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Residual effects of different N fertilizer treatments on growth, N uptake and yield of oilseed rape, wheat and barley

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Abstract

In the long term, changes of N input (e.g. amount of N fertilization) or N output (e.g. N offtake in the grain) can affect soil N content and, in consequence, potential soil N mineralization, which may promote crop growth and support yield formation. The aim of this study was to quantify the residual effects of a former N fertilization on N mineralization, crop growth, N uptake and grain yield. From 1990/1991 to 1998/1999, different N treatments including slurry (none, 80 kg N ha^{-1} as pig slurry in autumn, in spring, in autumn + spring) and mineral N fertilization (0–240 kg N ha^{-1}) were tested in a winter oilseed rape (OSR) – winter wheat – winter barley rotation on a pseudogleyic sandy loam (Luvisol) at Hohenschulen Experimental Station near Kiel in NW Germany. Each year, treatments occurred in all three crops of the rotation and were located on the same plots. Accumulated over the experimental period, the N balance (N supply − N offtake − N leaching) of the different N treatments varied between −740 and +1300 kg N ha^{-1}. In 1999/2000–2001/2002, all plots remained unfertilized in order to avoid interactions with the actual N fertilization.

The former N treatments enhanced dry matter and total N uptake of wheat in 2000–2002 compared with the former unfertilized control, however, differences were not significant ($P > 0.05$) at most sampling dates. Also soil mineral N (SMN) in 0–30 cm remained unaffected during spring growth. Lately, on average of all treatments, grain yield of wheat decreased from 692 g m^{-2} in 2000 to 687 g m^{-2} in 2001 and 357 g m^{-2} in 2002. Barley yielded 481, 462 and 207 g m^{-2}, and OSR 375, 350 and 176 g m^{-2}, respectively. Total N uptake in the above-ground biomass of wheat at harvest was reduced from 109 kg N ha^{-1} in 2000 to 76 kg N ha^{-1} in 2001 and 59 kg N ha^{-1} in 2002, respectively. Barley accumulated 69, 57 and 33 kg N ha^{-1} in the above-ground biomass, and OSR 120, 111 and 59 kg N ha^{-1}, respectively. In all crops, residual N effects were largest in the first year (2000) and decreased with the years. The residual effects of slurry and mineral N fertilizer were similar.

Considering the differences of 2000 kg N ha^{-1} in the N balance, the residual effect on N uptake remained at a very low level. The crops used on average 3% of the N surplus within the first three years without N fertilization, i.e. about 1% per year.

Keywords: Residual effect; Nitrogen treatment; Crop rotation; Mineralization; Soil mineral N; yield; N uptake

1. Introduction

In the long term, changes of N input (e.g. amount of N fertilization) or N output (e.g. N uptake in the grain) can affect soil N dynamics (Glendining et al., 1996). A negative N balance leads to nutrient exhaustion. In contrast, a large N surplus increases soil N amount, and, in consequence, potential soil N mineralization, which may promote crop growth and support yield formation, but also leaching losses.

In general, organic fertilizers as slurry or farmyard manure raise soil organic matter per unit of N input more compared to mineral fertilizers (Jenkinson et al., 1994). Ciardi et al. (1988) reported increased C and N contents of soil receiving farmyard manure, while no change was observed when plots receiving inorganic fertilizer were compared with unfertilized plots. According to Uhlen (1991), higher residual N percentages in the soil with N added in farmyard manure may largely be due to the much lower crop utilization percentages for farmyard manure N in the first year. Nardi et al. (2004) suggested that organic inputs could help maintain soil fertility by improving chemical and biological soil properties. After 40 years, they found farmyard

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Table 1
Mean air temperature (°C) and total rainfall ($l\,m^{-2}$) in the growing seasons 1999/2000–2001/2002 and the long-term average (Deutscher Wetterdienst, Station Kiel-Holtenau)

	Mean air temperature (°C)				Total rainfall ($l\,m^{-2}$)			
	Growing season			Long-term average	Growing season			Long-term average
	1999/2000	2000/2001	2001/2002		1999/2000	2000/2001	2001/2002	
August	16.8	16.0	17.8	16.3	83	43	90	71
September	17.1	13.8	12.7	13.3	53	63	144	64
October	9.5	11.1	12.8	9.4	47	81	38	73
November	5.3	7.3	5.2	5.0	27	35	74	64
December	2.7	4.1	0.7	2.5	171	46	67	74
January	3.0	1.5	3.3	0.7	62	35	80	61
February	4.3	1.7	5.0	1.0	70	42	115	37
March	4.6	2.5	5.0	3.3	80	48	44	47
April	9.2	6.5	7.6	6.7	34	70	45	49
May	13.2	12.1	13.1	11.5	33	45	40	53
June	15.1	13.5	16.4	15.1	48	64	85	65
July	15.2	18.0	17.6	16.3	44	87	222	88
Average or sum	9.6	9.2	9.9	8.4	752	659	1044	754

manure fertilization to sustain total organic carbon in the top layers while mineral treatments alone or combined with organic fertilization exhibited a minor influence on the development of organic matter in a continuous maize system.

Glendining and Powlson (1995) reviewed field trials dealing with the long-term effects (>7 years) of inorganic N fertilization. Even if timing and amount meet the need of the crop, mineral N fertilizer may increase soil organic N content in two ways: directly, by the immobilization of fertilizer N, and indirectly, by increasing both the amount of crop residues and their N concentration. Silgram and Chambers (2002) observed a strong relationship between organic carbon and long-term fertilizer N and a detectable effect of fertilizer N on readily mineralizable N in the plough layer. Also Boghal et al. (1997) reported that large N applications (as ammonium nitrate) over a 13-year period contributed to an observed build-up in soil organic N. However, N mineralization seemed to be more increased than total soil N content. Several results suggest that the small amount of additional organic N returned to the soil as a result of N fertilization is in fractions that turnover more rapidly than the N in other organic matter fractions (Bjarnason, 1989; Rasmussen et al., 1998; Shen et al., 1989). The effect of mineral fertilizer N appears to be greatest when measured in short-term incubations, also suggesting it is increasing the most readily mineralizable fractions of organic N. In long-term incubations, however, differences in N mineralization between long-term fertilizer treatments were much less marked (Glendining et al., 1996).

Many authors investigated the residual effects of mineral N fertilizers applied in 1 year on yield and N uptake of the following crop and found only small amounts of residual N fertilizers (1–7% of the applied N amount) taken up by the subsequent crop (Beims, 2004; Riga et al., 1980; Vilsmeier et al., 1988). However, information on the residual effects of long-term fertilization on soil N dynamics and their implication for crop growth and yield formation in the following years is scarce.

The aim of this study was to quantify the residual effects of the former N fertilization (slurry and mineral N) of a 9-year field trial on N mineralization, crop growth, yield and N uptake within an oilseed rape – wheat – barley rotation. In addition, N losses due to leaching were estimated.

2. Materials and methods

2.1. Soil and site

The experiment presented here was established in autumn 1990 on a pseudogleyic sandy loam (Luvisol: 170 g clay kg^{-1}, pH 6.5, 70 mg P kg^{-1}, 200 mg K kg^{-1}, 13 g C_{org} kg^{-1}) at the Hohenschulen Experimental Farm of the University of Kiel, located in NW Germany ca. 15 km west of Kiel (Schleswig-Holstein, 10.0°E, 54.3°N, 23 m a.s.l.). Plant available K and P were determined by using the CAL-method (Schüller, 1969). The climate of NW Germany can be described as humid. Mean air temperature throughout the year is about 8.4 °C. Total rainfall averages 750 $l\,m^{-2}$ annually at the experimental site, with ca. 400 $l\,m^{-2}$ received during April–September, the main growing season, and approximately 350 $l\,m^{-2}$ during October–March (Table 1).

2.2. Treatments and design

In the growing seasons 1990/1991–1998/1999, soil tillage (conservation tillage without ploughing, conventional tillage), application of pig slurry (none, 80 kg N ha^{-1} in autumn, 80 kg N ha^{-1} in spring, 80 kg N ha^{-1} in autumn + 80 kg N ha^{-1} in spring), mineral N fertilization (0, 120, 240 kg N ha^{-1}) and application of fungicides (none, applications against pathogens of the stem, leaves and ear) were all varied in a field trial. Crop rotation was oilseed rape (OSR) (cv. Falcon) – winter wheat (cv. Orestis) – winter barley (cv. Alpaca).

Practical constraints required the field trial design to be a none-replicate split-split-plot design with three levels of splitting. The tillage treatments were main plots, the slurry treatments were sub-plots split within main plots, the fungicide treatments were sub-sub-plots split within sub-plots and the mineral N fertilizer treatments were sub-sub-sub-plots split within sub-sub-plots. The sub-sub-sub-plot size was 12 × 3 m. Each crop was grown in each year and each main plot completed an entire rotation over the 3 years of the experiment. The same treatment regimes were applied to the same sub-plots, the same sub-sub-plots, and the same sub-sub-sub-plots in each year so that the cumulative effects of each treatment were balanced both for years and for previous crops. Detailed information about methods and results from this period is provided in Sieling et al. (1997, 1998a,b, 1999) and Sieling (2000).

For the period 1991/1992–1998/1999, a simple N balance was calculated:

N balance = N fertilization (mineral and slurry) − N uptake in the grain − N leached during the subsequent percolation period.

In the following three growing periods (1999/2000–2001/2002), the residual effects of the former N treatments were investigated. To avoid interactions with current N fertilization, no N fertilizers (neither slurry nor mineral N) were applied from 1999/2000 to 2001/2002. Soil tillage was maintained as before, and pesticides were applied if required. The straw remained on the plots. Crop management not involving the treatments (e.g. stubble cleaning, seed date, application of herbicides and insecticides) was handled according to standard farm practice.

2.3. Plant and soil sampling

In spring and summer (Table 2), wheat plant samples were taken fortnightly from 0.25 m^2, and tiller number and dry matter were determined. At harvest, grain plus straw yield and yield components of all three crops were measured. All values were corrected to 1 m^2. In addition, plant N concentration was measured using NIRS-method. Total N uptake was calculated by multiplying dry matter and corresponding N concentration.

Soil mineral N content (SMN = NO_3^- + NH_4^+-N) was determined on four dates (‘after drilling’, ‘end of autumn growth’ before winter, ‘beginning of spring growth’ before N fertilizer application, and ‘after harvest’). Two cores per plot, averaged to one sample, were taken to 90 cm in 30 cm horizons. Soil samples for SMN were taken to the laboratory and stored frozen until analysis. They were thawed overnight at room temperature. From one subsample, NO_3-N and NH_4-N were extracted using 0.033n $CaCl_2$ and analyzed colorimetrically. A further subsample was oven-dried to determine soil moisture content. For the calculation of SMN, bulk densities were assumed as followed: 1.45 g cm^{-3} for 0–30 cm, 1.60 g cm^{-3} for 30–60 cm, 1.70 g cm^{-3} for 60–90 cm. In spring, SMN in 0–30 cm was quantified according to plant sampling.

Table 2
Dates of plant sampling and growth stages of winter wheat

	Year		
	2000	2001	2002
1 (Beginning of spring growth)	19.03.2000	6.04.2001	26.03.2002
2 (GS[a] 25/29)	24.04.2000	23.04.2001	22.04.2002
3 (GS 31)	9.05.2000	7.05.2001	6.05.2002
4 (GS 32/33)	23.05.2000	21.05.2001	21.05.2002
5 (GS 49)	6.06.2000	5.06.2001	3.06.2002
6 (GS 65)	20.06.2000	20.06.2001	17.06.2002
7 (GS 75)	4.07.2000	5.07.2001	1.07.2002
8 (GS 85)	18.07.2000	18.07.2001	15.07.2002
9 (GS 92)	1.08.2000	8.08.2001	29.07.2002

[a] Growth stage according to the scale suggested by Zadoks et al. (1974).

2.4. Estimation of N leaching

In both experimental periods (1990/1991–1998/1999 and 1999/2000–2001/2002), N leaching was calculated by multiplying an estimated drainage volume with the respective NO_3^- concentration measured for each plot separately. Soil water at 90 cm was obtained using porous ceramic suction cups (two per plot, averaged to one sample) and analyzed for NO_3^- photometrically. During the leaching period, the cups were sampled at approximately fortnightly intervals. The vacuum of 65 kPa was maintained for 1–2 days depending on the soil water content. The drainage volume was estimated from daily meteorological observations. It was assumed that after the soil water content has reached field capacity in autumn, daily drainage equalled rainfall less the evapotranspiration. The return to field capacity was identified by tensiometers. Summing the NO_3^- leaching for all sample dates while percolation occurred gave a total N loss over winter. More details about the potential sources of errors are given in Sieling et al. (1997) and Sieling (2000).

2.5. Statistical analysis

Analyses of variance were done by using the procedure GLM of the SAS statistical package. Year was used as replication of main plots (crop). $LSD_{0.05}$ for former slurry treatment effects within the crops were based on year × tillage × slurry interaction effects, those for former mineral N treatments and slurry × mineral N interaction effects were based on year × tillage × slurry × mineral N interaction effects. $LSD_{0.05}$ apply only to individual treatment means. The effects of soil tillage and former fungicide treatments were small ($P > 0.05$) and are not presented.

Plant N concentration N_t (%) was related to the aerial biomass DM (t ha^{-1}) according to the general equation:

$$N_t = a\mathrm{DM}^{-b}$$

a and b are constants, which were estimated using the NLIN procedure of SAS.

3. Results

3.1. N balance

On average of 1991–1999 and all other treatments, wheat significantly took up more N in the grain and left less N in the system after harvest (residual N (Nres) = N supply − N uptake in the grain) (64 kg N ha^{-1}) than barley (96 kg N ha^{-1}) and OSR (92 kg N ha^{-1}) (Table 3). N leaching was lowest after barley under OSR and highest after OSR under winter wheat. Mean

Table 3
Annual N fertilization (kg N ha^{-1}), N uptake in the grain (kg N ha^{-1}), N leaching (kg N ha^{-1}) and N balance (kg N ha^{-1}) (mean of 1991–1999)

	N fertilization (kg N ha^{-1})	N uptake in the grain (kg N ha^{-1})	Residual N (kg N ha^{-1})	N leaching[a] (kg N ha^{-1})	N balance (kg N ha^{-1})
Crop					
Oilseed rape	183	91	92	68	24
Winter wheat	197	133	64	55	9
Winter barley	197	101	96	45	51
$LSD_{0.05}$		10.1	12.7	15.0	21.4
Slurry application					
None	115	98	17	36	−19
Autumn	199	108	91	58	33
Autumn + spring	263	122	141	71	70
$LSD_{0.05}$		2.9	3.0	3.0	4.4
Mineral N (kg N ha^{-1})					
0/0/0	80	67	13	41	-28
40/40/40	194	122	72	57	15
80/80/80	306	141	165	67	98
$LSD_{0.05}$		2.6	2.4	2.8	3.3
Slurry × mineral N					
No slurry, 0/0/0	0	48	−48	34	−82
Slurry in autumn, 0/0/0	86	61	25	40	−15
Slurry in autumn + spring, 0/0/0	149	90	59	48	11
No slurry, 40/40/40	116	107	9	35	-26
Slurry in autumn, 40/40/40	202	124	78	62	16
Slurry in autumn + spring, 40/40/40	265	134	131	75	56
No slurry, 80/80/80	228	139	89	40	49
Slurry in autumn, 80/80/80	312	140	172	73	99
Slurry in autumn + spring, 80/80/80	375	143	232	88	144
$LSD_{0.05}$		4.2	4.2	4.8	5.6

[a] In the subsequent leaching period, under the following crop.

annual N balance varied between +9 kg N ha^{-1} a^{-1} in wheat and +51 kg N ha^{-1} a^{-1} in barley.

Slurry application increased N uptake in the grain, but also Nres after harvest and N leaching (Table 3). Without slurry, N balance was negative, whereas two slurry applications led to a N surplus of 70 kg N ha^{-1} a^{-1}. Mineral N fertilization increased N uptake in the grain from 67 kg N ha^{-1} a^{-1} without mineral N up to 141 kg N ha^{-1} a^{-1}, if 240 kg N ha^{-1} were applied each year. The corresponding N balance ranged between −28 and +98 kg N ha^{-1} a^{-1}. The slurry and mineral N interaction revealed more pronounced effects of mineral N fertilization on N uptake in the grain compared to slurry application, whereas slurry led to higher N losses. Especially slurry applied in autumn and slurry in combination with high amounts of mineral N increased N leaching. However, compared with the unfertilized plots, the raising residual N up to 230 kg N ha^{-1} a^{-1} increased N leaching only by 2–23%.

Assuming that denitrification losses were small and similar in the different N treatments, the difference between residual N and N leaching remained in the plant–soil system. Summarized over 9 years, 740 kg N ha^{-1} were lost in the unfertilized treatment via grain and leaching. In contrast, the plots receiving 240 kg N ha^{-1} as mineral fertilizer plus 80 kg N ha^{-1} as slurry in autumn plus in spring each year accumulated 1300 kg N ha^{-1}, giving a difference of about 2000 kg N ha^{-1} between the two extreme treatments. The wide range of different N balances allowed to investigate the residual effects of the former N treatments on above-ground biomass, N uptake and N release during the growth period as well as on grain yield and N uptake in the grain.

3.2. Dry matter, N uptake, and N mineralization during the growth period

On average of the three experimental years, the former N treatments enhanced above-ground dry matter and total N uptake of wheat compared to the unfertilized control, varying at harvest between 945 and 1135 g DM m^{-2} and 72 and 93 kg N ha^{-1}, respectively (data not shown). Differences between the N treatments increased during the growth period, although being not significant ($P > 0.05$) in most cases. Soil mineral N content (SMN) in 0–30 cm varied between 10 and 20 kg N ha^{-1} without significant effects of the N applications in 1991–1999 (data not shown). Therefore, mineralization of soil N, calculated from total N uptake + SMN in 0–30 cm, followed a similar pattern as the total N uptake. At the beginning of spring growth, maximum difference was 10 kg N ha^{-1}. At harvest, N mineralization ranged from 92 kg N ha^{-1} in the unfertilized control and 120 kg N ha^{-1} in the treatment, which had received 80 kg N ha^{-1} as pig slurry in autumn plus in spring and 240 kg N ha^{-1} as mineral N fertilizer each year. Since the differences were not significant, we pass on the detailed presentation of the results. Additional analysis within the years revealed that soil N release

Table 4
Crop effects on total N uptake (kg N ha^{-1}) and N mineralization (total N uptake plus SMN in 0–30 cm) (kg N ha^{-1}) at the beginning of crop growth in spring and at harvest (2000–2002)

Crop	Beginning of spring growth		Harvest	
	Total N uptake (kg N ha^{-1})	N mineralization (kg N ha^{-1})	Total N uptake (kg N ha^{-1})	N mineralization (kg N ha^{-1})
Oilseed rape	63.0	77.2	101.9	121.6
Wheat	29.9	47.5	84.2	107.3
Barley	24.0	37.4	49.2	73.5
$LSD_{0.05}$	22.67	18.63	26.32	24.40

was intensified between the third decade of April and the first decade of May.

At the beginning of spring growth, OSR had accumulated significantly more N in the above-ground biomass than wheat and barley, due to its longer growth in autumn (Table 4). Until harvest, wheat took up 84 kg N ha^{-1} on average (+54 kg N ha^{-1}), whereas the corresponding values for OSR were 102 kg N ha^{-1} (+39 kg N ha^{-1}) and for barley 49 kg N ha^{-1} (+25 kg N ha^{-1}).

3.3. Changes in SMN (0–90 cm) and N leaching

In 2000/01 and 2001/02, soil mineral N content was measured directly after drilling, at the end of autumn growth, at the beginning of spring growth and after harvest in all three crops (Table 5). After drilling of OSR, N fertilization in 1991–1999 increased soil mineral N content regardless of its type. At the other sampling dates, OSR N uptake levelled the SMN. Under wheat and, in some cases, under barley, the former slurry application in autumn and in spring led to greater SMN values at both sampling dates in autumn. In spring and at harvest, however, no differences were observed due to the former N treatments, presumably because of N leaching during winter and crop N uptake.

Additional soil samples (0–30 cm) for SMN analysis were taken at two dates between harvest and drilling of the following crop. In general, SMN varied between 20 and 30 kg N ha^{-1} in the former N treatments, however, no clear trend could be observed (data not shown).

Average N leaching was only significantly affected by the former N fertilization after wheat under barley (Table 6). After OSR under wheat, larger N treatment effects occurred, however, they were not significant. Due to the higher autumn N uptake of OSR (Table 4), N leaching after barley under OSR remained at a low level.

3.4. Grain yield, yield components and N uptake

On average of all treatments, grain yield of wheat decreased from 692 g m^{-2} in 2000 to 687 g m^{-2} in 2001 and 357 g m^{-2} in 2002. Barley yields were 481, 462 and 207 g m^{-2}, and OSR 375, 350 and 176 g m^{-2}, respectively. N uptake in the grain and straw of wheat was reduced from 109 kg N ha^{-1} in 2000 to 76 kg N ha^{-1} in 2001 and 59 kg N ha^{-1} in 2002. Barley accumulated 69, 57 and 33 kg N ha^{-1} in the above-ground biomass, and OSR 120, 111 and 59 kg N ha^{-1}, respectively. Due to the exper-

Table 5
Soil mineral N content (SMN = NO_3^- + NH_4^+-N; kg N ha^{-1}) in 0–90 cm at four sampling dates under oilseed rape, wheat and barley (2000/2001 and 2001/2002)

	Sampling date			
	After drilling	End of autumn growth	Beginning of spring growth	After harvest
Oilseed rape				
No slurry, 0/0/0	44	22	19	25
No slurry, 80/80/80	51	24	19	25
Slurry in autumn + spring, 0/0/0	62	27	21	31
Slurry in autumn + spring, 80/80/80	61	32	19	33
$LSD_{0.05}$	4.0	n.s.	n.s.	n.s.
Wheat				
No slurry, 0/0/0	57	39	28	37
No slurry, 80/80/80	50	37	20	28
Slurry in autumn + spring, 0/0/0	78	60	34	23
Slurry in autumn + spring, 80/80/80	79	63	31	18
$LSD_{0.05}$	1.6	10.3	n.s.	n.s.
Barley				
No slurry, 0/0/0	60	31	19	27
No slurry, 80/80/80	47	27	16	23
Slurry in autumn + spring, 0/0/0	60	36	27	32
Slurry in autumn + spring, 80/80/80	77	42	21	44
$LSD_{0.05}$	n.s.	9.4	n.s.	n.s.

Table 6
Effect of slurry and mineral N fertilization in 1991–1999 on N leaching (kg N ha^{-1}) under different crops in the leaching periods 1999/2000–2001/2002

Application in 1991–1999	After winter barley, under oilseed rape	After oilseed rape, under winter wheat	After winter wheat, under winter barley
Slurry			
None	17	40	22
Autumn	22	45	30
Spring	20	44	23
Autumn + spring	25	54	35
$LSD_{0.05}$	n.s.	n.s.	6.9
Mineral N fertilizer			
0 kg N ha^{-1}	16	40	21
120 kg N ha^{-1}	23	48	25
240 kg N ha^{-1}	24	49	36
$LSD_{0.05}$	n.s.	n.s.	5.4

Table 7
Effect of former N treatments (slurry and mineral N fertilization in 1991–1999) on yield (g m^{-2}) and total annual N uptake (kg N ha^{-1}) of oilseed rape, winter wehat and winter barley at harvest without actual N fertilizers (mean of 2000–2002)

	Slurry application in 1991–1999					Mineral N fertilization (kg N ha^{-1}) in 1991–1999			
	None	Autumn	Spring	Autumn + spring	$LSD_{0.05}$	0/0/0	40/40/40	80/80/80	$LSD_{0.05}$
Grain yield (g DM m^{-2})									
Oilseed rape	256.2	281.2	312.5	345.3	44.00	267.3	291.8	337.7	52.85
Winter wheat	482.5	521.2	509.5	535.2	n.s.	485.6	502.3	548.4	40.95
Winter barley	349.4	381.6	404.3	397.9	32.50	364.5	377.5	407.9	26.27
Total N uptake (kg N ha^{-1})									
Oilseed rape	80.6	90.4	98.2	115.4	17.20	83.0	93.4	112.2	16.57
Winter wheat	74.6	82.7	80.9	86.4	7.72	74.7	80.8	88.0	7.77
Winter barley	46.6	54.1	54.5	56.1	5.20	50.1	51.5	56.9	3.44

imental design, no error estimates of the year effects within a single crop are possible.

The former slurry application significantly affected grain yield of barley and OSR (Table 7). Without slurry, grain yield of both crops was lowest. Spring applied slurry (alone or in combination with autumn slurry) increased grain yield more than autumn slurry. OSR yield effects could be attributed to the number of pods m^{-2} (data not shown). In wheat, similar yield effects, however, not significant, could be observed, mainly due to changes in the thousand grain weight (data not shown). In contrast to OSR and barley, spring slurry seemed to be less effective than autumn slurry. Compared to the plots without slurry, slurry, regardless of the application date, increased total N uptake at harvest (straw + grain) in cereals. In OSR, spring application led to a higher N uptake.

Annual mineral N fertilization of 240 kg N ha^{-1} a^{-1} in 1991–1999 significantly increased grain yield of all three crops in 2000–2002, due to a greater ear density in cereals and a greater pod density in OSR. In consequence, total N uptake in these treatments was higher ($P < 0.05$) than in the unfertilized control.

In wheat, average total N uptake varied between 72 kg N ha^{-1} a^{-1} in the unfertilized plots and 93 kg N ha^{-1} a^{-1} in the plots receiving slurry in autumn and in spring plus 240 kg mineral N ha^{-1} each year. Accumulated over the experimental period of 3 years, the former N treatments (no slurry, 0 kg mineral N ha^{-1} versus slurry in autumn and in spring, 240 kg mineral N ha^{-1}) caused a difference in N uptake of 65 kg N ha^{-1}.

Decreasing N uptake in all three crops during the experimental period could principally be attributed to a smaller N mineralization and/or to unfavourable growth conditions like drought stress or radiation shortage. On average of all crops and all treat-

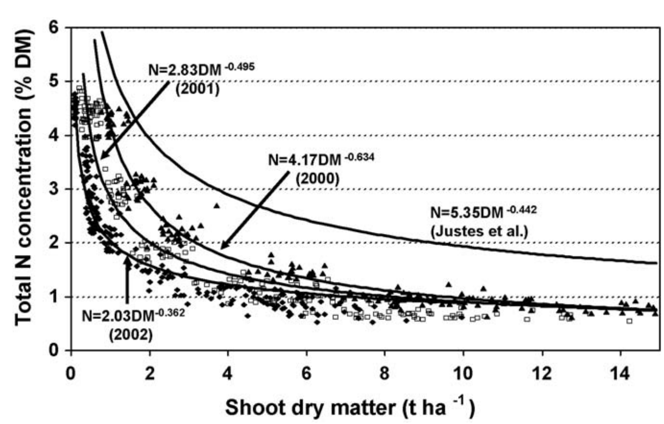

Fig. 1. Critical N dilution curve of wheat in 2000 (▲), 2001 (□) and 2002 (♦). The curve published by Justes et al. (1994) represents optimal growth conditions (2000: $r^2 = 0.98$, $P < 0.0001$; 2001: $r^2 = 0.97$, $P < 0.0001$; 2002: $r^2 = 0.98$, $P < 0.0001$).

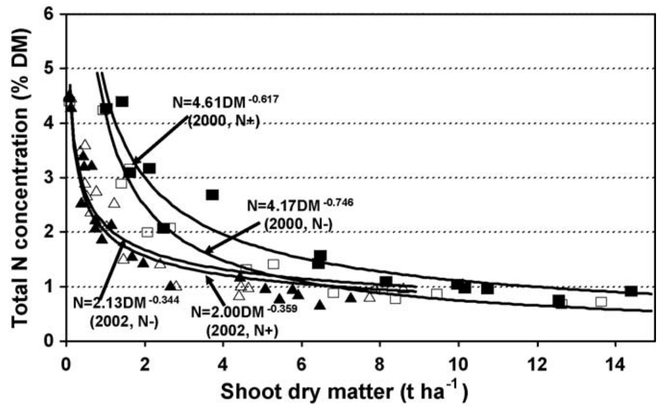

Fig. 2. Critical N dilution curve of wheat in 2000 (□) and 2002 (△). Open symbols represent the former unfertilized treatment (N−); solid symbols represent the treatment with slurry in autumn and in spring plus 240 kg mineral N ha^{-1} (N+) in 1991–1999 (2000, N−: $r^2 = 0.99$, $P < 0.0001$; 2000, N+: $r^2 = 0.98$, $P < 0.0001$; 2002, N−: $r^2 = 0.98$, $P < 0.0001$; 2002, N+: $r^2 = 0.98$, $P < 0.0001$).

ments, total N uptake at harvest decreased from 99 kg N ha^{-1} in 2000 to 80 kg N ha^{-1} in 2001 and 51 kg N ha^{-1} in 2002, respectively ($LSD_{0.05} = 21.3$). In addition, critical N curves in the 3 years were estimated exemplary for wheat. The lower level of the N dilution curve (Fig. 1) indicated a smaller N mineralization. The lower level of the curves compared with that published by Justes et al. (1994) represented optimal growth shows that the wheat crop suffered in all years from N shortage. In the first year (2000), the curves of the two extreme N treatments (no N fertilizers versus 80 kg N ha^{-1} as pig slurry in autumn and in spring plus 240 kg N ha^{-1} each year) differed clearly, whereas in the third year (2002) they were similar (Fig. 2).

4. Discussion

The presented work mainly focussed on the N dynamics after 9 years of highly different fertilization. According to the simple N balance after 9 years, the unfertilized plots lost about 740 kg N ha^{-1}, whereas the plots fertilized with two slurry applications plus 240 kg mineral N ha^{-1} each year accumulated about 1300 kg N ha^{-1}, of which >800 kg N ha^{-1} were due to the slurry application alone. Detailed analysis made by Brase (2003) revealed a significant correlation between the N balance and the measured N accumulation indicating that the N surplus was mostly (∼74%) retained in the soil and changed total soil N content accordingly to the differences in the simple N balance. However, the slope of the curve indicated that considerable quantities were not accounted for (270 kg N ha^{-1}, if the measured N_t changes were 1000 kg N ha^{-1}). Denitrification was not taken into account in the N balance. Especially in the (autumn) slurry treatments, higher N losses via denitrification might have been occurred, since slurry provided also a C-source for the soil microorganisms (Petersen, 1999; Kaiser and Ruser, 2000; Rochette et al., 2000). However, since under arable land annual denitrification losses were usually about 2–10 kg N ha^{-1}, other reasons than denitrification must be considered.

N leaching included in the N balance was estimated using suction cups at 90 cm depth to determine nitrate-N concentration in the soil water. The drainage volume was estimated from daily meteorological observations and evapotranspiration equations. It was assumed that after the soil water content has reached field capacity in autumn, daily drainage equalled rainfall less the evapotranspiration. Goulding and Webster (1992) and Webster et al. (1993) compared different methods for measuring the leaching of mineral nitrogen from arable land. They conclude that estimates of N losses using lysimeters and ceramic suction cups were in good agreement. Since in lysimeters the drainage volume can be measured directly it must be calculated from meteorological observations if suction cups are used. This provides that return to field capacity will be correctly identified in the field soil, which was done in our experiment by tensiometers. This date will differ between the plots depending on the soil conditions, cropping history, and N fertilization. In addition, preferential water flow as well as water movement through cracks may occur. However, it could be assumed that the differences between the treatments within one crop will not change fundamentally as detailed error estimations revealed (Sieling, 2000). The ceramic suction cups were installed at a depth of 90 cm. As winter wheat can use nitrogen down to 150 cm (Kuhlmann et al., 1989), one could argue that parts of the nitrogen subjected to leaching remained in the soil layer 90–150 cm and were taken up by wheat during the subsequent growth period. Because the N concentration of the soil water as well as the N leaching were greatest at the beginning of leaching period it might be that in the subsoil only little amounts of N were left.

Assuming a total N content in the soil of 5000 kg N ha^{-1} at the beginning of the experiment (Frey, 1998), total soil N content differed by 40% between the two extreme treatments as a result of the former N fertilization. Accumulated over three following years after fertilization, a surplus of 2000 kg N ha^{-1} caused a difference in total N uptake at harvest of 77 kg N ha^{-1} on average for all three crops. Total N uptake differed significantly between the crops ranging from 49 kg N ha^{-1} for barley to 102 kg N ha^{-1} for OSR (Table 4). On average, 61 kg N ha^{-1} (44–72 kg N ha^{-1}) were taken up in the grain and left the system. Therefore, the crops used 3% of the N surplus within the first three years without N fertilization, i.e. 1% per year. Slightly higher values were observed in OSR (1.2%), presumably due to its larger N uptake in autumn, and wheat (1.1%), whereas barley showed only a reduced N use of 0.7% per year. Under the climatic conditions of NW Europe, 1–2% of the total soil N is mineralized each year on average. Since N of recently incorporated organic matter is supposed to be released more quickly than the old humus fraction (Shen et al., 1989), a larger rate of mineralized N was expected when the experiment started.

In the first growth period without N fertilization (2000), N mineralization was highest and the wheat N dilution curves of the two extreme N treatments (no N fertilizers versus 80 kg N ha^{-1} as pig slurry in autumn and in spring plus 240 kg N ha^{-1} each year) differed clearly. N release decreased in the following years as indicated by the lower level of the N dilution curve (Fig. 1). The lower level of the curves compared with that published by Justes et al. (1994) which represented optimal growth demonstrated that the wheat crop suffered from N shortage in all years.

In the third year, no significant effects of the former N treatments on wheat growth could be observed (Fig. 2).

In the experiment presented here, both slurry and mineral N fertilizers led to similar N release and yield effects, which is in contrast to other experiments (e.g. at Rothamsted, GB), where large differences between the residual effects of organic and mineral N fertilizer were found (Glendining and Powlson, 1995; Glendining et al., 1996; Jenkinson et al., 1994). This may be due to the relatively short accumulation period of 9 years. On the other hand, pig slurry was used as organic fertilizer whose N content consists of 70–75% NH_4-N. The ammonium fraction can be assumed to be as effective as mineral N fertilizer (Sieling, 2000), resulting in a smaller amount of N remaining in the system compared to farmyard manure. Sørensen and Amato (2002) observed that more N was immobilized after slurry incorporation than after mineral N fertilizer application, but the remineralization rate in the following years was nearly similar for fertilizer- and slurry-derived N. From their results, they concluded a relatively low contribution of immobilized N to the residual N effect of pig slurry.

Changes in the N mineralization affected significantly the thousand grain weight of wheat and the number of pod m^{-2} of OSR. Due to the climate conditions at this site (slow soil temperature increase in spring), N release mainly occurred in May and June, when tillering was already completed. This is in good agreement with earlier results obtained by Teebken and Sieling (1995) at the same site.

5. Conclusion

Due to the former N treatments (slurry and mineral N fertilization in 1991–1999), simple N balances differed by 2000 kg N ha^{-1} accumulated over the experimental period. As a result, wheat dry matter and total N uptake were slightly increased during the following three growth periods without actual N supply. SMN in spring and at harvest remained unaffected. The former N treatments increased grain yield and N uptake in the grain of OSR, wheat and barley. The residual effects were highest in the first year (2000) and decreased with the years.

After 3 years without actual N fertilization (2000–2002), only 3% of N brought into the soil–plant system (61 kg N ha^{-1}) could be found in the N uptake in the grain of the crops. This low N use efficiency indicates that N incorporated into soil during the last 9 years was slowly released.

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