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Effects of ^{15}N Split-application on Soil and Fertiliser N Uptake of Barley, Oilseed Rape and Wheat in Different Cropping Systems

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With 1 figure and 11 tables

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Abstract

In intensive farming systems, farmers split up and apply the N fertilization to winter cereals and oilseed rape (OSR) at several dates to meet the need of the crop more precisely. Our objective was to determine how prior fertilizer N application as slurry and/or mineral N affects contributions of fertilizer- and soil-derived N to N uptake of barley (1997), oilseed rape (OSR; 1998) and wheat (1999). In addition, residual fertilizer N effects were observed in the subsequent crop. Since autumn 1991, slurry (none, slurry in autumn, in spring, in autumn plus in spring) and mineral N fertilizer (0, 12 and 24 g N m^{-2}) were applied annually. Each year, the treatments were located on the same plots. In 1997–1999, the splitting rates of the mineral N fertilization were labelled with ^{15}N. Non-fertilizer N uptake was estimated from the total N uptake and the fertilizer ^{15}N uptake. All three crops utilized the splitting rates differently depending on the time of application. Uptake of N derived from the first N rate applied at the beginning of spring growth was poorer than that from the second splitting rate applied at stem elongation (cereals) or third splitting rate applied at ear emergence or bud formation (all three crops). In contrast, N applied later in the growing season was taken up more quickly, resulting in higher fertilizer N-use efficiency. Mineral N fertilization of 24 g N m^{-2} increased significantly non-fertilizer N uptake of barley and OSR at most of the sampling dates during the growing season. In cereals, slurry changed the contribution of non-fertilizer N to the grain N content only if applied in spring, while OSR utilized more autumn slurry N. In OSR and wheat, only small residual effects occurred. The results indicate that 7 years of varying N fertilization did not change the contribution of soil N to crop N uptake.

Key words: ^{15}N labelled fertilizer — *Brassica napus* — *Hordeum vulgare* — N uptake — residual effects — soil N — *Triticum aestivum*

Introduction

In intensive farming systems, farmers split up and apply the N fertilization to winter cereals and oilseed rape (OSR) at several dates to meet the need of the crop more precisely leading to an increased fertilizer N-use efficiency (FNUE) and, in consequence, to reduce the impact on the environment (Retzer 1995, Sieling et al. 1998a,b).

In the literature, a lot of FNUE results are available for wheat ranging between 21 % and 87 % (e.g. Webster et al. 1986, Powlson et al. 1992, Sieling et al. 1998b, Raun et al. 1999). However, only a few investigations are dealing with FNUE of barley (31–84 %; Dowdell et al. 1984, Smith et al. 1988) or OSR (31–70 %; Chalmers and Darby 1992, Jensen et al. 1997, Macdonald et al. 1997, Sieling et al. 1998a). A short overview is given in Beims (2005).

During the growth period, fertilizer N uptake can vary considerably (Recous et al. 1988, Diekmann and Fischbeck 2005). If water supply is not limiting yield performance and N uptake at late growth stages, wheat utilizes generally spring applied N in the increasing order 'start of spring growth' < 'stem elongation' < 'ear emergence' (Recous et al. 1988, Destain et al. 1993, Retzer 1995). As N immobilization is depending on the availability of organic carbon, which may be assumed to be constant over the growth period, Recous and Machet (1999) suggested large gaseous N losses as the main cause for a reduced FNUE after early N application. Limaux et al. (1999) supposed that crop N demand at the time of N application determines the ability of the crop to compete for N with other processes as N microbial demand or gaseous losses and may be a major factor determining the division of N between crop and soil.

Fertilizer N additions continue to affect soil C and N dynamics after the crop is harvested, as only a portion of the added N is taken up by the plants. In general, greater N mineralization was found in previously fertilized plots compared to unfertilized plots, which may promote crop growth and support yield formation, but also leaching losses (Glendining et al. 1996).

The use of ^{15}N-labelled fertilizers also allows to quantify the residual effects in the subsequent crop. Several investigations showed that the subsequent crop recovered only a small proportion of the residual fertilizer N, varying between 3 % and 8 % (Thomsen and Christensen 1996, Glendining et al. 2001, Stevens et al. 2005). These results indicate a poor synchrony between the mineralization of ^{15}N-labelled organic matter and crop N uptake (Macdonald et al. 2002).

The objective of this paper was to quantify the effect of application time on the fertilizer N uptake by barley, OSR and wheat. In addition, the use of ^{15}N labelled fertilizers allows to investigate how different N fertilizer rates (slurry and/or mineral N) applied consistently from 1991 to 1996 would affect the interaction between N supply (slurry and/or mineral N fertilization) and soil N uptake. Furthermore, residual fertilizer effects in the subsequent crop are presented.

Materials and Methods

Site and soil

The trial was carried out on a pseudogleyic sandy loam (Luvisol: 170 g kg^{-1} clay, pH 6.7, 9 mg kg^{-1} P, 15 mg kg^{-1} K, 13 g kg^{-1} C_{org}, 1.13 g kg^{-1} N_{total}) at the Hohenschulen Experimental Farm (10.0°E, 54.3°N, 30 m a.s.l.) of the Kiel University, located in NW Germany 15 km west of Kiel (Schleswig–Holstein). The climate of NW Germany can be described as humid. Total rainfall averages 750 mm annually at the experimental site, with ca. 400 mm received during April–September, the main growing season and ca. 350 mm during October–March (Table 1).

Treatments and design

The field trial started in autumn 1991. Practical constraints required the design of the experiment to be a single-replicate split-split-plot design with two levels of splitting. The tillage treatments (minimum tillage, conventional tillage) were main plots, the slurry treatments (none, slurry in autumn, in spring, in autumn plus in spring) were sub-plots split within main plots and the mineral N fertilizer treatments (0, 12 and 24 g N m^{-2}) were sub-sub-plots split within sub-plots (Table 2). Each year, the treatments were located on the same plots. Winter barley (cv. Alpaca) following barley was grown in 1996/1997, winter oilseed rape (cv. Falcon) in 1997/1998 and winter wheat (cv. Orestis) in 1998/1999. The results presented here refer to the mean of minimum and conventional tillage.

In spring, mineral nitrogen fertilizer (calcium ammonium nitrate with 27 %N) was applied as a split-dressing at the beginning of spring growth, at the start of stem elongation and at ear emergence of cereals or at bud formation of OSR (except of the microplots). Pig slurry (each application was aimed at 8 g total N m^{-2}) was applied in autumn on the stubble of the preceding crop and immediately

Table 1: Monthly rainfall (mm) and mean air temperature (°C) at Hohenschulen, Germany

	Mean air temperature (°C)				Total rainfall (mm)			
	1996/1997	1997/1998	1998/1999	30-year mean	1996/1997	1997/1998	1998/1999	30-year mean
September	12.1	13.5	13.8	13.4	49	55	48	66
October	9.5	8.2	9.0	9.6	58	68	159	60
November	4.7	4.1	2.4	5.4	97	25	74	76
December	−0.6	2.9	1.3	2.4	37	58	63	74
January	−1.6	3.5	3.2	0.7	3	95	74	62
February	4.3	5.2	1.2	0.7	88	15	53	45
March	4.9	5.0	5.0	3.0	51	50	77	46
April	6.3	8.0	8.2	6.7	27	95	27	49
May	10.8	12.7	12.0	11.3	88	35	48	51
June	15.4	15.1	14.2	15.2	71	85	62	62
July	17.7	15.2	18.1	16.4	123	109	78	77
August	20.7	15.7	16.8	16.3	56	61	83	86

Table 2: Factors and factor levels of the field trial running at Hohenschulen experimental station (NW Germany)

1. Soil tillage	MT – minimum tillage technique without ploughing
	CT – conventional system using a plough followed by a harrow-drilling combination
2. Application of pig slurry	S1 – none
	S2 – in autumn (aim: 8 g total N m^{-2})
	S3 – in spring (aim: 8 g total N m^{-2})
	S4 – in autumn plus in spring (aim: 8 + 8 g N m^{-2})
3. Amount and application time of the mineral N fertilizer (g N m^{-2})	N1/N2/N3
Beginning of growth in spring	0/4/8
Beginning of stem elongation	0/4/8
Ear emergence of wheat and barley, bud formation of oilseed rape	0/4/8
Total N	0/12/24

Table 3: Dates of slurry and mineral N fertilizer application (in parenthesis: day of the year)

Winter barley 1996/1997	Oilseed rape 1997/1998	Winter wheat 1998/1999
Slurry application		
3 September (246): 13.7 g N m^{-2}	21 August (233): 11.7 g N m^{-2}	9 September (252): 9.7 g N m^{-2}
10 April (100): 9.9 g N m^{-2}	25 March (85): 9.1 g N m^{-2}	16 April (106): 5.6 g N m^{-2}
Mineral N fertilization		
7 March (66)	10 March (69)	15 March (74)
25 April (115)	30 March (89)	26 April (116)
23 May (143)	16 April (106)	4 June (155)

incorporated into the soil by cultivator. Spring application was made within one week around the second mineral N fertilizer application, e.g. at the end of March to OSR and April to cereals when soil and weather conditions were suitable. At both dates drag hoses were used. A subsample of each application was taken and analysed photometrically for its ammonium N content and for its total N content using the Kjeldahl method. Total N content was multiplied by the amount of applied slurry to give the rate of N applied. The dates of slurry and fertilizer application are given in Table 3. Crop management not involving the treatments (e.g. seed date, pesticide application) was according to standard farm practice. The straw remained on the plots. The sub-sub-plot size was 12 × 36 m.

^{15}N labelling and plant sampling

Within each crop, three microplots (2 × 2 m) within the sub-sub-plot were established to allow labelling each of the three N fertilizer splitting rates separately. Fertilizers were applied as calcium ammonium nitrate ($^{15}NH_4^{15}NO_3$, 5 atom% excess ^{15}N), dissolved in water and applied by a watering can. Each year, the microplots were moved to avoid interactions with labelled N applied to the preceding crop, to avoid errors due to soil movement and to estimate residual effects, which was performed in the centre of the microplots. Microplots received slurry, but were sheltered by plastic covers during the application of unlabelled fertilizers.

During the growth season, plant samples were taken from 0.25 m^{-2} in cereals and 0.5 m^{-2} in OSR outside of the microplots to measure aboveground plant dry matter (dates and growth stages see Table 4). Total N and ^{15}N concentration were analysed in plants derived from 2 × 0.1 m drill rows within the microplots. At harvest, grain and straw dry matter of an area of 0.5 m^{-2} in the centre of the microplots were determined and after grinding, analysed for corresponding total N using an autoanalyser (Traacs 800, Fa. Bran & Luebbe, Norderstedt, Germany) and for ^{15}N concentration using a Finnigan MAT Delta C mass spectrometer.

Table 4: Sampling dates (in parenthesis: day of the year)

Winter barley 1997	Oilseed rape 1998	Winter wheat 1999
1 April (91)	22 March (81)	29 March (88)
15 April (105)	6 April (96)	12 April (102)
29 April (119)	14 April (104)	26 April (116)
13 May (133)	4 May (124)	10 May (130)
27 May (147)	19 May (139)	26 May (146)
09 June (160)	3 June (154)	28 June (179)
25 June (176)	16 June (167)	12 July (193)
23 July (204)	14 July (195)	3 August (215)

In the following year, plants grown on the former microplots were sampled and analysed as described above to quantify residual fertilizer effects. ^{15}N recovery in the plant (N_F) and %^{15}N recovery (%N_F) or fertilizer N use efficiency (FNUE) was calculated according to Hauck and Bremner (1976):

$$N_F = N_t \times \frac{c - b}{a - b}$$

$$\%N_F \text{ or FNUE} = \frac{N_F}{f} \times 100$$

where N_t is the total plant N in g m^{-2}, f the total fertilizer N rate in g m^{-2}, a the atom% ^{15}N, b the atom% ^{15}N in the unfertilized plant and c the atom% ^{15}N in the fertilized plant. Soil and slurry N uptake was estimated from the difference between total plant N and total amount of fertilizer N in the plant.

Statistical analysis

Analyses of variance were performed by using the SAS statistical package. Due to the experimental design, no error estimates for the tillage effects were possible. All results are therefore presented as an average of both tillage treatments. $LSD_{0.05}$ for slurry effects were based on the tillage × slurry interaction, that for mineral N was based on tillage × slurry × mineral N interaction effects, and that for the split applications were based on residual effects. The $LSD_{0.05}$ applies only to individual treatment means.

Results

Total and fertilizer N uptake

At the beginning of spring growth, total N uptake of barley (3.5 g N m^{-2}) and wheat (1.8 g N m^{-2}) was lower than that of OSR (7.0 g N m^{-2}) on average of the 12 and 24 g N m^{-2} treatment (Fig. 1). In early spring till day of the year 104 (Table 4), OSR increased N uptake more rapidly than cereals; however, total N content decreased from 24.8 g N m^{-2} at the beginning of June down to 17.5 g N m^{-2} at maturity, due to the fall of leaves. In contrast, wheat N uptake started from a lower level, but increased until harvest (except day 191), achieving 24.3 g N m^{-2} as maximum. Barley took up less N than the other crops, presumably because of wheat as unfavourable preceding crop.

As ^{15}N application occurred about two weeks (barley: three) before plant sampling, fertilizer N uptake (range: 0.5 – 1.3 g N m^{-2}) remained small at the first sampling date, but increased during the growing season. In all crops, the increase of fertilizer N uptake was less sharp compared with total N uptake, indicating that the plants also used soil N. After mid of April, OSR took up only small

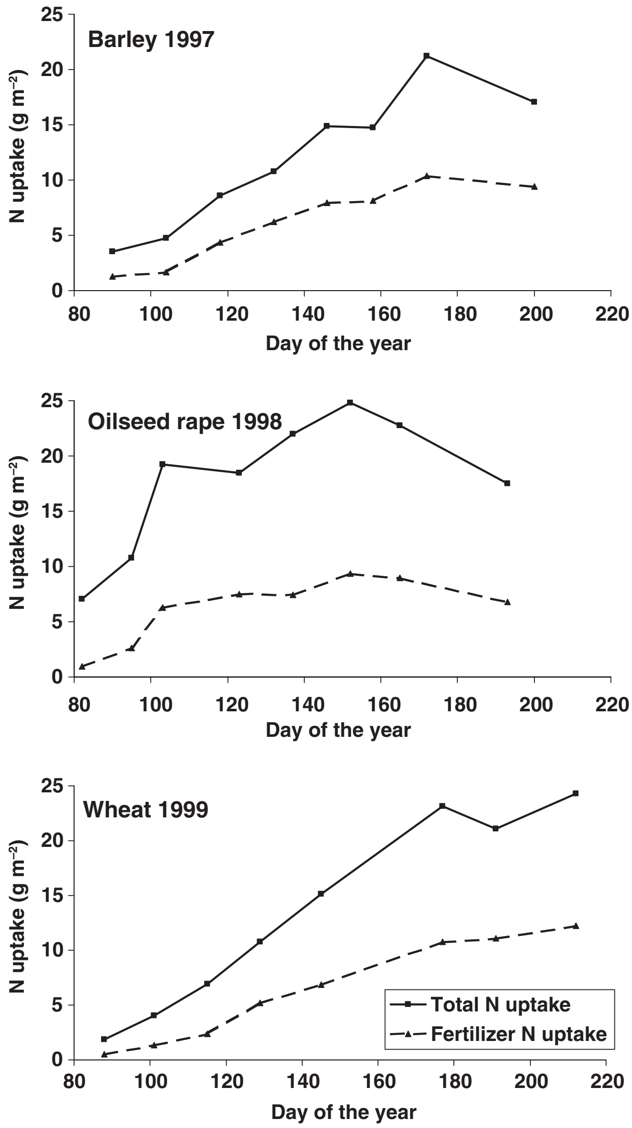

Fig. 1: Total N and fertilizer N uptake (g N m^{-2}) of barley in 1997, oilseed rape in 1998, and wheat in 1999 on average of the 12 and 24 g N m^{-2} treatments

amounts of fertilizer N uptake and, in consequence, utilized more soil N than fertilizer N.

Fertilizer N use efficiency (FNUE) of the splitting rates

All three crops utilized the splitting rates differently depending on the time of application (Tables 5–7). Uptake of N derived from the first N rate applied at the beginning of spring growth was poorer than that from the second (cereals) or third splitting (all three crops). In contrast, N applied later in the growing season was taken up more quickly, resulting in higher FNUE values.

On average of all treatments, barley accumulated at harvest 7.29 g N m^{-2} (41 % of the applied N) in

Table 5: Effect of the application time on fertilizer ^{15}N in the crop (g N m^{-2}; in parenthesis: % of applied ^{15}N = fertilizer N use efficiency FNUE) of barley during the growing season 1997

	Day of the year							Harvest		
Time of application	91	105	119	133	147	160	176	Grain	Straw	Total
1. Splitting	1.27 (21)	1.68 (28)	2.59 a (43)	2.86 b (48)	3.31 b (55)	2.68 b (45)	2.93 c (49)	2.09 b (35)	0.68 b (11)	2.77 b (46)
2. Splitting	–	–	1.78 a (30)	3.37 a (56)	4.65 a (78)	3.29 a (55)	4.21 a (70)	2.60 a (43)	0.82 a (14)	3.42 a (57)
3. Splitting	–	–	–	–	–	2.20 c (37)	3.26 b (54)	2.60 a (43)	0.62 b (10)	3.22 a (54)
Total	1.27 (21)	1.68 (28)	4.37 (36)	6.23 (52)	7.96 (66)	8.17 (45)	10.40 (58)	7.29 (41)	2.12 (12)	9.41 (52)

Within a column, means followed by the same letter are not significantly different at $P < 0.05$ according to LSD.

Table 6: Effect of the application time on fertilizer ^{15}N in the crop (g N m^{-2}; in parenthesis: % of applied ^{15}N = fertilizer N use efficiency FNUE) of oilseed rape during the growing season 1998

	Day of the year							Harvest		
Time of Application	81	96	104	124	139	154	167	Seeds	Straw	Total
1. Splitting	0.97 (16)	1.75 a (19)	3.78 a (63)	2.36 (39)	2.41 (40)	3.05 (51)	2.45 b (41)	1.51 ab (25)	0.65 (11)	2.16 b (36)
2. Splitting	–	0.91 b (15)	2.50 a (42)	2.65 (44)	2.41 (40)	3.27 (55)	3.18 a (53)	1.32 b (22)	0.67 (11)	1.99 b (33)
3. Splitting	–	–	–	2.50 (42)	2.59 (43)	3.48 (58)	3.32 a (55)	1.84 a (31)	0.88 (15)	2.72 a (45)
Total	0.97 (16)	2.66 (22)	6.29 (52)	7.50 (42)	7.41 (41)	9.39 (52)	8.95 (50)	4.57 (25)	2.20 (12)	6.77 (38)

Within a column means followed by the same letter are not significantly different at $P < 0.05$ according to LSD.

the grains and 2.12 g N m^{-2} (12 % of the applied N) in the straw (Table 5). The first splitting rate contributed significantly less ($P < 0.05$) N (2.1 g N m^{-2}) to the total grain N amount compared to the second and third rate (each 2.6 g N m^{-2}). The straw incorporated more N if applied at stem elongation compared to the other two splitting rates.

In OSR, only 25 % of the total fertilizer N was recovered in the seeds (Table 6). N applied at bud formation increased seed N more than N given at stem elongation ($P < 0.05$). OSR straw contained N amounts (2.2 g N m^{-2}) similar to barley straw. The contribution of the splitting rates showed no significant differences ($P > 0.05$).

At maturity, wheat utilized 52 % of the applied fertilizer N for grain production (9.40 g N m^{-2}) and 16 % for straw growth (2.83 g N m^{-2}; Table 7). The time of application significantly affected grain N and straw N content. N applied at ear emergence increased grain N more than application at stem elongation ($P < 0.05$). The effect of the first splitting rate was the lowest. The second splitting rate raised straw N more than the other rates. Considering the total N uptake (grain + straw), FNUE of the first application rate at the beginning of spring growth was significantly lower than the second and the third application rates ($P < 0.05$).

Husbandry effects on soil and slurry N uptake

On average of the slurry treatments, the experimental design allows no distinction between crop N deriving from the soil and N deriving from spring slurry. During the growing season, mineral N fertilization of 24 g N m^{-2} increased significantly soil and slurry N uptake of barley at most of the sampling dates and at harvest the N amount bound in the straw N (Table 8). However, the contribution of non-fertilizer N to barley grain N content was similar in both mineral N treatments. Autumn slurry had no significant effect on soil N uptake, whereas spring slurry increased grain N and total N uptake at harvest in the spring slurry and autumn + spring slurry treatments, presumably because of the actual N supply.

Mineral N treatment significantly affected OSR N uptake derived from the soil and slurry during the growing season ($P < 0.05$), but not at harvest (Table 9). In contrast to barley, autumn slurry increased non-fertilizer N uptake at several sampling dates compared to the treatment without

Table 7: Effect of the application time on fertilizer ^{15}N in the crop (g N m^{-2}; in parenthesis: % of applied ^{15}N = fertilizer N use efficiency FNUE) of wheat during the growing season 1999

Time of Application	Day of the year							Harvest		
	88	102	116	130	146	179	193	Grain	Straw	Total
1. Splitting	0.52 (9)	1.34 (22)	2.36 (39)	2.94 a (49)	3.10 (52)	3.68 b (61)	2.94 b (49)	2.34 c (39)	0.89 b (15)	3.23 b (54)
2. Splitting	–	–	–	2.31 b (39)	3.74 (62)	4.68 a (78)	3.96 a (66)	3.20 b (53)	1.21 a (20)	4.41 a (74)
3. Splitting	–	–	–	–	–	2.70 c (45)	4.20 a (70)	3.85 a (64)	0.72 b (12)	4.57 a (76)
Total	0.52 (9)	1.34 (22)	2.36 (39)	5.22 (44)	6.84 (57)	10.76 (60)	11.10 (62)	9.40 (52)	2.83 (16)	12.22 (68)

Within a column, means followed by the same letter are not significantly different at $P < 0.05$ according to LSD.

Table 8: Effect of slurry and mineral N fertilization on soil and slurry N uptake (g N m^{-2}) of barley during the growing season 1997 as average of the other treatments

	Day of the year							Harvest		
Treatment	91	105	119	133	147	160	176	Grain	Straw	Total
Slurry										
None	1.81	2.38	3.11	2.57	4.23	4.56	9.38 c	4.80 b	1.29	6.08 b
In autumn	2.74	3.37	3.39	4.59	4.92	6.21	7.33 c	4.64 b	1.43	6.07 b
In spring	1.78	3.10	5.43	5.65	7.10	7.81	11.97 b	6.89 a	2.28	9.17 a
In autumn + in spring	2.60	3.34	4.89	6.55	8.67	7.83	15.28 a	6.84 a	2.37	9.22 a
Mineral N (g N m^{-2})										
4/4/4	2.22	2.74	3.28 b	4.34	4.94 b	5.33 b	8.19 b	6.10	1.51 b	7.62
8/8/8	2.25	3.36	5.14 a	5.33	7.51 a	7.87 a	13.79 a	5.48	2.17 a	7.65
Mean	2.23 (64[1])	3.04 (64)	4.21 (49)	4.84 (45)	6.23 (42)	6.60 (45)	10.99 (52)	5.79	1.84	7.63 (45)

Within a treatment and a column, means followed by the same letter are not significantly different at $P < 0.05$ according to LSD.
[1]% of total N uptake.

Table 9: Effect of slurry and mineral N fertilization on soil and slurry N uptake (g N m^{-2}) of oilseed rape during the growing season 1998 as average of the other treatments

	Day of the year							Harvest		
Treatment	81	96	104	124	139	154	167	Seeds	Straw	Total
Slurry										
None	4.47	5.07 c	7.81 d	7.34	7.98 d	10.01	7.77 c	4.56 b	1.91 c	6.47 b
In autumn	7.95	8.58 b	14.59 b	10.49	11.28 c	11.69	10.16 c	8.35 a	3.13 b	11.45 a
In spring	5.21	7.61 b	11.65 c	13.25	16.33 b	17.23	16.70 b	8.55 a	3.82 b	12.37 a
In autumn + in spring	6.62	11.10 a	17.78 a	12.60	22.67 a	22.78	20.63 a	9.11 a	4.62 a	12.72 a
Mineral N (g N m^{-2})										
4/4/4	4.53	6.52 b	10.59 b	8.32 b	10.73 b	12.22 b	12.03	7.77	3.00	10.77
8/8/8	7.59	9.66 a	15.33 a	13.52 a	18.40 a	18.63 a	15.60	7.51	3.75	10.75
Mean	6.06 (86[1])	8.09 (75)	12.96 (67)	10.92 (59)	14.57 (66)	15.43 (62)	13.81 (61)	7.64	3.37	10.76 (61)

Within a treatment and a column, means followed by the same letter are not significantly different at $P < 0.05$ according to LSD.
[1]% of total N uptake.

slurry. Until day 104, autumn slurry led to higher non-fertilizer N uptake than spring slurry, whereas later in the growing season, the order changed. At harvest, slurry application resulted in larger N amounts derived from the soil and/or from the slurry accumulated in the seeds and in the total aboveground biomass.

In contrast to barley, mineral N fertilization showed only a tendency to increase non-fertilizer N accumulation in wheat (Table 10). Slurry application in spring increased soil and slurry N uptake by the grain more than spraying slurry in autumn. During the growing season, slurry application had no significant effects, although large differences between the treatments occurred.

Residual fertilizer effects

Due to the fact that the microplots were installed each year at another part of the plots, the residual effects of the ^{15}N fertilization applied to the preceding crop could be observed. In general, the subsequent crop recovered only small amounts of the former applied fertilizer N (Table 11). At harvest, OSR accumulated 2.8 % (0.5 g N m^{-2}) of the total ^{15}N supply to barley in the whole plant and 1.9 % (0.3 g N m^{-2}) in the seeds. Related to the N amount remaining in the soil and plant residues after barley harvest, the corresponding figures were 4.3 % and 2.9 %, respectively. In total, wheat recovered 2.3 % (0.4 g N m^{-2}) of the

Table 10: Effect of slurry and mineral N fertilization on soil and slurry N uptake (g N m^{-2}) of wheat during the growing season 1999 as average of the other treatments

	Day of the year							Harvest		
Treatment	88	102	116	130	146	179	193	Grain	Straw	Total
Slurry										
None	1.27b	2.45	2.80	3.46	5.63	9.52	7.85	7.34 b	2.09	9.43 c
In autumn	1.15 b	2.79	3.03	5.11	5.55	10.02	9.09	7.79 b	2.15	9.94 c
In spring	1.66 a	2.68	5.93	5.67	10.18	14.10	11.52	9.66 b	3.04	12.72 b
In autumn + in spring	1.16 b	3.04	6.47	8.05	13.32	16.19	11.50	12.38 a	4.37	16.76 a
Mineral N (g N m^{-2})										
4/4/4	1.25	2.41 b	3.90	5.33	7.88	10.85	9.10	9.47	2.33 b	11.80
8/8/8	1.37	3.06 a	5.23	5.81	9.55	14.07	10.88	9.13	3.50 a	12.63
Mean	1.31 (72[1])	2.74 (67)	4.57 (66)	5.57 (52)	8.72 (58)	12.46 (54)	9.99 (47)	9.30	2.92	12.22 (50)

Within a treatment and a column, means followed by the same letter are not significantly different at P < 0.05 according to LSD.
[1]% of total N uptake.

Table 11: Total uptake of N by oilseed rape and wheat (g N m^{-2}) derived from the ^{15}N fertilization to the preceding crop

	Oilseed rape 1997/1998			Wheat 1998/1999		
Treatment	November 1997	February 1998	Harvest	December 1998	March 1999	Harvest
Mineral N (g N m^{-2})						
4/4/4	0.114 b	0.141 b	0.354 b	0.009	0.019 b	0.294 b
8/8/8	0.258 a	0.292 a	0.663 a	0.015	0.034 a	0.510 a
Time of application						
1. Splitting	0.055	0.084	0.165	0.004	0.008	0.104 b
2. Splitting	0.050	0.069	0.164	0.004	0.009	0.099 b
3. Splitting	0.081	0.064	0.179	0.004	0.010	0.199 a
Total	0.186	0.217	0.508	0.012	0.026	0.402

Within a treatment and a column, means followed by the same letter are not significantly different at P < 0.05 according to LSD.

^{15}N applied to OSR (0.3 g N m^{-2} = 1.7 % in the grain). Taking the N offtake by the OSR seeds into account, N recovery increased to 3.0 % (total above ground biomass) and 2.3 % (grains). In both crops, larger residual effects could be observed in the plots fertilized with 24 g N m^{-2} compared with the 12 g N m^{-2} treatment.

Discussion

In the presented study, FNUE was estimated by using ^{15}N-labelled mineral fertilizer. This method allows a direct measurement of the crop N uptake derived from the fertilization and does not depend on similar soil N mineralization as the difference method. However, the isotope method ignores the pool substitution, where during the mineralization-immobilization-turnover labelled fertilizer N is incorporated into soil organic matter instead of non-labelled soil N (Hart et al. 1986). In general, FNUEs estimated by the difference method are higher than those of the ^{15}N isotope method (Powlson et al. 1992).

As each crop was grown in a single year, a distinction between the crop and year effects is not possible. However, some general conclusions can be drawn. Cereals utilized N applied at the beginning of spring growth to a smaller extent for grain formation than N applied later in the growing season (Tables 5 and 7). These results are consistent with other investigations, e.g. those of Recous et al. (1988), Recous and Machet (1999), Destain et al. (1993) and Retzer (1995).

Several reasons for the poor FNUE of the first splitting rate are discussed: in early spring, cereals are less developed than OSR and can hardly take up the entire N applied at this date. Due to the low crop competition, a large of N is incorporated by the soil microorganisms and, therefore, immobilized and must be remineralized before being plant available (Limaux et al. 1999, Gabrielle et al. 2001). In addition, N losses due to leaching and denitrification must be taken into account, as the soils normally are at field capacity after winter (Recous and Machet 1999). Especially rainfall within three weeks after fertilization increased denitrification losses (Addiscott and Powlson 1992, Powlson et al. 1992). In our study, highest FNUE in wheat occurred if N was applied at ear emergence. This seems to be a year-specific result, as in 1998/1999 enough rainfall in June and July allowed optimal grain filling. A 5-year trial (1996–2000) at the same site revealed similar FNUE of N applied at tillering and at ear emergence, using the difference method (Sieling 2002).

In maximum, OSR took up similar N amounts, as wheat; however, the portion of fertilizer N remained small. Due to the experimental design, OSR was, as cereals, fertilized at three dates, lying relative closely together compared to wheat or barley. Although the different application dates affected the amount of fertilizer N in the seeds (Table 6). The low FNUE of the second splitting was unexpected, perhaps due to the larger soil and/or spring slurry N released at this time (Table 9). It remains unclear how far changes in the N fluxes within the plant (storage, remobilization) were involved (Rossato et al. 2001).

The amount of plant N derived from the soil and/or from the slurry can be estimated from the total N uptake and the fertilizer N uptake. Due to its stronger growth in autumn, OSR took up more N derived from soil N and from autumn slurry N than cereals. Also during spring growth, OSR accumulated more non-fertilizer N than wheat or barley. It remains unclear, if this was a crop-specific effect or because of favourable conditions for soil N mineralization.

Fertilization of 24 g N m^{-2} increased the non-fertilizer N uptake at some dates during the growth period and at harvest in the straw fraction compared with the 12 g N m^{-2} treatment, indicating an 'Added Nitrogen Interaction' (ANI; Jenkinson et al. 1985). However, at harvest, no significant effect on the amount of grain N or total N could be observed in all crops.

In OSR, slurry applied in autumn or in spring resulted in similar non-fertilizer N amounts in the seeds and straw. In cereals, the effect of autumn slurry on non-fertilizer N uptake at harvest was negligible, whereas spring slurry applied to a growing crop significantly increased soil and/or slurry N in the grains. It can be assumed that most of the non-fertilizer N accumulated in this treatment was originated from the spring slurry itself and not from an enhanced soil N mineralization. This is all the more surprising as the trial was running since autumn 1991 and the treatments were located on the same plots, leading to an accumulation of the fertilization effects. Therefore, we conclude that 7 years of varying N fertilization did not change the contribution of soil N to crop N uptake. Solely the high values of non-fertilizer N in the wheat grains in the 'autumn + spring slurry' treatment suggested a trend to an increasing N release. Also other investigations indicated a very slow change of the soil N dynamic in the soil after modifying the N management (Glendining et al. 1996, Sieling et al. 2006).

The subsequent crops recovered only small amounts (0.4–0.5 g N m^{-2}) of the fertilizer N remained in the plant residues and/or in the soil (Table 11), corresponding to a N use efficiency of 3–4 % of the remaining N amount. The findings are consistent with results of other trials (e.g. Thomsen and Christensen 1996).

Conclusions

In the long-term, changes of N input (e.g. amount of N fertilization) or N output (e.g. N offtake by the grain) can affect soil N content and, in consequence, potential soil N mineralization, which may promote crop growth and support yield formation. To meet the need of the crop more precisely, information on the extent of additionally released soil N is necessary. Our results suggest no increase in the contribution of soil-borne N to the grain N of the crops after 7 years of highly varying N fertilization including pig slurry application. This finding indicates that changes in the soil N dynamic due to modifications in the N management need a long time to become apparent in yield formation. Fertilizer N use efficiency was higher if N was applied later in the growing season compared with the first splitting at the beginning of spring growth.

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