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Effects of long-term straw management and fertilizer nitrogen additions on soil nitrogen supply and crop yields at two sites in eastern England

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SUMMARY

The effects of straw incorporation (early and late cultivation) and straw burning were contrasted in a split-plot study examining the impact of long-term straw residue management, and six fertilizer nitrogen (N) rates on soil mineral nitrogen, crop fertilizer N requirements and nitrate leaching losses. The experiments ran from 1984 to 1997 on light-textured soils at ADAS Gleadthorpe (Nottinghamshire, UK) and Morley Research Centre (Norfolk, UK).

Soil incorporation of the straw residues returned an estimated 633 kg N/ha at Gleadthorpe and 429 kg N/ha at Morley on the treatment receiving 150 kg/ha per year fertilizer N since 1984. Straw disposal method had no consistent effect on grain and straw yields, crop N uptake, or optimal fertilizer N rates. In every year there was a positive response ($P<0{\cdot}001$) to fertilizer N in straw/grain yields, N contents and crop N offtakes at both sites. Nitrate leaching losses were slightly reduced by less than 10 kg N/ha where straw residues had been incorporated, while fertilizer N additions increased nitrate leached at both sites.

At both sites there was a consistent effect ($P<0{\cdot}001$) of straw disposal method on autumn soil mineral N, with values following the pattern burn > early incorporate > late plough. The incorporation of straw residues induced temporary N immobilization compared with the treatment where straw was burnt, while the earlier timing of tillage on the incorporate treatment resulted in slightly more mineral N compared with the later ploughed treatment. Fertilizer N rate increased ($P<0{\cdot}001$) soil mineral nitrogen at both sites. At Morley, there was more organic carbon in the plough layer where straw had been incorporated (mean 1·09 g/100 g) rather than burnt (mean 0·89 g/100 g), and a strong positive relationship between organic carbon and fertilizer N rate ($r^2=93{\cdot}2\%$, $P<0{\cdot}01$). There was a detectable effect of fertilizer N on readily mineralizable N in the plough layer at both Gleadthorpe ($P<0{\cdot}001$) and Morley ($P<0{\cdot}05$). At Morley, there was a consistent trend ($P=0{\cdot}06$) for readily mineralizable N to be higher where straw had been incorporated rather than burnt, indicating that ploughing-in residues may contribute to soil nitrogen supply over the longer term.

INTRODUCTION

At its peak in the 1980s, straw burning was used to dispose of 41% of wheat straw and 10% of straw from barley and oat crops in England and Wales (MAFF 1982). During the early 1990s, this declined to 14% and 6% respectively (MAFF 1992). Following the ban on straw and stubble burning in 1993, all straw is now either incorporated into the soil, or baled and removed. Results of the later straw disposal surveys (MAFF 1992, 1995) show that the majority of cereal straw is now baled, with a steady increase in this from 52% in 1992 to 79% in 1995. However, even after baling, Addiscott & Dexter (1994) estimated that 22% of straw remained on the soil surface as stubble.

The mineralization of nitrogen (N) from crop residues will depend on the nature of the organic N added, carbon/nitrogen (C/N) ratio and N content of the residue, residue placement, the degree of contact with the soil matrix, tillage and cropping practices, as well as soil temperature, moisture and aeration (Iritani & Arnold 1960; Frankenberger & Abdelmagid

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1985; Smith *et al.* 1987; Breland 1994; Kuo *et al.* 1996; Silgram & Shepherd 1999). Although straw contains less N than grain (*c.* 0·6 g 100 g in straw compared with *c.* 2 g 100 g in grain), N returned to the soil via straw incorporation for cereal crops yielding 7 12 t ha straw can amount to 40–70 kg N ha per year. Such residues' relatively high C N ratio (e.g. 70–100 for cereal straw) may promote rapid immobilization of about 10 kg ha of soil mineral nitrogen per tonne of straw incorporated (Addiscott & Dexter 1994) as microbial populations are unable to satisfy their N demand from such carbon-rich substrates.

This demand for N mainly occurs within the first 2–3 months after straw incorporation, with the quantity of soil mineral nitrogen limiting the immobilization which is likely to occur (Recous *et al.* 1995). Research suggests that fungal activity may play a more important role than bacterial biomass in this immobilization process (Cheshire *et al.* 1999). In such situations, much of the residue N is retained by incorporation into microbial cells with some of this subsequently converted into recalcitrant humic substances. In contrast, the carbon present is progressively released via CO_2 evolution so that after about a year, two-thirds of the carbon originally in the straw will have been lost as CO_2 regardless of the amount of mineral N the soil originally contained (Jenkinson 1985). As a result, the C N ratio of the residue narrows as decomposition proceeds, eventually resulting in a net release of N via mineralization. In a broader context, the management of straw residues is one strategy that could contribute to the long-term sequestration of carbon in soils, identified as one of the main options for carbon mitigation by the Intergovernmental Panel on Climate Change (Smith *et al.* 1997).

The magnitude and temporal duration of any microbial immobilization is of considerable agronomic importance as by reducing autumn soil mineral nitrogen supply, the incorporation of cereal residues may reduce a soil's susceptibility to over-winter nitrate leaching (Powlson *et al.* 1985; Stemmer *et al.* 1999) by up to 25 kg N ha per year (Darwis *et al.* 1994; Nicholson *et al.* 1997), and restrict N supply to a succeeding crop (Thompson 1992). However, in two experiments where this hypothesis was tested, the effect of straw incorporation on nitrate leaching was found to be negligible (Catt *et al.* 1992; Davies *et al.* 1996). Powlson *et al.* (1985) found that when straw containing 0·5% N was incorporated into a soil that was subsequently sown with winter wheat, 78% of the added N remained in the soil a year after incorporation. Powlson *et al.* (1987) also reported that long-term straw incorporation increased the quantity of mineralizable N in the soil by 40–50%. Thus, soil organic N reserves are likely to increase gradually as a result of straw incorporation and this N may subsequently be released through mineralization over a period of years. Whether this release is synchronized with crop N uptake requirements or occurs in the autumn and winter months will determine the fate of this mineralized N and any increased risk of loss via nitrate leaching.

This study was established to determine the effects of contrasting straw disposal cultivation techniques and fertilizer nitrogen regimes, on crop yield and N uptake, soil N supply and nitrate leaching losses on two light-textured soils in eastern England.

Table 1. *Research site details*

	Gleadthorpe	Morley
Mean annual rainfall (mm)	630	620
Soil association*	Newport	Ashley
Soil texture	Loamy sand over sand	Sandy loam over chalky boulder clay
% clay	7	11
pH	6·9	7·1
Organic carbon (%)	1·2	1·0

* Soil survey of England and Wales (1993).

METHODS

Site descriptions

The experiments were located at ADAS Gleadthorpe (Nottinghamshire, UK) on a loamy sand soil, and at Morley Research Centre (Norfolk, UK) on a sandy loam soil. The mean annual rainfall and selected soil characteristics for each site are given in Table 1.

Experimental design

The sites were established in 1984, and were initially designed to investigate the effects of timing and depth of straw incorporation on the establishment and yield of subsequent crops. The experiments were established using a randomized block design with split plots, with five straw cultivation treatments on the main plots and five nitrogen fertilizer timing regimes on the subplots. However, following the 1989 harvest, the objectives of the experiment changed to evaluate the effects of contrasting straw disposal practices on crop N requirements, soil mineral nitrogen supply and nitrate leaching losses. As a result, the number of cultivation treatments was reduced to three and fertilizer regimes modified to give six incremental rates of N application. This change was achieved by dropping two of the original five straw management treatments, and by an increment to the N rate on half of the plots that had previously received the highest of the original five N rates. The re-designed experiment from 1989 was a randomized block with split plots, with

Table 2. *Cropping history and estimated extra amounts of N returned as a result of straw incorporation on treatments receiving 150 kg N/ha per year, 1985–97*

	Gleadthorpe		Morley	
Harvest year	Crop	N returned (kg/ha)	Crop	N returned (kg/ha)
1985	Winter barley	35*	Winter barley	35*
1986	Winter oilseed rape	155*	Sugar beet	0†
1987	Winter wheat	50*	Winter wheat	50*
1988	Winter barley	35*	Winter wheat	50*
1989	Sugar beet	0†	Sugar beet	0†
1990	Spring barley	30*	Spring wheat	32*
1991	Winter barley	36	Winter oats	32
1992	Winter oilseed rape	155	Winter barley	56
1993	Winter wheat	38	Sugar beet	0†
1994	Winter barley	20	Spring wheat	30
1995	Winter barley	18	Winter wheat	44
1996	Winter barley	16	Winter barley	50
1997	Winter oats	45	Winter barley	50
Total N returned in straw		633		429

* Estimated values from Sylvester-Bradley (1993).
† Sugar beet residues were incorporated on all cultivation treatments.

four replicates of each treatment. There were three main straw disposal cultivation treatments:

(i) Burn straw, tine to incorporate ash, autumn plough ('burn').
(ii) Chop straw, tine to incorporate straw, autumn plough ('incorporate')
(iii) Chop straw, autumn plough ('plough').

Straw was chopped at harvest and either incorporated into the soil or burnt. The burn and incorporate treatments were both cultivated on the same date to a depth of 0·15 m. All three cultivation treatments were subsequently ploughed to a depth of 0·30 m on the same date using a mouldboard plough with a heavy, broad-ringed furrow press. The crop rotations at both sites are presented in Table 2. Where oilseed rape was grown, the straw was treated in the same way as the cereal straw. Where sugar beet was grown, the leaves and crowns were ploughed into the soil on all the cultivation treatments.

Six rates of fertilizer N were superimposed on the cultivation treatments as subplots. These ranged from 0 to 250 kg N/ha per year in 50 kg increments for winter cereals, 0 to 150 kg N/ha per year in 30 kg increments for spring cereals and sugar beet; and from 0 to 300 kg N/ha per year in 60 kg increments for winter oilseed rape. The area of each subplot was 64 m^2 at Gleadthorpe and 69 m^2 at Morley. Nitrogen was applied to the subplots by hand as 34·5% ammonium nitrate prills in two applications. Phosphate and potash were applied at rates consistent with current fertilizer recommendations (MAFF 2000). In all other respects the crops were managed according to standard farm husbandry.

Sample collection and analysis

Combinable crops were harvested using a small plot combine, with grain yields adjusted to 85% dry matter. Nitrogen harvest index was assessed by hand threshing whole crop samples taken to ground level immediately prior to combine harvesting. Grain and straw samples taken at harvest were analysed to determine their total N content (MAFF 1986). The optimum fertilizer N application rate (Nopt) was calculated using a linear plus exponential model (Sylvester-Bradley *et al.* 1984), with the coefficient *R* fixed at 0·99 and assuming a break-even grain to fertilizer N price ratio of 3:1.

In autumns 1990 to 1997, soil samples were taken from selected plots in four depth increments (0–0·15, 0·15–0·3, 0·3–0·6 and 0·6–0·9 m) before the soil returned to field capacity. Samples were frozen and analysed for mineral N (nitrate and ammonium N) by extraction with 2 M KCl (MAFF 1986). Additionally, in autumn 1994, topsoil samples (0–0·15 m) were analysed for readily mineralizable N using 'hot' KCl following an adaptation of the method described by Gianello & Bremner (1986), in which 40 g of fresh soil was boiled for 4 h with 200 ml of 2 M KCl, and the extract analysed for nitrate and ammonium N. Readily mineralizable nitrogen was calculated by

Table 3. *Optimum fertilizer N rate (Nopt, kg/ha) and estimated grain/seed yields at optimum N (Yopt, t/ha)*

	1990		1991		1992		1993		1994		1995		1996		1997	
Harvest year	Nopt	Yopt	Nopt	Yopt	Nopt	Yopt	Nopt	Yopt	Nopt	Yopt	Nopt	Yopt	Nopt	Yopt	Nopt	Yopt
Gleadthorpe																
Crop	S. barley		W. barley		Oilseed rape		W. wheat		W. barley		W. barley		W. barley		W. oats	
Burn	101	3·40	188	5·56	122	1·65	170	8·07	156	4·42	136	3·70	127	3·48	136	4·81
Incorporate	81	2·95	179	5·48	130	1·50	166	7·64	117	4·40	131	3·70	141	3·48	138	4·73
Plough	82	3·08	171	5·40	127	1·49	182	7·87	124	4·64	152	3·64	148	3·29	140	4·88
Morley																
Crop	S. wheat		W. oats		W. barley		Sugar beet		S. wheat		W. wheat		W. barley		W. barley	
Burn	250*	9·00*	78	7·16	156	8·10	ND	ND	122	4·02	186	9·84	>250*	8·76*	131	7·00
Incorporate	189	8·66	93	7·09	177	7·98	ND	ND	141	4·14	215	9·88	>250*	8·43*	123	7·46
Plough	>250*	>8·85*	89	7·28	163	7·91	ND	ND	89	4·25	178	9·76	>250*	8·29*	139	6·99

ND, not determined; S, summer; W, winter.
* Highest N rate yield taken as optimum value.

difference between the 'hot' KCl and normal 'cold' KCl mineral N determinations. Topsoil samples were also analysed for total N and organic carbon using standard methods (MAFF 1986). In autumn 1997, further topsoil samples were analysed for total nitrogen, organic carbon and readily mineralizable nitrogen, which was this time determined by 7-day anaerobic incubation (Keeney 1982).

In autumn 1994, porous ceramic cups were installed in two N rates (control and 150 kg N/ha per year at Gleadthorpe, control and 200 kg N/ha per year at Morley) on the burn and incorporate treatments, to measure the effect of these treatments on nitrate leaching losses. Five cups were installed in each plot at a depth of 0·9 m at Gleadthorpe and 0·6 m at Morley (Lord & Shepherd 1993). The cups were shallower at Morley due to the presence of a layer of chalky clay at depths greater than 0·6 m. Porous cup water samples were collected at approximately fortnightly intervals during the drainage season and analysed for nitrate-N using standard methods (MAFF 1986). Drainage volumes were estimated using the hydrological model IRRIGUIDE (Bailey & Spackman 1996).

RESULTS AND DISCUSSION

Some preliminary results from this work were reported by Nicholson *et al.* (1997); the emphasis of this paper is therefore on the last four years of the study from 1994 to 1998. Table 2 shows the cropping history at the two sites, together with an estimate of N returns at each harvest as a result of straw incorporation on the fertilized plots. Cropping typically consisted of winter cereals with sugar beet (Morley) and oilseed rape (Gleadthorpe) as break crops. Total N returns during the experiment were substantially greater at Gleadthorpe than Morley, primarily due to the greater N returns from the two oilseed rape crops grown at this site.

Crop yield and N uptake

Results from both the first phase of the experiment (1985–89) and later years (1990–97) showed no differences ($P > 0·05$) in grain yield between the incorporate and burn treatments at either site in any year. With only two exceptions (discussed below), the method of straw disposal also had no significant effect on straw yield, the partitioning of dry matter and nitrogen between grain and straw at harvest, or the amount of N accumulated in the harvested material at either site. This contrasts with a number of previous studies (e.g. Tomar & Soper 1981; Nyborg *et al.* 1995*b*) where incorporating rather than baling or burning cereal straw tended to decrease subsequent crop yields, possibly because N immobilization by soil microbes decreased crop N supply during early

Table 4. *ΔY (t/ha)* for Gleadthorpe and Morley, 1990–97*

Harvest year	1990	1991	1992	1993	1994	1995	1996	1997
Gleadthorpe								
Crop	S. barley	W. barley	Oilseed rape	W. wheat	W. barley	W. barley	W. barley	W. oats
Burn	1·45	4·03	1·02	5·17	2·60	2·44	2·43	2·74
Incorporate	0·86	3·65	0·85	4·73	2·56	2·63	2·38	2·60
Plough	1·15	4·07	0·94	4·55	2·85	2·41	2·54	2·51
Morley								
Crop	S. wheat	W. oats	W. barley	Sugar beet	S. wheat	W. wheat	W. barley	W. barley
Burn	1·97	1·84	4·67	–	1·70	5·08	>6·05†	3·74
Incorporate	1·62	1·97	4·20	–	1·93	5·77	>5·27†	3·72
Plough	1·16	2·41	4·04		1·90	5·34	>4·58†	3·68

S, summer, W, winter.

* ΔY = (estimated optimum grain yield) minus (actual grain yield at nil nitrogen)

† Optimum nitrogen rate exceeded the highest rate tested.

plant growth (Christian & Bacon 1991). Other research by Njos & Borresen (1991) found that over a period of 20 years, burning straw significantly increased crop yields by 0·1–0·3 t/ha compared with straw incorporation: similar results have been reported by Johnston (1986). However, as in the work reported here, Johnson & Smith (1996) also failed to find any cultivation/straw disposal effects on winter barley yields over a 5-year period from 1989 to 1994.

At Morley in 1995, straw yields were higher ($P < 0·05$) and dry matter harvest index lower ($P = 0·07$) on the burn compared with the incorporate treatment. However, in 1996 there was an indication ($P = 0·08$) that at nil and 50 kg N/ha rates, grain yields were greater in the incorporate and plough treatments (e.g. nil N; burn 2·71, incorporate 3·16, plough 3·71 t/ha). In 1997, higher grain yields were also recorded on the incorporate treatments receiving from nil to 150 kg N/ha per year, resulting in a higher ($P < 0·05$) overall yield for the incorporate treatment. In every year there was a positive response ($P < 0·001$) in grain and straw yields, crop N contents and total crop N offtake to fertilizer N at both sites, with grain yields generally doubling at the optimum rate of fertilizer N application. Although Nopt differed between years depending on the season and crop grown, straw disposal technique had no consistent effect on the optimum N rate (Table 3). Overall, in five out of the seven harvests at Morley and seven out of the eight at Gleadthorpe, Yopt (i.e. yield at optimum N) was slightly higher where straw residues had been burnt compared with where residues had been ploughed (Table 3).

Estimated optimum grain yield less actual grain yield at nil nitrogen (ΔY) was calculated for each cultivation treatment for each harvest year at both sites (Table 4). These derived figures provide a measure of the effects of differences in soil nitrogen supply during the growing season, which may have resulted from different straw residue management strategies. Results for Morley showed no consistent pattern across harvest years. At Gleadthorpe, ΔY on the incorporate treatment was almost always less than the burn treatment, suggesting that the contribution to grain yield from mineralized nitrogen was often greater where straw residues had been incorporated shortly after harvest. This could be due to the delayed mineralization of the N contained in the straw residues from earlier years following any initial immobilization phase.

Calculation of straw N returns

Measurements of straw N uptake were used to estimate the amount of N returned to the soil after repeated straw incorporation on the treatments receiving 150 kg N/ha per year fertilizer N (Table 2). Typical straw N content values were used for crops where measurements were not available (Sylvester-Bradley 1993). In the years where sugar beet was grown in the rotation, crop residues were incorporated on all treatments, and hence were not included in calculations of N returns.

At the end of the study in autumn 1997, nitrogen returns via straw incorporation following 12 years of comparative treatments at Gleadthorpe and 10 years at Morley totalled 633 kg N/ha per year and 429 kg N/ha per year respectively (Table 2). The N returned through straw incorporation was equivalent to 18% (Gleadthorpe) and 10% (Morley) of the total topsoil N measured on the 150 kg N/ha per year treatment in autumn 1997, with calculations assuming a topsoil depth of 0·3 m and a soil bulk density of 1·3 g/cm³. However, these increased N returns were not reflected in differences in topsoil total N measurements between the different straw disposal treatments in either autumn 1994 or 1997. This was not altogether unexpected as these calculated N returns are small in

Table 5*a*. *Nitrate leaching losses (kg N/ha) during winters 1994/95 to 1997/98*

	1994/95		1995/96		1996/97		1997/98	
Fertilizer rate (kg N/ha)	Nil	150–200	Nil	150–200	Nil	150–200	Nil	100–125
Gleadthorpe								
Burn	41	70	14	34	10	41	18	29
Incorporate*	40	60	17	28	13	44	17	31
Drainage (mm)		267		108		101		81
Morley								
Burn	48	121	1·2	14	8	19	55	67
Incorporate*	30	92	2·1	12	6	12	46	52
Drainage (mm)		174		70		86		188

* Chopped then tined.

Table 5*b*. *Corresponding* S.E.D. *values for data presented in Table* 5a

	1994/95	1995/96	1996/97	1997/98
Gleadthorpe				
Straw disposal method (3 D.F.)	3·5	3·0	2·7	4·2
Fertilizer (6 D.F.)	3·7	2·0	2·1	3·5
Interaction (6 D.F.)	5·1	3·6	3·4	5·5
Interaction for same straw disposal method	5·2	2·8	2·9	4·9
Morley				
Straw disposal method (3 D.F.)	9·3	1·6	4·7	4·6
Fertilizer (6 D.F.)	12·1	5·3	5·3	6·1
Interaction (6 D.F.)	15·3	5·5	7·0	7·6
Interaction for same straw disposal method	17·1	7·5	7·5	8·6

comparison with the total topsoil N reserves and could not be detected within the range of experimental and analytical errors in total soil N analysis.

Nitrate leaching

All except the first winter studied were not particularly wet, with drainage volumes typically in the range 80–120 mm, with the lower values at the Morley site. Nitrate leaching losses over winter 1995/96 at ADAS Gleadthorpe and Morley were lower than in 1994/95 largely due to lower drainage volumes at Gleadthorpe (108 mm *v.* 267 mm) and Morley (70 mm *v.* 174 mm) (Table 5). Losses were substantially greater at Morley than Gleadthorpe in winter 1997/98 as Morley was left fallow over-winter in preparation for a sugar beet break crop.

Over the four winters 1994–98, nitrate leaching losses were often similar or slightly reduced where straw residues had been incorporated rather than burnt (Table 5; Fig. 1). However, any reduction in nitrate leaching losses due to straw incorporation was typically small ($<$ 10 kg N/ha per year) and not significant, except at Morley in the wet winter 1994/95 when straw incorporation reduced ($P < 0·05$) nitrate leaching losses by *c.* 25 kg N/ha per year. In winter 1997/98 at Morley, there was a trend for lower (*c.* 12 kg N/ha per year) nitrate leaching losses ($P = 0·08$) and lower nitrate-N concentrations ($P = 0·07$) where straw residues had been incorporated rather than burnt (Figs 1 and 2; Table 5). These data, together with the autumn soil mineral nitrogen results which showed a similar trend (see later) provide some evidence of immobilization of soil mineral nitrogen due to the addition of residues with a wide C:N ratio. These findings are in broad agreement with Catt *et al.* (1998) who reported that although straw incorporation decreased nitrate leaching in the winter following incorporation, it had no consistent long-term effect because the N immobilized by repeated straw incorporation was approximately balanced by the N mineralized from an enlarged microbial biomass and the cultivation process per se. Fertilizer N additions increased nitrate leaching losses ($P \leqslant 0·01$) in all years at Gleadthorpe (mean 21 kg N/ha per year; range 11–31 kg/ha), and in 1994/95 only at Morley by 68 kg N/ha per year (Table 5; Figs 1 and 2), supporting evidence of the limited efficiency associated with fertilizer use which means that crops take up variable proportions (typically 40–90%) of spring-applied fertilizer N (Sylvester-Bradley 1993; Williams *et al.* 1996).

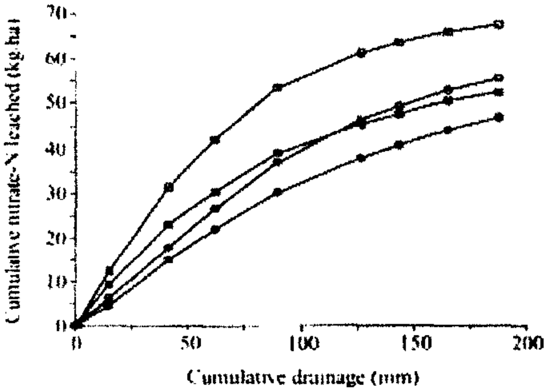

Fig. 1. Cumulative nitrate leaching loss against drainage for contrasting fertilizer N and straw disposal treatments at Morley, winter 1997/98. Treatments are straw incorporation at nil N (●), straw incorporation at high N (■), straw burning at nil N (○) and straw burning at high N (□).

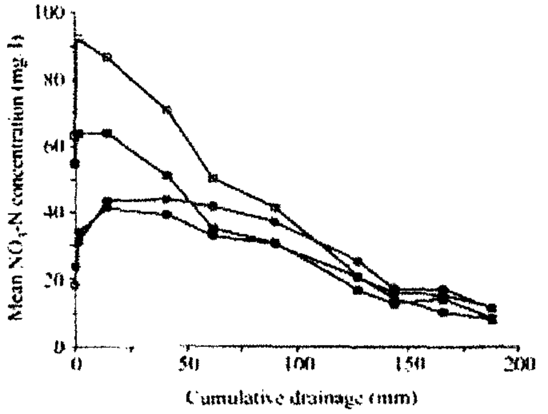

Fig. 2. Mean nitrate-N concentrations against drainage for contrasting fertilizer N and straw disposal treatments at Morley, winter 1997/98. Treatments are straw incorporation at nil N (●), straw incorporation at high N (■), straw burning at nil N (○) and straw burning at high N (□).

Effect of straw disposal treatments on autumn soil mineral nitrogen

At Gleadthorpe, soil mineral nitrogen data from 1991 to 96 at 0–30, 30–60, 60–90 and 0–90 cm depths were analysed to identify whether consistent year, straw disposal or fertilizer N treatment effects were evident when results for the whole time period were considered together. Fertilizer N rate had a strong positive effect ($P < 0.001$) on 30–60, 60–90 and 0–90 cm soil mineral nitrogen, with mean 0–90 cm soil mineral nitrogen across all straw disposal treatments of 54, 60, 65 and 71 kg N/ha on treatments receiving 0, 100, 150 and 200 kg N/ha respectively. Unlike the results reported by Chaney (1990) and Sylvester-Bradley & Chambers (1992), there was no evidence of a sharp increase in autumn soil mineral nitrogen once optimum fertilizer N rates had been exceeded. The results (Table 6) also showed that there was a strong effect of year ($P < 0.001$) on 0–90 cm soil mineral nitrogen, but no significant year × straw interaction term, indicating that the effects of residue management were consistent across years. Straw disposal method consistently influenced soil mineral nitrogen at all depths ($P < 0.05$), with measurements following the trend burn > incorporate > plough (Fig. 3*b*). Mean 0–90 cm soil mineral nitrogen across all fertilizer N rates was 68 (burn), 61 (incorporate) and 58 (plough) kg N/ha. Reports in the literature on the effects of straw incorporation on soil mineral nitrogen are variable. For example, Allison *et al.* (1992) found that incorporated straw reduced soil mineral nitrogen levels by a third in one experiment and had no effect in two similar experiments. In a second study (Allison & Hetschkun 1995), there was an indication that previous cereal straw incorporation reduced soil mineral nitrogen at drilling and mid-season, but increased levels at harvest.

Table 6. *Significance matrix of treatment effects on autumn soil mineral nitrogen from 1991/96 at Gleadthorpe and Morley due to year, straw disposal method and N rate*

	Significance (*P* value) from analysis of variance		
Autumn soil mineral nitrogen site depth	Year	Straw	N applied
Gleadthorpe			
0–30 cm	<0·001	0·031	NS
30–60 cm	0·002	0·018	<0·001
60–90 cm	<0·001	0·014	<0·001
0–90 cm	<0·001	0·012	<0·001
Morley			
0–30 cm	0·009	NS	0·048
30–60 cm	<0·001	<0·001	<0·001
60–90 cm	<0·001	0·020	<0·001
0–90 cm	<0·001	0·010	<0·001

NS, not significant ($P < 0·05$).

A similar analysis of autumn soil mineral nitrogen data at Morley from 1991 to 96 was undertaken, excluding 1994, which followed a sugar beet break crop grown without differential N rates. The results (Table 6) revealed an effect due to year ($P < 0·05$) and N rate ($P < 0·01$) at all soil depths. Straw disposal method influenced soil mineral nitrogen levels ($P < 0·05$) at the 30–60, 60–90 and 0–90 cm depths, with autumn soil mineral nitrogen again consistently following the pattern burn > incorporate > plough. Over all years and

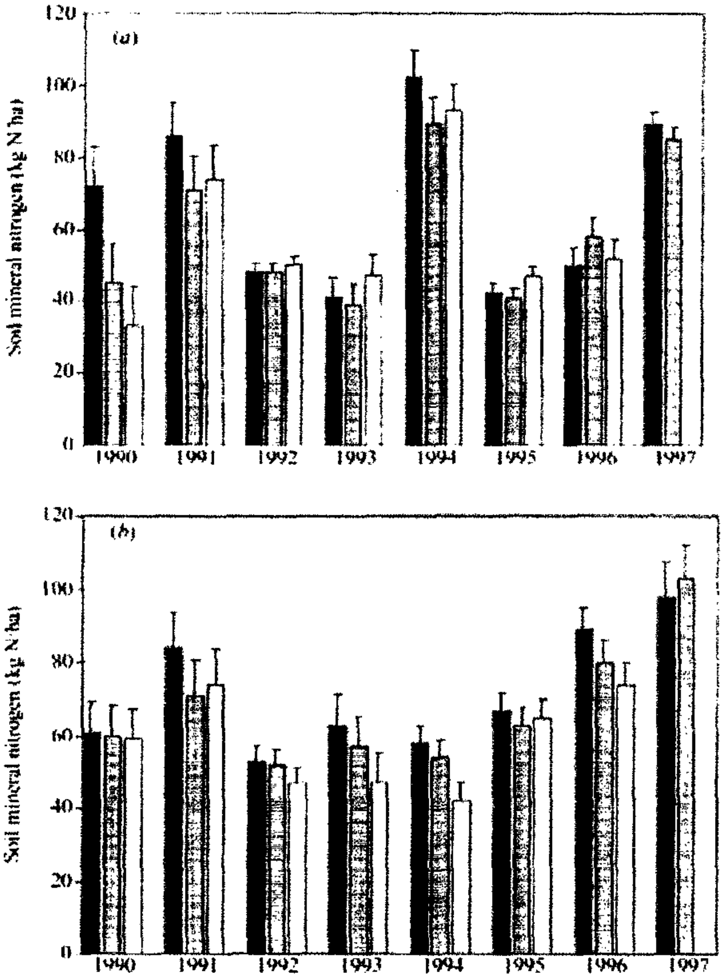

Fig. 3. The effect of straw disposal method on autumn soil mineral nitrogen (0 90 cm depth). (*a*) at Morley, 1990 97 and (*b*) at Gleadthorpe, 1990-97. Standard error bars of means across all fertilizer N rates are shown. ■, Burn, ⊟, incorporate; , plough

fertilizer N rates, mean 0 90 cm soil mineral nitrogen was 51, 46 and 43 kg N ha on burn, incorporate and plough treatments respectively. In individual years, there were differences in 0 90 cm soil mineral nitrogen between the straw disposal treatments in 1990 and 1991 (Fig. 3*a*), when soil mineral nitrogen on the burn treatment was greater ($P < 0{\cdot}05$) than the incorporate or plough treatments (e.g. 1990 means: burn 72, incorporate 45, plough 32 kg N ha). Similarly, soil mineral nitrogen at the 30-60 cm depth was lower in 1991, 1992, 1995 and 1997 ($P \leq 0{\cdot}05$) where straw had been incorporated rather than burnt (e.g. 1997 means: burn 43, incorporate 39 kg N ha). The high soil mineral nitrogen levels in autumn 1994 (Fig. 3*a*; Table 2) were probably a result of the mineralization of N-rich sugar beet tops (Williams *et al.* 1996). These results show that, for both sites, incorporating straw residues with their wide C N ratios induced temporary N immobilization compared with where straw was burnt.

The consistently earlier timing of tillage on the incorporate treatments had a small effect on soil mineral nitrogen compared with the late ploughed treatment (Fig. 3*b*). Soil mineral nitrogen samples taken from 60 to 90 cm depth at Gleadthorpe in autumn 1992 contained more ($P < 0{\cdot}01$) soil mineral nitrogen where early cultivation had taken place in August to incorporate straw compared with where the soil was left undisturbed until later ploughing in October. This effect of early cultivation in stimulating

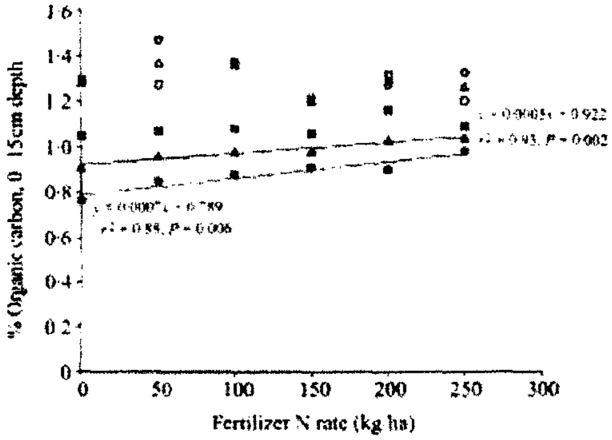

Fig. 4. The effect of straw disposal method and fertilizer N rate on soil organic carbon. Treatments are Gleadthorpe straw burn (○), straw incorporation (□) and mean (△); and Morley straw burn (●), straw incorporation (■) and mean (▲). ▲–▲, linear: Morley mean, ●–●, linear: Morley burn.

soil N mineralization is well established (Shepherd *et al.* 1993), with cultivations typically responsible for increasing soil mineral nitrogen by 5–25 kg/ha (Silgram & Shepherd 1999). Earlier cultivations also tend to coincide with the time when the soil is warm and moist, conditions known to promote mineralization. Watson *et al.* (1993) and Vinten *et al.* (1994) reported that delaying ploughing operations until late winter could reduce nitrate leaching losses compared with earlier autumn ploughing.

Effects on total nitrogen, organic carbon and readily mineralizable nitrogen

There was no effect ($P > 0·05$) of straw treatment on topsoil total nitrogen. However, total nitrogen on the incorporate treatment at Morley was almost always greater than that under the equivalent burn treatment. These results support the conclusion of Njøs & Borresen (1991) that any effects of straw incorporation on soil fertility are small when compared with its valuable role as a means of disposing of unwanted surface residues. Fertilizer N additions apparently increased topsoil total nitrogen at Gleadthorpe from 0·083 g/100 g on the nil N treatment to 0·087 g/100 g on the treatment receiving 250 kg N/ha per year, and at Morley from 0·104 g/100 g (nil N) to 0·108 g/100 g (250 kg N/ha per year treatment), although these differences were not statistically significant ($P > 0·05$). Thus, the larger quantities of organic residues returned when crops were grown with fertilizer N additions of 250 kg N/ha per year resulted in a 4–5% increase in topsoil total nitrogen content compared with the nil N treatment at both sites. These results concur with work reported from the Broadbalk Experiment at Rothamsted Experimental Station (Glendining *et al.* 1996) which showed increases in topsoil total nitrogen of up to 21% on plots where 144 kg N/ha per year had been applied for 135 years; differences in total nitrogen between the fertilized and unfertilized treatments were established within the first 30 years. Similarly, Bhogal *et al.* (1997) found a 6% increase in topsoil total nitrogen on plots at Ropsley (Lincolnshire) where on average 255 kg N/ha per year had been applied for 14 years.

Although there was no clear pattern in the response of topsoil organic carbon to fertilizer N rate or straw residue management at Gleadthorpe in November 1997, organic carbon levels at Morley increased by 14 g/100 g from 0·91 g/100 g in the nil N treatment to 1·04% in the treatment receiving 250 kg N/ha per year. At Morley (Fig. 4), there was a positive linear relationship between fertilizer N rate and topsoil organic carbon on the burn ($r^2 = 0·88$, $P < 0·01$) and straw incorporate treatments ($r^2 = 0·93$, $P < 0·01$). There was also a consistent trend at Morley for higher topsoil organic carbon levels where straw residues had been incorporated rather than burnt which was evident across all fertilizer N rates, with a mean organic carbon of 0·89 on the burn treatment compared with 1·09 g/100 g where straw residues had been incorporated, i.e. straw incorporation increased organic carbon by *c.* 23 g/100 g compared with the burn treatment. These findings support research by Powlson *et al.* (1987) and Nyborg *et al.* (1995*a*) who reported that straw incorporation for 18 and 11 years increased soil organic carbon content by 5% and 0–18% respectively. Such changes in soil organic carbon as a result of straw incorporation are likely to take many years to reach a level where they become

Table 7. *Effect of straw disposal method and fertilizer N rate on readily mineralizable N (kg/ha), 0–15 cm depth, autumn 1997*

Cultivation treatment	Fertilizer N rate (kg/ha) 0	50	100	150	200	250	Mean
Gleadthorpe			(S.E.D. ±5·88*, $P=0·319$, 30 D.F.)				(S.E.D. ±4·19, $P=0·650$, 3 D.F.)
Burn	56·0	48·8	59·7	62·0	49·7	42·2	53·1
Incorporate	48·2	53·8	57·3	55·2	46·9	44·5	51·0
			(S.E.D. ±3·20, $P<0·001$)				
Mean	52·1	51·3	58·5	58·6	48·3	43·4	
Morley			(S.E.D. ±6·73†, $P=0·565$, 30 D.F.)				(S.E.D. ±4·09, $P=0·065$, 3 D.F.)
Burn	46·4	49·7	49·2	55·3	55·9	53·9	51·6
Incorporate	53·6	54·4	60·5	65·9	64·5	65·3	60·8
			(S.E.D. ±4·13, $P=0·018$, 30 D.F.)				
Mean	50·0	52·0	54·9	60·6	60·2	60·4	

* Except when comparing means on the same disposal treatment, S.E.D. ±4·52.

† Except when comparing means on the same disposal treatment, S.E.D. ±5·85.

detectable treatment effects which can be confirmed statistically, with the magnitude of changes being dependent on N returns to the soil, soil type and prevailing climatic conditions.

The effect of straw disposal method on readily mineralizable nitrogen at Gleadthorpe was variable and showed no clear pattern. However, at Morley there was a consistent trend ($P=0·06$) for topsoil readily mineralizable nitrogen to be higher where straw had been incorporated rather than burnt and this was apparent at all N levels (Table 7). These results are consistent with those reported by Powlson *et al.* (1987) in a 60-day laboratory incubation of soils where straw had been burnt or incorporated for 18 years, which indicated that long-term straw incorporation increased mineralizable N by 40–50% and increased soil total nitrogen by 10%. There was also a detectable effect of fertilizer N on topsoil readily mineralizable nitrogen at both Morley ($P<0·05$) and Gleadthorpe ($P<0·001$). At Morley, there was a positive linear relationship between readily mineralizable nitrogen and fertilizer N for the burn ($r^2=0·75$, $P<0·05$), incorporate ($r^2=0·83$, $P=0·01$) and overall residue disposal treatment means ($r^2=0·88$, $P=0·01$), with higher fertilizer N rates increasing the pool of readily mineralizable organic N in the topsoil.

CONCLUSIONS

By autumn 1997, N returns via straw incorporation following 12 years of comparative treatments at Gleadthorpe and 10 years at Morley resulted in relative differences of 4–5% in total topsoil N between the nil and 250 kg N/ha per year fertilizer treatments, reflecting the larger quantities of organic residues returned where crops were grown with fertilizer N additions and the inefficient use of such fertilizer by arable crops. At Morley, there was a consistent trend for more topsoil organic carbon (mean 23%) where straw residues had been incorporated rather than burnt which was evident across all fertilizer N rates, with a mean organic carbon of 0·89 on the burn treatment compared with 1·09 g/100 g where straw residues had been incorporated. There was also a positive relationship between topsoil organic carbon and fertilizer N rate ($r^2=0·93$, $P<0·01$), with organic carbon increasing from 0·91 g/100 g on nil N plots to 1·04 g/100 g on those receiving 250 kg N/ha per year.

At both sites, there was a consistent effect ($P<0·05$) across years (1991–96) of straw disposal method on profile soil mineral nitrogen, with soil mineral nitrogen following the pattern burn > incorporate > plough. This shows that incorporating carbonaceous straw residues induced temporary immobilization compared with where the straw was burnt. The earlier timing of tillage on the incorporate treatment resulted in slightly more soil mineral nitrogen compared with the late plough treatment. Over the whole time-series, fertilizer N rate increased ($P<0·001$) soil mineral nitrogen at both sites at every depth, except Gleadthorpe 0–30 cm.

Fertilizer N increased topsoil readily mineralizable nitrogen at both Gleadthorpe ($P<0·001$) and Morley ($P<0·05$), with a positive linear relationship at Morley ($r^2=0·88$, $P=0·01$) between fertilizer N rate and readily mineralizable nitrogen. At Morley there was also a consistent trend ($P=0·06$) for readily mineralizable nitrogen to be higher where straw had been incorporated rather than burnt, and this was apparent at all nitrogen levels. This indicates that ploughing-in straw residues rather than burning will make a contribution to soil nitrogen supply over the longer term (i.e. following the initial immobilization phase) by increasing the size of the labile soil organic nitrogen fraction available for subsequent mineralization.

In every year there was a positive response ($P < 0{\cdot}001$) in straw and grain yields, grain straw N contents and total crop N offtakes to fertilizer N. The method of straw disposal only rarely had an effect ($P < 0{\cdot}05$) on grain or straw yields, the partitioning of dry matter and nitrogen between grain and straw at harvest, or the amount of N accumulated in the harvested material. In 1997 at Morley, higher grain yields were recorded on the straw-incorporated treatments at the nil, 50, 100 and 150 kg N ha per year rates, resulting in higher ($P < 0{\cdot}05$) overall straw yields on the incorporation treatment. These results contrast with Johnston (1986), who reported yields increased by *c.* 10% where straw residues had been incorporated compared with burnt at comparable fertilizer loadings. At Gleadthorpe, the difference between estimated optimum grain yield and actual grain yield at nil nitrogen (ΔY) was almost always less on *incorporate treatments* than where straw residues had been burnt. This suggests that soil mineral nitrogen typically made a larger contribution to grain yield where residues had been incorporated rather than burnt. Such results could be due to the delayed release of N from incorporated residues following any initial immobilization phase, indicating that such residues may contribute to the N supply and yield of succeeding crops over the longer term.

Nitrate leaching losses were often similar or slightly reduced on the treatments where straw residues had been incorporated rather than burnt, although reductions were typically small (< 10 kg N ha), and usually not statistically significant. However, at Morley in the wet winter of 1994/95, straw incorporation reduced ($P < 0{\cdot}05$) nitrate leaching losses by *c.* 25 kg N ha per year. Also, in winter 1997/98 at Morley, there was a trend for lower soil solution nitrate-N concentrations ($P = 0{\cdot}07$) and nitrate leaching losses ($P = 0{\cdot}08$) where straw residues had been incorporated rather than burnt which, together with autumn soil mineral nitrogen data, provide some evidence of N immobilization caused by the straw residue's wide C:N ratio. Fertilizer N additions increased ($P \leqslant 0{\cdot}01$) the quantity of nitrate leached in drainage water every year at Gleadthorpe and in 1994/95 only at Morley.

The results from this project have confirmed that straw can successfully be incorporated into soils without compromising crop yields and quality, and that farmers do not need to adjust their fertilizer N application policies either to apply more fertilizer N in the short term (annually) to mediate N immobilization by straw or, in the longer term (*c.* 10 years) to apply less *fertilizer N to allow for increased N mineralization* from the added straw N reserves. Our results indicate that the current practice of annually incorporating cereal straw is unlikely to have a significant beneficial effect in reducing nitrate leaching or increasing crop production over the longer term.

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