Effects of cover crops on the nitrogen fluxes in a silage maize production system

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Abstract

Rye and grass cover crops can potentially intercept residual soil mineral nitrogen (SMN), reduce overwinter leaching, transfer SMN to next growing seasons and reduce the fertilizer need of subsequent crops. These aspects were studied for 6 years in continous silage maize production systems with nitrogen (N) input levels ranging from 20 to 304 kg total N ha^{-1}, on a sandy soil in The Netherlands.

Rye and grass cover crops were able to absorb on average 40 kg N ha^{-1} in the aboveground plant parts. The actual N uptake was largely determined by winter temperatures and hardly by residual SMN. At low N input levels cover crops reduced N leaching in accordance with their N uptake. At high N input levels, however, the reduction of leaching losses exceeded the storage capacity of the cover crop, suggesting that cover cropping can have stimulated the loss of N via denitrification or immobilisation.

Cover crops had no positive effect on maize yields at larger N rates and under these conditions cover crops did not improve the conversion of SMN into crop N. This was only partly reflected by an increase of residual SMN on plots where cover crops had been incorporated, as a large part of the excess N on maize was already lost during the growing season. In N-deficient maize production systems, however, cover crops increased the dry matter yield of maize. Their effect was equivalent to the effect of fertilizer N rates amounting to 105% and 44% of the aboveground N in rye and grass, respectively.

In the first few years cover crops decomposed incompletely during the growing season following their incorporation. In the course of the years, however, effects on subsequent maize crops increased. This supports the hypothesis that effects of cover crops can cumulate when grown repeatedly. Averaged over the 6 years, 115% and 73% of the aboveground rye N and grass N, respectively, were recovered in the crop-soil system.

Keywords: apparent recovery, cover crop, fertilizer value, maize, nitrate leaching, nitrogen

Introduction

Mineral nitrogen (N) remaining in the soil at the end of the growing season, may leach during winter and contaminate ground and surface water. Maize crops can leave large amounts of soil mineral N (SMN). Excessive use of organic and mineral fertilizers on maize land is only one of the reasons (Schlegel *et al.*, 1996). Crop characteristics, however, also play a role. Soil organic N mineralized after the end of July, accumulates in the soil due to an early cessation of N uptake (e.g. Pollmer *et al.*, 1979). Moreover, current row spacings of 0.75 m and a limited horizontal root extension (Barber & Kovar, 1991) may lead to an incomplete exploitation of the inter-row soil volume (Aufhammer *et al.*, 1991; Clay *et al.*, 1995). Maize responds positively to large N concentrations in the rooted soil volume (Schröder & Dilz, 1987; Touchton, 1988; Maddux *et al.*, 1991; Sawyer *et al.*, 1991). Therefore, an economically optimal N supply may be associated with more residual SMN than is environmentally desirable (Jokela & Randall, 1989; Jokela, 1992; Schröder *et al.*, 1993; Vanotti & Bundy, 1994). Such a situation demands the development of cropping techniques that either avoid the accumulation of residual SMN or reduce the risk of leaching.

Cover crops can take up residual SMN and reduce the downward movement of nitrate due to their transpiration (Steffens & Vetter, 1984; Martinez & Guiraud, 1990; McCracken *et al.*, 1994). However, maize is harvested late in the season and growing conditions after maize are unfavourable compared to those after crops that allow earlier sowing (Schweiger, 1967; Elers & Hartmann, 1988). Undersown cover crops may therefore perform better than cover crops sown after the harvest of maize. If undersown cover crops are planted too early, however, they may compete for N and water with maize (Stemann & Lütke Entrup, 1991).

N uptake by cover crops will only reduce leaching risks in the long run when their decomposition is properly synchronised with the demands of subsequent crops and when their contribution to the N supply of these crops is taken account of in deciding on subsequent rates of fertilizer N. If not, losses are only postponed. Cover crops have a residual nature and research questions need to be addressed in experiments lasting more than just one season.

From 1988 to 1994 we conducted a long-term field experiment to find out how much residual SMN left by maize crops can be intercepted by cover crops that are either undersown in maize or sown after its harvest. In addition to it we studied the effects of these cover crops on nitrate leaching and the N uptake and dry matter yield of subsequent maize crops.

Materials and methods

Soil characteristics

The experiment was carried out in Heino (52° 26′ N, 6° 14′ E), The Netherlands, on a sandy soil during the period 1988–1994. Soil characteristics are presented in Table 1.

Table 1. Soil characteristics of upper 0.2 m of the sandy soil in Heino.

organic matter	silt	total N	water soluble	exchangeable		pH-KCl
			P	K	Mg	
(%)	(%)	(%)	(mg/liter)	(mg/100g)	(mg/100g)	
3.1	7	0.107	30	6.6	4.3	4.6

Rooting on the experimental site concentrated in the top 0.3 m due to a penetrometer resistance of 3 MPa in the deeper layers. The average depth of the groundwater table is 0.85 and 1.60 m during winter and summer, respectively. Excess precipitation is discharged vertically through the profile without significant horizontal transport. Uprise of water from the groundwater does not occur. Pedological and hydrological details are given in Schröder *et al.* (1992).

In the years preceding the start of the experiment, the site had been used for silage maize production and cattle slurry was regularly applied during that period at annual rates of 50–70 m^3 ha^{-1}. No organic or mineral fertilizers were applied during the 6 months prior to the experiment.

Treatments

The experiment was set up as a split plot design in 4 replicates with 3 cover crop treatments on the mainplots and 5 N application rates on the subplots. Treatments remained on the same plots during the experimental period. Subplot size measured 14 m × 6 m.

Cover crop treatments included fallow, rye (*Secale cereale* L., cv. Admiraal) and Italian ryegrass (*Lolium multiflorum* L., cv. Combita). Fallow plots were weed free during winter. Italian ryegrass was sown in the first half of June as a 0.45 m wide strip between the maize rows (crop height approximately 0.4 m) at a rate of 30 kg ha^{-1}. In the last year of the experiment, no undersowing of grass took place. Rye was sown immediately after harvest of maize at a rate of 200 kg ha^{-1} between September 22 and 28 except for 1993 when sowing had to be postponed to October 10.

The cover crops were mechanically destroyed at the end of March-beginning of April with a rotavator to avoid further loss of soil moisture and to stimulate decomposition. In 1989 the destruction of rye was postponed to the end of April. Crop residues were completely incorporated into the soil by mould board plough (ploughing depth 0.25 m) plus packer in the second half of April.

Treatments on the subplots included 5 combinations of broadcast applied fertilizer N (calcium ammonium nitrate) and cattle slurry N, including a control that only received a subsurface side dressing of 20 kg fertilizer N ha^{-1}. Treatments of the subplots are referred to as N1–N5 (Table 2).

Cattle slurry was injected (tine width 0.5 m, depth 0.15 m) between cover crop destruction and ploughing, 7–13 days before maize planting. Injection was carried out with a precision injector especially developed for field trials. From 1990 the applica-

Table 2. Annual treatments on subplots.

Code	Fertilizer N (kg ha^{-1})		Slurry N (kg ha^{-1})	
	broadcast	side dressing	NH_4–N	organic N
N1	0	20	0	0
N2	0	20	74*	90*
N3	40	20	74*	90*
N4	80	20	74*	90*
N5	120	20	74*	90*

* in 1988 and 1989 116 kg NH_4–N and 109 kg organic N ha^{-1} y^{-1} were applied

tion rate was reduced from 45 to 33 m^3 ha^{-1} y^{-1}. Cattle slurry contained on average 96 kg dry matter, 5.0 kg total N, 2.3 kg NH_4–N, 0.8 kg P and 5.7 kg K m^{-3}. Fertilizer N was broadcast manually within several days after maize planting.

Crop husbandry

Silage maize (*Zea mays* L., cv. LG 2080) was planted between April 22 and May 4 on all subplots resulting in final plant densities of 9.9–12.0 plants m^{-2}. Within years, plant densities were similar in all treatments ($P > 0.98$).

Weeds were succesfully controlled with a pre-emergence application of aclonifen, a post-emergence application of pyridate, bromoxynil or bentazone, and hoeing. Maize was harvested between September 14 and September 28. Subsequently, the soil was loosened with a rigid tine cultivator with the exception of the plots with undersown grass.

All plots received a fertilizer dressing of 9 kg P (side dressing) and 110 kg K ha^{-1} y^{-1} in spring. Additionally, subplots without slurry application (N1) received 27 kg P, 140 kg K and 18 kg Mg ha^{-1} y^{-1} to compensate for the P, K and Mg applied with manure on N2–N5 plots. The site was limed in autumn whenever necessary.

Measurements

Each year slurry was analysed in duplicate for its dry matter, NH_4–N, organic N, P and K contents. Soil samples from N1, N2 and N5 subplots were taken annually in April before the incorporation of cover crops and the application of fertilizer or manure (T1) and in September (T2). They were analysed for SMN (i.e. NO_3–N and NH_4–N). Six core samples were taken per subplot at random (T1) or at a distance of 0.15–0.2 m from the plant row (T2) to a total depth of 0.6 m. From September 1989 onwards, the 0.6–1.0 m layer of fallow and grass covered N1 and N5 subplots was also sampled. Unless stated otherwise, SMN data refer to the 0.6 m sampling, only. Samples were pooled per treatment before analysis.

Dry matter yields of cover crops were determined just before their destruction in spring by weighing the aboveground fresh material from a net area of 9 m^2 per subplot. Grass yields referred to the weighted average of the grass-covered inter row strip and the uncovered former maize row. After weighing, residues were evenly spread over their subplot, except for a 0.8 kg sample. The dry matter content of this sample was assessed by drying for 48 h at 70 °C. N content was determined in the dried material after pooling samples from identical treatments. The carbon (C) content was assumed to be 400 g kg^{-1} dry matter (Thorup-Kristensen, 1994; Wyland *et al.*, 1995). Heights of intact cover crops and their stubbles after harvesting, were measured annually with a tempex disc (diameter 0.5 m, weight 0.345 kg; according to Keuning (1984)). The difference in height before and after harvesting was related to the observed N uptake. This relationship (26 kg N per 0.1 m for both cover crops, $P < 0.001$) was used to estimate the N uptake in the stubble.

Dry matter yields of maize were determined by weighing the fresh material from the inner 12 m × 3 m area of each subplot. Dry matter content was determined by drying a subsample of 0.8 kg at 105 °C for 48 h. Dried samples were pooled per treatment and analyzed for total N.

Nitrate leaching was assumed to start after the soil was recharged to field capacity in autumn. Tensiometers were installed, groundwater levels were monitored and a pF curve was determined, to make an accurate estimate of the onset of the leaching season (Schröder *et al.*, 1992). Nitrate leaching was calculated as the integral of the product of nitrate concentration and precipitation surplus over time. Nitrate concentrations were determined 4–10 times at regular intervals in samples of the soil solution derived from ceramic cups at 1 m depth in the first replicate of the experiment. Four cups per subplot (except the N3-rye and -grass plots) were installed.

Precipitation surplus was estimated as the difference between precipitation and evapotranspiration. The latter was set equal to 0.3 × potential evapotranspiration (ET_o) for fallow and 0.9 × ET_o for fully established cover crops (Schneider & Van Boheemen, 1986), a stage that was reached somewhat earlier for grass than for rye. ET_o was calculated from data collected on a meteorological station in Twente at a distance of 50 km from Heino, whereas precipitation and temperature were recorded at a distance of 500 m from the experimental site.

Definitions

The apparent N mineralisation during summer (AMS, kg ha^{-1}), inclusive gains due to deposition and losses due to immobilisation, denitrifcation and leaching, was derived from balance sheet calculations accounting for the major mineral N inputs and outputs on N1 subplots:

$$\text{AMS} = (\text{N uptake of maize} + \text{SMN at T2}) - (\text{SMN at T1} + \text{fertilizer N}) \quad (1)$$

with T1 = April, before fertilizer and slurry application, and T2 = September

The apparent N mineralisation during winter on N1 subplots (AMW, kg ha^{-1}), inclusive gains due to deposition and losses due to immobilisation and denitrifcation, was defined as:

$$AMW = \text{(N uptake in shoot and stubble of cover crop + SMN at T1) +} \\ \text{(leached N)} - \\ \text{(SMN at T2 in the previous year)} \qquad (2)$$

Dry matter yield response data of maize was fitted to the sum of SMN at T1 (before fertilizer and slurry application), fertilizer N and NH_4–N in slurry with quadratic regression models. The economically optimum amounts of available N that may be calculated from this relationship will be discussed in a separate paper.

The apparent N recovery of slurry N in the maize crop (ANR_{slc}, %) was defined as:

$$ANR_{slc} = 100 \times \\ \text{(N uptake of maize on N2 subplot} - \\ \text{N uptake of maize on N1 subplot) /} \\ \text{(total N input from slurry)} \qquad (3)$$

The apparent N recovery of slurry N in the soil and maize crop together (ANR_{slsc}, %) was defined as:

$$ANR_{slsc} = 100 \times \\ \text{(N uptake of maize on N2 subplot} - \text{N uptake of maize on N1 subplot +} \\ \text{(SMN at T2 on N2 subplot} - \text{SMN at T1 on N2 subplot)} - \\ \text{(SMN at T2 on N1 subplot} - \text{SMN at T1 on N1 subplot)) /} \\ \text{(total N input from slurry)} \qquad (4)$$

For the calculation of the apparent recoveries of broadcast fertilizer N, the differences between the N5 and N2 treatments were used instead.

The apparent recovery of cover crop N (ANR_{CC}, %) was calculated as the difference in N uptake of a maize crop preceded by a cover crop at the lowest N rate ($NY_{N1,CC}$) and a maize crop preceded by fallow at the lowest N rate ($NY_{N1,FW}$) and expressed as a percentage of the aboveground N uptake of the cover crop (NYCC):

$$ANR_{CC} = 100 \times (NY_{N1,CC} - NY_{N1,FW}) / NYCC \qquad (5)$$

The fertilizer value of a cover crop (FV, kg N ha^{-1}) was determined in three steps. First, the dry matter yields of maize (preceded by fallow) were fit to the sum (SUMN, kg N ha^{-1}) of SMN at T1 (before fertilizer and slurry application), fertilizer N and NH_4–N in slurry, with a quadratic response function for each individual year. Subsequently, SUMN was solved from this function for the dry matter yield of a maize crop preceded by a cover crop at the lowest N rate ($DMY_{N1,CC}$, kg ha^{-1}), using the a, b and c coefficients obtained from the first step:

$$DMY_{N1,CC} = a \times (SUMN)^2 + b\,(SUMN) + c \quad (6a)$$

Finally, FV was calculated from:

$$SUMN = FV + \text{subsurface side dressed fertilizer N} + \text{SMN at T1 on a cover cropped N1 subplot} \quad (6b)$$

When the increase of the dry matter yield of maize (preceded by fallow) at rates larger than N2 was insufficient to yield a significant fit with a quadratic response function, a linear plus plateau response function was used for the calculation of FV instead. Such a function assumes a linear positive response between N1 and N2 only. The slope (S) of the response equals:

$$S = (DMY_{N2,FW} - DMY_{N1,FW}) / (NH_4\text{–N in slurry} + \text{SMN at T1 on fallow N2 subplot} - \text{SMN at T1 on fallow N1 subplot}) \quad (7a)$$

As the dry matter yields of maize preceded by a cover crop ($DMY_{N1,CC}$) were always lower than the dry matter yields of maize preceded by fallow at the N2 rate ($DMY_{N2,FW}$), the yield response can now be described as:

$$DMY_{N1,CC} = DMY_{N1,FW} + S * (FV + \text{SMN at T1 on cover cropped N1 subplot} - \text{SMN at T1 on fallow N1 subplot}) \quad (7b)$$

from which FV can be solved.

The relative fertilizer value of a cover crop (RFV, %) was defined as the fertilizer value (FV) expressed as a percentage of the aboveground N uptake of the cover crop (NYCC):

$$RFV = 100 \times FV / NYCC \quad (8)$$

Weather conditions

Average daily temperature during summer were relatively low in 1991 and considerably higher than average in 1992 and 1994. In the other years temperature was close to the long term average (Table 3). Precipitation during summer exceeded the long term average, especially in 1988, 1993 and 1994. Dry spells, lasting 4–6 weeks occurred in May 1989 and July–August 1991. Average daily temperature during winter was much higher during the first 4 years. The winters of 1990–1991 and 1993–1994 were relatively dry and wet, respectively.

Table 3. Weather conditions recorded in Twente (temperature) and Heino (precipitation).

Year	Summer (April 1 - September 30)		Winter (October 1 - March 31)	
	Precipitation (mm)	Average daily temperature (°C)	Precipitation (mm)	Average daily temperature (°C)
1988	467	13.9		
			352	6.7
1989	289	14.2		
			320	6.9
1990	361	13.7		
			298	5.2
1991	301	13.3		
			323	5.5
1992	402	14.8		
			387	5.0
1993	593	13.8		
			491	4.6
1994	460	14.4		
Long term av.*	386	13.8	365	4.9

* long term average 1961–1990

Results

Cover crop N uptake and overwinter losses

Averaged over the first 5 winters, the amount of N taken up by the aboveground plant parts on former maize N1 plots, was 36 and 39 kg ha^{-1} for rye and grass, respectively. On maize plots that had been fertilized with cattle slurry and/or broadcast fertilizer N (N2–N5), rye and grass took up 46 kg ha^{-1} on average, without consistant differences between cover crop species and N-rates. During the winter of 1993–1994 rye failed completely due to excessive rainfall and only 7–9 kg N ha^{-1} was stored in grass. Variation in N uptake of cover crops among years (5 and 6 years for rye and grass, respectively) was positively ($P < 0.01$) related to the temperature sum (threshold 5 °C) between the sowing date (rye) or maize harvest date (grass) and the date of destruction of the cover crop (Figure 1), and hardly to the N rates on maize. If winter temperatures had been more close to the long term average, less N would have been taken up by the cover crops.

Estimated C to N ratios at the time of harvest ranged from 13 to 22 for rye and from 15 to 22 for grass, during the first 5 experimental years without any effect from the N rates applied to maize. In the final year all grass cover crops had an estimated C to N ratio of 35.

Cover crops reduced leaching during winter substantially at all N rates, grass being more effective than rye (Figure 2). This reduction was related to the N storage in the cover crops rather than to their water consumption since the estimated downward

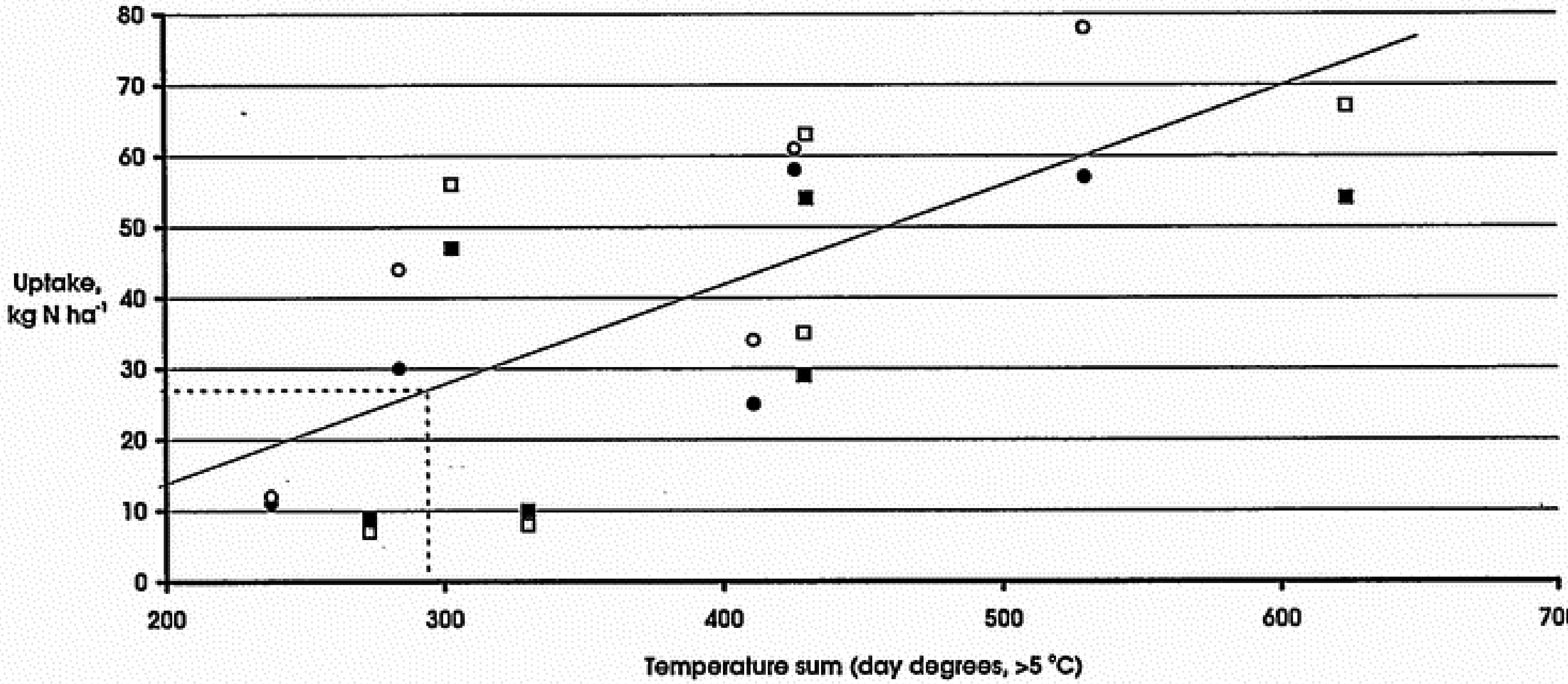

Figure 1. Aboveground N uptake of rye and grass (stubble included) in spring as affected by mineral N rates on a preceding maize crop (N1 = 20 kg mineral N ha^{-1} y^{-1}, N2–N5 = 94–214 kg mineral N ha^{-1} y^{-1}) and the temperature sum (threshold 5 °C) between the dates of sowing (rye) or maize harvest (grass) and destruction in the subsequent spring (● = Rye N1, ○ = Rye N2–N5, ■ = Grass N1, □ = Grass N2–N5, —: y = 0.14 × –14.2, ---- = Long term average: 1961–1990)

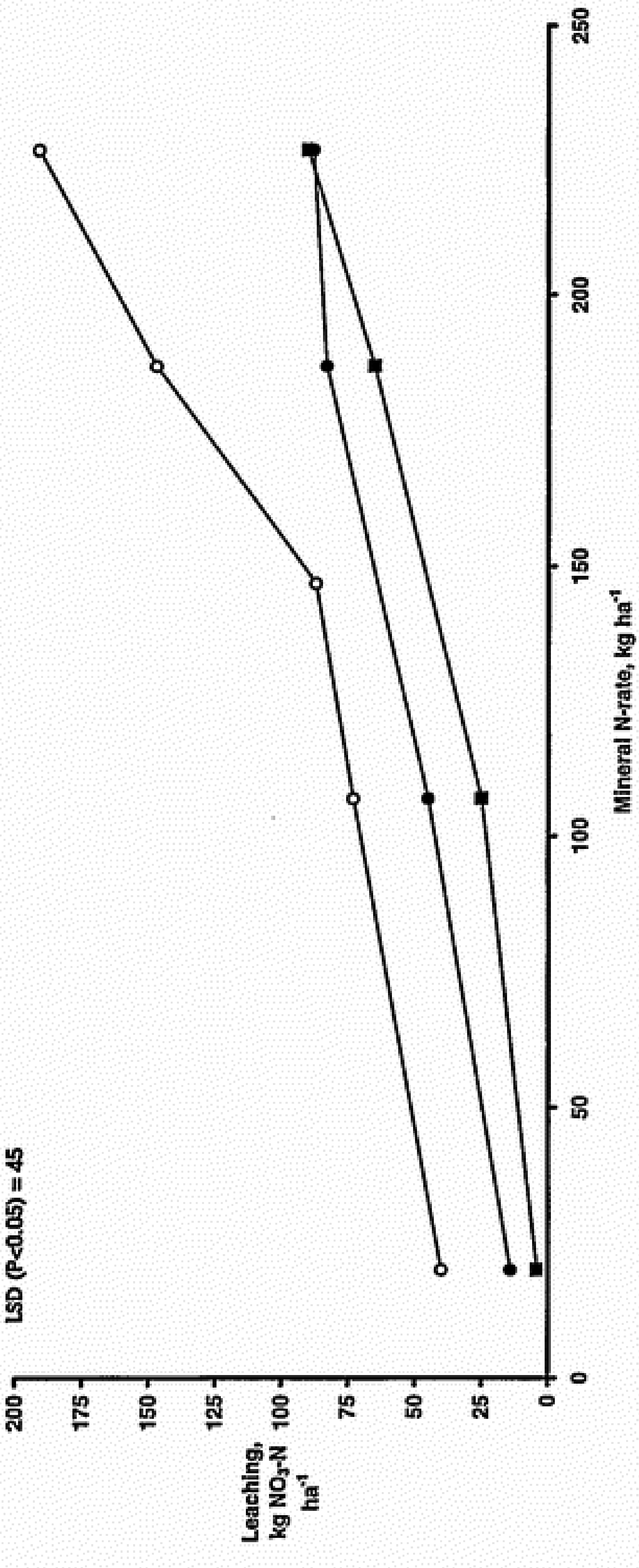

Figure 2. Relationship between the summed input of soil mineral N in spring (0.6 m layer), fertilizer N and NH_4–N in slurry applied to maize, and N leaching during winter (average from 1988–1989 to 1993–1994) as affected by cover crops (○ = Fallow, ● = Rye, ■ = Grass).

Table 4. Difference between the apparent N mineralisation (kg ha^{-1}) during winter (September-April) on cover cropped plots and on fallow plots.

Contrast	Code	Mineral N rate (kg ha^{-1})	Year: 1988	1989	1990	1991	1992	1993	Average 1988–1993
Rye-Fallow	N1	20	0	9	−30	−26	1	−17	−11 NS**
	N2	94*	14	31	−63	−28	−3	−12	−10 NS
	N5	214*	−118	−41	−303	−29	−24	−30	−91 (P<0.05)
Grass-Fallow	N1	20	16	−3	−33	−9	−12	−10	−9 NS
	N2	94*	6	−30	−89	−55	−20	6	−30 (P<0.05)
	N5	214*	−69	−160	−264	1	−6	−19	−86 (P<0.05)

* in 1988 and 1989 42 kg ha^{-1} more

** significance of difference with corresponding fallow treatment in pairwise t-test; NS = not significant

water transport was on average 251 mm when plots were fallow and 216 mm when plots were cover cropped.

The storage of N in cover crops was not sufficient to absorb all residual SMN, as illustrated by the increase of leaching with N rates in both fallow and cover cropped plots. Balance sheet calculations of the apparent N mineralisation during winter (with leaching losses accounted for) on fallow N1 plots showed that the gains of SMN due to mineralisation and deposition matched or exceeded the losses due to denitrification and immobilisation in all winters (range 9–72 kg ha^{-1}). The apparent mineralisation (AMW) on cover cropped plots was lower than on corresponding fallow plots, as indicated by the negative difference of the apparent mineralisation on cover cropped plots and fallow plots (Table 4). It is not likely that this was caused by our disregard of SMN in the 0.6–1.0 m soil layer. Inclusion of the 0.6–1.0 m layer in our balances of fallow and grass covered N1 and N5 treatments (separate data not presented here), made clear that the negative difference of the AMW even became slightly larger in all years.

Maize reponse to N

Dry matter yields of maize after winter fallow responded significantly to N in all years. In 1990 and 1994 no further increase of maize dry matter yields took place at rates larger than N2 (Table 5). The apparent mineralisation during summer showed a downward trend in time and the dry matter yields of N deficient (N1) maize reacted accordingly. Drought stress and low temperatures depressed yields at all N rates in 1991.

On average, 58% of the total N in cattle slurry was recovered in the soil and maize crop together, as calculated from the difference of balance sheets from N1 and N2 plots. Especially in later years, a larger fraction of the N in slurry was absorbed by the maize crop (Figure 3). Except for the drier years 1989 and 1991, much of the broadcast fertilizer N was lost during the growing season, as indicated by the differ-

Table 5. Dry matter yield of silage maize (t ha^{-1}) after winter fallow as affected by the mineral N rate (kg ha^{-1}) and the daily N mineralisation during summer (April-September) on N1-plots (kg ha^{-1} d^{-1}).

Code	Mineral N rate (kg ha^{-1})	Year: 1988	1989	1990	1991	1992	1993	1994	Average 1988–94
N1	20	14.94	13.61	11.87	8.16	11.07	10.09	10.04	11.40
N2	94*	15.24	16.96	14.13	12.21	15.68	14.51	15.82	14.94
N3	134*	15.39	17.28	14.20	12.44	16.98	15.13	15.35	15.25
N4	174*	15.49	17.50	13.52	12.69	17.26	14.74	16.08	15.33
N5	214*	14.99	16.50	14.01	12.24	16.23	15.01	15.77	14.96
LSD	($P < 0.05$)	1.30	1.21	1.37	1.51	1.75	1.03	1.10	0.613
Apparent N mineralisation	(kg ha^{-1} d^{-1})	1.11	0.75	0.53	0.43	0.59	0.39	0.37	0.60

* in 1988 and 1989 42 kg ha^{-1} more

ence of balance sheet calculations from N2 and N5 plots. On average, only 50% of the broadcast fertilizer N was recovered in the soil and maize crop together and only 7% was recovered in the maize crop (Figure 4).

Cover crop effects on maize yield

When N limited maize yields (especially on N1 and to a lesser extent on N2 plots), cover crop incorporation improved the availability of N significantly ($P < 0.05$), as indicated by the increase of the N uptake in maize (Table 6). At higher N rates (N3–N5) rye cover crops had no effect on the N uptake and undersown grass even re-

Table 6. N uptake of silage maize (kg ha^{-1}) as affected by winter treatments and the mineral N rate (kg ha^{-1}).

Winter treatment	Code	Mineral N rate (kg ha^{-1})	Year: 1988	1989	1990	1991	1992	1993	1994	Average 1989–94
Fallow	N1	20	161	120	125	83	144	95	82	108 a**
	N2	94*	189	197	184	150	193	181	209	186 c
	N3	134*	194	192	185	156	207	194	209	191 c
	N4	174*	194	207	184	169	226	180	222	198 c
	N5	214*	180	206	174	155	245	194	210	197 c
Rye	N1	20	–	134	156	114	164	104	104	129 b
	N2	94*	–	208	194	152	201	189	224	195 c
Grass	N1	20	147	143	130	78	164	113	119	125 b
	N2	94*	167	206	182	141	217	174	213	189 c

* in 1988 and 1989 42 kg ha^{-1} more

** different letters denote significant differences ($P < 0.05$) in F-test

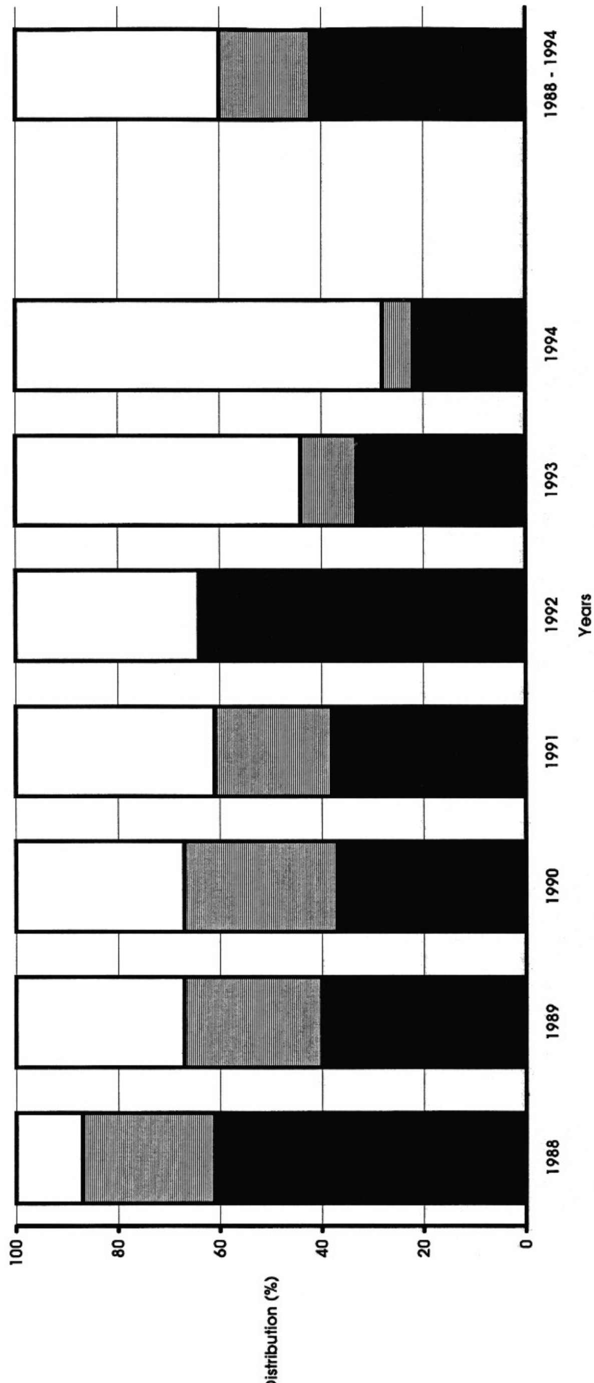

Figure 3. Recovery of total N in slurry (approximately 164 kg N ha^{-1}) in the maize crop and as soil mineral N after the harvest of maize (□ = in the crop, = in the soil, ■ = not accounted for).

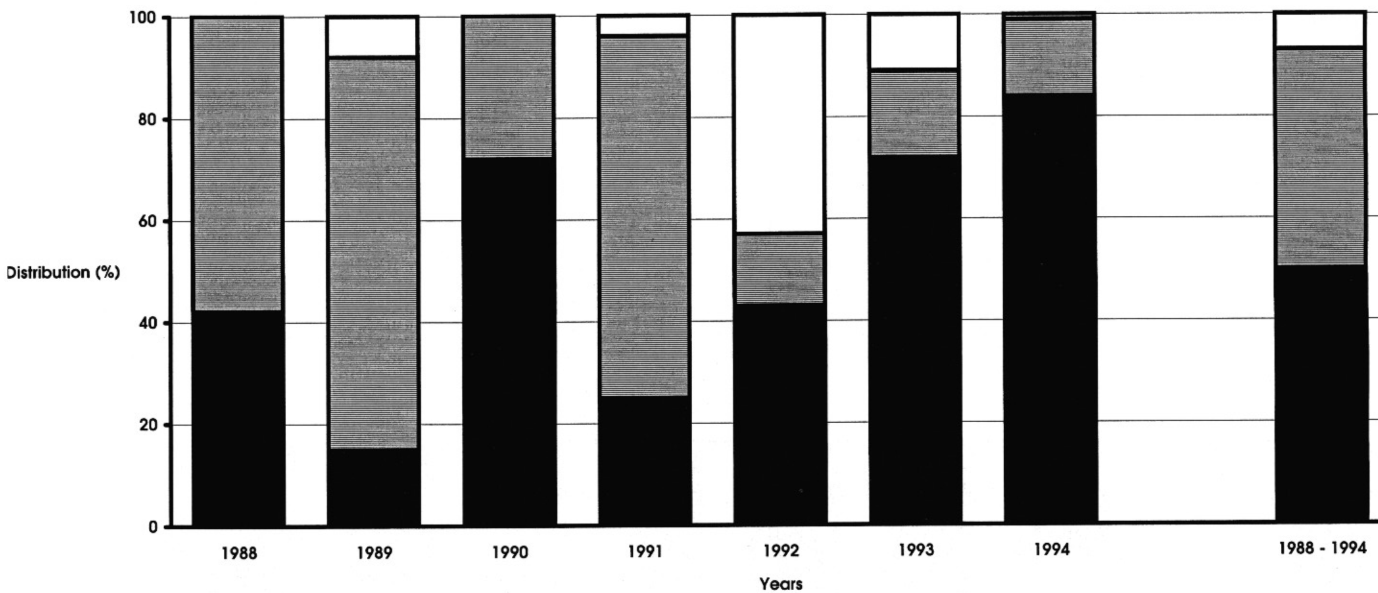

Figure 4. Recovery of broadcast fertilizer N (120 kg N ha^{-1}) applied in addition to subsurface side dressed fertilizer N (20 kg ha^{-1}) and slurry N (approximately 164 kg N ha^{-1}), in the maize crop and as soil mineral N after the harvest of maize (□ = in the crop, ▤ = in the soil, ■ = not accounted for).

Table 7. Fertilizer value of cover crops (FV, kg N ha^{-1}) and, in parentheses, their relative fertilizer value (RFV, expressed as a percentage of the aboveground N uptake of cover crop).

Winter treatment	Year:							
	1989	1990	1991	1992	1993	1994	1989–1993	1989–1994
Rye	25	94	25	25	21	29	38 (105)	37 (122)
Grass	31	19	−18	34	18	47	17 (44)	22 (65)

duced dry matter yields of maize by 4%, 6%, and 5% (not significantly) in 1988, 1991 and 1993, respectively. Averaged over the complete experimental period, the yield depression associated with undersown grass amounted to 2%.

The N uptake of cover crops decreased in the course of the experiment, as winters happened to be colder in later years. The availability of N from cover crops to subsequent maize crops, however, increased over the years. In the last 2 years, in particular, the effect of cover crops on the N uptake of maize and residual N exceeded the aboveground N uptake of the cover crop itself (Figure 5). Even in 1994 when rye establisment had failed in the preceding autumn, the N uptake of maize on the former rye N1 subplot was 22 kg ha^{-1} larger than on the corresponding fallow plot. On average 115 and 73% of the aboveground rye N and grass N, respectively, were recovered in the soil and maize crop together, and 70% and 48% when evaluated by the recoveries in the maize crop only.

Despite the decrease in the N uptake of cover crops, the fertilizer value (FV) remained fairly constant over the years (Table 7). The difference in the average fertilizer value of both cover crops in favour of rye, was mainly caused by the larger fertilizer value of rye in 1990 and 1991. In the other 3 years when both cover crops were grown, differences were negligible. The relative fertilizer value (RFV) increased from circa 50% in 1989 to circa 190% in 1993. Averaged over the whole period the relative fertilizer values were 122% and 65% for rye and grass, respectively.

Table 8. Linear regression models relating the residual soil mineral N in the upper 0.6 m soil layer (RSMN, kg ha^{-1}) after the harvest of silage maize (September) to the sum (SUMN, kg N ha^{-1}) of soil mineral N in the upper 0.6 m soil layer in spring (before fertilizer and slurry application), fertilizer N and NH_4–N in slurry and to the cumulative precipitation between May 1 and the date of autumn soil sampling (RAIN, mm): RSMN = a + (b x $SUMN^2$) + (c x RAIN).

Constant	Terms of the model:	
	$SUMN^2$	$SUMN^2$, RAIN
a	28.9*	123.6***
b	0.001444***	0.001271***
c		−0.2661**
Variance accounted for (%)	59	76

*, ** and *** denote significance at $P < 0.05$, $P < 0.01$ and $P < 0.001$, respectively

Table 9. Residual soil mineral N (kg ha^{-1}, 0.6 m) after the harvest of silage maize (September) as affected by winter treatments and the mineral N rate.

Winter treatment	N rate	Year:							Average
		1988	1989	1990	1991	1992	1993	1994	1989–94
Fallow	20	55	39	48	49	23	19	38	36 ab**
	94*	113	116	116	88	28	33	39	70 bc
	214*	192	211	159	173	49	54	55	117 cd
Rye	20	–	41	55	49	29	25	32	39 ab
	94*	–	111	166	92	32	43	48	82 c
	214*	–	191	264	162	63	63	72	136 d
Grass	20	46	35	45	34	26	19	39	33 a
	94*	95	148	133	100	47	38	46	85 c
	214*	138	325	170	144	85	63	67	142 d

* in 1988 and 1989 42 kg ha^{-1} more

** different letters denote significant differences ($P < 0.05$) in F-test

Residual soil mineral N

Residual SMN at T2 was positively related to N rates. The variance accounted for was increased by including summer rainfall into a multiple regression model. According to the model, a 100 mm increase of the summer rainfall reduces the residual SMN by about 27 kg ha^{-1} (Table 8). Residual SMN was much larger in the earlier years of the experiment (Table 9). A significant increase of residual SMN on plots where cover crops had been incorporated was not observed.

Variation in residual SMN was not reflected in the amount of SMN in the subsequent spring on fallow plots, indicating that the magnitude of N losses during the winter period, generally exceeded the potential N uptake of cover crops (Figure 6).

Discussion

Cover crop N uptake and overwinter losses

The aboveground N uptake of cover crops grown in combination with continous maize cropping, varied from 50–70 kg ha^{-1} in mild winters to less than 10 kg ha^{-1} in cold winters (Figure 1). This is considerably less than the N uptake of cover crops grown after cereals (Schröder *et al.*, 1997). We estimate that under normal conditions, about 30 kg N ha^{-1} can be taken up by the aboveground plant parts of both rye and grass grown after maize. The larger uptake potential of grass due to its earlier establishment, was apparently offset by its initially stripwise presence between the maize rows and its greater sensitivity to low temperatures (Shipley *et al.*, 1992). Differences in favour of grass might have become visible, however, if the N that was

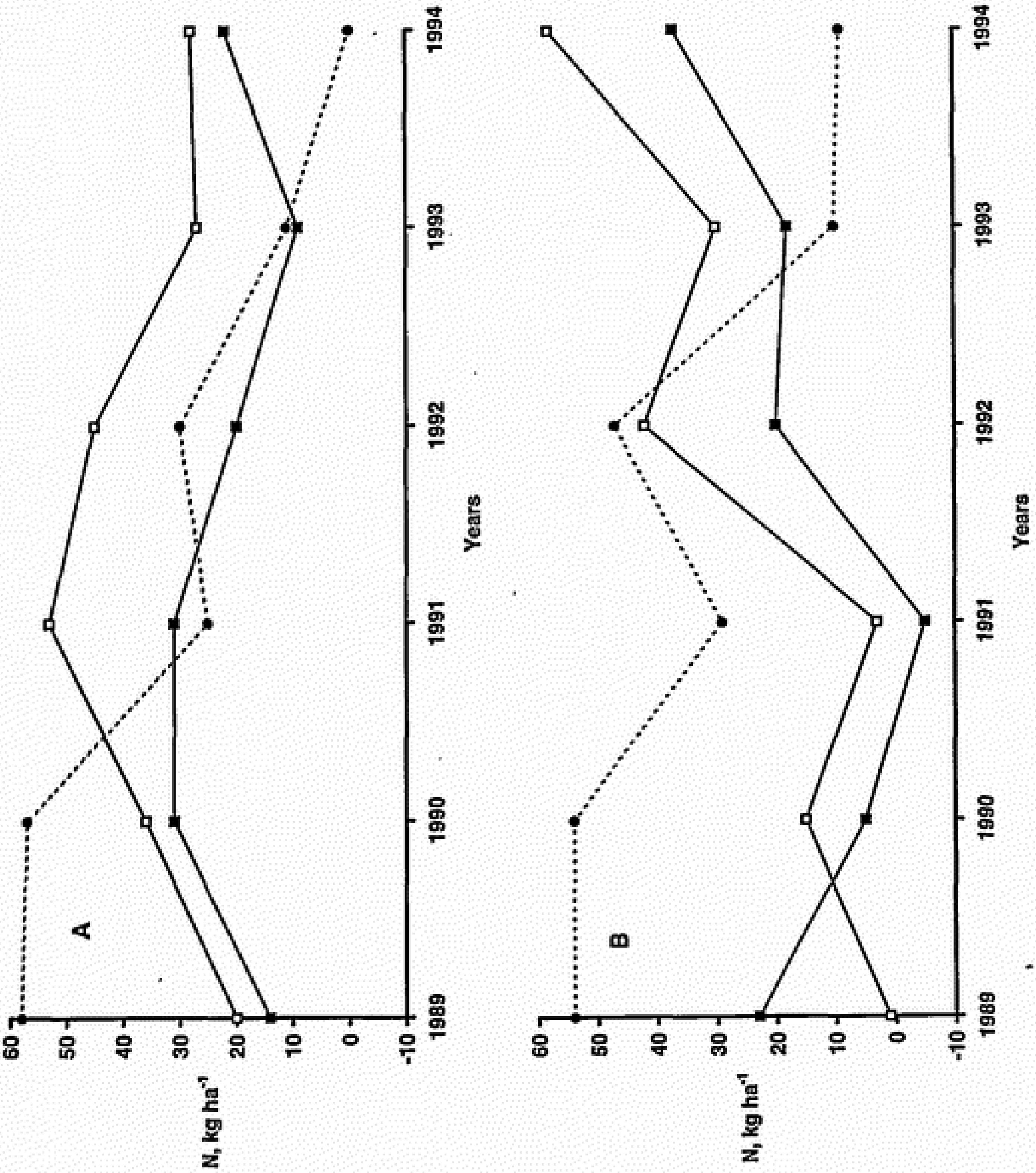

Figure 5. The N uptake of rye (A) and grass (B) in spring and the amount of N recovered in the maize crop only and as soil mineral N at the harvest and maize N together (● = N in cover crop, ■ = N in maize crop, □ = N in the soil and maize crop together).

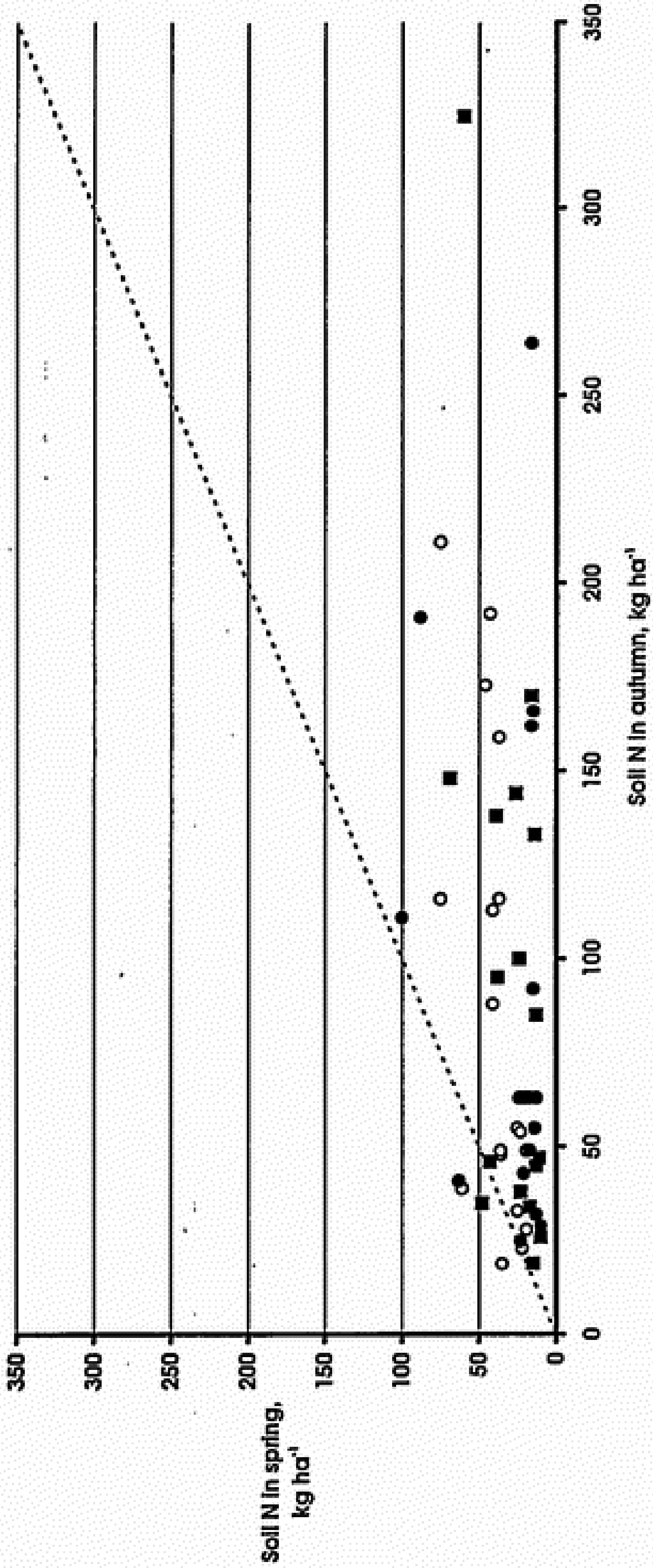

Figure 6. Relationship between soil mineral N (0.6 m layer) in the autumn and in the subsequent spring (○= Fallow, ● = Rye, ■ = Grass, -----; y = x).

absorbed in roots had been included, as grass roots contain a larger amount of N than rye roots (Scott *et al.*, 1987). The uptake of N in cover crops was hardly affected by N application rates to maize although N rates had a distinct effect on residual SMN.

Cover crops reduced N leaching during winter by about 55% (Figure 2). Similar reductions were found by Martinez & Guiraud (1990). We estimated that cover crops reduced the precipitation surplus by 16% (35 mm). This is in agreement with changes of water discharge measured in lysimeter studies (Steffens & Vetter, 1984; Martinez & Guiraud, 1990). Hence, the 55% reduction of N leaching resulted from a reduced concentration of N in the soil solution rather than from a reduction of the discharged volume. The results indicated that the recovery of residual SMN by cover crops was incomplete. Consequently, nitrate leaching under cover cropped plots at high N rates, exceeded leaching under fallow plots at low N rates. Our findings suggest that the cropping techniques of maize should therefore aim at creating conditions in which cover crops are able to absorb the amount of residual SMN. Reduced N inputs and all measures that support an early cover crop establishment, can contribute to this.

Reduction of leaching as a result of cover cropping (Figure 2) exceeded the N uptake in the aboveground plant parts of the cover crops (Figure 5). This was also reflected by the lower overwinter apparent N mineralisation on covered plots (Table 4). On N1 plots the magnitude of this effect matched well with the estimated storage of N in roots of 5–15 kg ha^{-1}, based on combined data from Welbank *et al.* (1974), Renius & Lütke Entrup (1985), Reeves *et al.* (1993) and Jackson *et al.* (1993). In general, the apparent N mineralisation on grass plots was lower than on rye plots. This may result from a larger N storage in grass roots than in rye roots (Scott *et al.*, 1987). Also, the apparent mineralisation may have been smaller on grass plots, as these plots were not tilled in autumn contrary to rye plots (Stokes *et al.*, 1992). Especially on N5 plots, however, the reduction of the apparent N mineralisation was large indicating that additional losses may have occurred under cover crops. Possibly, cover crops have stimulated denitrification due to their oxygen demand (Trolldenier, 1989; Scaglia *et al.*, 1985; Vos *et al.*, 1994) or promoted the immobilisation of N via carbohydrate exudation (Bottner *et al.*, 1984). This aspect deserves more attention in future research.

Maize reponse to N

Maize was responsive to N in all years. Calculations of the apparent N mineralisation during summer suggest that during the first few years, all plots still benefitted from heavy manure applications in the recent past (Table 5).

Almost 60% of the N in spring injected cattle slurry was recovered in the crop-soil system (Figure 3). Especially during the last 4 years, the fraction absorbed by the crop was much larger than reported earlier for maize (Schröder & Dilz, 1987; Schröder *et al.*, 1993). This was probably due to the relatively low application rate, favourable weather conditions and a gradual decrease of the N supplying capacity of the soil.

On average, half of the broadcast fertilizer N applied in addition to cattle slurry and subsurface side dressed fertilizer N left the crop-soil system during the growing season. Only a very small fraction was absorbed by the crop (Figure 4). Recoveries were negatively related to summer rainfall. Similar losses were reported by Jokela & Randall (1989) and Schröder *et al.* (1993).

Cover crop effects on maize yield

Results from our study indicated that only N-deficient maize crops benefited from the N provided via cover crop incorporation. In the first 2 years maize recovered 9–54% of the aboveground cover crop N. In the course of the years, however, recoveries gradually increased (Figure 5). This was probably partly due to the combined effects of factors improving the recovery of all sources of N in general, as discussed earlier. Moreover, the gradual increase of recoveries may point at an accumulation of residual effects of cover crops from previous years. Averaged over the 6 years 70% and 48% of the aboveground rye N and grass N, respectively, were recovered by subsequent maize crops. This superiority of rye over grass was also reported in a 2-year study of Thorup-Kristensen (1994) who found that barley recovered 43% and 17% of the N in rye and grass cover crops, respectively, when expressed as a percentage of their aboveground N uptake. When changes of SMN between spring and autumn were also accounted for, recoveries in our experiments increased to 115% and 73% for rye and grass, respectively. The N in grass cover crops, especially, may have decomposed too slowly to be fully at disposal of the maize, as average relative fertilizer values were 105% for rye and only 44% for grass (Table 7). Although rye and grass had similar C to N ratios in the aerial plant parts in our experiments, grass may decompose more slowly due to its larger root mass. The C to N ratio of roots of Graminaceous crops is usually more than 40 (Reeves *et al.*, 1993). The observed relative fertilizer values for grass in the present study are slightly less than the value of about 50% recently reported for fertilized grass ploughed down on clay soils in November (Schröder *et al.*, 1997).

Contrary to our findings, Scott *et al.* (1987), Wagger (1989a, b) and Wyland *et al.* (1995) reported that cover crops had negative effects on subsequent crops. However, their cover crops had C to N ratios between 30 and 45 whereas it ranged from 10 to 30 in the relatively young cover crops in our experiment and that of Thorup-Kristensen (1994). As C to N ratios of cover crops are positively related to plant mass per unit area and, hence, N uptake (Scott *et al.*, 1987; Wagger, 1989a; Laurent & Mary, 1992; Bollero & Bullock, 1994), the reduction of leaching and the need for a timely destruction of the cover crop may be conflicting goals.

In most of the years, the effects of cover crops on maize yields could be fully understood by their positive effect on the availability of N. In 1988 and 1991, however, a negative effect of grass cover crops was observed at all N rates. As 1988 was a relatively wet year, competition for N rather than water is the most likely reason for it. Under the dry and cold weather conditions of 1991, undersown grass developed vigorously and competition for both N and water may have played a role. In the wet summer of 1993 grass had a negative effect on maize yields at larger N rates, only. The reason for this effect remained unclear.

The soil aggregates of the seedbed were more stable on plots where cover crops had been incorporated. Emergence and final plant density were not affected, however. After 6 years we could not detect any significant cover crop effect on the organic matter content of the soil (data not presented here).

Residual soil mineral N

Residual SMN was positively ($P < 0.01$) related to N inputs (Table 8). Variance accounted for was improved when summer rainfall was included in the regression model ($P < 0.01$). In a wet summer like 1993, the model predicted a 50 kg ha^{-1} decrease of residual SMN. According to the model, residual SMN resulting from the currently recommended SMN supply (early spring, 0.6 m) of 180 kg ha^{-1}, would be 61 kg N ha^{-1} under average summer rainfall conditions (390 mm). This is reasonably in line with the 54 kg N ha^{-1} that can be predicted from a similar model proposed by Schröder *et al.* (1993).

Residual SMN decreased in the course of the years (Table 9). This downward trend probably results from the combined effects of a reduction of the N-rate from 1990 onwards, substantial losses of N in the summers of 1993 and 1994 and a gradual decrease of the N supplying capacity of the soil (Table 5).

Cover crops effects on residual SMN were insignificant. The N mineralised from cover crops in excess of the demand of maize, may well have been lost during the growing season, similarly to fertilizer N. This implies that cover crops may have postponed some of the losses from the winter to the summer season.

It should be noted that we assumed that the effective N inputs from slurry were equal to the ammoniacal N input. Consequently, gains due to the mineralization of organic slurry N on the one hand and losses due to ammonia volatilization on the other hand, were discounted. Therefore, coefficients of our models describing the response of residual N and maize yields (and the fertilizer values of cover crops deduced from them) to N inputs, could have been slightly different when mineral fertilizers had been the only N input.

In conclusion, cover crops grown after maize and incorporated in spring, reduced the overwinter leaching losses of SMN residues by about 55% over a broad range of N input levels. The fraction of the cover crop N that decomposed within the growing season appeared to increase in the course of the years. This was hardly reflected by an increase of residual SMN on plots where cover crops had been incorporated because mineralised N was either taken up by the present maize crop or already lost between early spring and late summer. Averaged over the 6 years of our experiment, the positive effect on the dry matter yield of N-deficient maize was equivalent to the effect of a fertilizer N rate amounting to 105% and 44% of the aboveground N in rye and grass, respectively. As N released from overwintering cover crops will not be reflected in the amount of SMN in early spring, N recommendations for maize based on SMN measurements need a downward adjustment when cover crops are grown.

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