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Integration of nitrate cover crops into sugarbeet (*Beta vulgaris*) rotations. I. Management and effectiveness of nitrate cover crops

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SUMMARY

Between 1989 and 1993, 17 experiments tested the effect of cover crop species, sowing date and destruction date on cover crop dry matter (DM) yield, N uptake and on soil mineral nitrogen (SMN) content. All the experiments were carried out in Suffolk, Norfolk, Lincolnshire and Yorkshire on sandy-loam textured soils after crops of cereals or oilseed rape had been harvested. The largest DM yields were obtained with early sowings and averaged 1·6 t/ha. Cover crop N uptake was less dependent upon sowing date and averaged 35 kg N/ha. The average reduction in SMN was from 46 to 32 kg N/ha. Differences between cover crop species were small when compared with season/site variations.

Cereal cover crop DM yields were closely related to the thermal time accumulated from the first significant rainfall after sowing, whilst the yields of non-cereal cover crops were more affected by the moisture content of the soil at sowing. The amount of SMN in the soil at sowing had little or no effect on cover crop yield. The yields of cereal cover crops were much more predictable than those of non-cereal cover crops. Water usage by cover crops was estimated to be 20 mm/t DM and large cover crops delayed the onset of leaching and reduced the amount of water leached. However, even in dry autumns and winters, soils are likely to reach field capacity before the following beet crop is sown. Due to their large C:N ratio (20:1) little N would be mineralized after cover crop destruction. Cover crops comprising volunteer cereals and weeds often performed as well as the other cover crops and in most cases will be the most cost-effective cover crops.

INTRODUCTION

The UK sugarbeet crop is grown on 170000 ha of land. Half this area has a sandy or sandy-loam texture with a small water-holding capacity. In addition, *c.* 90% of the beet crop is grown after a winter or spring cereal. These cereals will be harvested in July or August, but will have stopped taking up soil mineral nitrogen (SMN) several weeks earlier. Most of the beet crop is sown in late March or early April and, due to slow growth, will not take up much SMN until late May or June. Consequently, there is almost a 12-month period during which there is no significant sink for SMN. Stubble cultivations and ploughing minimize the growth of cereal volunteers and weeds, limiting their ability to take up nitrate, and may also stimulate mineralization of nitrate from soil organic matter. Nitrate remaining in the soil after harvest of the cereal crop, or mineralized post-harvest will be at risk from leaching (Addiscott *et al.* 1991). Recent European studies (i.e. Muller *et al.* 1989; Christian *et al.* 1990; Rogasik *et al.* 1992; Knott 1996; Richards *et al.* 1996) have shown that cover crops can successfully be established and used to reduce the amount of SMN at risk from leaching. Within the UK, cover crops grown over the winter are a requirement within Nitrate Sensitive Areas (MAFF 1990) and are advised under the *Code of Good Agricultural Practice for the Protection of Water* (MAFF 1991), but to-date we have little information on the effectiveness of cover crops within beet rotations.

The experiments reported here investigated how management options (i.e. sowing date, destruction date and species) affect cover crop performance; how effective these cover crops are in reducing SMN; and

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how other soil processes may be affected by cover crops. The effects of cover crops on the agronomic and economic performance of subsequent beet crops are described in a subsequent paper (Allison *et al.* 1998).

MATERIALS AND METHODS

Experimental designs and treatments

There were 17 experiments on sandy-loam or loamy-sand textured soils in Suffolk, Lincolnshire and Yorkshire between 1989 and 1993. These tested the effect of cover crop species, sowing and destruction on cover crop yield, N uptake and soil processes.

Time of cover crop destruction experiments assessed the effect of three dates of crop destruction on cover crop dry matter (DM) production, N uptake, SMN content and the growth and yield of subsequent beet crops. The cover crop and N response experiments tested the effect of cover crops sown on one date and destroyed at one time on the N requirement of the following beet crop. In the cover crop species and sowing date experiments, several cover crop species were sown on several dates to observe the effects on cover crop yield and N uptake, and the N nutrition of the subsequent beet crop. Details of experiment locations, cover crop species, sowing, sampling and destruction dates are given in Table 1. Minimum plot size was 36 m^2 throughout.

Cover crop husbandry, sampling and analysis

All cover crops were established after the harvest of crops of winter barley, spring oilseed rape, spring barley or winter wheat. Crop residues from preceding cereal crops were removed by baling or burning, except the crop of oilseed rape which was destroyed before harvest by mowing and incorporation. No experimental site had a history of organic manure input except the Pakenham site in 1989 that had received FYM in 1987. The cover crops were established by broadcasting or drilling into land that had been cultivated to *c.* 5 cm or by broadcasting or drilling into land which was then cultivated. Seed rates for phacelia (*Phacelia tanacetifolia* Benth.), oil radish, fodder radish, buckwheat and mustard were as recommended by the suppliers. For winter barley and rye cover crops, the seed rates were 200 and 170 kg/ha, respectively.

Three types of control cover crops were used: an uncultivated stubble control where vegetation was removed by repeated applications of broad spectrum herbicides (CH); an uncultivated stubble control where volunteers were allowed to grow (CS); and a control where the stubble was cultivated to 5 cm to encourage the growth of volunteers and weeds (VW).

Cover crop and control yields were measured by collecting the leaves, stems and taproots from one

Table 1. *Details of the 17 experiments done between 1989 and 1993, showing site, type, cover crop species, and sowing and destruction dates. Apart from North Duffield (Yorkshire) and Heighington (Lincolnshire), the experiments were done in Suffolk*

Season	Site	Type of experiment	Cover crop species	Sowing date	Destruction date
1989/90	Broom's Barn	Time of destruction	Winter barley	10/8/89	16/11/89, 26/1/90, 28/2/90
	Broom's Barn	Species × sowing date	Winter barley, Mustard, Phacelia	12/8/89, 24/8/89, 13/9/89	14/11/89
	Higham	Nitrogen response	Phacelia	15/8/89	26/2/90
	North Duffield	Nitrogen response	Phacelia	8/8/89	9/3/90
	Pakenham	Species × sowing date	Phacelia, Mustard	14/8/89, 29/8/89, 12/9/89	20/2/90
1990/91	Broom's Barn	Nitrogen response	Phacelia	28/7/90	7/12/90
	Broom's Barn	Species × sowing date	Phacelia, Mustard, Rye	27/7/90, 30/8/90, 27/9/90	7/12/90
	Pakenham	Time of destruction	Rye	27/7/90	10/12/90, 31/1/91, 25/2/91
	Pakenham	Species × sowing date	Phacelia, Mustard	23/7/90, 15/8/90, 14/9/90	4/3/91
	North Duffield	Nitrogen response	Phacelia	25/7/90	24/3/91
1991/92	Broom's Barn	Nitrogen response	Buckwheat	5/9/91	2/1/92
	Broom's Barn	Species × sowing date	Oil radish, Buckwheat, Winter barley	28/8/91, 23/9/92	2/1/92
	Barningham	Time of destruction	Fodder radish	7/8/91	5/12/91, 29/1/92, 28/2/92
	Barningham	Species × sowing date	Winter barley, Fodder radish	8/8/91, 27/8/91, 18/9/91	28/2/92
	Heighington	Nitrogen response	Fodder radish	14/8/91	11/2/92
1992/93	Broom's Barn	Nitrogen response	Winter barley	23/7/92, 15/9/92	21/12/92
	Coney Weston	Nitrogen response	Fodder radish	5/8/92, 8/9/92	10/2/93

0·25 m² quadrat taken from each plot. An initial sampling was done immediately after the first significant frost and where possible a further sampling was done immediately before cover crop destruction (Table 1). Any straw or plant debris from the previous crop was carefully removed from each sample, which was then dried to constant weight at 85 °C. After drying, the samples were weighed and then milled to < 2 mm. Yields are expressed as t DM/ha. In 1989 and 1990, the N content of the milled samples was determined by a Kjeldahl digestion modified to include nitrate (AOAC 1955), and in 1991 and 1992 it was determined by an automated Dumas combustion method (LECO Corporation, St Joseph, Michigan, USA).

Soil mineral N (nitrate + ammonium) was measured by taking one soil core, 0–90 cm in 30 cm increments, from the centre of each plot. The inorganic N was then extracted with 1 M KCl and measured using an automated colorimetric method. The results are expressed as kg N/ha using bulk densities typical for the soil type. Soil moisture contents were measured by drying 100 g of field-moist soil to constant weight at 105 °C.

All cover crops were destroyed by ploughing to *c*. 25 cm. Just before the cover crops were destroyed P, K, Mg and Na fertilizers were applied for the beet crop at rates in accordance with current recommendations (Jaggard *et al*. 1995) and based on soil analyses.

RESULTS AND DISCUSSION

Cover crop yields

At the first sampling, *c*. 90 days after sowing, the yield of all cover crops was 1·6 t/ha (mean of 58 samples). At the same time, the yield of the volunteer/weed and stubble controls was 1·2 t/ha (mean of 11 samples). The smallest DM yield was 0·2 t/ha, from phacelia grown at Broom's Barn in 1989/90; the largest (6·8 t/ha) was from fodder radish grown at Coney Weston in 1992/93. Only two other crops, mustard grown at Pakenham in 1989/90 and spring barley grown at Broom's Barn in 1989/90, produced > 4 t/ha.

At the first sampling, earlier sowings (July–early August) generally produced the largest DM yields (Table 2). On some occasions, the middle sowing gave larger yields than the earlier sowing, e.g. winter barley and mustard (Broom's Barn 1989/90), phacelia (Broom's Barn 1990/91), mustard and phacelia (Pakenham 1990/91) and winter barley (Broom's Barn 1991/92). The latest sowings never yielded more than the middle sowings, although in some cases the yields were not significantly different. Elers & Hartman (1987), Christian *et al*. (1992) and Richards *et al*. (1996) obtained similar results to these. Overall, differences in yield between cover crop species were

Table 2. *Summary of effect of cover crop sowing date and species on dry matter (DM) yield (t/ha), N uptake (kg N/ha) and C:N ratio at the first sampling date. All* S.E.*s are based upon 34* D.F.

	First sowing		Second sowing		Third sowing	
Species	Mean	S.E.	Mean	S.E.	Mean	S.E.
Barley						
Yield	1·85	0·400	0·96	0·400	0·85	0·555
N uptake	24·7	8·01	15·9	8·01	14·4	11·12
C:N ratio	28	2·2	22	2·2	23	3·1
Rye						
Yield	1·09	0·783	0·90	0·783	0·89	0·783
N uptake	23·1	15·68	21·1	15·68	23·0	15·68
C:N ratio	19	4·4	17	4·4	16	4·4
Phacelia						
Yield	1·71	0·297	1·46	0·352	0·56	0·39
N uptake	35·9	5·95	37·3	7·05	16·8	7·87
C:N ratio	20	1·7	18	2·0	14	2·2
Mustard						
Yield	1·79	0·352	1·49	0·352	0·93	0·393
N uptake	32·3	7·05	34·6	7·05	22·00	7·87
C:N ratio	22	2·0	18	2·0	18	2·2
Radish						
Yield	2·98	0·433	0·92	0·459	0·92	0·780
N uptake	57·05	8·67	27·4	9·19	25·9	15·68
C:N ratio	23	2·4	16	2·6	14	4·4
Buckwheat						
Yield	0·85	0·780				
N uptake	19·1	15·68				
C:N ratio	18	4·4				
Controls						
Yield	1·16	0·259				
N uptake	21·5	5·20				
C:N ratio	21	1·4				

small when compared to the effects of sowing date and season.

By the second sampling, *c*. 180 days after sowing, the mean cover crop yield had increased to 1·9 t/ha (25 samples) and the yield of the controls to 1·3 t/ha (four samples). The yield of the phacelia always increased, whereas the yield of the fodder radish always decreased. There were no consistent trends for cover crops of mustard or cereals. Destruction date had little effect on cover crop yield and N uptake (Table 3), since most growth occurred between sowing and the first destruction date.

Regression analysis was used to investigate the relationship between cover crop DM yield and growing period. For this analysis, cereals and non-cereals were analysed separately and only the yield data from the first sampling occasion were used, i.e. before any DM was lost because of frost damage. Meteorological data were obtained from the closest meteorological site to each experimental site. For

Table 3. *Effect of cover crop destruction date on yield* (*t/ha*), *N uptake* (*kg N/ha*) *and C:N ratio*

	Destruction date			S.E.
	Early	Mid	Late	(3 D.F.)
Yield	2·51	3·55	2·38	0·971
N uptake	39	56	59	17·9
C:N ratio	26	27	23	1·3

both cereals and non-cereals, there was a poor relationship between yield and growth period measured in days (Table 4). For cereals, more of the yield variation was explained by using thermal time from sowing (above a base temperature of 3 °C) or by using thermal time from the first significant rainfall after sowing (> 5 mm in 48 h). For cereals, including the topsoil moisture content at sowing did little to improve the regressions. Conversely, for the non-cereals, the use of thermal time did little to improve the regressions, but topsoil moisture content at sowing gave significant improvements.

Analysis showed that the gradients and intercepts of the regressions for cereals and non-cereals were similar, showing that both types of cover crop responded in a similar way to climate. The increased sensitivity to rainfall and to topsoil mositure content by the non-cereals may have been because they had small seeds which resulted in poor seed/soil contact, as suggested by Shepherd & May (1992). Including variation in topsoil mineral nitrogen at sowing had no effect on the regressions for cereals or non-cereals and it is likely that in most circumstances SMN is not a limiting factor for cover crop growth.

Overall, the effects of site and season on yield were more important than differences between cover crop species. Under warm and moist conditions, phacelia, mustard and radish cover crops performed better than cereals, particularly in the early stages of growth. Cereals, however, were less sensitive to frost, which caused severe loss of DM in the non-cereal cover crops, as noted by Shepherd & May (1992).

Cover crop N uptake

The average cover crop N uptake was 35 kg/ha, ranging from only 4 kg/ha (phacelia, Broom's Barn 1989/90) to 136 kg/ha (fodder radish, Coney Weston 1992/93). Nitrogen uptake was usually larger in the earlier sown crops (Table 2). The average uptakes for the early, middle and late sowings were 41, 35 and 21 kg N/ha, respectively.

Radish, phacelia and mustard crops took up more N than the barley, rye or buckwheat (Table 2). Due to frost damage and senescence, N uptake, like yield, was often smaller at later samplings. The average N uptake for the first crop sampling was 42 kg N/ha and 39 kg N/ha for the second. Whilst the difference in average N uptake between the first and second samplings was small, there were large differences between species at individual sites and years (Table 2). For example, the N uptake of the fodder radish crop at Barningham 1991/92 did not change between the first and second sampling dates, but at Heighington

Table 4. *Relationship between yield of cereal and non-cereal cover crops and days after sowing* (*DAS*), *topsoil moisture content* (*SMC*), *day degrees from sowing* (*DDS*) *and day degrees from the first significant rain after sowing* (*DDR*). *The standard errors* (*and degrees of freedom*) *are for a target yield of 2 t DM/ha*

Regression equation	Variation explained (%)	P	S.E. (t DM/ha)
Cereal cover crops			
Yield = 0·00714DAS + 0·84	1·0	0·304	0·582 (13 D.F.)
Yield = 0·00904DAS + 0·110SMC − 0·24	*	0·413	—
Yield = 0·00159DDS + 0·252	31·3	0·018	0·278 (13 D.F.)
Yield = 0·00181DDS + 0·143SMC − 1·12	36·8	0·025	—
Yield = 0·00241DDR − 0·130	62·7	< 0·001	0·176 (13 D.F.)
Yield = 0·00244DDR + 0·077SMC − 0·79	63·1	< 0·001	—
Non-cereal cover crops			
Yield = 0·0150DAS + 0·24	10·1	0·018	0·268 (44 D.F.)
Yield = 0·01134DAS + 0·2090SMC − 1·31	32·4	< 0·001	—
Yield = 0·0083DDS + 0·83	1·5	0·199	0·425 (44 D.F.)
Yield = 0·00094DDS + 0·233SMC − 1·32	30·4	< 0·001	—
Yield = 0·00182DDR + 0·232	11·5	0·012	0·258 (44 D.F.)
Yield = 0·00162DDR + 0·218SMC − 1·56	36·5	< 0·001	—

* Residual variance exceeds variance of yield.

(1991/92) it increased from 6 to 27 kg N/ha and at Coney Weston (1992/93) it decreased from 85 to 36 kg N/ha. As was the case for yield, there were no clear differences in species performance, the more dominant effect being site/season.

Yield and N uptake of controls

The yields on the herbicide-treated controls ranged from 0 to 0·7 t/ha, with a mean of 0·1 t/ha. At the first sampling, there was no difference in yield and N uptake between the uncultivated stubble control and the volunteer/weed control. At the second sampling, yields and N uptakes had increased at some sites, but had decreased at others. Generally the performance of the controls was similar to those of the cover crops: they had similar yields and N uptakes. Also, seasons that produced large cover crop yields and N uptakes also produced large control yields and N uptakes.

Cover crops and soil moisture content

The influence of cover crop growth on soil water status was measured gravimetrically at the time of soil sampling for SMN. In most experiments the cover crop reduced the soil moisture content relative to the vegetation-free control plots (Table 5). Averaged over the entire profile (0–90 cm), the mean reduction was 20 g water/kg oven-dry soil (equivalent to *c*. 25 mm). The largest decreases in the whole soil profile were 32 g/kg oven-dry soil (*c*. 40 mm). Reductions in water content were most noticeable in the 30–60 cm layer, where decreases of 50 g/kg oven-dry soil (*c*. 63 mm) were measured. The largest reductions were produced by the largest cover crops; the phacelia grown at North Duffield in 1990/91 (which produced 5·2 t/ha) and the fodder radish crop grown at Coney Weston in 1992/93 (6·8 t/ha). For smaller cover crops, the amount of water evaporated from the soil surface becomes more dominant and there were no clear relationships between yield and reductions in soil moisture content. However, the largest reductions in moisture content usually occurred at the time of maximum cover crop DM production (i.e. at about the time of the first severe frost). There was no relationship between cover crop species and soil moisture and, in all cases, there were no significant differences in the moisture content of the soil when the beet was sown.

From our data, the water-use efficiency was estimated to be *c*. 20 mm/t DM. German (Rogasik *et al*. 1992) and French (J. C. Muller, personal communication) studies have found that cover crops need *c*. 40 mm/t. Meisinger *et al*. (1991) quotes water-use efficiencies of *c*. 30 mm/t DM. This difference may be due to larger evaporation and transpiration losses of water from leaves in warmer and drier continental climates.

A more detailed study of the effects of cover crops on soil water content was made using the SUNDIAL model (Smith *et al*. 1996). Two sets of simulations were made using meteorological, soil and cropping data from Broom's Barn. The first used long-term average weather data (450 mm of rain between July and the following March). The second set used data from a drier than average autumn and spring (only 322 mm of rain between July and March). Both sets compared the effect of growing a 3 t/ha cereal cover crop with a bare soil control. In both cases, the cover crop delayed the onset of drainage by one month and reduced the total amount of drainage by one third. However, both sets of simulations showed that the cover crop had no effect on soil moisture content in the spring.

The effect of cover crops on soil mineral nitrogen content

At the start of the experiments, just after the previous crop had been harvested, the average SMN to a depth of 90 cm was 70 kg N/ha. About 45% of this N was contained in the top 30 cm of soil. The effectiveness of the cover crops in reducing SMN was variable (Table 6). The largest decrease (80%) at the first sampling was achieved by phacelia grown at North Duffield in 1990/91, where SMN was reduced from 55 to 11 kg/ha. Only two other cover crops reduced SMN by > 40 kg N/ha (barley at Broom's Barn in 1989/90 and radish at Pakenham in 1991/92). At the first sampling date, the average reduction due to the cover crop was 30%, equivalent to an average reduction from 46 to 30 kg N/ha. In line with yield and N uptake, reductions in SMN were generally larger when the cover crop was sown early. However, there was no significant relationship between yield or N uptake and reductions in SMN content. Unlike the effects of straw incorporation on SMN (Allison & Hetschkun 1995), cover crops were effective at reducing the SMN content in the 30–60 and 60–90 cm soil layers.

When the subsequent beet crop was sown, in March or April, any effect of the cover crop on SMN had generally disappeared. The exception was at North Duffield (1989/90) where the phacelia cover crop reduced the SMN at beet sowing from 41 to 23 kg N/ha. Cover crops never significantly increased the amount of SMN by the time of beet drilling. Consequently, the costs of using cover crops into beet rotations will not be offset by savings in the amounts of N fertilizer applied to the beet crop.

Assuming that cover crop DM comprises *c*. 40% carbon, the C:N ratios of the cover crops were estimated from the N concentration. The average C:N ratio for all species and sowing dates was 20. Early-sown cover crops had an average ratio of 22 compared to 17 for later sowings. Cereals had larger

Table 5. *Examples of the effect of cover crops on gravimetric soil moisture content (%) measured in late November for four sites in three seasons. The yields (t/ha) of the crops at the time of soil sampling are shown in parentheses*

	Higham 1989/90			North Duffield 1990/91			Pakenham 1990/91					Barningham 1991/92		
Depth (cm)	Control (1·5)	Phacelia (2·9)	S.E. (3 D.F.)	Control (0·0)	Phacelia (5·2)	S.E. (5 D.F.)	Control (0·0)	Phacelia (1·5)	Mustard (0·9)	Volunteer (1·2)	S.E. (8 D.F.)	Control (1·1)	Radish (2·5)	S.E. (2 D.F.)
0–30	10·8	8·5	0·75	17·3	15·7	0·26	11·0	11·9	12·3	11·4	0·54	13·6	13·0	0·18
30–60	9·0	7·3	1·13	13·5	9·3	0·19	8·7	8·7	9·7	9·4	0·53	10·3	10·2	0·34
60–90	10·5	6·7	1·54	14·4	8·6	0·61	6·2	6·3	7·3	7·9	1·59	9·9	9·4	0·13

Table 6. *Examples of the effect of cover crops on soil mineral nitrogen content (kg N/ha) measured in late November for four sites in three seasons. The yields (t/ha) of the crops at the time of soil sampling are shown in parentheses*

	Higham 1989/90			North Duffield 1990/91			Pakenham 1990/91					Barningham 1991/92		
Depth (cm)	Control (1·5)	Phacelia (2·9)	S.E. (3 D.F.)	Control (0·0)	Phacelia (5·2)	S.E. (5 D.F.)	Control (0·0)	Phacelia (1·5)	Mustard (0·9)	Volunteer (1·2)	S.E. (8 D.F.)	Control (1·1)	Radish (2·5)	S.E. (2 D.F.)
0–30	34	8	9·6	19	5	1·0	14	4	4	4	2·4	35	18	5·3
30–60	18	7	2·3	27	3	1·0	17	4	4	7	2·6	28	12	3·5
60–90	6	4	1·0	9	3	0·8	8	5	3	7	0·8	20	9	1·7

C:N ratios than non-cereals (Table 2). Similar results are quoted by Jensen (1992) and Reeves (1994), but those quoted by Richards *et al*. (1996) were less, with an average C:N ratio of 11. Richards *et al*. (1996) did not include root material in their samplings. Jensen (1992) showed that including root material affected the C:N ratio for perennial ryegrass but not for white mustard. A consequence of large C:N ratios is that, in the short term, little or no N will be released from the crop residues when they are incorporated into the soil. Thus, in dry winters, when N losses by leaching would be small, the use of a cover crop could decrease the SMN available to the subsequent crop, possibly increasing the fertilizer requirement.

These experiments have shown that cover crops can be grown successfully in cereal beet rotations. In favourable conditions, the cover crops can produce large yields, take up large amounts of N and significantly reduce the amount of SMN. Leaching losses of N will therefore be reduced due to a reduction in the amount of SMN and reductions in the amounts of water moving through the soil profile (Rogasik *et al*. 1992). There was little difference in performance between cover crop species or between controls. Consequently, in most circumstances, a farmer would be advised to grow the cheapest cover crops available, which are volunteers/weeds. To maximize the effectiveness of the cover crop, they need to be established by late July or early August. Later sowings are unlikely to produce much yield or take up much N.

Whilst cover crops may reduce the total quantity of N leached, the concentration of nitrate in leachates may be increased (Steenvorden 1989). In practice, the widespread use of cover crops could result in less water being available for aquifer recharge and that water having a larger nitrate content. The use of cover crops in the drier regions of the UK could cause problems.

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