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An analysis of the agronomic, economic and environmental effects of applying N fertilizer to sugarbeet (*Beta vulgaris*)

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SUMMARY

The effects of different rates of N fertilizer (0–180 kg N/ha) were tested on the growth, yield and processing quality of sugarbeet in 34 field experiments in England between 1986 and 1988. The experiments were performed using soil types, locations and management systems that were representative of the commercial beet crop in the UK. The responses obtained showed that current recommendations for N fertilizer use are broadly correct, but large differences occurred on some soil types, in some years, between the recommended amounts and the experimentally determined optima for yield. The divergence was largest when organic manures had been applied in the autumn before the beet crop. Calculations using a simple nitrate-leaching model showed that much of the N in the manures was likely to be leached, the extent of leaching being much less if the manure application was delayed until spring. In these circumstances, spring measurement of inorganic mineral N in the soil could improve fertilizer recommendations. In situations where higher than optimum rates of fertilizer N were used, the extra N had little effect on yield. Increasing the rate from 0 to 180 kg N/ha increased the amount of nitrate left in the soil at harvest by only 8 kg N/ha. The amount of inorganic N released into the soil from crop residues at harvest increased by 50 kg N/ha with N application rate, and the fate of this N has not been established.

INTRODUCTION

Each year, *c.* 18 kt of fertilizer N (worth more than £5 million) is applied to the UK sugarbeet crop. Whilst the fertilizer nitrogen (N) is cheap compared to other inputs – it accounts for only *c.* 5% of the total variable costs (Nix 1993) – there are sound physiological reasons, and obvious economic and environmental ones, for ensuring that the correct amount is applied. Sugar yield is closely correlated with the amount of solar radiation intercepted by the foliage of the beet crop (Milford *et al.* 1980; Scott & Jaggard 1993). Yields are increased by nitrogen primarily through increased leaf size (Milford *et al.* 1985*a*), acceleration of leaf area expansion (Milford *et al.* 1985*b*), and more efficient interception of solar radiation (Armstrong *et al.* 1983). However, overuse of nitrogen can decrease the biological and economic yield of sugar in several ways: first, large amounts of N unduly prolong leaf and shoot development at the expense of the growth and size of the storage root (Milford *et al.* 1988); second, excessive N alters the pattern of development and morphological structure of storage roots, thereby decreasing their sugar concentration (Milford 1973); finally, N increases the concentrations of α-amino nitrogen compounds within the storage root and this will decrease the efficiency of extraction of sugar at the factory (Pocock *et al.* 1990).

Current N fertilizer recommendations (i.e. MAFF 1994; Jaggard *et al.* 1995) are based upon the results of several hundred nitrogen response experiments, performed over many years using diverse soil types and management conditions. These recommendations are generally accurate when averaged over many sites and years, but problems may occur at individual sites or in particular seasons. Methods that are more site- and season-specific have been sought and one, the N_{min} method (Boon & Vanstallen 1983; Walther 1983), is now used commercially in Western Europe. However, this method still needs to be assessed for UK conditions. Better information is needed on the consequences of applying too much or too little nitrogen, either because N recommendations were wrong for a particular site or year, or because the grower did not follow a correct N recommendation.

Environmental concerns about nitrate in water have increased greatly since many of the N response studies were performed, and data specific to the UK sugarbeet crop, relating environmental risk to N fertilizer policy, need to be updated. The experiments described in this paper address these requirements.

MATERIALS AND METHODS

A series of experiments that tested application rates of nitrogen fertilizer ranging from 0 (N_0) to 180 (N_{180}) kg N/ha in 30 kg increments was undertaken on sugarbeet crops at 12 locations in East Anglia, Lincolnshire, Yorkshire and the West Midlands each year between 1986 and 1988. The sites were chosen to include the major soil types and management practices used to produce sugarbeet in the UK. The details of location, soil type and field management are given in Table 1. Where possible, each site was represented by a single farm, with the experiments on a different field each year according to the farm's normal rotation. The experiments at Shereford in 1987 and Ramsey in 1988 were abandoned because of uneven plant populations and pest and disease damage. All crops were sown between mid-March and mid-April and were grown according to standard commercial practice for basal fertilizers and pesticides (Jaggard *et al.* 1995). Cultivars sometimes differed between sites and years. Crops grown at Broom's Barn were irrigated using a boom irrigator so that limiting soil moisture deficits were not exceeded (Jaggard *et al.* 1995).

The seven N fertilizer treatments (N_0–N_{180}) were randomized within each of five blocks. The fertilizer was applied by hand as ammonium nitrate; 30 kg N/ha was applied at drilling (where appropriate) and the remainder when the crop had 2–4 true leaves. Each plot was 12 × 3 m, of which the centre 8 × 2 m was harvested manually to assess yield in the autumn.

At harvest, plants were topped at the height of the first leaf scar and the roots counted. Twenty tops (i.e. crown plus petioles and leaves) from each plot were weighed in the field and a subsample of five tops was dried at 85 °C for 48 h and weighed. All of the beet from each plot were washed and weighed (clean beet weight) and a subsample of the roots was taken with circular saws. This subsample was extracted with basic lead acetate, for measurement of the sucrose, α-amino N, Na and K contents by standard methods (Last *et al.* 1976). A further subsample of brei was dried at 85 °C. The dried samples of tops and brei were milled (< 1 mm), and their total N contents determined by Kjeldahl digestion modified to include nitrate (AOAC 1955).

Just before sowing, the soil ammonium and nitrate

Table 1. *Locations of the experimental fields in the three years 1986–88 and the percentages of carbon (C), sand (S, 60–2000 μm) and silt (Z, 2–60 μm) in the topsoil, previous cropping, and use and year of application of farmyard (FYM) and poultry manures (PM)*

		Typical topsoil analysis			Crops preceding the sugarbeet crop			Organic manure usage		
Experimental site	County	%C	%S	%Z	1986 Expt	1987 Expt	1988 Expt	1986 Expt	1987 Expt	1988 Expt
Broom's Barn	Suffolk	0·7	72	17	Winter barley	Winter barley	Winter barley	None	None	None
Shereford	Norfolk	1·6	78	15	Triticale	Winter barley	Winter barley	None	None	None
Norton	Shropshire	1·7	50	34	Winter wheat	Winter barley	Winter wheat	FYM 1985	FYM 1986	FYM 1987
Shifnal	Shropshire	1·3	81	12	Grass ley	Grass ley	Winter barley	None	None	None
Bracebridge	Lincolnshire	1·9	74	11	Vining peas	Spring barley	Vining peas	None	None	None
Elkesley	Nottinghamshire	1·2	75	18	Winter barley	Winter barley	Winter barley	None	None	None
Heslington	N. Yorkshire	1·8	78	10	Potatoes	Winter wheat	Winter wheat	PM 1985	None	None
Litlington	Cambridgeshire	2·8	32	45	Winter wheat	Winter barley	Winter wheat	None	None	None
Bedingfield	Suffolk	2·1	58	17	Winter wheat	Winter wheat	Winter wheat	None	PM 1986	None
Walpole	Norfolk	2·2	7	61	Winter wheat	Winter wheat	Winter wheat	None	None	None
Ramsey	Cambridgeshire	12·6	0	46	Winter wheat	Winter wheat	Winter wheat	None	None	None
Ridlington	Norfolk	1·3	43	46	Winter barley	Winter barley	Winter barley	PM 1985	PM 1986	PM 1987

Table 2. *Variance ratios for year and year × site effects and for N, N × year, and N × year × site effects and means for the main effects of season and nitrogen on yield, quality attributes and N uptake. Means for years are averaged over sites, and N treatments and those for N treatments are averaged over years and sites*

	Variance ratios and source of variation				
Variate	Year (2 D.F.)	Year × Site (31 D.F.)	N (6 D.F.)	N × Year (12 D.F.)	N × Year × Site (186 D.F.)
Plant population density (1000s/ha)	129·0	40·4	18·9	0·7	1·1
Clean beet yield (t/ha)	170·6	71·4	298·0	5·0	3·7
Root sugar content (%)	786·1	104·2	93·2	1·1	2·0
Sugar yield (t/ha)	184·0	82·2	235·6	6·8	4·3
Adjusted tonnage clean beet (t/ha)	207·5	86·5	207·6	7·3	4·4
Amino-N impurities (mg/100 g sugar)	37·7	49·8	420·2	1·4	2·5
K impurities (mg/100 g sugar)	110·6	131·6	19·9	6·9	2·2
Na impurities (mg/100 g sugar)	413·2	64·5	80·7	5·0	2·4
Top N uptake (kg N/ha)	6·7	15·6	217·1	1·1	1·4
Total N uptake (kg N/ha)	0·9	26·8	374·9	1·3	1·4

Table of means

Year				N application rate (kg N/ha)							
1986	1987	1988	S.E.	0	30	60	90	120	150	180	S.E.
83·8	85·0	93·0	0·44	89·7	88·9	88·1	86·9	86·9	84·6	85·0	0·44
48·3	53·7	56·3	0·32	45·4	49·8	52·3	54·2	55·2	55·4	56·1	0·23
18·6	17·3	18·5	0·02	18·3	18·3	18·3	18·2	18·1	18·0	17·8	0·02
8·98	9·30	10·38	0·053	8·29	9·12	9·58	9·87	9·98	9·96	9·96	0·04
59·6	60·0	68·7	0·35	54·6	60·1	63·2	65·0	65·5	65·2	65·0	0·63
96·6	80·7	89·5	1·30	57·1	65·1	73·9	84·6	98·4	112·7	130·4	1·27
944	1012	921	4·3	946	943	942	958	961	970	991	4·0
50·9	84·4	44·0	1·04	48·7	49·6	53·7	58·7	64·1	67·7	74·3	1·07
114·1	121·2	111·9	1·85	79·1	91·1	103·5	116·2	128·7	137·5	153·8	1·80
185	188	185	2·0	132	151	170	188	205	218	239	2·0

There were 136 residual D.F. on the year × sites × block stratum and 801 D.F. on the year × sites × block × N stratum.

nitrogen content (N_{min}) of the N_0 plots of blocks 1, 3 and 5 was measured to a depth of 90 cm in 30 cm increments. At harvest in the autumn, the N_0 plots were sampled again, together with the N_{180} plots and the plots that had received the N fertilizer rate closest to the currently recommended amount for the particular site. One soil core was taken per plot. All soils were refrigerated and extracted within 2–3 days of sampling with 0·5 M K_2SO_4 and the nitrate and ammonium content determined by steam distillation and titration. Appropriate values of bulk density for each soil were used to convert the measured inorganic N content to kg N/ha.

The amounts of inorganic N mineralized from the soil organic matter during the growing season were indirectly estimated by subtracting the amount of mineral N present in the soil in spring from that contained in the crop and soil at harvest.

The yields were converted to adjusted tonnages of clean beet (ACB) by standardizing their sugar concentrations to 16%. These tonnages were further corrected by subtracting a weight of beet equivalent in value to the cost of the N fertilizer. In calculating these corrected and adjusted yields of clean beet (CACB) the clean beet was valued at the 1992 'C contracted tonnage' price of £14.48/tonne (Allison & Hetschkun 1995), and the N fertilizer at £0.29/kg. The CACB yields (y) were related to rates of applied N (x) using the exponential plus linear model as used by George (1984) and Neeteson & Zwetsloot (1989):

$$y = a + br^x + cx \qquad (1)$$

Best fit values were obtained for the parameters r and c by using all the data, but different values were calculated for parameters a and b for each site in each year. This produced curves of similar shape in which the asymptotes were displaced horizontally and vertically in accordance with the effects of site and season. The intersept of the asymptote with the ordinate gave the optimum economic yield (N_{opt}) and its intersect with the abscissa, the optimum amount of N fertilizer required to achieve the optimum economic yield (N_{opt}). The efficiency of use of fertilizer N was estimated as the slope of the linear regression relating the total N content of the crop at harvest to the amount of N fertilizer applied. The N content of the crops at optimum economic yield were calculated by substituting values of N_{opt}, obtained from the response curve, into the linear regressions.

The effects of N rate and season, and their interaction with site, on the actual and maximum economic yields, quality attributes, N_{opt} and N uptake at maximum economic yield were analysed by analysis of variance.

RESULTS AND DISCUSSION

Plant population densities, yield and fertilizer N requirement

The overall mean plant population for the 12 sites ranged from 83800 plants/ha in 1986 to 93000/ha in 1988, and plant numbers were significantly decreased by high rates of fertilizer N (Table 2). Even so, the plant populations usually exceeded the 75000 plants/ha needed to attain maximum yield potential (Jaggard *et al.* 1995). The effect of N fertilizer on plant population density is well known (Draycott 1972, 1993).

The yield of clean beet, averaged over all sites, years and N treatments was 52·6 t/ha. Increasing the amount of N fertilizer from 0 to 180 kg N/ha increased beet yield by *c.* 10 t/ha. Conversely, the effect of N on sugar percentage was to decrease it by *c.* 0·5%. The net result was that maximum white sugar yield was attained at *c.* 120 kg N/ha (Table 2).

The exponential and linear model fitted the data well (Fig. 1). Standard errors for yield averaged *c.* ±1 t/ha, whilst the standard errors for fertilizer N averaged *c.* ±10 kg N/ha (Table 3). Overall, the optimal economic yield ranged from 35 t/ha at Litlington to 90 t/ha at Ridlington in Norfolk, both in 1986 (Table 3). The particularly small yield at Litlington was probably due to damage from herbicide residues. Generally, there was no consistent effect of soil type on yield, although peaty soils (Ramsey) always yielded more, and chalk soils (Litlington) less, than average. The mean, national adjusted yields of clean beet in 1986, 1987 and 1988 were 46·6, 42·5 and 46·3 t/ha respectively (Licht 1989). The large difference between our experimental and the national yields may be due to the selected field sites not being wholly representative of the national crop, but is more likely to be due to the experiments being hand-harvested and grown in the more productive parts of the field and specifically excluding the low-yielding headlands (Scott & Jaggard 1993). The amounts of N fertilizer required to achieve the economic optimum yield ranged from nil at Ramsey in 1987 to 158 kg N/ha at Shereford in 1986 (Table 3). The mean values of N_{opt} in 1986, 1987 and 1988 were 96, 81 and 115 kg N/ha respectively, and the corresponding value for currently recommended rates (based on soil type and

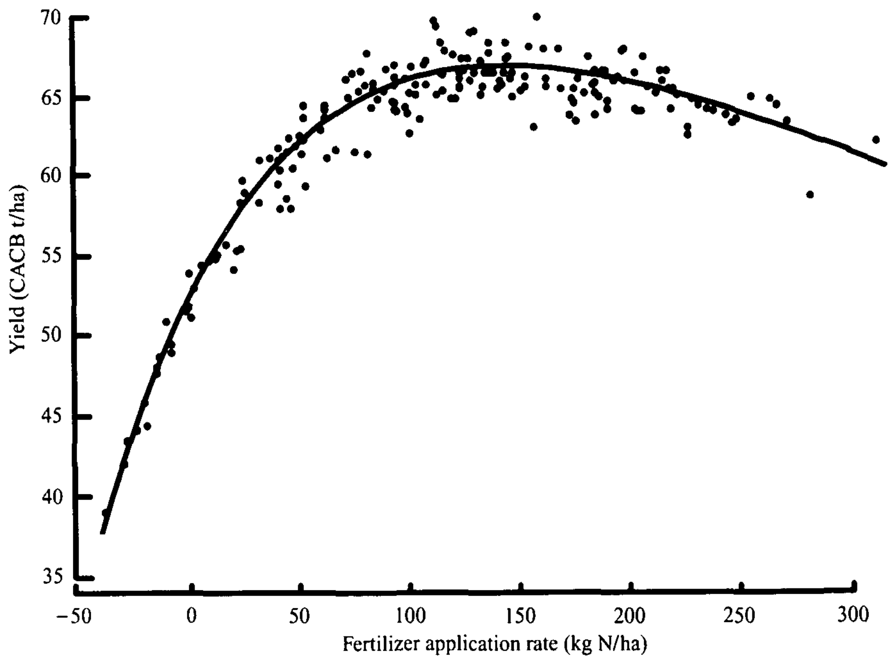

Figure 1. The relationship between corrected adjusted clean beet yield and N application rate for 34 experiments performed between 1986 and 1988. Curves for individual sites have been adjusted horizontally and vertically so that they correspond to the fitted line for Broom's Barn 1986.

Table 3. *Uptake of unfertilized N_0 crop and efficiency of fertilizer use as estimated by the intercept and slope of regressions of N uptake against N applied, and the economic optimal yield and crop N content at Y_{opt} for sugar beet crops grown at 12 sites between 1986 and 1988. Means are averaged over sites. Standard errors* (S.E.) *are in parentheses*

	Nitrogen uptake parameters				Yield, N requirement and N uptake at optimum					
Year/Site	N uptake of N_0 crop (kg N/ha)		Efficiency of fertilizer use (%)		Y_{opt} (t/ha)		N_{opt} (kg N/ha)		N uptake (kg N/ha)	
1986										
Broom's Barn	121	(4·9)	40	(4·5)	66	(0·8)	120	(6·6)	169	(4·6)
Shereford	57	(8·6)	76	(8·0)	65	(0·9)	158	(6·3)	184	(4·3)
Norton	124	(7·0)	76	(6·4)	68	(0·7)	78	(9·7)	170	(4·8)
Shifnal	154	(10·0)	66	(9·3)	40	(0·7)	80	(9·5)	203	(5·6)
Bracebridge	92	(1·2)	62	(1·1)	57	(0·8)	126	(6·4)	177	(6·2)
Elkesley	76	(3·8)	87	(3·5)	56	(0·9)	147	(6·1)	218	(5·3)
Heslington	116	(7·0)	74	(6·5)	67	(0·8)	139	(6·2)	183	(4·2)
Litlington	100	(6·6)	51	(6·1)	35	(0·6)	53	(13·3)	235	(5·6)
Bedingfield	155	(9·9)	40	(9·2)	71	(0·7)	71	(10·5)	234	(4·3)
Walpole	151	(10·1)	89	(9·3)	67	(0·6)	32	(17·6)	126	(4·8)
Ramsey	223	(10·9)	35	(10·1)	72	(0·6)	35	(17·0)	207	(4·1)
Ridlington	185	(10·0)	46	(9·3)	90	(0·7)	108	(7·2)	180	(5·7)
1987										
Broom's Barn	93	(3·2)	53	(3·0)	66	(0·9)	142	(6·1)	168	(5·4)
Norton	150	(6·4)	62	(5·9)	62	(0·7)	95	(8·1)	213	(6·0)
Shifnal	131	(7·6)	45	(7·1)	45	(0·6)	51	(13·6)	158	(4·1)
Bracebridge	111	(2·6)	53	(2·4)	49	(0·7)	88	(8·7)	187	(5·0)
Elkesley	89	(5·6)	74	(5·2)	62	(0·8)	133	(6·2)	231	(4·3)
Heslington	191	(8·7)	58	(8·1)	69	(0·6)	69	(10·8)	208	(4·1)
Litlington	109	(6·7)	51	(6·2)	55	(0·7)	107	(7·2)	198	(8·3)
Bedingfield	203	(11·1)	36	(10·3)	73	(0·7)	27	(19·0)	202	(4·5)
Walpole	139	(8·8)	56	(8·2)	60	(0·7)	74	(10·3)	164	(4·3)
Ramsey	204	(5·3)	36	(4·9)	72	(1·1)	−16	(34·5)	154	(4·9)
Ridlington	120	(3·5)	70	(3·3)	75	(0·8)	118	(6·7)	181	(4·2)
1988										
Broom's Barn	133	(4·2)	58	(3·9)	81	(0·8)	117	(2·0)	202	(4·5)
Shereford	125	(6·1)	61	(5·6)	78	(0·8)	134	(6·2)	174	(5·7)
Norton	138	(5·0)	65	(4·6)	70	(0·7)	82	(9·3)	190	(4·2)
Shifnal	179	(7·8)	56	(7·2)	72	(0·7)	85	(9·0)	179	(4·8)
Bracebridge	136	(3·2)	53	(3·0)	67	(0·7)	104	(7·5)	207	(5·1)
Elkesley	108	(5·0)	56	(4·6)	71	(0·8)	126	(6·4)	233	(5·2)
Heslington	141	(11·4)	66	(10·5)	86	(0·8)	138	(6·2)	192	(4·1)
Litlington	119	(6·7)	45	(6·2)	68	(0·8)	135	(6·2)	225	(4·1)
Bedingfield	87	(6·3)	59	(5·8)	66	(0·9)	147	(6·1)	179	(5·1)
Walpole	124	(10·6)	70	(9·8)	62	(0·7)	97	(8·0)	226	(4·1)
Ridlington	160	(7·5)	66	(7·0)	76	(0·7)	98	(7·9)	191	(4·1)
Table of means										
1986	129		62		63		96		191	
1987	140		54		63		81		188	
1988	131		60		72		115		200	
	(11·6)		(4·1)		(3·3)		(11·6)		(7·7)	
Mean 1986–88	134		59		66		97		193	

previous history: MAFF 1994, Jaggard *et al.* 1995) were 105, 88, and 95 kg N/ha (Table 4). The reasonable agreement between these values suggests that current recommendations are broadly correct. However, the current N fertilizer recommendations were within ±25 kg/ha of the experimentally determined value in only 19 out of the 36 site × season experimental combinations. The current recommendations underestimated the N requirement by 25–50 kg/ha on four occasions and by 70–90 kg/ha on four more. Surprisingly, most of these soils had received inputs of organic manures or were grown

Table 4. *Values for the currently recommended N application rate for each site (Nr) and the amount of inorganic N in the soil (0–90 cm) at sowing and at harvest for three N application rates; no N fertilizer (N0), Nr and 180 kg N/ha (N180). The amount of N mineralized during the growing season was estimated from soil and crop measurements made on the N0 plots*

	Currently recommended N rate	Amount of soil inorganic N at sowing		Amount of N mineralized during season		Amount of inorganic N in soil at harvest (kg N/ha)			
Year/Site	(kg N/ha)	(kg N/ha)	S.E.	(kg N/ha)	S.E.	N0	Nr	N180	S.E.
1986									
Broom's Barn	120	34	0·9	99	13·6	11	13	18	1·0
Shereford	120	50	8·6	58	26·7	46	21	25	10·1
Norton	60	73	3·8	72	2·4	18	22	26	0·7
Shifnal	90	59	3·0	132	28·5	23	29	42	1·7
Bracebridge	120	41	2·3	68	7·3	13	17	21	0·9
Elkesley	120	46	1·5	74	1·9	22	29	34	0·9
Heslington	120	104	13·4	26	14·7	23	28	36	1·5
Litlington	120	79	5·1	52	12·7	29	36	43	4·8
Bedingfield	90	120	34·0	38	35·2	30	36	45	2·7
Walpole	120	66	2·3	101	15·9	15	22	25	1·3
Ramsey	60	129	5·7	132	12·8	41	104	109	35·4
Ridlington	120	56	1·6	141	2·5	20	22	28	0·8
1987									
Broom's Barn	120	67	1·7	39	7·5	17	16	20	3·8
Norton	60	82	4·3	114	14·1	30	28	28	4·6
Shifnal	90	119	17·7	45	21·7	29	34	54	5·7
Bracebridge	120	60	1·9	60	5·9	12	13	20	2·0
Elkesley	120	45	4·9	61	4·7	15	21	22	1·0
Heslington	120	58	4·9	161	36·1	38	38	42	1·1
Litlington	90	42	4·7	88	10·9	18	23	31	1·5
Bedingfield	90	59	7·0	192	48·3	25	20	24	3·4
Walpole	120	62	4·4	101	7·1	11	15	24	2·0
Ramsey	60	90	7·3	128	17·0	26	30	30	2·7
Ridlington	60	54	5·9	87	10·2	16	16	22	1·0
1988									
Broom's Barn	120	26	0·7	121	16·1	18	21	13	2·6
Shereford	120	7	3·1	131	13·3	16	38	25	9·0
Norton	90	52	21·2	102	26·6	15	35	22	6·3
Shifnal	90	38	5·2	180	24·6	50	36	41	6·2
Bracebridge	120	35	3·7	119	12·6	20	17	25	4·2
Elkesley	120	28	1·5	97	1·2	24	30	29	4·7
Heslington	120	28	4·8	110	10·2	13	9	11	2·1
Litlington	90	37	6·3	114	14·5	27	32	32	2·7
Bedingfield	90	35	4·7	57	2·9	13	15	24	5·7
Walpole	120	51	20·1	79	26·4	16	16	16	*
Ridlington	60	21	3·0	149	3·2	16	22	25	4·7
Table of means									
1986		71		83		N0	Nr	N180	
1987		67		98		22	27	30	1·3
1988		33		115					
S.E.		7·0		11·9		1986	1987	1988	
						31	25	23	2·6

* Values from one replicate only.

after crops leaving large amounts of N residues. On a further five occasions, the current recommendations overestimated the requirement by 50–70 kg/ha.

One explanation of the large underestimate of fertilizer requirement on organically manured soils could be that little of the nitrate N derived from the manures was recovered by the beet crop. The SUNDIAL model (Bradbury *et al.* 1993) was used to simulate N dynamics in these experiments. The model showed that nitrate released from autumn-applied organic manures could be leached beyond the fibrous root system of beet, or would be taken up late in the season. Most manures are ploughed down and this, too, could increase the depth to which the nitrate was leached. Pocock *et al.* (1990) showed that organically manured sugarbeet crops usually have large N uptakes, and large concentrations of α-amino N compounds. The total N uptakes by the plant and α-amino N concentration in the beet in crops grown at Norton (where farmyard manure was used) and Ridlington (where poultry manure was used) were similar to those of unmanured crops (data not shown). This also supports the suggestion that nitrate mineralized from the organic manures was leached beyond the reach of the crop.

Surveys made by British Sugar plc between 1990 and 1994 show that *c.* 25% of the national beet crop receives organic manure, mainly as farmyard or poultry manure. About 60% of the fields that receive organic manures are sands or sandy loams i.e. soils with small water-holding capacity that readily leach. The average rates of application are 30 t/ha for farmyard manure and 15 t/ha for poultry manure, and these manures are capable of releasing *c.* 45 and 150 kg N/ha as nitrate, respectively (Archer 1985). At these rates and times of application, organic manures represent a potential waste of a useful resource and a significant environmental problem.

Relationships between N_{min}, N mineralized and N fertilizer requirement

Several workers have shown that the optimal amount of fertilizer N required by the sugarbeet crop to achieve maximum economic yield is inversely proportional to the amount of mineral N present in the soil in spring (Boon & Vanstallen 1983; Walther 1983; Last *et al.* 1994). In the current experiments, the soil N_{min} present within the top 90 cm of soil at drilling, averaged over all sites, was *c.* 70 kg/ha in 1986 and 1987 but only 33 kg/ha in 1988 (Table 4). At individual sites, the amounts in the first two years ranged from 34 kg/ha at Broom's Barn to 129 kg/ha at Ramsey. In 1988, the amounts ranged from only 7 kg/ha at Shereford to 51 kg/ha at Walpole and Ridlington. There were much greater amounts in peat soils (i.e. Ramsey in 1986 and 1987), at sites where the preceding crops were potatoes (Heslington in 1986) or grass leys (Shifnal in 1987 and 1988), and where farmyard manure had been applied (Norton in all three years). An exceptionally large amount was present at Bedingfield in 1986, without apparent cause. The amounts present at Ridlington in all three years and Bedingfield in 1987 were relatively small (averaging *c.* 50 kg N/ha) even though large amounts of poultry manure had been applied: probably much N had been lost by leaching or ammonia volatilization. Linear regressions showed that this variation in soil mineral N to 90 cm depth accounted for only 28% of the variance in N_{opt} and 33% of the variance if the top 60 cm depth is considered (Fig. 2). These percentages are similar to those observed by Neeteson & Zwetsloot (1989), who concluded that, during spring and early summer, soil within the 60–100 cm horizon contributed little mineral N to the crop. However, Brown & Dunham (1986) showed that the soil is exploited by the fibrous root system of sugarbeet to a depth of 60 cm within *c.* 70 days of sowing, and deeper within the following few weeks. Also, measurements of soil mineral N at harvest in the present experiments indicated that the soil below the 60 cm layer had been depleted. One explanation for the discrepancy could be that the greatest influence on growth and sugar yield are the extent of foliage growth and solar radiation interception between May and June when solar radiation receipts are greatest, i.e. between 60 and 120 days from sowing (Scott & Jaggard 1993). At this time, mineral N present at depth is unlikely to be exploited and thus influence yield, even though it may be taken up later.

The drainage capacity of the soil can be taken into account when relating N_{opt} to the mineral N within the top 60 cm of the soil in spring by including the percentage of sand in the uppermost 30 cm of soil as an additional variate in the regression. By doing this, the regression equations in Fig. 2 can be improved:

$$N_{opt} = 98 - 0{\cdot}83N_{min60} + 0{\cdot}63\,\%S \quad (r^2 = 46{\cdot}4\,\%) \quad (2)$$

where N_{min60} is the N_{min} to 60 cm and S is the percentage sand (i.e. particle size 2 mm–60 μm) in the 0–30 cm soil layer. This may be due to the extra variate accounting for any or all of the following: the increased risk of leaching, the reduced N mineralization capacity or interactions between crop growth and water supply. None of the above measurements predicted N_{opt} particularly well and hence may only be of limited value in predicting the N fertilizer requirement, but combining measurements of N_{min} with models of soil water and nitrate movements may improve predictions (Addiscott & Darby 1991) and this needs further investigation. The relationship between N_{opt} and N_{min} may also be of more use where the amounts of mineral N in spring are likely to be variable, such as on organic soils or those receiving large inputs of organic manures, as has been shown to be the case for winter wheat (Shepherd 1993).

The amounts of N mineralized from soil organic matter during growth were estimated indirectly from the soil and crop N balances of crops grown without fertilizer N. Large amounts (> 120 kg/ha) were apparently mineralized where crops were grown on organic soils (Ramsey), after ploughing down grass leys (Shifnal), where poultry manures had been applied (Ridlington, Bedingfield and Heslington in

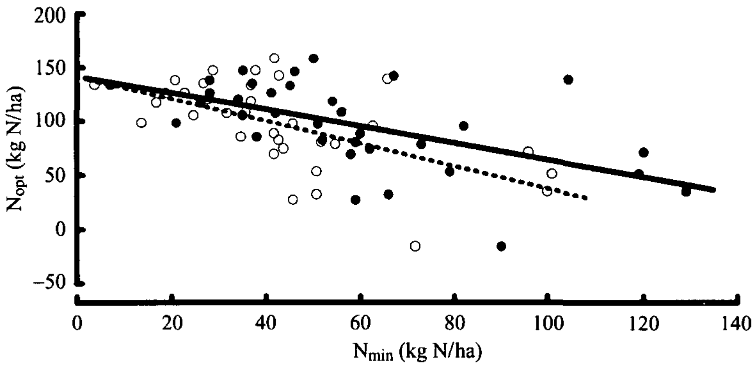

Figure 2. The relationship between the optimal N application (N_{opt}) and the amount of soil inorganic N (N_{min}) at drilling to a depth of 90 cm (—) and to a depth of 60 cm (– – –). The variables are related by the regression $N_{opt} = 142 - 0{\cdot}78\ N_{mins90}$ ($r = -0{\cdot}53$, $P < 0{\cdot}001$); or the regression $N_{opt} = 142 - 1{\cdot}04\ N_{mins60}$ ($r = -0{\cdot}58$, $P < 0{\cdot}001$).

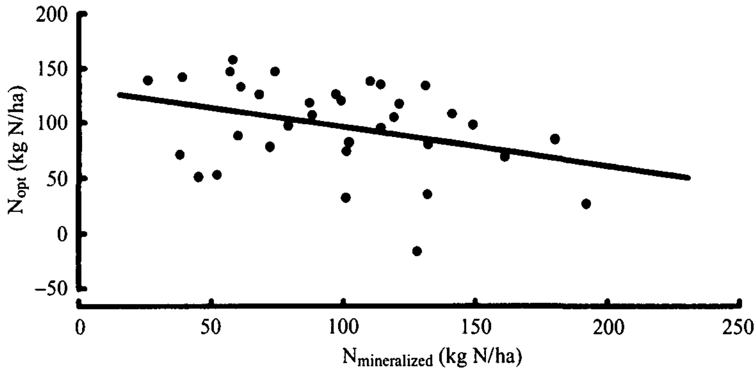

Figure 3. The relationship between the optimal N application (N_{opt}) and the amount of N mineralized during the growing season ($N_{mineralized}$). The variables are related by the regression $N_{opt} = 131 - 0{\cdot}35\ N_{mineralized}$ ($r = -0{\cdot}31$, $P = 0{\cdot}042$).

1987) and sometimes after vining peas (Bracebridge, 1988). However, amounts almost as large were sometimes mineralized at other sites (e.g. Broom's Barn and Shereford in 1988) for which there was no immediately apparent reason. Soil temperature and moisture may have been factors (Allison 1994). These results indicate that the assumption of a typical mineralization value for a particular site in the estimation of the N fertilizer requirement could lead to large errors.

The method used to estimate N mineralization is prone to large errors (Allison 1994), so although mineralization supplied *c*. 40% of the N requirement of the crop, it was not surprising that the weak inverse correlation with N mineralization accounted for < 10% of the variance in fertilizer N requirement (Fig. 3).

The sum of mineral N present in the soil in spring and that mineralized from soil organic matter during growth is an estimate of a soil's total supply of inorganic N. This total explained a larger proportion of the variation (51%) in N_{opt} than in its individual components (Fig. 4). However, this is of little practical use in estimating the fertilizer requirement because the mineralized amount can only be estimated retrospectively.

Nitrogen uptake and efficiency of fertilizer N use

It has been suggested that a nitrogen uptake of 200–250 kg/ha is necessary to obtain maximum yield (Armstrong & Milford 1985; Draycott 1993). The uptakes of 15 of the 34 crops studied in the experiments reported here were within this range, but 19 of the crops contained < 200 kg N/ha with seven having uptakes < 175 kg/ha (Table 3). The latter uptakes were probably for crops whose growth was restricted by drought, virus yellows disease or other factors.

The variability of N uptake at N_{opt} precludes the use of an average N uptake value in calculations to estimate fertilizer requirement. A more robust method may be to use the relationship between the increase in

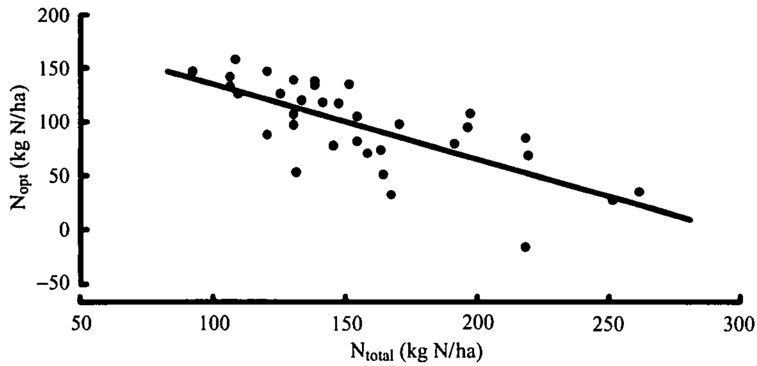

Figure 4. The relationship between the optimal N application (N_{opt}) and the total amount of soil-derived inorganic N available to the crop (N_{total}). The variables are related by the regression $N_{opt} = 206 - 0{\cdot}70\ N_{total}$ ($r = -0{\cdot}71$, $P < 0{\cdot}001$).

leaf area and N uptake (Scott & Jaggard 1993). Each unit of leaf area requires 40 kg N/ha, and efficient crops have leaf area indices of *c.* 3·5. Fertilizer N could then be added, to supplement N_{min}, so that this leaf area can be created rapidly and without N limitation.

The apparent efficiency of fertilizer N use was estimated from the slopes of the linear regressions relating crop uptake to the amount applied. These regressions explained, on average, 86% of the variation in N uptake. The efficiencies of fertilizer use varied from 35% at Ramsey to 89% at Walpole, both in 1986. The average efficiencies in 1986, 1987 and 1988 were 62, 54 and 59%. Hills *et al.* (1978), using ^{15}N-labelled fertilizer showed that efficiency of uptake decreased from 56 to 22% as the application rate increased from 56 to 280 kg N/ha; at the mean recommended rate of 112 kg N/ha the efficiency was 46%. Other workers, using ^{15}N fertilizers, have obtained recoveries at the recommended rate of 48% (ITB 1988) and 60% (Powlson 1994).

The main determinants of fertilizer efficiency are the amounts of fertilizer immobilized by the soil microflora and the amount lost from the crop/soil system. Both French and British research has shown that insufficient or excessive rainfall between April and June decreases the efficiency of fertilizers (ITB 1987; Powlson 1994). The decrease in efficiency with increasing amounts of rain was most likely due to denitrification, since the rainfall was unlikely to leach nitrate beyond the reach of the fibrous root system.

Variable amounts of fertilizer N are immobilized by the soil microflora. The French and British studies referred to above showed that between 21 and 24% of the fertilizer N was immobilized; Abshahi *et al.* (1984), however, found that 45% of the applied ^{15}N was immobilized. The differences may be due to soil type or the effect of season although in the case of sugarbeet, recent work indicates that cultivar and plant population density may also be important (M. F. Allison, unpublished).

The economic and environmental consequences of N fertilizer application

Applying too little fertilizer N causes loss of yield; too much may also reduce yield and will certainly reduce processing quality and increase the risk of N loss to the environment.

Losses of yield resulting from over- or under-application of fertilizer can be estimated from the response curve (Fig. 1). Because of the shape of the curve, small deviations in the amounts of N applied have only a small effect on yield near the optimum, but under-applications of N cause larger yield losses than over-applications. Under-applications of 30 or 60 kg N/ha would result in yield losses of *c.* 0·4 or 1·7 t/ha respectively, whilst over-applications would decrease yields by 0·3 and 1·4 t/ha respectively. In some experiments the recommended amounts of N fertilizer were between 75 and 90 kgN/ha less than optimal, equivalent to a loss of *c.* 4·5 t/ha in ACB yields. This loss was independent of site or year and therefore was relatively larger at sites where yields were small than at sites where they were large. Most growers aim to grow 10–20% of beet in excess of their contracted tonnage so as not to jeopardize their future allocation. Under-applications of N by as much as 60 kg/ha are, therefore, unlikely to threaten contracted tonnage production. A failure to meet the required yield through inadequate N is more likely when the yields have already been reduced by environmental stresses or pests and diseases. However, an over-application is likely to affect beet quality adversely.

Beet processing quality

The effect of fertilizer N on processing quality is well known (Draycott 1972). Large amounts of N fertilizer increase the quantities of soluble-N (mainly as α-amino N and betaine) in the root (Pocock *et al.* 1990) and this reduces the efficiency of sucrose extraction within the factory. Application of N fertilizer caused a shallow, exponential increase in α-amino N impurity, on average from 57 to 130 mg/100 g sugar at the extreme rates of fertilization (Table 2). The two monovalent cations, Na and K, are also impurities: both were increased by applications of N fertilizer, but the relative increase was much smaller in the case of K (Table 2). For a fuller analysis of the effect of N on root impurities see Pocock *et al.* (1990).

In all three seasons, < 50 kg/ha remained in the soil at harvest at most sites. An exception was Ramsey in 1986 when > 100 kg N/ha was left after harvest of N-fertilized crops. The amount of N left in the soil increased slightly with the amount of N fertilizer applied (Table 4). The inorganic N was predominantly nitrate (*c.* 95%). On average, increasing the N fertilizer rate from 0 to 180 kg N/ha increased the amount of inorganic N residues by only 8 kg N/ha. Powlson (1994) showed that *c.* 1% of ^{15}N fertilizer remained as inorganic N at harvest. Similar results were obtained by Abshahi *et al.* (1984) in the USA.

The amount of N contained within the tops, and therefore likely to be returned to the soil, was increased by N fertilization (Table 2), and the C:N ratio of the tops decreased. An empirical relationship between C:N ratio and the mineralization of N from crop residues (Jenkinson 1985) has been used to estimate the effects of N fertilization on N release. Over the fertilizer input range 0–180 kg N/ha, the amount of N mineralized from ploughed-in tops was likely to increase linearly from *c.* 20 to 70 kg N/ha. The fate of this N is not clear. Widdowson (1974) showed that only 8 kg of the 130 kg N/ha returned to the soil as beet tops was recovered in a subsequent barley crop, and Destain *et al.* (1990), using an ^{15}N technique, showed that only 7% of the N in sugarbeet tops was recovered in a subsequent winter wheat crop and 67% was lost from the crop/soil system, probably through denitrification. Using ^{15}N, Abshahi *et al.* (1984) showed that 27% of the N in sugarbeet tops was recovered by a subsequent wheat crop, 39% remained in the soil and 34% was not accounted for and was assumed to be lost to the atmosphere. Olsson & Bramstorp (1994) estimated that, of the 100 kg N/ha returned to the soil in sugarbeet tops, 20–30% was lost as ammonia, 10% was leached as nitrate and 55% was retained in the soil; the remaining 10–15% was unaccounted for. Gaseous loss of N therefore seems important. Currently, beet tops are ploughed-in on *c.* 90% of the sugarbeet acreage in the UK. In total, these contain *c.* 18 kt N, an amount equivalent to the total amount of fertilizer N used on the crop. Improved management systems are needed to minimize the impact of this nitrogen on the environment whilst retaining its value in maintaining or improving soil fertility.

CONCLUSIONS

This paper shows that current recommendations for the N fertilization of the sugarbeet crop, although generally correct, need to be made more site-specific. Recommendations are often inaccurate when organic manures have been applied. Organic manure applied in the autumn preceding beet is vulnerable to N leaching, particularly when applied to sandy and sandy loam soils and when rainfall is above average. The large amounts of N contained within organic manures is a potential environmental risk and, ideally, organic manures should be applied in spring to reduce the risk of leaching and make them a more predictable source of N. Measurements of mineral N in the soil in spring may be useful in estimating the required amounts of fertilizer, particularly on organically manured or organic soils. The cost of soil sampling, analysis and interpretation is, at present, only likely to be justified by fertilizer saved or in increased yield or improved processing quality on crops that have received a large dressing of organic manures. On an individual farm, the over- or under-application of N fertilizer is unlikely to result in a failure to achieve contracted tonnage; however, this may occur on sites where yields are already low for other reasons. On a national or regional industrial scale, small changes in yield and processing quality may significantly affect processing efficiency and long-term competitiveness. The amount of nitrate-N left in the soil at harvest is insensitive to N fertilizer input and any modification of fertilizer regime is unlikely to have much effect on nitrate leaching immediately after harvest. However, large amounts of N are returned to the soil within ploughed-in beet tops. With larger rates of N fertilizer, more of the N derived from the tops is mineralized to nitrate and lost to the environment. Management techniques need to be developed to minimize these losses so that the tops may be used more efficiently in maintaining soil fertility.

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