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Effects of nitrification inhibitors and time and rate of slurry and fertilizer N application on silage maize yield and losses to the environment

J.J. Schröder, L. ten Holte, H. van Keulen & J.H.A.M. Steenvoorden*
**DLO Centre for Agrobiological Research (CABO-DLO), PO Box 14, NL 6700 AA Wageningen, The Netherlands; DLO Staring Centre for Integrated Land, Soil and Water Research (SC-DLO) PO Box 125, NL 6700 AC Wageningen, The Netherlands*

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Abstract

Field experiments with silage maize during eight years on a sandy soil in The Netherlands, showed that dicyandiamide (DCD) addition to autumn-applied cattle slurry retarded nitrification, thus reducing nitrate losses during winter. Spring-applied slurry without DCD, however, was on average associated with even lower losses and higher maize dry matter yields.

Economically optimum supplies of mineral N in the upper 0.6 m soil layer in spring (EOSMN), amounted to 130-220 kg ha^{-1}. Year to year variation of EOSMN could not be attributed to crop demand only. According to balance sheet calculations on control plots, apparent N mineralization between years varied from 0.36 to 0.94 kg ha^{-1} d^{-1}. On average, forty percent of the soil mineral N (SMN) supply in spring, was lost during the growing season. Hence, the amounts of residual soil mineral N (RSMN) were lower than expected. Multiple regression with SMN in spring, N crop uptake and cumulative rainfall as explanatory variables, could account for 79 percent of the variation in RSMN.

Postponement of slurry applications to spring and limiting N inputs to economically optimum rates, were insufficient measures to keep the nitrate concentration in groundwater below the EC level for drinking water.

Introduction

Animal manure is frequently spread in autumn because storage capacity for manure is insufficient to allow postponement till the next spring. Moreover, spring application may damage soil structure, especially on heavier soils. The long residence time of autumn-spread manure may result in more nitrogen (N) being lost through runoff, volatilization, leaching and denitrification.

Ammonia N present in, or mineralised from manure, can rapidly be nitrified. This process continues during winter in Northwestern Europe (Vilsmeier and Amberger, 1987). In mild and wet winters, nitrate may be lost through denitrification or leaching. Apart from financial considerations, N losses also deserve attention from an environmental point of view. Nitrous oxide resulting from denitrification has a detrimental effect on the ozone layer and contributes to the greenhouse effect (Bach, 1989) and N leaching may eventually lead to nitrate concentrations in groundwater exceeding 11.3 mg nitrate-N L^{-1}, the European Community (EC) standard for drinking water (Anon., 1980).

In cereal dominated rotations, N losses from manure can be restricted by immobilization with straw or N-storage in cover crops. However, in regions with high livestock densities, cereals have been substituted by continous silage maize, partly because of its tolerance for excessive manure applications (Schröder and Dilz, 1987). Therefore maize cropping is associated with great risks for N losses in these regions. Crop characteristics augment the risks even more; the quantity and quality of maize residues restrict microbial immobolization of soil mineral nitrogen (SMN) and its late harvest does not always allow timely establishment of a cover crop (Schröder *et al.*, 1992). Moreover, the roots of the subsequent maize crop will not explore deeper soil layers until June, thus limiting interception of leached nitrogen. Where incorporation of straw or growth of cover crops is not feasible, denitrification and leaching may be reduced by the use of nitrification inhibitors which delay the transformation of ammonium into nitrate. Dicyandiamide (DCD) and 2-chloro-6-(trichloromethyl)pyrimidine (N-Serve) have demonstrated their usefulness in this respect (Hauck, 1980). DCD effectiveness may be low, however, when its decomposition is stimulated by high temperatures (Solansky, 1981).

Between 1981 and 1989 we conducted field experiments to investigate the effect of time and rate of fertilizer and slurry application, and nitrification inhibitors on soil mineral N, leaching and N availability for maize.

Materials and methods

Setup and treatments

Experiments were executed between autumn 1981 and autumn 1989 in Wageningen, The Netherlands (52° N, 6° E), on a sandy soil with 34 g of organic matter, 50 g of silt, 18 mg of water soluble P, 83 mg exchangeable K per kg soil and a pH-KCl of 5.5 in the top 0.2 m. Depth of the groundwater table varied between 0.7 and 1.0 m for most of the time. The trials were located at different sites except for the growing seasons of 1986-1989 when treatments returned to exactly the same plot each year.

Between 1982 and 1985 combinations of autumn-applied cattle slurry (either with or without DCD) and spring-applied mineral fertilizer N (calcium ammonium nitrate, CAN) were investigated. Cattle slurry rates included a control and will be discussed later. Mineral fertilizer rates were 0, 50 (not in 1982), 100 and 200 kg N ha^{-1}. In 1984 and 1985 the experiment was extended to include spring-applied cattle slurry treatments with or without DCD. From 1986 till 1989 a comparison was made between the effect of 160 kg mineral fertilizer N (calcium nitrate, CN) and approximately 250 and 500 (130 and 260 in 1986) kg total N ha^{-1} from cattle slurry, applied either without nitrification inhibitor, with DCD or with N-Serve. Slurry was applied in either the second half of October (late summer), the end of November (autumn) or in March (spring). The experiments were set up as a split plot or strip plot trial with 3 (4 in 1982) replicates. Main plots (strips) consisted of cattle slurry rates with or without DCD in 1982, N rates in 1983-1985 and application times in 1986-1989. Subplot size varied between 45 and 90 m^2.

Silage maize (*Zea mays* cv. LG11 in 1982 and Splenda in 1983-1989) was planted around May

Table 1. Annual N applications (total N, kg ha^{-1}) in cattle slurry from autumn 1981 till spring 1989

year	exp. site	application time	approximate rate (kg N ha^{-1} yr^{-1}): 85	145	255	465
1981	a	autumn		165	335[a]	
1982	b	autumn		143	283[a]	570
1983	c	autumn	83	145	228[a]	
1984	c	spring	76	153	237[a]	
	d	autumn			312[a]	439
1985	d	spring		133	255[a]	368[a]
	e	late summer		132	239	
	e	autumn	89		178[a]	
1986	e	spring			180[a]	354
	e	late summer			253	507
	e	autumn			279[a]	552
1987	e	spring			245[a]	490
	e	late summer			207	438
	e	autumn			225[a]	443
1988	e	spring			248[a]	487
	e	late summer			247	474
	e	autumn			247[a]	505
1989	e	spring			276[a]	553

[a] treatments used for the preparation of Figure 2 and Table 2.

1st at a density of 110.000 plants ha^{-1} and harvested each year in October. Weeds were controlled chemically with atrazine-containing compounds. All plots received equal amounts of P, K and Ca mineral fertilizer to maintain soil fertility for these elements at recommended levels (Anon., 1989).

Cattle slurry was injected at a depth of 0.15 m (tine distance of 0.5 m) with a precision injector especially developed for field trials. The slurry was analysed for dry matter, total N, NH_4-N, P and K at each application date. Total N concentrations varied, mainly among experiments, between 3.0 and 5.6 g per kg fresh matter. Averaged over experiments concentrations amounted to 78 g dry matter, 4.3 g total N, 2.0 g NH_4-N, 0.7 g P and 4.5 g K per kg fresh matter. Changes in the experimental setup also caused the total N input from slurry to vary in the course of the years (Table 1). Until autumn 1984 DCD was applied at rates of 30 kg ha^{-1}, from 1985 at rates of 25 kg for late summer and autumn applications and 15 kg ha^{-1} (20 kg in 1985) for spring applications. The N concentration of DCD was 0.67 kg per kg. N-Serve (0.216 kg active ingredient per liter xylene) was applied at a rate of 3 L ha^{-1}. DCD and N-serve were thoroughly mixed with the slurry before spreading.

Observations

Each year initial SMN and residual SMN (RSMN) supplies were assessed in spring (March-April) and autumn (October-November), respectively, before fertilizer application. From 1982 till 1987 SMN supply was also determined in late spring (June). SMN is defined as the sum of NO_3- and NH_4-N. Between 1981 and 1985 sampling was restricted to subplots receiving no mineral fertilizer N except for the autumn samplings. Per subplot eight core samples were taken to a total depth of 0.6 m. Dry matter (DM) yield of the maize was determined by weighing the fresh material from a net area of 21 m^2 per subplot, DM content by drying a subsample of 0.8 kg at 105°C for 16 hr. Dried samples were analyzed for total N.

Nitrate leaching was assessed during the winter of 1985-1986, 1986-1987 and 1987-1988 in all subplots of the second replicate where no CN was applied in late summer or autumn. Leaching was assumed to start after the soil had been recharged to field capacity and calculated as the integral of the product of concentration and precipitation surplus over time. Nitrate concentrations were determined regularly in samples of the soil solution collected from four ceramic cups installed at 0.9 m depth. Precipitation surplus was estimated as the difference between precipitation and evapotranspiration (ET) taking account of the water storage capacity of the soil. ET was set equal to 0.3 $*$ potential evapotranspiration (Penman) as calculated from data collected at a meteorological station 3 km from the experimental site.

Definitions

The relative increase in SMN supply due to slurry application is defined as: (SMN in spring on fertilized plots − SMN on non-fertilized plots)/(total N input with slurry and DCD).

Apparent mineralization during summer, inclusive losses, was derived from the difference between total mineral N inputs and N outputs per treatment: (N yield of the harvested maize + RSMN) − (SMN in spring + mineral fertilizer N + ammonia-N in spring applied cattle slurry + N from DCD). For the winter period apparent mineralization, inclusive all non-leaching losses, equals: (SMN in spring + leached mineral N) − (RSMN in preceding autumn + ammonia-N in late summer- or autumn-applied cattle slurry + N from DCD).

Economically optimum SMN supply (EOSMN) was estimated by setting the first derivate of the relationship between SMN supply in spring and silage maize DM yields, obtained from quadratic regression analysis, equal to a price ratio of silage maize and N of 7. SMN supply is defined as the sum of SMN in spring (0-0.6 m), NH_4-N in spring-applied slurry and mineral fertilizer N. Values exceeding 300 kg N ha^{-1} were excluded from the regression analysis.

Apparent N recovery (ANR) of fertilizer N was defined as the difference in N yield between a fertilized and a non-fertilized crop expressed as a percentage of the N rate (N from DCD included), ANR of SMN as the difference in N yield between a fertilized crop and the estimated

N uptake at zero SMN expressed as a percentage of the SMN supply. Strictly speaking, non-fertilized crops were absent between 1986 and 1989, hence subplots that received CN in the preceding late summer were used as a reference. This seems justified as only 22–44 kg SMN ha^{-1} (0–0.6 m) was found in these plots in spring, even less than the 26–55 kg ha^{-1} on non-fertilized plots during the 1982–1985 period. Apparently, the 160 kg N ha^{-1} from CN was completely lost from the surface 0.6 m during winter.

Weather

For the experimental period precipitation between October and March was close to average (374 mm) except for 1984–1985 (312 mm) and 1987–1988 (517 mm). Precipitation between April and September was more or less average (388 mm), except for 1982 (287 mm), 1985 (448 mm), 1986 (303 mm) and 1987 (462 mm). Average daily temperature between October and March was close to normal (4.8°C) except for 1985–1986 (3.4°C), 1987–1988 (6.0°C) and 1988–1989 (6.7°C). Average daily temperature between April and September was close to normal (13.8°C) except for 1984 (12.8°C).

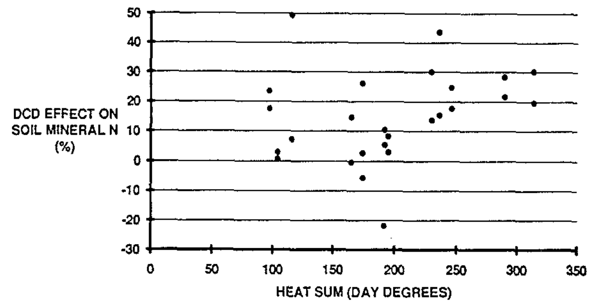

Fig. 1. Change due to DCD in the relative increase in soil mineral N supply in spring (upper 0.6 m soil layer, expressed in percent of total N input) resulting from slurry applied in late summer or autumn, as affected by the heat sum (> 0°C) during the first six weeks after spreading (1982–1989).

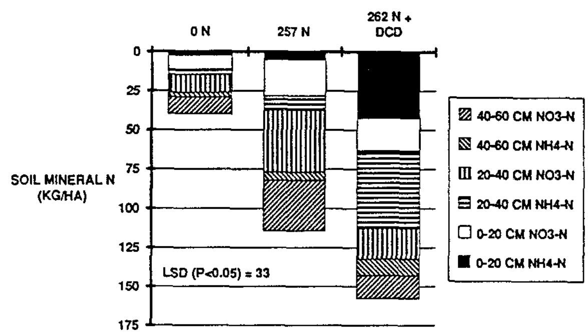

Fig. 2. Effects of DCD addition to late summer- and autumn-applied cattle slurry on the amounts of nitrate and ammonia in the upper 0.6 m soil layer in spring (average 1982–1989).

Results

Nitrification inhibitors and application time

DCD augmented the relative increase of the SMN supply derived from late summer- and autumn-applied slurry from 20 to 35 percent on average; however, the values varied considerably among years. This variation was not related to the heat sum during the first 6 weeks after DCD application (Fig. 1). DCD-addition to autumn-applied slurry reduced nitrification and the subsequent transport of N to deeper layers (Fig. 2), and increased the N yield of maize in all years except 1984 and DM yields in all years except 1984 and 1985; averaged over the years, ANR of autumn-applied slurry increased from 21 to 26 percent (Table 2). Soil sampling in June during the 1984–1987 period showed that SMN supply in June was similar on plots where slurry had been applied in autumn with DCD and in spring with or without DCD. Nevertheless, N yields and DM yields of maize were higher in 4 out of 6 and 3 out of 6 years, respectively, with spring-applied slurry without DCD than with DCD-treated autumn-applied slurry. The effect of spring-applied slurry on N yields and DM yields of maize was further improved by addition of DCD in 5 out of 6 and 3 out of 6 years, respectively. Averaged over the 1984–1989 period, ANR of autumn-applied slurry without, autumn-applied slurry with, spring-applied slurry without and spring-applied slurry with DCD was 20, 27, 29 and 33 percent, respectively. N-Serve addition to autumn-applied slurry had less effect than DCD on SMN supply in spring and N and DM yields of maize (Table 2).

Table 2. Dry matter and N yield of silage maize and apparent recovery of total N from cattle slurry as affected by application time and nitrification inhibitor addition

exp. period	application time	nitrif. inhibitor	total N input ($kg\ ha^{-1}\ yr^{-1}$): with slurry	with inhibitor	DM yield ($t\ ha^{-1}\ yr^{-1}$)	N yield ($kg\ ha^{-1}\ yr^{-1}$)	ANR (%)
1982–89	autumn	—	0	0	11.5	117	—
		—	257	0	14.8	170	21
		DCD	262	18	15.6	191	26
			(LSD < 0.05)		0.4	7	
1984–89	autumn	—	0	0	10.8	111	—
		—	239	0	14.3	159	20
		DCD	247	18	15.1	182	27
	spring	—	249	0	15.4	184	29
		DCD	249	12	15.7	198	33
			(LSD < 0.05)		0.5	8	
1986–89	autumn	—	0	0	10.5	100	—
		—	227	0	14.0	144	19
		DCD	232	17	15.5	178	31
		N-Serve	238	0	14.5	155	23
	spring	—	237	0	15.7	177	32
		DCD	237	10	15.7	184	34
		N-Serve	237	0	15.3	177	32
			(LSD < 0.05)		1.0	17	

N availability during the growing season

EOSMN supplies in spring ranged from 130 to 220 kg N ha^{-1} (Table 3). In seven out of eight years N yields could be described significantly by a quadratic function of the SMN supply in spring. ANR of SMN at optimum SMN supply varied between 30 and 82 percent; the ANR was

Table 3. Calculated constants of the equation $DMY = a + (0.01{*}b)SMN - (0.00001{*}c)SMN^2$ (derived from regression analysis) between DM yield (DMY, t ha^{-1}) and SMN supply in the upper 0.6 m soil layer in spring (kg ha^{-1}), the variance accounted for (VAF, %), the economically optimum SMN supply (EOSMN, kg ha^{-1}) and the calculated (see Table 4) N yield at this EOSMN (NYOP, kg ha^{-1})

exp. year	value/ significance[a]	constants: a	b	c	VAF	EOSMN	NYOP
1982	value	9.42	5.255	10.44	92	218	196
	sign.	***	***	***			
1983	value	12.55	4.02	7.91	65	210	217
	sign.	***	***	***			
1984	value	8.43	3.321	8.39	45	156	169
	sign.	***	***	***			
1985	value	13.67	4.01	8.61	15	192	256
	sign.	***	**	*			
1986	value	13.48	4.57	15.06	25	128	182
	sign.	***	**	*			
1987	value	8.97	2.42	4.26	32	202	144
	sign.	***	NS	NS			
1988	value	10.75	5.54	12.53	64	193	219
	sign.	***	***	***			
1989	value	7.47	9.51	20.58	88	214	221
	sign.	***	***	***			

[a] NS not significant, $*p < 0.10$, $**p < 0.05$, $***p < 0.01$.

Table 4. Calculated constants of the equation $NY = a + (0.01 * b)SMN - (0.00001 * c)SMN^2$ (derived from regression analysis) between N yield (NY, kg ha^{-1}) and SMN supply in the upper 0.6 m soil layer in spring (kg ha^{-1}), the variance accounted for (VAF, %), apparent N recovery of SMN (ANR, %) at economically optimum SMN supply (EOSMN, see Table 3) and at half the EOSMN and calculated (see Table 3) relative DM yield (RY, in % of DM yield at EOSMN) at half the EOSMN

exp. year	value/ significance[a]	constants: a	b	c	VAF	SMN supply: EOSMN: ANR	0.5 * EOSMN: ANR	RY
1982	value	73.4	78.4	100.8	94	56	90	87
	sign.	* * *	* * *	* * *				
1983	value	151.4	36.4	25.4	66	31	34	91
	sign.	* * *	* * *	NS				
1984	value	96.1	66.8	130.0	70	47	57	95
	sign.	* * *	* * *	* * *				
1985	value	172.4	57.3	72.5	37	43	50	92
	sign.	* * *	* * *	*				
1986	value	138.1	42.5	63.0	39	34	38	90
	sign.	* * *	NS	NS				
1987	value	82.9	43.7	67.3	52	30	37	91
	sign.	* * *	* *	*				
1988	value	103.3	91.8	166.0	78	60	76	89
	sign.	* * *	* * *	* *				
1989	value	46.2	121.8	188.5	88	81	102	83
	sign.	* * *	* * *	* * *				

[a] NS not significant, $*p < 0.10$, $**p < 0.05$, $***p < 0.01$.

higher at suboptimum levels of SMN supply. At half the optimum SMN supply, yield was depressed between 5 and 17 percent (Table 4).

Apparent mineralization between March and October on plots without N fertilizer amounted to 110 kg N ha^{-1} yr^{-1} on average (range 68–162), equivalent to 0.54 (range 0.36–0.94) kg ha^{-1} d^{-1}. Lowest values were found in years with low temperatures (1984) and high precipitation (1987). On fertilized plots the calculated apparent mineralization was generally lower, suggesting that N losses during the growing period were related to SMN supplies. Linear regression analysis of the initial SMN supply in spring on the sum of N yield of maize and RSMN suggested that apparent mineralization would have been 138 kg N ha^{-1} yr^{-1} at a hypothetical initial SMN supply of zero (Fig. 3). The sum of N yield and RSMN, however, was always substantially lower than the sum of SMN supply in spring and the estimated mineralization of 138 kg N ha^{-1}. In general, about 40 percent of the SMN supply could not be accounted for in either N yield or RSMN. As SMN supplies increased from 50 to 200 kg ha^{-1}, ANR of SMN by the crop decreased from 47 to 39 percent and RSMN increased from 32 to 54 kg ha^{-1}.

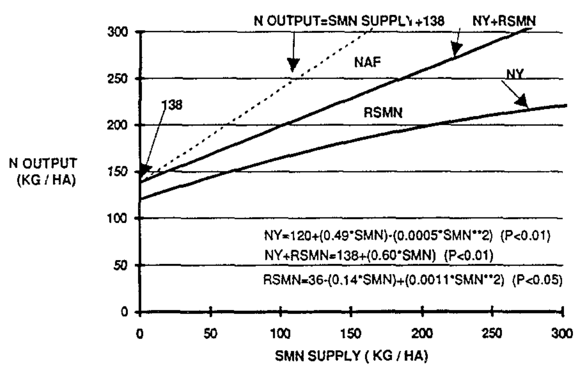

Fig. 3. Allocation of soil mineral N (SMN) in spring (upper 0.6 m soil layer) to uptake in the aerial plant parts of maize (NY), residual soil mineral N (RSMN, upper 0.6 m soil layer) and losses not accounted for (NAF); (average 1982–1989).

Residual N and subsequent losses

RSMN was strongly influenced by the SMN supply in spring but the relation varied from year

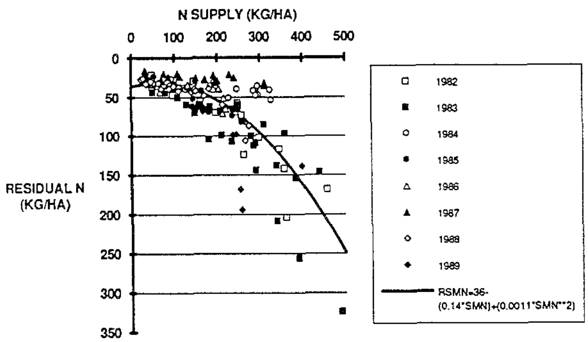

Fig. 4. Residual soil mineral N (upper 0.6 m soil layer) after the harvest of silage maize as affected by the SMN supply in spring (upper 0.6 m soil layer).

to year (Fig. 4). Relatively large quantities were found following dry seasons (1982, 1983, 1989), whereas only moderate amounts were observed after wet summers (1984, 1987), despite low N yields in those years. Variance accounted for (VAF) increased from 60 to 79 percent if the linear regression model relating RSMN to SMN supplies was extended to include cumulative rainfall between May 1st and the date of post harvest soil sampling and N yield (Table 5). According to this model any increase in rainfall or in N yield up to 50-100 kg ha^{-1}, reduced RSMN. Predictability of RSMN was not improved by including temperature as a variable.

Measurements on the fate of N during winter showed SMN in spring to be lower than the sum of RSMN and mineral N from slurry applied in the preceding late summer or autumn (Fig. 5). With only few exceptions this also occurred in plots where DCD had been added. These apparent losses are partly the result of N leaching. In the first two winters when leaching was moni-

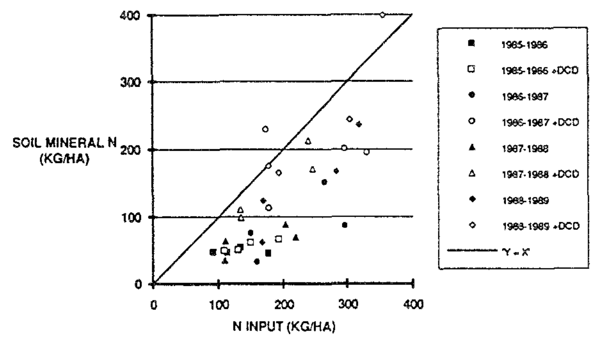

Fig. 5. Soil mineral N in spring (upper 0.6 m soil layer) as affected by the N input from residual soil mineral N left by the preceding maize crop (upper 0.6 m soil layer), NH_4-N from late summer- or autumn-applied cattle slurry and N from DCD.

Table 5. Linear regression models relating the amount of residual soil mineral N in the upper 0.6 m soil layer in autumn (RSMN, kg ha^{-1}) to the soil mineral N supply in the upper 0.6 m soil layer in spring (SMN, kg ha^{-1}), cumulative preciptation between May 1st and autumn soil sampling date (RAIN, mm) and N yield of maize (NY, kg ha^{-1}): $RSMN = a + b*SMN + c*SMN^2 + d*RAIN + e*RAIN^2 + f*NY + g*NY^2$

Constant:	Value/ Significance[a]	Terms of the model:		
		SMN	SMN, RAIN	SMN, RAIN, NY
a	value	36.1	−92.3	110.0
	sign.	* * *	* *	* * *
b	value	−0.138	−0.0865	−0.2269
	sign.	*	*	* * *
c	value	0.001126	0.000995	0.001029
	sign.	* * *	* * *	* * *
d	value		0.919	
	sign.		* * *	
e	value		−0.001507	−0.0001510
	sign.		* * *	* * *
f	value			−0.868
	sign.			* * *
g	value			0.003511
	sign.			* * *
variance accounted for (%)		60	72	79

[a] NS not significant, $*p<0.05$, $**<0.01$, $***p<0.005$.

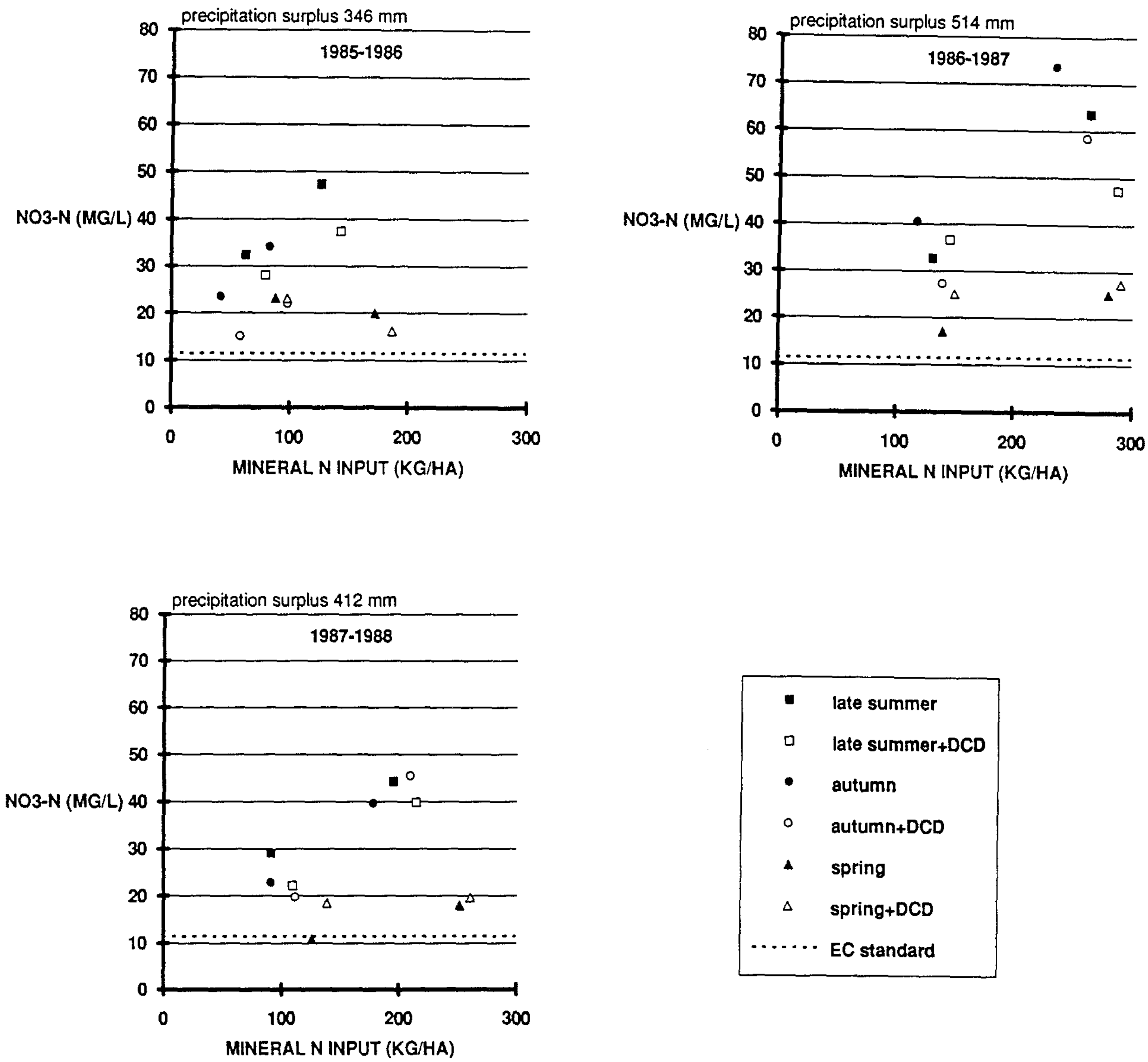

Fig. 6. Nitrate concentrations (weighted average over complete leaching period) at 0.9 m below soil surface as affected by time and rate of cattle slurry application and addition of DCD.

Table 6. Net change in mineral N supply in the upper 0.6 m soil layer (kg ha^{-1}) during winter excluding leaching losses

application time	total N input (kg ha^{-1} yr^{-1}):		year:		
	with slurry	with DCD	1985–86	1986–87	1987–88
late summer	191	0	−20	−38	23
	191	17	−31	−32	24
	392	0	−62	−62	−7
	399	17	−67	−56	50
autumn	192	0	−13	−23	23
	199	17	−30	85	42
	378	0	−29	−14	1
	397	17	−48	−55	111

tored, only half the leaching (both in terms of water volume and N) actually took place in winter, the remainder occurring between March and June (data not shown). Generally, nitrate concentrations (weighted average over the complete leaching period) were higher and more responsive to rates for late summer- and for autumn-applied slurry than for spring-applied slurry. DCD restricted nitrate leaching only slightly under late summer or autumn-applied slurry; when added to spring-applied slurry it even resulted in higher nitrate concentrations in subsequent winters (Fig. 6). Ammonia leaching was restricted to 1–2 kg N ha^{-1} yr^{-1} in both DCD- and non-DCD-treated plots.

Balance sheet calculations for the winter period indicated net gains in SMN in the mildest of the three winters. Averaged over years the net change in SMN (excluding leaching losses) was inversely related to slurry rate (Table 6).

Discussion

Results of field experiments with silage maize on a sandy soil between 1981 and 1989 revealed strong relationships between DM yield, N yield and SMN supply in spring; SMN was a function of both fertilizer rate and application time. Apparently, risks for losses are related to the residence time of a fertilizer in the soil system. Leaching and denitrification are the major loss processes (Addiscott and Powlson, 1992). Our results indicate that DCD addition to late summer- or autumn-applied cattle slurry delayed nitrification and hence reduced subsequent losses of nitrate to a certain extent. However, DCD effects on the SMN supply varied greatly among years. We could not relate this variation to differences in cumulative temperatures after application although such a relationship between the decomposition rate of DCD and temperature has been reported (Solansky, 1981). In all years but 1984 and 1985, DCD addition to late summer- or autumn-applied slurry had a positive effect on maize DM yields as reported earlier (Amberger, 1986). However, DM yields in the present experiment were generally higher following application of similar amounts of slurry without DCD in spring. DCD addition to spring-applied slurry resulted in increased maize DM yields only in 1984, 1985 and 1987. 1984 was exceptionally cold, whereas 1985 and 1987 were much wetter than average. Low temperatures retarded crop development and N uptake in 1984 and may have reduced root extension during the juvenile stage (Tardieu and Pellerin, 1991). Abundant precipitation in 1985 may have promoted downward transport in early spring as it did in 1987, when monitored in our experiment. Under these circumstances DCD may have improved "synlocalization" (De Willigen and van Noordwijk, 1987) between SMN and active maize roots. The addition of N-Serve to autumn-applied slurry had a much smaller positive effect on SMN in spring than DCD. Consequently, N and DM yields of silage maize were intermediate between those from the control and DCD-treated plots.

ANR from cattle slurry by maize in this experiment was similar to that observed in many other studies (e.g. Schröder and Dilz, 1987; Schröder, 1990; Schröder *et al.*, 1992). As reported earlier (van Dijk, 1985; Görlitz, 1989) recovery was improved by postponement of the application to spring.

EOSMN supply in spring, as defined in this paper, varied between 130 and 220 kg ha^{-1}. This variation could not simply be attributed to crop demand for N as both high and low optima may coincide with low and high N yield. The relation between N yield and supply may also depend on such factors as the magnitude of losses and N mineralization during the growing season, rooting pattern and root functioning. In six out of eight years optimum SMN supply varied between 190 and 220 kg N ha^{-1}. This is in close agreement with the results of others (Bassel *et al.*, 1987; Beauchamp and Kachanoski, 1989; Blackmer *et al.*, 1989). SMN supply as we defined it, did not include the mineralizable N from cattle slurry. EOSMN supplies, as calculated here, may therefore be lower than in cropping systems where only mineral fertilizer N is used. This possible underestimate of the contribution of manure N is counteracted, however, by increased losses associated with manure such as ammonia volatilization and denitrification. We did not account for these losses, although balance sheet calculations suggest that major losses occurred.

According to balance sheet calculations for the growing season, apparent mineralization on non-fertilised plots varied on average between 0.36 and 0.94 kg N ha^{-1} d^{-1}. Apparent absolute losses increased with increasing N input. On average they amounted to 40 percent of the SMN supply in spring. As N storage in the root system can only account for about 25 kg ha^{-1} (Thom and Watkin, 1978), high summer losses must have other causes. At least in 1986 and 1987 losses could be attributed to leaching after crop emergence. Losses under young maize crops were also reported in (Wantulla *et al.*, 1988). Moreover, greater availability of easily decomposable organic matter from animal manure may have stimulated loss through denitrification (Guenzi *et al.*, 1978; Rice *et al.*, 1988). Although we injected the slurry, ammonia volatilization losses from the injection slots cannot be completely discounted (Schröder, 1990). However, substantial summer losses also occurred on plots where only mineral fertilizer N had been applied, in agreement with data from (Jokela and Randall, 1989) showing losses in the order of 30 percent. Greenwood *et al.*, (1992) reported similar findings with onion crops.

At half the economically optimum SMN supply, yield was never depressed more than 17 percent. Prolonged suboptimal fertilization, however, may lead to larger yield reductions as suggested by results from the continuous experiment between 1986 and 1989 and by other evidence (e.g. Motavalli *et al.*, 1992).

As a result of losses during the growing season, RSMN was lower than expected from the difference between SMN supply and N yield, especially in wet years. In agreement with (Lorenz, 1992), RSMN already started to increase in the suboptimum SMN range. Almost eighty percent of the variation in RSMN could be accounted for by multiple regression based on SMN supply, crop N uptake and cumulative summer rainfall.

Losses during winter were strongly related to N inputs from RSMN and late summer- or autumn-spread slurry. Leaching losses from cattle slurry were negligibly lower if application was postponed from late summer to autumn and only slightly lower following DCD addition. Lowest leaching losses from slurry were generally associated with spring application. For all treatments (except for the low rate of spring-applied slurry in 1988), concentrations were well above the EC standard for drinking water, however. Observations during winter in the continuous experiment from autumn 1985 to spring 1988, showed that leaching did not account for the total loss. Apparently other processes such as denitrification played a role as well.

Conclusions

Addition of nitrification inhibitors to autumn-applied slurry did not improve the N recovery by maize sufficiently to justify recommendation of this practice as an alternative for slurry application in spring. Even with spring application, however, high N losses occurred both during the growing season and after harvest. The soil mineral N supply in spring associated with the highest financial return, resulted in nitrate-N concentrations in the upper groundwater that exceeded the EC standard for drinking water.

Our results indicate that pollution risks from maize can be limited by adding N at rates below economically optimum levels. Improved management practices such as N placement (Maddux *et al.*, 1991; Sawyer *et al.*, 1991), conditional post emergence N dressings (Magdoff, 1991) and winter cover crops (Schröder et al., 1992), seem necessary to ensure that economic and environmental goals can both be realized.

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