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Growth stage-specific application of slurry and mineral N to oilseed rape, wheat and barley

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SUMMARY

Farmers commonly apply slurry when soil conditions are suitable for spreading. In order to improve slurry nitrogen (N) use efficiency, effects of split application of pig slurry according to the crop N demand on yield were tested in 1994/95–2001/02. The crop rotation was winter oilseed rape (OSR) – winter wheat – winter barley. N was applied as pig slurry or as mineral N fertilizer (each of 0, 40 or 80 kg N/ha, total N amount: 0–240 kg N/ha) at three dates. Each year, the treatments occurred in all three crops of the rotation and were located on the same plots. On average, mineral N fertilizer led to higher grain yields in all crops (+0·33 t/ha in OSR, +0·57 t/ha in wheat, and +0·20 t/ha in barley) compared with slurry application, presumably due to a slower N mineralization of the organic fraction. However, the large year to year variation resulted in high error estimates, leading to no significant differences in yield. Taking only the ammonium amount of the slurry into account, there was no significant difference in yield between the two N sources. Yield potential was similar in both slurry and mineral N treatments, but higher N amounts were necessary on the slurry plots. Therefore, slurry N-use efficiency (NUE) remained lower than that of mineral N. However, compared with a single dose, growth-specific slurry application according to the crop demand, as made with mineral N fertilizers, increased NUE.

INTRODUCTION

Nitrogen (N) fertilizers allow farmers in modern farming systems to influence plant growth and to improve the site- and year-specific yield level, giving large economic gains (Jenkinson 2001). However, N losses due to inadequate N supply can damage the environment and reduce the profit margin of the farmers. In order to use N as efficiently as possible, total N amount is split and applied at several dates to meet the needs of the crop more precisely. On the loamy soils in NW Germany, for example, at least three N applications to winter cereals (start of spring growth, stem elongation and ear emergence) are common.

During the growth period, N-use efficiency (NUE) can vary considerably. N applied in spring to a growing crop is used more efficiently than N applied in autumn (Hayward *et al.* 1993; Jackson & Smith 1997). In spring, NUE of winter wheat generally increases in the order: start of spring growth < stem elongation < ear emergence, if water supply does not limit yield performance and the uptake of N at later growth stages (Recous *et al.* 1988; Destain *et al.* 1993; Retzer 1995). Recous & Machet (1999) suggested large gaseous N losses cause a reduced NUE after early N application, because N immobilization depended on the availability of organic carbon being constant over the growth period. Results from Limaux *et al.* (1999) suggest that crop N demand at the time of N application determines the ability of the crop to compete for N with other processes, and may be a major factor determining the division of N between crop and soil.

However, growth stage-specific N fertilization is usually made only with mineral N fertilizers. In contrast, organic manures are mostly applied when soil and weather conditions are suitable for spreading, but not when a crop can take up the nutrients. In consequence, NUE of slurry remains small, and the potential of nitrate leaching increases (Sieling *et al.* 1998*a*, *b*; Nicholson *et al.* 1999). In addition, the availability of slurry N to plants is lower than that of mineral fertilizer N, because only *c.* 0·5

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Table 1. *Rainfall (mm) in the growing seasons 1994/95–2001/02 and the long-term average (Deutscher Wetterdienst, Station Kiel-Holtenau)*

	Growing season								Long-term mean
	1994/95	1995/96	1996/97	1997/98	1998/99	1999/2000	2000/01	2001/02	
Aug	143	24	48	34	52	83	43	90	71
Sept	121	82	66	39	38	53	63	144	64
Oct	69	23	60	83	167	47	81	38	73
Nov	53	22	129	37	74	27	35	74	64
Dec	117	20	38	63	63	171	46	67	74
Jan	125	1	3	110	74	62	35	80	61
Feb	71	28	86	29	53	70	42	115	37
Mar	69	8	57	65	77	80	48	44	47
Apr	41	24	25	96	27	34	70	45	49
May	69	54	81	66	48	33	45	40	53
June	71	27	73	98	62	48	64	85	65
July	63	39	104	129	78	44	87	222	88
Total	1012	352	770	849	813	752	659	1044	754

(cattle slurry) or *c.* 0·75 (pig slurry) of the total N is ammonium N (NH_4-N) thought to be as effective as mineral N. According to Thomsen *et al.* (1997), urine N was available to a larger extent than faeces N. Sørensen & Amato (2002) attributed the lower NUE of pig slurry partly to the immobilization of NH_4-H during microbial decomposition of organic matter in the slurry soon after application to the soil. However, taking only the NH_4 amount into account, Petersen (1996) observed a similar NUE of both slurry and mineral N if applied to spring barley before sowing. In a laboratory experiment using slurry labelled with ^{15}N-ammonium, Chadwick *et al.* (2001) and Pahl *et al.* (2001) showed the advantages of injection of pig slurry compared with surface application. Plant uptake of N was increased and N losses from the soil–plant system were reduced.

Each year, large amounts of slurry are produced which should be utilized efficiently in the crop production. The hypothesis of the current project was that fertilizing oil seed rape (OSR), wheat and barley with pig slurry at the same time as mineral N fertilizers are applied, e.g. split application according to the need of the crop, results in similar grain yields. In addition, yield performance and NUE of winter wheat are presented.

MATERIALS AND METHODS

Site and soil

The experiment presented was established in autumn 1994 on a pseudogleyic sandy loam (Luvisol) at the Hohenschulen Experimental Farm of the University of Kiel, located in NW Germany *c.* 15 km west of Kiel (Schleswig–Holstein). 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 mm annually at the experimental site, with *c.* 400 mm occurring during April–September, the main growing season, and *c.* 350 mm during October–March (Tables 1 and 2).

Treatments and design

The experiment was based on the crop rotation winter oilseed rape (OSR; cv. Express) – winter wheat (cv. Pepital) – winter barley (cv. Cita). The following factors and factor levels were tested in each crop:

1. N type: 1 – organic N as pig slurry
   2 – mineral N as calcium ammonium nitrate (CAN) with 270 g N/kg.
2. N treatment: 3 splits, each of 0, 40 or 80 kg N/ha (total of 27 treatments).

Practical constraints required the field trial design to be a split-plot design with one level of splitting. The N types were main plots; the N treatments were subplots split within main plots. Subplot size was 12 × 3 m. In year one of the trial, each of the three crops of the rotation, OSR, winter wheat and winter barley, were grown separately on three main plots. Each main plot was then used for a complete rotation of the three crops with the rotation on any particular main plot beginning at the point in the rotation cycle corresponding to the initial main plot crop. Each crop was grown in each year. The same treatment regimes were applied to the same subplots in each year so that the cumulative effects of each treatment were balanced both for years and for previous crops.

N fertilizers were applied at the beginning of spring growth (N1), at the beginning of stem elongation (N2) and at ear emergence of cereals (N3) or bud formation of OSR (N3). At each date, 0, 40 or

Table 2. *Mean air temperature (°C) in the growing seasons 1994/95–2001/02 and the long-term average (Deutscher Wetterdienst, Station Kiel-Holtenau)*

	Growing season								Long-term mean
	1994/95	1995/96	1996/97	1997/98	1998/99	1999/2000	2000/01	2001/02	
Aug	17·3	18·6	18·1	21·1	15·5	16·8	16·0	17·8	16·3
Sept	13·1	13·7	12·5	13·2	13·7	17·1	13·8	12·7	13·3
Oct	7·8	11·7	9·6	8·1	8·8	9·5	11·1	12·8	9·4
Nov	7·0	4·0	4·7	4·2	2·4	5·3	7·3	5·2	5·0
Dec	4·2	−1·9	−0·4	2·9	1·3	2·7	4·1	0·7	2·5
Jan	1·1	−2·3	−1·4	3·5	3·2	3·0	1·5	3·3	0·7
Feb	4·6	−2·7	4·2	5·4	1·2	4·3	1·7	5·0	1·0
Mar	3·3	−0·1	4·5	5·0	5·0	4·6	2·5	5·0	3·3
Apr	6·8	7·5	6·1	7·8	8·2	9·2	6·5	7·6	6·7
May	10·8	9·5	10·4	12·4	12·0	13·2	12·1	13·1	11·5
June	14·0	14·1	15·4	15·0	14·2	15·1	13·5	16·4	15·1
July	18·4	15·4	17·7	15·1	18·1	15·2	18·0	17·6	16·3
Mean	9·0	7·3	8·5	9·5	8·6	9·6	9·2	9·9	8·4

80 kg N/ha were applied, resulting in 27 N treatments across the crops with total N amounts of 0–240 kg N/ha.

Pig slurry was applied using a slurry spreader with drag hoses, modified for use in the field trials. During the application, subsamples were taken and later analysed photometrically for ammonium N concentration and for total N concentration (Mulvaney 1996), revealing an average total N concentration of 3·97 (±0·75) kg N/m^3 (dry matter: 0·383 (±0·137) g/kg). Of the total N, 0·74 (±0·081) was NH_4-N. Gaseous losses during application and atmospheric N input were not taken into account.

Crop management not involving the treatments (e.g. seed date, P and K fertilization, application of pesticides) was the same in all plots and according to standard farm practice. Straw remained on the plots. All plots were ploughed before plant establishment. Sowing date was aimed at the last decade in August and September for OSR (50–60 seeds/m^2) and cereals (250–300 kernels/m^2), respectively. Barley and OSR were harvested at the end of July, wheat at the beginning of August. All crops received 35 kg P/ha each year. Annual K fertilization was 130 kg K/ha in OSR and 100 kg K/ha in cereals.

After ear emergence of barley and wheat, the number of ears/m^2 was counted. At harvest, an area of 9 m^2 was harvested by combine and yield was standardized to t/ha at 0·86 proportional dry matter (wheat and barley) or 0·91 proportional dry matter (OSR) based on the moisture content of a grain or seed subsample. Number of grains/ear was calculated from grain yield, ear density and mean grain weight. In 1997–2002, N uptake of wheat with the grain was obtained by multiplying the total dry matter by the N concentration of the combine-harvested grain, which was measured by NIRS (near-infrared-spectroscopy). Due to unfavourable weather conditions in autumn 2001 with >200 mm rain in September, no barley was drilled in that year.

Apparent N-use efficiency (NUE) of wheat was calculated for both N types and at each N application separately using the difference method, which compares the N uptake of a fertilized plot with the N uptake of the corresponding unfertilized plot in relation to the amount of applied N. The difference method requires a same soil N mineralization in both fertilized and unfertilized plots.

Slurry NUE was calculated on the base of the total slurry N concentration (not only the NH_4-H), because the organic N will be released sooner or later and, therefore, must be considered when discussing the ecological impact of slurry application.

Statistical analysis

Analyses of variance were performed separately for each crop, using the GLM procedure of the SAS statistical package (SAS Institute 1999). The year was used as blocking factor. Standard errors for N type are based on year × N type interactions; those for N treatments are based on year × N type × N treatment interactions. The standard errors apply only to individual treatment means.

For each crop and each N type, two models for the N response curves were fitted to the crop data:

$$Y = a + bN_T + cN_T^2 \qquad (1)$$

$$Y = a + bN1 + cN2 + dN3 + eN1^2 + fN2^2 + gN3^2 + hN1N2 + iN1N3 + jN2N3 \qquad (2)$$

Table 3. *Estimates of parameters in Eqn 1 relating grain yield (t/ha) of winter wheat, winter barley and winter oilseed rape to applied total N amount (kg N/ha). Standard errors of the estimates are shown in parentheses*

	Winter wheat		Winter barley		Winter oilseed rape	
Parameter	Slurry	Mineral N	Slurry	Mineral N	Slurry	Mineral N
a: Intercept	4·67 (0·253)	4·19 (0·244)	4·17 (0·325)	4·00 (0·3444)	1·84 (0·164)	1·84 (0·162)
b: Total N_T	0·033 (0·0044)	0·053 (0·0042)	0·033 (0·0056)	0·040 (0·0059)	0·010 (0·0028)	0·017 (0·0028)
c: (Total N_T)^2	−0·00005 ($1{\cdot}7 \times 10^{-5}$)	−0·00013 ($1{\cdot}6 \times 10^{-5}$)	−0·00006 ($2{\cdot}2 \times 10^{-5}$)	−0·00009 ($2{\cdot}3 \times 10^{-5}$)	−0·00001 ($1{\cdot}1 \times 10^{-5}$)	−0·00004 ($1{\cdot}1 \times 10^{-5}$)
RMSE	1·01	0·97	1·21	1·28	0·64	0·65
R^2	0·57	0·66	0·45	0·44	0·35	0·36

RMSE = root mean squared error of model; R^2 = multiple regression coefficient.

Table 4. *Estimates of parameters in Eqn 2 relating grain yield (t/ha) of winter wheat to N amount (kg N/ha) applied at different times. Standard errors of the estimates are shown in parentheses*

	N type	
Parameter	Slurry	Mineral N
a: Intercept	4·64 (0·242)	4·17 (0·216)
b: N1 rate	0·048 (0·0080)	0·068 (0·0071)
c: N2 rate	0·039 (0·0080)	0·066 (0·0071)
d: N3 rate	0·019 (0·0080)	0·033 (0·0071)
e: N1^2	−0·00019 ($8{\cdot}6 \times 10^{-5}$)	−0·00022 ($7{\cdot}7 \times 10^{-5}$)
f: N2^2	−0·00007 ($8{\cdot}6 \times 10^{-5}$)	−0·00019 ($7{\cdot}7 \times 10^{-5}$)
g: N3^2	−0·00001 ($8{\cdot}6 \times 10^{-5}$)	−0·00012 ($7{\cdot}7 \times 10^{-5}$)
h: N1×N2	−0·00017 ($6{\cdot}1 \times 10^{-5}$)	−0·00050 ($5{\cdot}4 \times 10^{-5}$)
i: N1×N3	−0·00007 ($6{\cdot}1 \times 10^{-5}$)	−0·00013 ($5{\cdot}4 \times 10^{-5}$)
j: N2×N3	−0·00006 ($6{\cdot}1 \times 10^{-5}$)	−0·00013 ($5{\cdot}4 \times 10^{-5}$)
RMSE	0·96	0·86
R^2	0·62	0·74

RMSE = root mean squared error of model; R^2 = multiple regression coefficient.

where Y is the grain yield (t/ha), and N_T the total amount of N fertilizer applied (kg N/ha). N1, N2 and N3 are the amounts of N fertilizer applied at different growth stages. a, b, c, d, e, f, g, h, i and j are constants. The constants in these equations were estimated using the REG procedure of SAS, Release 8.02. The estimates of parameters are shown in Tables 3 and 4.

RESULTS

On average for the years 1995–2002, mineral N fertilizer outyielded slurry application by 0·33 t/ha in OSR, 0·57 t/ha in wheat, and 0·20 t/ha in barley (Table 5). However, the large year to year variation resulted in high error estimates, leading to no significant differences in yield. In some years, slurry application led to similar yields as mineral N. In wheat and barley, N type mainly affected the number of ears/m^2, whereas the number of grains/ear and the mean grain weight showed no significant differences ($P > 0{\cdot}05$) (Table 6). In addition, mineral N fertilization resulted in significantly higher grain N concentration and N uptake by the grain of wheat and barley compared with slurry application (Table 6).

The slurry N response curve in OSR had a linear increase of *c.* 0·01 t/kg N within the range of N amounts tested in this trial (Fig. 1). In contrast, mineral N fertilizer increased seed yield more than slurry N with a maximum yield response to a N rate of approximately 220 kg N/ha. The differences were largest at 120 kg N/ha. In wheat, the slope of the mineral N response curve was higher than that of the slurry treatment, so that mineral N fertilizer led to higher yields in most of the N rates tested (Fig. 2). Only small differences between both N types occurred in barley (Fig. 3). In all three crops, yield potential seemed to be similar with both N fertilizers, but N amounts needed to achieve the maximum were higher in the slurry than in the mineral N treatments.

In the previous paragraph, the effects of the total N amount have been considered. Figs 4 and 5 show the interaction between N1 and N2 application for slurry and mineral N fertilization in wheat (N3 = 80 kg N/ha). If applied as slurry, both applications at N1 and N2 independently increased grain yield. Maximum yield was achieved when 80 kg N/ha were given at both dates. In the mineral N treatment, yield increase due to N1 depended on the amount of N2 and vice versa. Yield effect of N1 was highest if no nitrogen was applied at the beginning of stem elongation (N2 = 0 kg N/ha), and lowest if N2 was 80 kg N/ha. Yield maximum in both N types differed only by 0·2 t/ha. Effects of the different N application times on barley and OSR yield were less pronounced (data not shown).

In order to obain information about the yield potential, yield maxima were estimated from the N

Table 5. *Effect of the fertilizer N type on the yield (t/ha at 0·91 and 0·86 proportional dry matter for OSR and cereals, respectively) of oilseed rape, wheat and barley in 1995–2002*

	Oilseed rape		Wheat		Barley	
Year*	Slurry N	Mineral N	Slurry N	Mineral N	Slurry N	Mineral N
1995	3·30	3·69	6·54	7·74	6·15	6·64
1996	3·44	3·74	8·98	9·16	6·91	6·70
1997	2·86	2·73	7·79	8·61	7·57	7·92
1998	3·38	3·24	7·83	7·34	6·67	6·26
1999	2·82	3·25	7·50	8·34	5·78	6·53
2000	1·99	2·83	8·05	8·95	8·24	8·13
2001	2·99	3·70	7·98	8·20	8·20	8·73
2002	2·24	2·68	6·85	7·76	–	–
Mean	2·90	3·23	7·69	8·26	7·07	7·27
S.E. (D.F.)	0·088 (7)		0·139 (7)		0·116 (6)	

* No error estimate is possible.

Table 6. *Effect of the fertilizer N type on the yield components grain N concentration* (g/kg) and N uptake by the grain* (kg N/ha) of wheat and barley (1995–2001)*

	Slurry N	Mineral N	S.E. (D.F.)
Wheat			
Grain yield (t/ha)	7·81	8·33	0·156 (6)
Grain N concentration (g/kg)	15·4	17·4	0·18 (6)
N uptake (kg N/ha)	102	124	3·3 (6)
Ears/m^2	507	544	5·9 (6)
Grains per ear	32·1	32·2	0·09 (6)
Mean grain weight (mg)	49·6	49·3	0·30 (6)
Barley			
Grain yield (t/ha)	7·07	7·27	0·116 (6)
Grain N concentration (g/kg)	15·4	17·3	0·19 (6)
N uptake (kg N/ha)	98	113	3·0 (5)
Ears/m^2	498	525	11·0 (6)
Grains per ear	31·2	31·0	0·08 (6)
Mean grain weight (mg)	46·3	45·9	0·27 (6)

* Grain N concentration and N uptake were determined in 1997–2002 in wheat and in 1997–2001 in barley.

response curves (Eqn 1) separately for each N type, each crop and each year. Total N applied was limited to 240 kg N/ha in this trial. Yield maxima (Y_{max}) of the three crops varied considerably between years, especially those of barley and OSR (Table 7). However, differences between both N types remained small and no clear trend occurred. The corresponding N amounts (N_{max}) were larger in the slurry N treatment compared with mineral N application. Also at a lower N level of 120 kg N/ha, both N types showed a similar behaviour in all crops (data not shown).

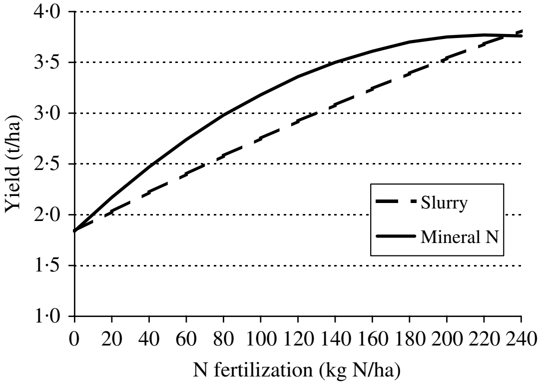

Fig. 1. Effect of increasing slurry and mineral N fertilization on seed yield (t/ha) of oilseed rape in 1995–2002.

Additionally, yield of the unfertilized plots are presented to identify possible N exhaustion. OSR yield significantly ($P<0·001$) decreased within the running period of the trial, whereas wheat and barley yields showed no clear trend ($P>0·05$). Therefore, apparent N-use efficiency (NUE) can be estimated in wheat using the difference method.

On average, wheat used the N application at ear emergence (N3) more efficiently than that at the beginning of spring growth (N1) or at stem elongation (N2) (Table 8). At all application dates, NUE of mineral fertilizer (0·52–0·70) was significantly higher compared with slurry (0·38–0·45) ($P<0·05$). At the first application date, increasing N amount reduced NUE regardless of the N type.

DISCUSSION

Between 1995 and 2002, the effects of a growth stage-specific application of pig slurry and mineral N to

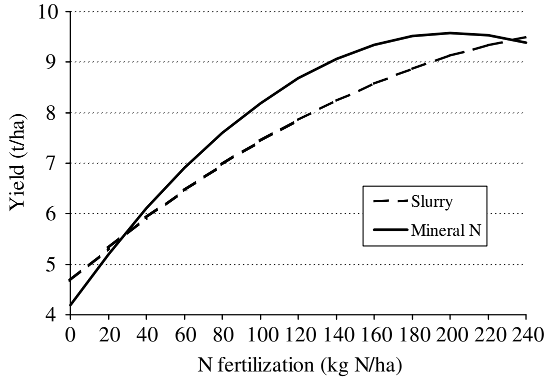

Fig. 2. Effect of increasing slurry and mineral N fertilization on grain yield (t/ha) of winter wheat in 1995–2002.

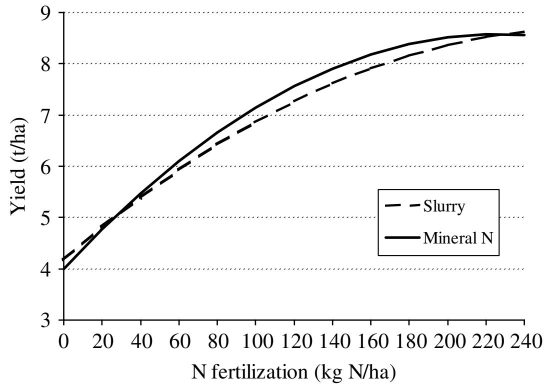

Fig. 3. Effect of increasing slurry and mineral N fertilization on grain yield (t/ha) of winter barley in 1995–2001.

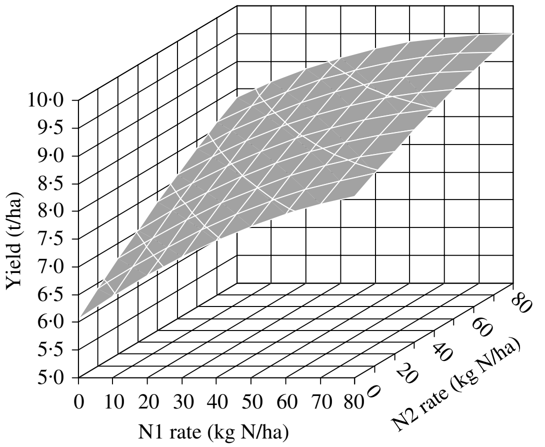

Fig. 4. Effect of the first and second slurry N application on grain yield (t/ha) of winter wheat in 1995–2002.

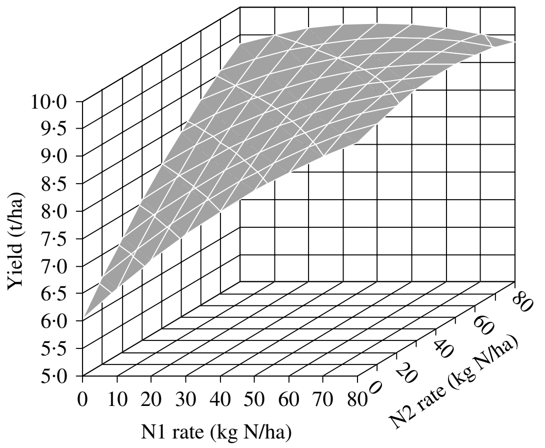

Fig. 5. Effect of the first and second mineral N application on grain yield (t/ha) of winter wheat in 1995–2002.

OSR, wheat and barley were tested in a field trial. On average, mineral N fertilization resulted in significantly higher grain yields in wheat (+7%) and OSR (+10%) than slurry N ($P<0{\cdot}05$), whereas the difference was less pronounced in barley (+3%). In addition, slurry N response curves increased in wheat and OSR to a smaller extent compared with those of mineral N fertilizer (Figs 1 and 2). However, slurry amount applied was calculated on the basis of total N concentration, including 0·25–0·30 proportional organic N mainly derived from faeces. Since organically bound N has to be mineralized before plant uptake, availability is less than that of NH$_4$-N (Thomsen *et al.* 1997; Jensen *et al.* 1999). The experiments of Chadwick *et al.* (2000) suggested only 0·27 proportion of the organic N fraction of pig slurry being available for the crop within 6 months.

Against this background, yield differences between the two N types are surprisingly small. Taking the lower plant availability of slurry N into account resulted in similar wheat and OSR grain yields in both N types over a broad range of N amounts (Figs 1 and 2: e.g. 160 kg/ha slurry N *v.* 120 kg/ha mineral N). This finding is in good agreement with results of other experiments (e.g. Petersen 1996; Thomsen *et al.* 1997; Sieling *et al.* 1998*a*, *b*).

Slurry application led to a lower number of ears/m^2 in wheat ($P<0{\cdot}05$) and in barley ($P<0{\cdot}10$), whereas both the number of grains/ear and the mean grain weight remained unaffected (Table 6). Pommer & Fink (1989) also observed a reduced ear density after slurry application. Together with the nearly linear increase of the slurry N response curve for the splitting doses N1 and N2 in wheat (Fig. 4) and for OSR (Fig. 1), it can be assumed that N availability was restricted in the slurry treatments. Under the weather

Table 7. *Measured grain yield without N fertilization* (Y_0, *t/ha at 0·91 and 0·86 proportional dry matter for OSR and cereals, respectively*), *predicted maximum grain yield* (Y_{max}, *t/ha at 0·91 and 0·86 proportional dry matter for OSR and cereals, respectively*) *and corresponding N amount* (N_{max}, *kg N/ha*) *of oilseed rape, wheat and barley calculated from Eqn 1 in 1995–2002. Standard errors of the predicted yield are shown in parentheses*

		Slurry N		Mineral N	
Year	Y_0 (t/ha)	N_{max}* (kg N/ha)	Y_{max} (t/ha)	N_{max} (kg N/ha)	Y_{max} (t/ha)
Oilseed rape					
1995	3·14	240	4·07 (0·189)	240	4·08 (0·286)
1996	2·16	240	4·12 (0·162)	175	4·11 (0·352)
1997	1·85	240	4·13 (0·190)	206	3·19 (0·238)
1998	2·21	211	3·80 (0·095)	182	3·62 (0·216)
1999	1·23	240	4·71 (0·336)	240	4·00 (0·571)
2000	1·55	240	2·55 (0·480)	240	3·93 (0·431)
2001	1·27	240	4·16 (0·285)	205	4·57 (0·104)
2002	1·69	240	2·79 (0·146)	220	3·15 (0·186)
Wheat					
1995	4·20	235	7·50 (0·485)	240	9·71 (0·588)
1996	5·90	181	9·81 (0·466)	163	10·00 (0·469)
1997	4·92	240	10·42 (0·592)	226	10·35 (0·510)
1998	4·33	240	10·45 (0·489)	233	9·02 (0·664)
1999	4·39	240	9·82 (0·456)	226	9·94 (0·481)
2000	5·43	231	9·39 (0·601)	212	10·37 (0·436)
2001	4·27	240	10·30 (0·521)	152	9·13 (0·560)
2002	3·81	240	8·73 (0·330)	230	9·47 (0·512)
Barley					
1995	3·77	240	8·40 (0·410)	240	8·32 (0·783)
1996	3·18	240	9·06 (0·469)	202	7·82 (0·587)
1997	3·87	214	9·20 (0·413)	236	9·30 (0·811)
1998	4·29	240	7·68 (0·459)	191	6·95 (0·194)
1999	2·46	240	8·10 (0·738)	212	8·05 (0·244)
2000	5·36	202	8·97 (0·214)	240	9·70 (0·814)
2001	5·07	231	9·23 (0·502)	219	10·19 (0·332)

* N_{max} was limited to 240 kg N/ha as maximum.

conditions of NW Germany, considerable N net mineralization normally occurs at the end of April and beginning of May (Teebken & Sieling 1995). Due to the slow increase of soil temperature, mineralization of faeces N was reduced which might otherwise have compensated for the lower availability of urine N providing a similar crop N uptake in manured plots compared with mineral fertilized ones (Thomsen *et al.* 1997). Since most tillering in barley took place in autumn, N supply in early spring was not so important as for wheat or OSR, and therefore only small yield differences between slurry and mineral N fertilization occurred.

Table 8. *Slurry and mineral N use efficiency of wheat in the different N treatments* (*mean of 1996/97–2001/02*)

	N type			
	Slurry N	Mineral N	Mean	S.E. (D.F.)
N1 amount (kg N/ha)				
0	–	–	–	
40	0·446	0·552	0·499	0·0164 (5)
80	0·412	0·482	0·447	
Mean	0·429	0·517		
S.E. (D.F.)	0·0291 (5)			
N2 amount (kg N/ha)				
0	–	–	–	
40	0·361	0·538	0·449	0·0156 (5)
80	0·379	0·523	0·451	
Mean	0·375	0·530		
S.E. (D.F.)	0·0341 (5)			
N3 amount (kg N/ha)				
0	–	–	–	
40	0·394	0·707	0·551	0·0073 (5)
80	0·495	0·684	0·589	
Mean	0·445	0·695		
S.E. (D.F.)	0·0256 (5)			

In wheat, unfertilized plots showed no yield trend over the years (Table 7). In addition, results of other trials at the same site showed that changes in the soil N release due to differences in the N input will take place to a greater extent only after 10 years (Sieling 2001), so that the difference method to calculate apparent NUE could be used (Table 8). At all three application dates, wheat utilized mineral N more efficiently than slurry N. One reason for the lower NUE of slurry could be NH_3 volatilization during application. However, Bless & Sattelmacher (1993) observed only small NH_3 losses (<10 kg N/ha) if drag hoses were used, so that it is assumed that NH_3 volatilization only partly accounted for the lower slurry NUE. In contrast to the yield effects, taking only the NH_4-N into account increases slurry NUE, but it remains lower than mineral NUE, except for the first application at the beginning of spring growth. However, compared with one single application sometime in spring, NUE was increased if slurry was applied according to the demand crop (Sieling *et al.* 1998*a*, *b*).

CONCLUSIONS

The results presented here clearly show that timely application of (pig) slurry could achieve similar grain yield compared with mineral N fertilizers (Table 7).

Growth-specific slurry application increases NUE and should result in a lower rate of N losses to the environment. However, higher N amounts are needed for the slurry-based N fertilization compared with mineral N, because of a lower N availability. This results in higher residual N amounts left in the system, with implications on leaching potential. Further investigations are needed to establish the long-term effects of continuous slurry application and to quantify the environmental impacts. For practical application, driving with heavy machines on wet soils remains problematic.

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