-N-mineralization in relation to the use of different levels of pig slurry versus N-fertilizer. Furthermore, the aspects of undersown grass as a catch crop, and autumn application of slurry were investigated at the coarse sandy soil site.

Results of denitrification and net-N-mineralization in the same project are given by *Maag* (14) and *Debosz* (2), respectively. A detailed description of the experimental design, the experimental areas and the climatic condition, plant production, N-uptake, N-content in roots and mineral N in the soil are given in the first paper (5).

In this paper the concentration of nitrate, as well as the accumulated nitrate leaching will be discussed in relation to the treatments, the climatic conditions in general and other Danish results of nitrate leaching. Furthermore, the results will be discussed in relation to applied mineral N minus removed N in grain and straw.

In this paper only the materials and methods relevant to the nitrate leaching will be described.

Besides the leaching as nitrate, nitrogen might be leached as NH_4^+-N and organic-N. Since NH_4^+-N is adsorbed to the soil colloids, the leaching of NH_4^+-N is, generally, insignificant (7,24). However, leaching of organic-N might be of importance when estimating the total nitrogen leaching from the root zone. Hence *Hansen* (7) has estimated the leaching of organic-N to range from 5 to 30 kg N/ha/year with the highest values probably caused by heavy application of slurry/manure. In this project the highest application of nitrogen corresponds with 'normal' application. Thus leaching of nitrate was assumed to account for the major part of the leaching of total-N in this experiment.

Materials and methods

Field sites

The experiment was carried out at the experimental stations Askov and Jyndevad. The soil at Askov is a sandy loam and the soil at Jyndevad is a coarse sand.

At both localities the crop was spring barley. The treatments at Askov, with the abbreviations given in brackets, were:

1. Unfertilized (0 N).
4. Pig slurry, 100 kg NH_4^+-N/ha in the spring (PS S 100 N).
8. N-fertilizer, 133 kg N/ha (NPK 133 N).

At Jyndevad the treatments were:

1. Unfertilized in the actual year (0 N). In the previous years – starting in 1987 – the plots were treated as in treatment 3.
2. Pig slurry, 50 kg NH_4^+-N/ha in the spring (PS S 50 N).
3. Pig slurry, 100 kg NH_4^+-N/ha in the spring (PS S 100 N).
4. Pig slurry, 100 kg NH_4^+-N/ha in the autumn (PS A 100 N).
5. Pig slurry, 100 kg NH_4^+-N/ha in the spring. Ryegrass as an undersown catch crop *(Lolium perenne* L., cv. Sisu) (PS S 100 N CC). The amount of grass seed was 8 kg/ha.
6. N-fertilizer, 120 kg N/ha (NPK 120 N).

In PS S 100 N CC at Jyndevad, the grass was ploughed under in spring.

At Askov the present field experiment was started in 1985. The experiment was carried out as a randomized block design with 2 replications. At Jyndevad the experiment was started in 1987. The experiment was carried out as a randomized block design with 4 replications.

At Askov, before the experiment started, the field was grown with spring barley from 1982 to 1984 and fertilized with degassed pig slurry (110-120 kg NH_4^+-N/ha). At Jyndevad, the field was used from 1982 to 1983 for an experiment with grass and clover receiving from 0 to 450 kg N/ha in N-fertilizer. From 1984 to 1986 the field was grown uniformly with spring barley, maize and potatoes fertilized with 90 kg N/ha in N-fertilizer, 150 kg N/ha in N-fertilizer supplemented with about 50 kg NH_4^+-N/ha in slurry from young cattle, and 140 kg N/ha in N-fertilizer, respectively.

Because the field experiment at Jyndevad was started in the spring 1987 the treatment with autumn applied slurry was amended with slurry in the spring 1987 as PS S 100 N. At Askov the unfertilized plots have not received fertilizer since 1984.

The incorporation of the slurry was carried out within 1-3 hours and 1/2-1 hour after application at Askov and Jyndevad, respectively.

The field experiment at Askov was not irrigated, while the field experiment at Jyndevad was irrigated at an estimated water deficit of about 30 mm.

Nitrate in soil water

Soil water solution from the bottom of the root zone was obtained by use of porous ceramic suction cups. The equipment and installation were as described by *Djurhuus* (4). At Askov the centre of the cups was placed at 100 cm depth and at Jyndevad at 80 cm depth. At both locations 2 cups were installed per replication corresponding to 4 and 8 per treatment for Askov and Jyndevad, respectively. Soil water samples were taken weekly or biweekly. The soil water samples were obtained using the falling head method. 2 1/2-3 days before the soil water had to be taken a suction of about 0.7 bar was imposed. The samples were deep-frozen for subsequent analysis of nitrate. During the main leaching period from autumn to March the samples in pairs in each replication were bulked equally except once a month where each sample was analyzed separately. Nitrate was determined by a Technicon Autoanalyzer.

Climate and soil water

Daily values of standard meteorological observations of precipitation, potential evapotranspiration and air temperature were obtained for each location. At Askov the potential evapotranspiration was calculated according to the Makkink-equation (15). At Jyndevad the calculation was in general done according to a modified Penman-equation (15), otherwise Makkink. The precipitation was corrected to the soil surface according to *Allerup* and *Madsen* (1).

During the period from May to the end of November the soil water content was measured weekly by neutron scattering. At Askov the measurements were carried out at 10 depths: 10, 20 ... 100 cm. At Jyndevad the measurements were carried out at 8 depths: 10, 20 ... 80 cm. At Askov access tubes for the neutron probe were installed in 0 N and NPK 133 N and at Jyndevad in 0 N, PS S 100 N CC and NPK 120 N. At each location there was one access tube per replication. At Askov the standard calibration for the given bulk density was used. At Jyndevad the equipment was calibrated for each soil layer using gravimetric measurement of water content in soil samples. Pressure potential was measured by means of tensiometers twice a week in the same period as neutron scattering. At Askov the pressure potential was measured at the following depths: 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 120 and 140 cm. At Jyndevad the pressure potential was measured at the following depths: 10, 20, 30, 40, 50, 60, 70, 80, 100 and 120 cm. The tensiometer cups were placed in the same plots as the access tubes for the neutron probe.

Calculations

Water balance

From May to about the end of November the water balance was calculated according to *Simmelsgaard* (23) by use of soil water content obtained by means of the neutron scattering. For the winter period the water balance was calculated according to *Hansen* and *Aslyng* (10).

Nitrate leaching

Nitrate leaching from the root zone was estimated by combining the calculated percolation from the root zone with the corresponding values of measured nitrate concentrations in the soil water thus assuming that the nitrate concentrations obtained by use of the ceramic suction cups are the flux concentration. The nitrate leaching has been summarized for the periods spring to harvest and harvest to spring as well as for spring to spring the next year. The start and end of each period was determined by the dates of soil sampling with the purpose to make N-balances, for later publication.

In general, missing values were estimated by means of linear interpolation in relation to the dates. When it was evident that linear interpolation was not appropriate, estimation was done by use of the other replications in the same treatment on the relevant date and the dates before and after.

The nitrate leaching was calculated for each replication by using the mean percolation from the root zone for each treatment and not for each block. At Askov no water balance was made separately for PS S 100 N thus it was assumed that the water balance in this treatment was the same as in NPK 133 N. At Jyndevad the water balance calculated for NPK 120 N was also used for PS S 50 N and PS S 100 N and the water balance calculated for 0 N was used for PS A 100 N because the yield in this treatment was close to that of 0 N (5).

Statistics

The nitrate leaching for the given periods was analyzed by use of analysis of variance. In the analysis of variance the degree of freedom was not reduced due to the missing/estimated values of nitrate concentration.

Results

The investigations started at both locations in May 1987 and ended in March 1990. Fig. 1 and 3 show the results of nitrate concentration as the arithmetic mean for each treatment for the 3 year period from Askov and Jyndevad, respectively. In Fig. 1 and 3 the standard errors are given as vertical bars, thus also showing how often the nitrate concentrations have been measured. The standard errors of the means for each treatment were calculated from an analysis of variance for each date. When calculating the standard errors for Jyndevad, PS A 100 N was omitted. This was done because the level of nitrate concentration in this treatment was often considerably higher compared with the other treatments, and because the variation in nitrate concentration depends on the level as can be seen from Fig. 1 and 3.

In Fig. 2 and 4 the accumulated nitrate leaching for each year and treatment together with the daily percolation from the root zone is shown for Askov and Jyndevad, respectively. For Askov (Fig. 2) the percolation is for NPK 133 N and for Jyndevad (Fig. 4) the percolation is for NPK 120 N. At Jyndevad the field experiment started in 1987, thus PS A 100 N was treated as PS S 100 N in 1987, until autumn application 1987. Therefore

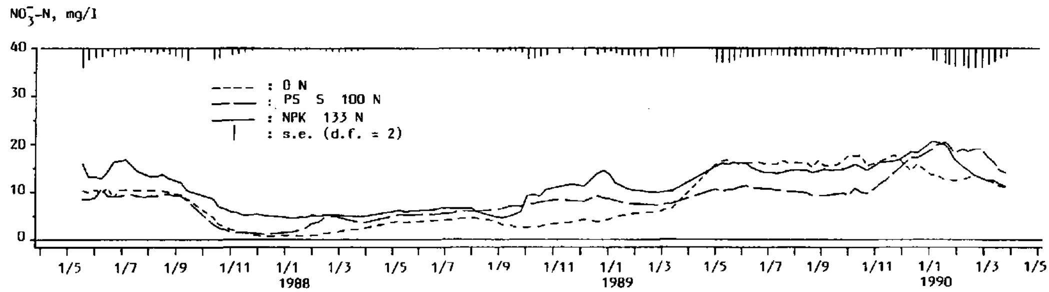

Fig. 1. Askov. Concentration of NO_3^--N in soil water, 100 cm depth. The s.e.'s are for the mean of each treatment.
Askov. Koncentration af NO_3^--N i jordvand, 100 cm dybde. De angivne s.e.'s er for gennemsnittet af hvert led.

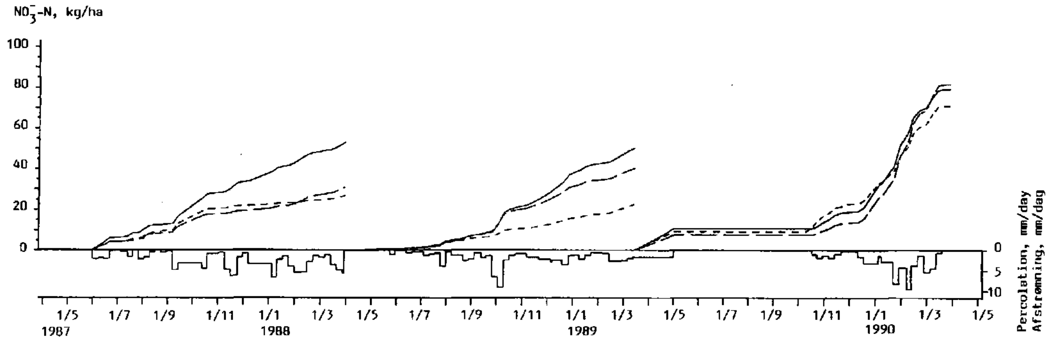

Fig. 2. Askov. Accumulated leaching of NO_3^--N and percolation from the root zone. See Fig. 1 for legend.
Askov. Akkumuleret udvaskning af NO_3^--N og afstrømning fra rodzonen. Se fig. 1 for signaturforklaring.

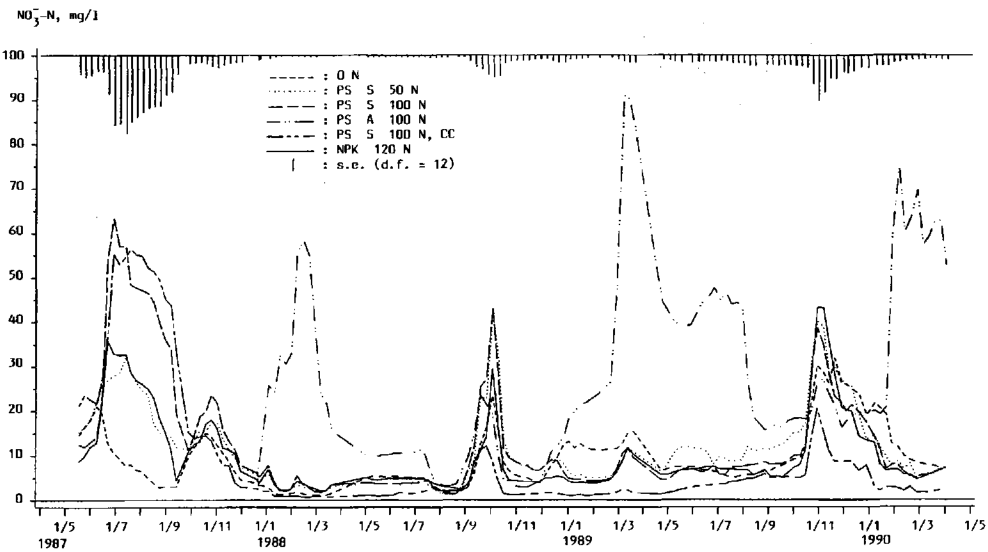

Fig. 3. Jyndevad. Concentration of NO_3^--N in soil water, 80 cm depth. The s.e.'s are for the mean of each treatment.
Jyndevad. Koncentration af NO_3^--N i jordvand, 80 cm dybde. De angivne s.e.'s er for gennemsnit af hvert led.

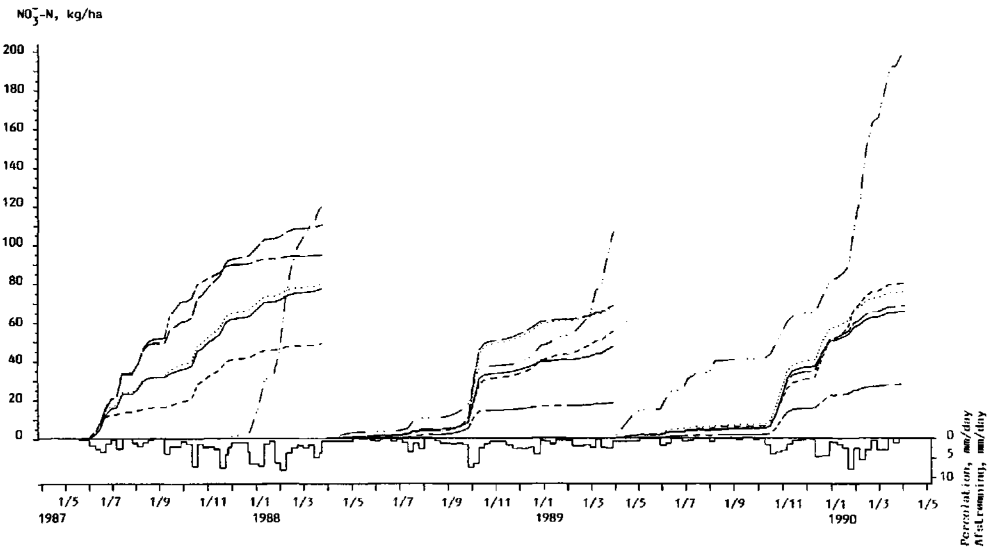

Fig. 4. Jyndevad. Accumulated leaching of NO_3^--N and percolation from the root zone. See Fig. 3 for legend.
Jyndevad. Akkumuleret udvaskning af NO3-N og afstrømning fra rodzonen. Se fig. 3 for signaturforklaring.

the measurements in this treatment were not started before just after the autumn application.

At Askov soil water samples were taken on 123 dates during the 3 year period, which is equivalent to a planned number of 1476 samples of which 105 were missing. At Jyndevad the corresponding figures were 133 dates and 6160 samples of which 352 were missing.

In Table 1 and 2 annual values of nitrate leaching are given for Askov and Jyndevad, respectively. Table 1 and 2 also show the leaching from spring to harvest and from harvest until spring next year. Concerning the results from Jyndevad the LSD-values have, for most of the periods, been calculated both by including and omitting PS A 100 N, because the leaching in this treat-

Table 1. Askov. Leaching of NO_3^--N, kg/ha. Annual and from spring to harvest and from harvest until spring next year.
Askov. Udvaskning af NO_3^--N, kg/ha. Årlig og opdelt på perioderne fra forår til høst og fra høst til forår næste år.

	18.05.87 - 30.03.88					31.03.88 - 13.03.89			14.03.89 - 26.03.90		
	Spring to harvest (15.09) *Forår til høst (15.09)*		Harvest to spring *Høst til forår*	Total		Spring to harvest (22.08) *Forår til høst (22.08)*	Harvest to spring *Høst til forår*	Total	Spring to harvest (17.08) *Forår til høst (17.08)*	Harvest to spring *Høst til forår*	Total
0 N	13.3	(14.7*)	13.6	26.9	(28.3*)	4.9	17.7	22.5	9.3	61.8	71.1
PS S 100 N	11.8	(12.9*)	19.1	30.9	(32.0*)	5.5	34.8	40.3	7.8	74.1	81.9
NPK 133 N	17.0	(19.2*)	36.2	53.2	(55.4*)	5.9	44.4	50.4	10.9	68.5	79.4
LSD_{95}	n.s.		n.s.	n.s.		0.6	1.0	1.1	n.s.	n.s.	n.s.

* Extrapolated from 01.04.87. *Ekstrapoleret fra 01.04.87.*

Table 2. Jyndevad. Leaching of NO_3^--N, kg/ha. Annual and from spring to harvest and from harvest until spring next year.
Jyndevad. Udvaskning af NO_3^--N, kg/ha. Årlig og opdelt på perioderne fra forår til høst og fra høst til forår næste år.

	18.05.87 - 24.03.88			25.03.88 - 28.03.89			29.03.89 - 26.03.90		
	Spring to harvest (21.09) *Forår til høst (21.09)*	Harvest to spring *Høst til forår*	Total	Spring to harvest (18.08) *Forår til høst (18.08)*	Harvest to spring *Høst til forår*	Total	Spring to harvest (16.08) *Forår til høst (16.08)*	Harvest to spring *Høst til forår*	Total
0 N	18.2 (21.7[1])	30.8	49.0 (52.5[1])	4.9	50.4	55.3	6.1	74.1	80.2
PS S 50 N	36.5 (40.0[1])	43.3	79.8 (83.3[1])	3.6	64.5	68.1	6.5	69.0	75.6
PS S 100 N	58.2 (61.7[1])	52.2	110.4 (113.9[1])	3.9	64.5	68.4	4.4	63.9	68.4
PS A 100 N	-	-	211.5** (215.0[1])	10.5	95.8	106.3	40.0	157.7	197.7
PS S 100 N CC	67.1 (70.6[1])	27.7	94.8 (98.3[1])	1.9	16.5	18.3	1.8	26.0	27.8
NPK 120 N	34.6 (38.1[1])	43.0	77.5 (81.0[1])	4.6	42.6	47.2	4.7	60.7	65.4
LSD_{95}	32.9	13.6	37.9*	1.2	21.2 (16.6*)	21.1 (17.0*)	8.5 (2.8*)	49.4 (24.9*)	43.3 (26.1*)

* Without PS A 100 N. *Uden PS A 100 N.*

** The experiment started in 1987. Thus PS A 100 N was treated as PS S 100 N until autumn application 1987. The leaching in PS A 100 N was calculated as the sum of the leaching in PS S 100 N until application of slurry plus the leaching in PS A 100 N after this date.
Forsøget startede i 1987. PS A 100 N blev derfor gødet som PS S 100 N indtil efterårsudbringning af gylle i 1987. Udvaskningen i PS A 100 N er beregnet som udvaskningen i PS S 100 N indtil efterårsudbringningen plus udvaskningen i PS A 100 N efter denne dato.

1 Extrapolated from 01.04.87. *Ekstrapoleret fra 01.04.87.*

Table 3. Askov. Precipitation (P, mm) corrected to the soil surface, actual evapotranspiration (E_a, mm) and percolation from the root zone (mm).
Askov. Nedbør korrigeret til jordoverfladen (P, mm), aktuel evapotranspiration (E_a, mm) og afstrømning fra rodzonen (mm).

	18.05.87-30.03.88			31.03.88-13.03.89			14.03.89-26.03.90		
	P	E_a	Percolation *Afstrømning*	P	E_a	Percolation *Afstrømning*	P	E_a	Percolation *Afstrømning*
0 N	1118 (1182*)	332 (381*)	763 (777*)	1001	435	564	891	388	534
NPK 133 N	1118 (1182*)	344 (393*)	759 (772*)	1001	457	547	891	416	506

* From 01.04.87. *Fra 01.04.87.*

Table 4. Jyndevad. Precipitation (P, mm) corrected to the soil surface, actual evapotranspiration (E_a, mm) and percolation from the root zone (mm).
Jyndevad. Nedbør (P, mm) korrigeret til jordoverfladen, aktuel evapotranspiration (E_a, mm) og afstrømning fra rodzonen (mm).

	18.05.87-24.03.88			25.03.88-28.03.89			29.03.89-26.03.90		
	P*	E_a	Percolation *Afstrømning*	P**	E_a	Percolation *Afstrømning*	P***	E_a	Percolation *Afstrømning*
0 N	1153 (1232[1])	341 (396[1])	808 (832[1])	1013	476	553	980	481	515
PS S 100 N CC	1153 (1232[1])	358 (413[1])	795 (820[1])	1013	485	547	980	500	485
NPK 120 N	1153 (1232[1])	349 (404[1])	792 (817[1])	1013	485	544	980	498	493

* Incl. 23 mm irrigation. *Inklusiv 23 mm vanding.*
** Incl. 30 mm irrigation. *Inklusiv 30 mm vanding.*
*** Incl. 139 mm irrigation. *Inklusiv 139 mm vanding.*
1 From 01.04.87. *Fra 01.04.87.*

ment was at least a factor 2-3 higher than the other treatments.

From 1 April 1987 to 18 May 1987 the estimated percolation from the root zone was 14 and 24 mm for Askov and Jyndevad, respectively. The water balance for this period was calculated by EVACROP (18). Extrapolation by using the nitrate concentration on 18 May for the period 1 April to 18 May 1987 gives leaching values of 1.4, 1.1 and 2.2 kg NO_3^--N/ha at Askov for 0 N, PS S 100 N and NPK 133 N, respectively. Calculated the same way, the average leaching at Jyndevad for the same period was 3.5 kg NO_3^--N/ha. Because the investigation started at Jyndevad in 1987 it is not relevant to distinguish between the treatments in this period.

The annual water balance for each location is given in Table 3 and 4. A more detailed description of the climate is given by *Djurhuus* and *Lind* (5).

In Table 5 and 6 the average annual concentrations in the percolate from 100 and 80 cm depth are given for Askov and Jyndevad, respectively.

Discussion

Nitrate concentration and nitrate leaching

As the nitrate concentration in the percolate from the root zone is the result of the management in general, the microbial activity in the root zone and the percolation through the root zone, it can be very difficult to interpret the results of the nitrate concentration in the percolate from the root zone. In this context the results from Jyndevad are easier to interpret than the results from Askov. Firstly, because the field capacity at Jyndevad to 80 cm depth is only 139 mm at pF = 1.7 compared with 248 mm to 100 cm depth at pF = 2.0 at Askov. Secondly, because the denitrification at Jyndevad is insignificant while the denitrification at Askov can be of importance (14). This means that the management and mineralization/immobilization are reflected faster and more clearly at Jyndevad compared with Askov. These differences are very clearly reflected in the results from Askov (Fig. 1) compared with Jyndevad (Fig. 3).

Askov

At Askov the concentrations change only slowly, mainly due to the climatic conditions. During the

Table 5. Askov. Annual mean concentration of NO_3^--N, mg/l, in the percolation from 100 cm depth.
Askov. Årlig middelkoncentration af NO_3^--N, mg/l, i afstrømningen fra 100 cm dybde.

	1987/88*	1988/89	1989/90
0 N	3.5	4.0	13.3
PS S 100 N	4.1	7.4	16.2
NPK 133 N	7.0	9.2	15.7
LSD_{95}	n.s.	0.2	n.s.

* From 18.05.87. *Fra den 18.05.87.*

Table 6. Jyndevad. Annual mean concentration of NO_3^--N, mg/l, in the percolation from 80 cm depth.
Jyndevad. Årlig middelkoncentration af NO_3^--N, mg/l, i afstrømningen fra 80 cm dybde.

	1987/88*	1988/89	1989/90
0 N	6.1	10.0	15.6
PS S 50 N	10.1	12.5	15.3
PS S 100 N	13.9	12.6	13.9
PS A 100 N	26.2	19.2	38.4
PS S 100 N CC	11.9	3.4	5.7
NPK 120	9.8	8.7	13.3
LSD_{95}	4.8**	3.1**	5.3**

* From 18.05.87. *Fra den 18.05.87.*
** Without PS A 100 N. *Uden PS A 100 N.*

summer 1987, unlike the following years, there was considerable percolation from the root zone which was reflected in the decrease in nitrate concentration in autumn 1987. However, the leaching during the summer period was not statistically different (Table 1). During the winter period 1987/88, 0 N showed a slight increase in nitrate concentration, while PS S 100 N showed a higher increase during January and February, as a contrast to NPK 133 N which was at the same level during the entire winter period. For the period spring 1987 to spring 1988 the nitrate leaching was the highest in NPK 133 N and the lowest in the unfertilized treatment, while PS S 100 N was slightly higher than the unfertilized treatment, even though the differences were not statistically significant. The next year the concentrations were fairly constant during the summer period due to little percolation from the root zone. During the winter period NPK 133 N showed a considerable increase compared with the other treatments. For the period spring 1988 to spring 1989 the results of nitrate leaching showed the same trend as the previous year, but this year the results are statistically significant. The last year was characterised by a dry summer and autumn period followed by a relatively warm and wet winter period. Thus, probably due to these climatic conditions, the net-N-mineralization and hence the nitrate leaching was quite high in all the treatments during this period. The results from the last year are in agreement with the results of *Hansen* (8) and *Olsen* (19).

Jyndevad

At Jyndevad the nitrate concentrations in the percolate showed great fluctuations during the 3 year period. In the autumn the concentrations showed a significant increase followed by a subsequent decrease as the result of the mineralization and the percolation from the root zone. As at Askov, the first summer was very wet but with considerably higher leaching because of the lower field capacity relative to Askov. The peak in summer 1987 in the fertilized treatments compared with the unfertilized treatment may be ascribed partly to the amount of inorganic nitrogen in the N-fertilizer and slurry, and considering the slurry applied treatments, partly to the amount of organic nitrogen. Thus the organic nitrogen was equal to about 76% of NH_4^+-N in the slurry (5) which was considerably higher than the other years. During autumn and winter 1987/88 the catch crop caused a significant decrease in the nitrate leaching which can be seen in Table 2 by comparing PS S 100 N with PS S 100 N CC even though the effect was not as marked this year as the following years. The differences in the effect of the catch crop can be explained in view of the date of harvest in late September 1987 caused by a very wet August and September, thus the growth of the catch crop was delayed this year compared with the following years. Therefore the nitrogen uptake in the above ground biomass of the catch crop (5) was lower in 1987/88 than the other years, even though the reduced leaching was not fully reflected in the nitrogen uptake.

On average, the catch crop reduced the nitrate leaching in the 3 years by 35 kg N/ha/year.

Applying slurry in the autumn/early winter resulted in very high nitrate concentrations during the following winter period and to some extent also in the following summer period, especially in 1989. In winter 1987/88 the nitrate leaching after applying slurry was equivalent to the amount of NH_4^+-N in the slurry. In the winter periods 1988/89 and 1989/90 66 kg NO_3^--N/ha and 133 kg NO_3^--N/ha were leached in the same period, respectively. These differences in the leaching patterns were also very clearly reflected in the figures of the soil mineral N in the spring and in the N-uptake in the following growth period (5). In spring 1988 soil mineral N in PS A 100 N was at the same level as the other treatments, while in 1989 and 1990 the surplus of mineral N in PS A 100 N compared with the other treatments was about 40 and nearly 20 kg N/ha, respectively. In spring 1989 the remaining nitrogen was mainly below the plough layer, and it was leached during the spring and the growing season. Thus the extra N-uptake in grain and straw in PS A 100 N compared to the unfertilized treatment for 1988, 1989 and 1990, was only 2.8, 4.2 and 7.0 kg N/ha, respectively.

Considering the level of nitrogen fertilization (0 N, PS S 50 N, PS S 100 N and NPK 120 N) no clear conclusion can be drawn except for the first year which has already been discussed. In the second year, there was a tendency to a higher leaching in the slurry applied treatment compared with NPK 120 N which might be explained in view of the mineralization of some of the organic nitrogen applied with the slurry. The last year the leaching in 0 N, PS 50 N, PS S 100 and NPK 120 N was at the same level indicating that the leaching was mainly caused by the 'background' mineralization probably due to the same climatic conditions as mentioned for Askov.

Leaching in relation to applied mineral N minus removed N in straw and grain

N-utilization defined as nitrogen uptake as percent of nitrogen applied decreases with increasing application of nitrogen (13). Therefore it cannot be expected to find a simple linear relation between applied mineral N and nitrate leaching. Instead nitrate leaching might be expected to be linear increasing with increasing surplus of nitrogen defined as applied mineral N minus removed N in grain and straw as shown by *Kyllingsbæk* and *Simmelsgaard* (13).

Askov

In Fig. 5 the annual leaching results from Askov are shown as a function of applied mineral N minus removed N in grain and straw.

Because of the microbial activity in the root zone, the main part of the surplus of N is not left as mineral nitrogen at harvest but is immobilized or left in the roots and stubble (5). This fact is illustrated by the results from *Kjellerup* and *Kofoed* (12). Using ^{15}N-labelled N-fertilizer in a lysimeter experiment they found that only 3% of the applied N-fertilizer was leached during the first year. The rest was either taken up by the plant, immobilized or lost by denitrification/volatilization. Similarly, *Power* and *Broadbent* (20), in a review of immobilization/mineralization measured with isotopically labelled fertilizer N, give figures of 20-40% of applied fertilizer, which has been incorporated into the soil organic fraction. These results also correspond well with the results from a 3 year field experiment on a sandy loam grown with spring barley, in which isotopically labelled fertilizer N was also used (17, 21, 22). It was shown, that shortly after fertilization with nitrogen there seems to be a rapid disappearance of inorganic nitrogen, whereafter some of it reemerges rather soon after disappearance. Furthermore, it was found that in general the inorganic soil nitrogen at harvest was rather low at all levels of N-fertilization (0-150 kg N/ha) and that the amount of fertilizer applied nitrogen in the above ground parts of the barley at maturity ranged from 35% to 57% of the total N content for the plant at the 2 highest levels of N-fertilization (120 and 150 kg N/ha) and for the 3 years, respectively. Thus the effect of applied nitrogen on the nitrate leaching, in general, is indirect through the mineralization of nitrogen in the organic pool. This includes the mineralization of the roots, which are left for mineralization during the following autumn and winter, and the stubble, which will cause some immobilization followed by a later mineralization due to its high C/N-ratio.

At Askov the applied mineral N minus removed N in grain and straw in 1987/88 and 1988/89, reflected partly in the mineral nitrogen at harvest and in the N content in the roots and

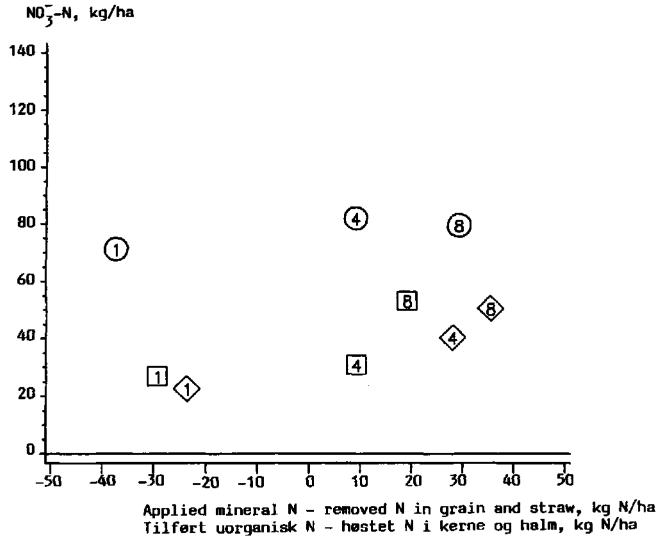

Fig. 5. Askov. Annual leaching of NO_3^--N as function of applied mineral N – removed N in grain and straw. 1 (0 N), 4 (PS S 100 N), 8 (NPK 133 N): Treatments; □: 1987/88; ◇: 1988/89; ○: 1989/90.
Askov. Årlig udvaskning af NO_3^--N som funktion af tilført uorganisk N – høstet N i kerne og halm. 1 (0 N), 4 (PS S 100 N), 8 (NPK 133 N): Forsøgsled; □: 1987/88; ◇: 1988/89; ○: 1989/90.

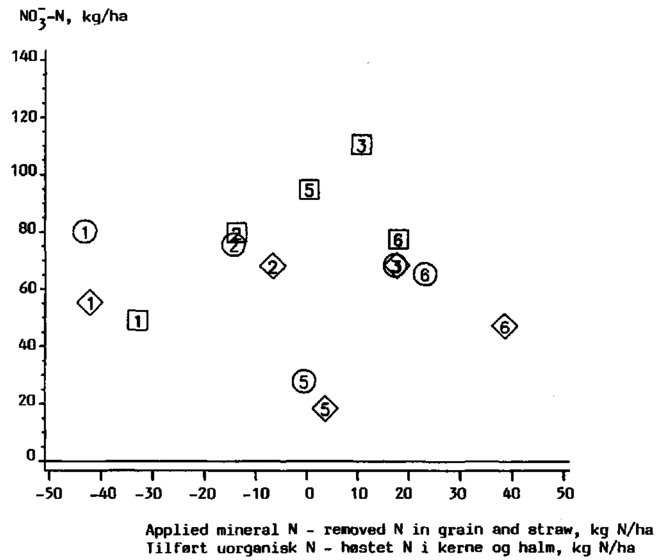

Fig. 6. Jyndevad. Annual leaching of NO_3^--N as function of applied mineral N – removed N in grain and straw. 1 (0 N), 2 (PS S 50 N), 3 (PS S 100 N), 5 (PS S 100 N CC), 6 (NPK 120 N). Treatments; □: 1987/88; ◇: 1988/89; ○: 1989/90.
Jyndevad. Årlig udvaskning af NO_3^--N som funktion af tilført uorganisk N – høstet N i kerne og halm. 1 (0 N), 2 (PS S 50 N), 3 (PS S 100 N), 5 (PS S 100 N CC), 6 (NPK 120 N). Forsøgsled; □: 1987/88; ◇: 1988/89; ○: 1989/90.

stubble (5), and partly by the mineralization during the autumn and winter period, might explain the differences between the leaching from the different treatments. Thus for the first 2 years, the highest leaching was found in the N-fertilized treatment, which has received about 33 kg N/ha/year more in mineral N compared with the mineral N in the slurry applied treatment, while the lowest leaching was found in the unfertilized treatment. The last year, the high and nearly equal nitrate leaching in the treatments may be ascribed more to the 'background' mineralization than to the surplus of N, including the mineralization of the roots.

Jyndevad

In Fig. 6 the results from Jyndevad of annual nitrate leaching are shown as function of applied mineral N minus removed N in grain and straw. In Fig. 6 PS A 100 N has been omitted because this treatment is exceptional in this context. In 1987 there was a clear relation between the nitrate leaching and the surplus of nitrogen which can be explained in view of the above mentioned high percolation from the root zone during the summer period. Looking at the last 2 years and even when omitting PS S 100 N CC there is no relation between the surplus of nitrogen and the nitrate leaching. One of the reasons for this lack in relation is probably that the surplus of nitrogen was not reflected in the soil mineral N at harvest (5) opposite to the results from Askov. When judging the unfertilized treatment at Jyndevad in relation to the results from Askov, and in general, it must be remembered that this treatment was only unfertilized the actual year of measurements as opposed to Askov where the plots have been unfertilized since 1985. Besides, the results are in accordance with the results of *Nielsen* and *Jensen* (16) who found that only 1% of the total variation in nitrate concentration in the percolate could be explained by the level of fertilizer nitrogen application. Their investigation was carried out on 9 sites on loamy soils during a 3 year period with the following treatments: 0 N, ½ N and 1 N (1 N is optimal fertilization) with a previous history of 1 N. By this, it cannot be concluded that the level of nitrogen fertilization does not influence the level of nitrate leaching, thus *Ersbøll* and *Simmelsgaard* (6) found an exponential correlation between relative leaching and fertilizer nitrogen level based on 12 and 10 years of results from a loam soil and fine loamy sand, respectively, receiving 4 different levels of nitrogen fertilization (0 N, ½ N, 1 N and 1.5 N). Furthermore *Hansen* (8), in a leaching investigation with spring barley at Jyndevad, found a statistically significant lower leaching when the N-fertilization was decreased from 120 to 60 kg N/ha. Thus, the annual leaching, as average of 4 years, was reduced from 63 kg N/ha to 43 kg N/ha. Lysimeter experiments at the research station at Askov carried out with a loam and a sandy loam also stress the significance of increasing fertilization with nitrogen (9, 12). In general, the results show a slight increase of nitrate leaching up to what is considered as optimal fertilization whereafter the leaching increased considerably.

The virtual lack of relations at Jyndevad between both the amount of applied nitrogen and the surplus of nitrogen in 1988/89 and 1989/90, in general, underline the relations between the net-N-mineralization during the autumn and winter period and the nitrate leaching. Because of this blurring effect of the net-N-mineralization, the effect of the amount of applied nitrogen on the nitrate leaching can only be estimated in long term field or lysimeter experiments or by use of a simulation model as DAISY (11), which was run for both Askov and Jyndevad for the years 1987/88 and 1988/89 with relatively good correspondance between estimated values of nitrate leaching, shown in this paper, and simulated values (11).

Besides, the direct effect of application of nitrogen, the decrease in fertilization can cause a decrease in the actual evapotranspiration with a following higher percolation during the first part of the period of percolation, and thus other things being equal, cause a higher leaching (3, 9, 12). As it can be seen from Table 3 and 4 this happened in 1989/90 at both localities, but for the actual year this effect must be regarded as minor.

Comparison with other Danish results

With the purpose of comparing the level of nitrate leaching in this experiment with other Danish results, results of annual nitrate leaching (April to April) fertilized with optimal amount of N-fertilizer or slurry applied at optimal times are shown in Fig. 7 and 8 for 2 groups of soils, respectively. The results are shown as function of percolation from the root zone. In Fig. 7, which

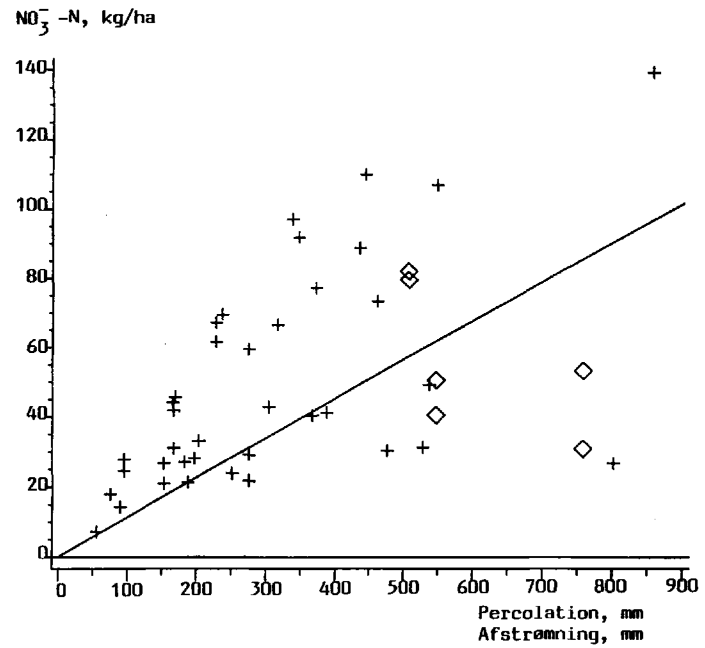

Fig. 7. Annual leaching of NO_3^--N as function of percolation on fine sand with clay, clay with coarse sand, clay with fine sand and clay (15-25% clay) grown with spring barley and optimal fertilized with N-fertilizer or slurry. ◇: Results from this investigation (Askov); +: Results from other investigations (from *Simmelsgaard* (25)). —: Corresponding values of percolation and NO_3^--N leaching equivalent to an annual mean concentration of 11.3 mg NO_3^--N/l.
Årlig udvaskning af NO_3^--N som funktion af afstrømning fra rodzonen på JB nr. 4-7 dyrket med vårbyg optimalt gødet med handelsgødning eller gylle. ◇: Resultater fra denne undersøgelse (Askov); +: Resultater fra andre undersøgelser (efter Simmelsgaard *(25)). —: Sammenhørende værdier for afstrømning og udvaskning af NO_3^--N svarende til en årlig gennemsnitskoncentration på 11,3 mg NO_3^--N/l.*

represents the group of soils which Askov belongs to, only data of spring barley followed by bare soils during the autumn and winter period are shown. In Fig. 8, which represents the group of soils which Jyndevad belongs to, data of spring barley with an undersown catch crop comparable to PS S 100 N CC at Jyndevad are also shown. The results in Fig. 7 and 8 represent the Danish results from the last 20 years. The results have been collected by *Simmelsgaard* (25). The results from Fig. 7 show a clear relation between percolation and nitrate leaching but also quite a high variation with increasing percolation which is also reflected when looking separately at the data from Askov. Not surprisingly because the 3 year period was very wet, the data from Askov are characterized by very high annual percolation especially the first year (Table 3). In relation to the percolation the annual nitrate leaching at Askov considering the years 1987/88 and 1988/89 was relatively low, especially 1987/88. The first year is an 'outlier' because the percolation was relatively high with the result that the soil was leached to a very low level of nitrate concentration during the autumn 1987 and, in general, one can only expect to find a clear relation between percolation and nitrate leaching up to a given level of percolation.

The data in Fig. 8 do not show the same clear relations between percolation and nitrate leaching, probably because the variation in the percolation is not as high as for the data in Fig. 7. The data in Fig. 8 show that the data from Jyndevad are characterized by a relatively high percolation, especially the first year (Table 4), but not as marked as the data from Askov. The reason for this might be the lower root zone capacity for the soils in Fig. 8 compared with the soils in Fig. 7

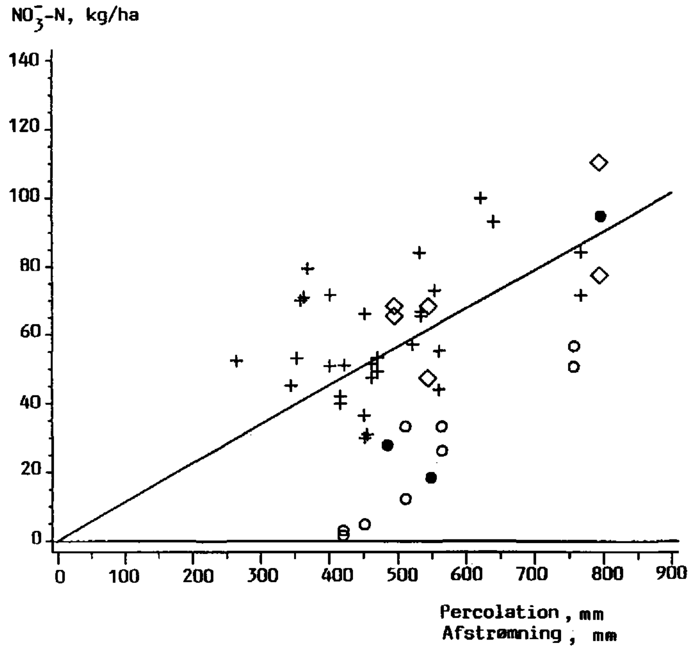

Fig. 8. Annual leaching of NO_3^--N as function of percolation on coarse sand, fine sand and coarse sand with clay grown with spring barley (◇, +) or spring barley with grass as an undersown catch crop (●, ○) and optimal fertilized with N-fertilizer or slurry. ◇, ●: Results from this investigation (Jyndevad); +, ○: Results from other investigations (from *Simmelsgaard* (25)). —: Corresponding values of percolation and NO_3^--N leaching equivalent to an annual mean concentration of 11.3 mg NO_3^--N/l.

Årlig udvaskning af NO_3^--N som funktion af afstrømning fra rodzonen på JB nr. 1-3 dyrket med vårbyg (◇, +) eller vårbyg med isået udlæg af græs som efterafgrøde (●, ○) og optimalt gødet med handelsgødning eller gylle. ◇, ●: Resultater fra denne undersøgelse (Jyndevad); +, ○: Resultater fra andre undersøgelser (efter Simmelsgaard *(25)). —: Sammenhørende værdier for afstrømning og udvaskning af NO_3^--N svarende til en årlig gennemsnitskoncentration på 11,3 mg NO_3^--N/l.*

which means that the soils in Fig. 7 can be left with a higher deficit at harvest compared with the sandy soils resulting in a higher variation in the percolation during the following leaching period. Another reason is that all the data in Fig. 8 are from Jutland while the data in Fig. 7 originate from all over Denmark. Thus the difference in the data reflects the geographical variation with the highest precipitation in the western part of the country. Looking at the level of the nitrate leaching in relation to the percolation the results from Jyndevad must be regarded as being on the same level as the other results shown in Fig. 8.

Average nitrate concentration

The annual average concentration would be the expected nitrate concentration in the groundwater if no chemical reduction or denitrification takes place in the vadose zone. From this point of view it may be more relevant to look at the average nitrate concentration than the annual nitrate leaching. The limit value for NO_3^--N in drinking water is 11.3 mg N/l, which is equivalent to 50 mg NO_3^-/l. At Askov nitrate concentration for the years 1987/88 and 1988/89 was below the limit value (Table 5). In 1989/90 the nitrate concentrations were on average about 30% above the limit value. The average concentration for 0 N, PS S 100 N and NPK 133 N, weighted by the percolation, for the 3 year period was 6.5, 8.4 and 10.1 mg NO_3^--N/l, respectively. At Jyndevad it is only the treatment with the catch crop which on average for the 3 year period was well below the limit value (Table 6). The unfertilized treatment and the N-fertilized treatment were slightly below the limit value, while PS S 50 N and PS S 100 N were slightly above the limit value. Given as average concentration, weighted by the percolation, the figures for the 3 year period for treatment 0 N, PS S 50 N, PS S 100 N, PS S 100 N CC and NPK 120 N at Jyndevad were 9.8, 12.2, 13.5, 7.7 and 10.4 mg NO_3^--N/l, respectively. At Jyndevad the concentration for each year in PS A 100 N was considerably higher than the limit. In real farming autumn application would have been supplemented with spring application of slurry and/or N-fertilizer; and if so, the concentration in 1988/89 and 1989/90 would have been even higher than the given figures.

As the average concentration is the leaching divided by the percolation it can be seen from Fig. 7, that the average concentrations at Askov are somewhat lower than most of the results represented in Fig. 7 mainly due to the high percolation during the period of these investigations. Concerning Jyndevad the results from these investigations can be regarded as being representative for the data in Fig. 8.

Conclusions

On the basis of these investigations the following main conclusions can be drawn:

- Ryegrass as an undersown catch crop can significantly reduce the nitrate leaching during the autumn and winter period. As an average of the 3 years the reduction was 35 kg N/ha/-year. The effect depends of the harvest time and the following growth conditions, thus early harvest gave the highest reduction.
- Applying pig slurry on coarse sandy soils in late autumn can cause an increase in the nitrate leaching during the following winter period equivalent to the amount of NH_4^+-N in the slurry.
- Due to the higher field capacity and denitrification the nitrate leaching from a sandy loam compared with a coarse sandy soil can on an average be expected to be slightly lower.
- Percolation in the summer period caused a closer correlation between applied nitrogen and annual nitrate leaching compared with the years when most of the percolation took place in the autumn and winter period. This effect was most significant at the coarse sandy soil.
- The mineralization during the autumn and winter period has a significant influence on the nitrate leaching thus often blurring the influence of different amounts of applied mineral N, especially when the amount of applied mineral N is not above what is considered as optimal and when the date of application is optimal.

Literature

1. *Allerup, P. & Madsen, H.* 1979. Accuracy of point precipitation measurements. Danish Meteorological Institute, Climatological Papers No. 5. Copenhagen, 84 pp.
2. *Debosz, K.* 1992. N-transformation and N-transport in a sandy loam and a coarse sandy soil cropped with spring barley. IV. N-mineralization. Tidsskr. Planteavl (In preparation).
3. *Djurhuus, J.* 1985. Actual evapotranspiration in spring barley in relation to soil tillage and straw incorporation. Tidsskr. Planteavl 89, 47-59. (In Danish with English Summary).
4. *Djurhuus, J.* 1990. A comparison of soil water nitrate by coring and solution extraction techniques. Tidsskr. Planteavl 94, 487-495. (In Danish with English Summary).
5. *Djurhuus, J. & Lind, A.-M.* 1992. N-transformation and N-transport in a sandy loam and a coarse sandy soil cropped with spring barley. I. Description of the experimental areas, climate, plant production and mineral N in soil. Tidsskr. Planteavl. (In print).
6. *Ersbøll, A. & Simmelsgaard, S.E.* 1991. A parsimonious statistical model for the nitrate leaching at different levels of N-fertilizer. Tidsskr. Planteavl, Beretning nr. S 2129.
7. *Hansen, B.* 1990. Næringsstofudvaskning fra arealer i landbrugsdrift. NPo-forskning fra Miljøstyrelsen, Nr. A8 1990, 48 pp.
8. *Hansen, E.M.* 1992. (Personal communication).
9. *Hansen, J.F.; Klausen, P. Søndergaard & Petersen, J.* 1989. Lysimeter experiments with combinations of nitrogen, phosphorus and potassium in mineral fertilizer. II. Leaching of nutrients. Tidsskr. Planteavl 93, 209-223. (In Danish with English Summary).
10. *Hansen, S. & Aslyng, H.C.* 1984. Nitrogen balance in crop production. Simulation model NITCROS. Hydrotechnical Laboratory, The Royal Veterinary and Agricultural University, Copenhagen, 113 pp.

11. *Hansen, S.; Jensen, H.E.; Nielsen, N.E. & Svendsen, H.* 1990. DAISY-Soil Plant Atmosphere System Model. NPo Research in the NAEP, Nr. A10 1990, 272 pp.
12. *Kjellerup, V. & Kofoed, A. Dam* 1983. Nitrogen fertilization in relation to leaching of plant nutrients from soil. Lysimeter experiments with ^{15}N. Tidsskr. Planteavl 87, 1-22. (In Danish with English Summary).
13. *Kyllingsbæk, A. & Simmelsgaard, S.E.* 1986. Kvælstofudnyttelse og kvælstoftab på sandjord. Tidsskr. Planteavl, Beretning nr. S 1853, 113 pp.
14. *Maag, M.* 1992. N-transformation and N-transport in a sandy loam and a coarse sandy soil cropped with spring barley. III. Denitrification. Tidsskr. Planteavl. (In print).
15. *Mikkelsen, H.E. & Olesen, J.E.* 1991. Comparison of methods for estimating potential evapotranspiration. Tidsskr. Planteavl, beretning nr. S 2157, (In Danish with English Summary), 67 pp.
16. *Nielsen, N.E. & Jensen, H.E.* 1990. Nitrate leaching from loamy soils as affected by crop rotation and nitrogen application. Fertilizer Research 26, 197-207.
17. *Nørlund, T.; Gottschau, A.; Thorhauge, K.; Nielsen, N.E. & Jensen, H.E.* 1985. The dynamics of nitrogen under grown spring barley as affected by nitrogen application, irrigation and undersown catch crops. Dept. of Soil Fertility and Plant Nutrition and Hydrotechnical Laboratory. The Royal Veterinary and Agricultural University, Copenhagen, Research Report No. 1129, 210 pp.
18. *Olesen, J.E. & Heidmann, T.* 1990. EVACROP. Et program til beregning af aktuel fordampning og afstrømning fra rodzonen. Dept. of Agrometeorology, Research Centre Foulum, Research note No. 9, 65 pp.
19. *Olsen, P.* 1992. (Personal communication).
20. *Power, J.F. & Broadbent, F.E.* 1989. Proper accounting for N in cropping systems. In Follett, R.F. (Ed.). Nitrogen management and ground water protection. Elsevier, 160-182.
21. *Schjørring, J.K.; Nørlund, T.; Gottschau, A.; Nielsen, N.E. & Jensen, H.E.* 1988. The dynamics of nitrogen in the root zone of field-grown spring barley as affected by nitrogen application, irrigation and undersown catch crops. Experimental results 1983. Dept. of Soil and Water and Plant Nutrition. The Royal Veterinary and Agricultural University, Copenhagen. Research Report No 1208, 166 pp.
22. *Schjørring, J.K.; Nørlund, T.; Gottschau, A.; Nielsen, N.E. & Jensen, H.E.* 1988. The dynamics of nitrogen in the root zone of field-grown spring barley as affected by nitrogen application, irrigation and undersown catch crops. Experimental results 1984. Dept. of Soil and Water and Plant Nutrition. The Royal Veterinary and Agricultural University. Copenhagen. Research Report No 1213, 142 pp.
23. *Simmelsgaard, S.E.* 1985. Water balance and nitrogen leaching for 4 soil types. II. Water balance, actual evapotranspiration, drainage and percolation. Tidsskr. Planteavl 89, 117-131. (In Danish with English Summary).
24. *Simmelsgaard, S.E.* 1985. Water balance and nitrogen leaching for 4 soil types. III. Nitrogen concentration, -leaching and -balance. Tidsskr. Planteavl 89, 133-154. (In Danish with English Summary).
25. *Simmelsgaard, S.E.* 1991. In Rude, S. 1991. Nitrogen Fertilizers in Danish Agriculture – present and future application and leaching. Statens Jordbrugsøkønomiske Institut, Rapport nr. 62, 135-150.

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