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DEVELOPMENT AND PREDICTION OF SULPHUR DEFICIENCY IN WINTER OILSEED RAPE

by

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ABSTRACT

Amounts of sulphur (S) deposited from the atmosphere and of extractable S in the soil at 30, 60 and 90 cm depths were monitored at periodic intervals through the growing season in 16 field experiments evaluating crop response to spring-applied S fertilizer (40 or 50 kg S/ha) during the 1991-92 and 1992-93 seasons. Large significant ($P < 0.1$) increases in seed yield, ranging from 15% to 74%, were obtained at 5 sites located on sandy soils or shallow soils over chalk in Scotland, northern, south-west and eastern England. Transient symptoms of S deficiency were observed at a further 4 sites in these areas but there was no yield response. Seed glucosinolate concentrations were increased 2-3 fold by application of S at S-deficient sites, although this was not consistent. Total amounts of S deposited from the atmosphere in 1993 ranged from 9.3 to 17.6 kg/ha and were lowest in Scotland. There was wide variation between sites in the amounts of S in the soil profile to 90 cm but no difference in amounts of S at any depth between autumn and spring. Crop uptake of S was significantly increased by addition of fertilizer S at most sites but did not exceed 55 kg/ha.

Yield responsive sites were distinguished by a low (< 4 mg/g) concentration of S in young fully expanded leaves at flowering. There was a significant relationship between leaf S content at this growth stage and the concentration in the soil, either to 30 cm or averaged over the soil profile, of extractable sulphate-S as measured by ion chromatography (IC) and extractable total S as measured by inductively coupled plasma atomic emission spectrometry (ICP-AES). Inorganic SO_4-S measured by IC was, on average, 50%, 60% and 70% of soil S measured by ICP-AES at 30, 60 and 90 cm, respectively. Yield responsive sites were generally but not exclusively associated with extractable SO_4-S and S concentrations in the soil of < 4 and < 8 mg/kg, respectively. It was concluded that soil analysis in autumn or spring was a useful but less reliable guide to S deficiency in winter oilseed rape than leaf analysis.

OBJECTIVES

1. To measure atmospheric sulphur deposition and soil sulphur status in relation to crop uptake of sulphur, seed yield and glucosinolate content.

2. To develop a method of prediction of sulphur deficiency in winter oilseed rape.

INTRODUCTION

Sulphur (S) deficiency has become important in limiting winter oilseed rape production in the UK. Yield benefits to S fertilizer applications have commonly been obtained in field crops since 1989 (Walker & Booth 1992; Zhao *et al.* 1993; Withers & O'Donnell 1994) and a recent crop survey suggests that at least 20% of the winter oilseed rape grown in England is potentially deficient in S (Withers, unpublished). Although S deficiency is more likely to occur on free draining soils in areas receiving only small amounts of S from the atmosphere (Withers & O'Donnell 1994), the need for S fertilizer is difficult to predict with any certainty because of the seasonal variation in the amounts of S and nitrogen (N) available for crop uptake. Sites which show severe deficiency in one year may not show deficiency the next year (Walker & Booth 1992).

Whether S deficiency occurs or not in any one year depends on the amounts of S deposited from the atmosphere, the amount of S in the soil available for plant uptake during periods of rapid growth and the crop's ability to utilise soil S through its rooting system. The distribution of soil S within the soil profile has an important influence on crop S uptake (Hue & Cope 1987; Mahler *et al.* 1993; Zhao & McGrath 1994), and deficiency is known to be more prevalent in years when crop establishment has been delayed and/or rooting is poor (Oates & Kamprath 1985; Chalmers *et al.* 1992). This report details the results of field experiments set up in 1992 to obtain a better understanding of the relationship between the supply of S from the atmosphere and from the soil, the uptake of S by the crop and the occurrence of S deficiency in winter oilseed rape in the UK.

MATERIALS AND METHODS

The effect of 40 or 50 kg/ha of S, applied either as potassium sulphate or agricultural gypsum, on seed yield, seed glucosinolate (GLS) content and S and N content of winter oilseed rape was compared to an untreated control in field experiments at 6 sites in 1992 and 10 sites in 1993. At one site (Woburn in 1993), the winter oilseed rape crop failed over winter and a crop of spring oilseed rape was grown. The majority of sites were chosen as having a high risk of S deficiency. Site location, soil type and treatment details are given in Table 1. Further soil characteristics of selected sites are provided by Zhao & McGrath (1994). The nil S and fertilizer S treatments were replicated 3 or 4 times, either as part of larger experiments (Milford *et al.* 1994) or as paired (with and without S) plots in a single block. The S fertilizer treatment was applied by hand in early spring before stem extension stage (GS 2,1 - Sylvester-Bradley *et al.* 1984) to plots of minimum area 36 m^2. Inputs of potassium in the potassium sulphate fertilizer were balanced by additions of potassium chloride fertilizer to ensure all plots received the same amount of potassium. The amount of N applied varied between sites (Table 1) and the crops received other agronomic inputs according to commercial practice.

The amount of plant-available S in the soil was measured at 30, 60 and 90 cm depths at crop emergence (GS 0,8), just prior to treatment application in the spring (GS 1,2) and at early flowering (GS 4,3). At each sampling time, six cores were taken at each depth from each plot. Bulked plot samples were air-dried prior to extraction with 0.016M potassium dihydrogen phosphate (Scott 1981). In 1992, inorganic sulphate-S (SO_4-S) in the filtered extract was measured using an ion chromatograph (IC) with conductivity detection (*Dionex*). In 1993, the total amount of S in the extract was measured by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES). The results of both determinations were expressed as mg/kg of air-dried soil. A comparison of the two determinations was carried out on 300 selected samples from either autumn or spring sampling times and representing both years. Soil bulk density at each depth was measured (Anon. 1982), except at Fochabers where it was assumed to be 1.3 g/cm^3 of soil, and the amount of S in the soil profile at 30, 60 and 90 cm was calculated.

Crop uptake of S was measured just prior to treatment application in spring (GS 1,2) and at early flowering (GS 4,3) but not at all sites. At Sessay, Raynham, Great Tew, Shifnal and Wimborne, the amount of S in straw, chaff and seed at harvest was also measured. All measurements were based on at least 5 replicates of a known crop area from each plot. Total N and total S were determined on bulked replicates from each plot and expressed on a dry matter (DM) basis. At early flowering, samples of young fully expanded leaves from each plot were also taken at selected sites for determination of N, S and SO_4-S content (Withers & O'Donnell 1994). Total N was determined titrimetrically after a Kjeldahl digestion with a copper catalyst. Total S was determined by ICP-AES after digestion with fuming nitric acid and potassium nitrate (Zhao *et al.* 1994). SO_4-S in a hydrochloric acid digest was determined turbidometrically after addition of barium chloride.

TABLE 1

Site location, soil type and treatment details.

Year	Site location	Grid reference	Soil series	Topsoil texture	Treatment Amount (kg/ha)	Form	N applied (kg/ha)
1992	Cockle Park, Northumberland	NZ 201888	Dunkeswick	Clay loam	40	KS[2]	200
	Flodden, Northumberland	NT 927364	Wick	Sandy loam	40	KS	250
	Fochabers, Morayshire	NJ 321604	Corby	Sandy loam	40	KS	180
	Bridgets, Hampshire	SU 341518	Andover	Silty clay loam[1]	40	G[3]	250
	Rothamsted, Hertfordshire	TL 132134	Batcombe	Silty clay loam	50	G	250
	Woburn, Bedfordshire	SP 964360	Cottenham	Loamy sand	40	G	250
1993	Etal, Northumberland	NT 928417	Wick	Sandy loam	40	G	150
	Fochabers, Morayshire	NJ 321604	Corby	Sandy loam	40	KS	180
	Bridgets, Hampshire	SU 341518	Andover	Silty clay loam[1]	40	KS	250
	Rothamsted, Hertfordshire	TL 132134	Batcombe	Silty clay loam	40	KS	250
	Woburn, Bedfordshire	SP 964360	Stackyard	Sandy loam	40	G	230
	Sessay, North Yorkshire	SE 450760	Sessay	Sandy loam	40	KS	300
	Raynham, Norfolk	TF 886248	Barrow	Loamy sand	40	KS	220
	Great Tew, Oxon	SP 406275	Elmton	Silty clay loam[1]	40	KS	120
	Shifnal, Shropshire	SJ 763091	Salwick	Loamy sand	40	KS	160
	Wimborne, Dorset	ST 962122	Upton	Silt loam[1]	40	KS	185

[1]Shallow soils over chalk
[2]KS - potassium sulphate
[3]G - agricultural gypsum

The amount of S deposited in rainfall was measured at Cockle Park, Flodden, Fochabers, Bridgets, Rothamsted and Woburn in both years. The volume of rainfall collected in a receiving dish of 152 mm diameter was measured at approximately fortnightly intervals during the growing season and a sub-sample analysed for S by ICP-AES. Amounts of S (kg/ha) deposited over the monitoring period were calculated and adjusted to cover a 12 month period. The monitoring period varied between sites but was not less than 168 days. Dry deposition of S was measured at all sites in 1993 but not in 1992. Two diffusion tubes were suspended at a height of 2 m above the soil surface in an open position at each site and changed at monthly intervals. Suphur dioxide diffusing into the tubes was adsorbed by a solution of potassium hydroxide and glycerol. The tubes were extracted with hydrogen peroxide and SO_4-S was measured by IC. Calculated amounts of S (kg/ha) deposited over the monitoring period, which was not less than 235 days, were adjusted to cover a 12 month period. Total S deposition in 1993 was taken as the sum of wet and dry values.

Seed yields (t/ha at 91% DM) were measured at harvest by plot combine, except at Great Tew where yield was based on five 1 m^2 quadrats per plot because of a very patchy crop. Seed GLS content (µmol/g whole seed) was determined by glucose release (Smith and Dacombe 1987) at the Woburn and Rothamsted sites and by X-ray fluorescence (XRF) after drying at 85°C for 70 minutes (Schnug & Haneklaus 1988) at all other sites. One-way statistical analysis of variance was used to evaluate the effect of the fertilizer treatment on soil S content, crop S and N content, seed yield and GLS content. Regression analysis evaluated the relationship between leaf S concentration and extractable $S0_4$-S and S in the soil.

RESULTS

Seed yield

Significant ($P < 0.1$) seed yield responses to applied S fertilizer were obtained at 6 of the sites (Table 2). The magnitude of the yield response at Flodden, Woburn in 1992, Fochabers in 1993, Raynham, Great Tew and Wimborne was +0.36, +0.67, +0.73, +0.84, -0.23 and +0.36 t/ha, respectively. The negative yield response at Great Tew was obtained on the basis of quadrat samples on a very patchy crop and it is doubtful whether this is a real response. Sites showing a positive yield response were located in Scotland, northern, south-west and eastern England on sandy and shallow soils over chalk. Symptoms of severe S deficiency were recorded on nil S treated plots, and to a lesser extent on S treated plots at Fochabers in 1992, but there was no affect of applied S on yield. This site

TABLE 2

Effect of fertilizer sulphur on seed yield and glucosinolate (GLS) content at harvest.

Year	Site	Variety	Yield (t/ha at 91% DM)		GLS (μmol/g whole seed)	
			Nil S	40 kg/S/ha[1]	Nil S	40 kg/S/ha
1992	Cockle Park	Falcon	3.82	4.13	11.8	13.9
	Flodden	Falcon	2.46	2.83[a]	16.9	28.1[c]
	Fochabers	Falcon	2.97	2.94	5.7	8.5[c]
	Bridgets	Falcon	3.53	3.60	13.1	13.5
	Rothamsted	Falcon	3.50	3.62	13.7	13.5
	Woburn	Falcon	1.03	1.70[a]	9.3	12.3[a]
1993	Etal	Envol	3.68	3.76	12.6	13.9[b]
	Fochabers	Falcon	1.31	2.04[b]	8.5	14.2[c]
	Bridgets	Falcon	4.81	5.04	7.0	19.6[d]
	Rothamsted	Falcon	3.69	3.79	18.8	18.2
	Woburn	Starlight[2]	4.14	4.40	ND[3]	ND
	Sessay	Bristol	4.81	5.06	12.5	20.5[d]
	Raynham	Bristol	1.13	1.97[b]	6.7	14.7[d]
	Great Tew	Libravo	1.31	1.08[a]	10.2	13.2[b]
	Shifnal	Rocket	3.20	3.02	10.2	12.2[b]
	Wimborne	Bristol	2.43	2.79[c]	6.0	15.5[d]

[1]50 kg S/ha at Rothamsted in 1992.
[2]spring oilseed rape.
[3]ND denotes not determined.
Statistically significant effects compared to the nil S treatment are denoted by [a]0.1, [b]0.05, [c]0.01 and [d]0.001.

was affected by deer grazing. Transient symptoms of mild S deficiency were also observed at Bridgets, Woburn and Sessay in 1993 but there was no yield response at these sites. At Etal, all plots received 14 kg/ha of S in early spring and a yield response was less likely.

Seed glucosinolate content

Seed GLS contents varied from 5.7 to 18.8 μmol/g on nil S treated plots. Lowest values (< 7 μmol/g) were obtained at Fochabers in 1992 and at Bridgets, Raynham and Wimborne on calcareous soils in 1993. Application of S produced large increases in GLS at Flodden, Bridgets and Fochabers in 1993, Sessay, Raynham and Wimborne (Table 2).

These were sites which either showed a yield response to applied S or where S deficiency symptoms occurred. At Flodden, Bridgets in 1993 and Sessay, the increase was sufficient to prevent the use of the seed for sowing the following year. Much smaller but still statistically significant increases in GLS were obtained at Fochabers and Woburn in 1992, Etal, Great Tew and Shifnal. There was no effect of S on seed GLS content at Rothamsted in both years and at Cockle Park and Bridgets in 1992.

Crop uptake of sulphur during the growing season

At sites where it was measured, crop uptake of S over the winter was very variable and ranged from 0.6 to 10.6 kg/ha by early spring (Table 3). Crops which established poorly (Rothamsted in 1992 and Bridgets in 1993), over wintered badly (Woburn) or which suffered severe pigeon damage (Great Tew) contained the least amount of S. By early flowering, crops contained up to 37.9 kg/ha of S on nil S treated plots and up to 53.5 kg/ha of S on S fertilized plots. At Great Tew the crop did not recover from the

TABLE 3

Uptake of sulphur (kg/ha) during the growing season at selected sites.

Year	Site	Spring (GS 1, 2)	Summer (GS 4, 3)	
			Nil S	40 kg/S/ha
1992	Bridgets	4.7	15.1	22.1^{b}
	Rothamsted	1.6	20.1	36.2[1] ^{c}
	Woburn	0.6	1.9	12.6^{c}
1993	Fochabers	ND[2]	4.4	10.1[3] ^{c}
	Bridgets	3.1	13.8	27.9^{b}
	Rothamsted	8.4	37.9	38.5
	Sessay	4.4	16.3	53.5^{b}
	Raynham	7.8	20.2	38.4
	Great Tew	1.7	3.3	4.3
	Shifnal	10.6	ND	ND
	Wimborne	5.0	11.4	28.2^{b}

[1]50 kg S/ha was applied at this site.
[2]ND denotes not determined.
[3]Uptake was measured at GS 3,4 at this site.
Statistically significant effects compared to the nil S treatment are denoted by ^{a}0.1, ^{b}0.05, ^{c}0.01, ^{d}0.001.

pigeon damage and continued to show poor S uptake even where S was applied. Likewise at Woburn in 1992 and Fochabers in 1993, the amount of S taken up on S treated plots was very small. There was no effect of S fertilizer on crop S uptake at Rothamsted in 1993. The lack of a statistically significant effect on S uptake at Raynham was due to variability in crop growth on the S-deficient plots. The largest response in crop S content to applied S was at Sessay where crop yellowing was observed on nil S treated plots.

Crop composition at harvest

The effect of S fertilizer on above-ground DM, crop S concentration and crop S content at harvest was assessed at five of the sites in 1993 (Table 4). The seed, straw and chaff DM on nil S treated plots was typically 30%, 50% and 20%, respectively of the total above-ground DM. There was little variation in these proportions either between sites or when S fertilizer was applied. Large increases in total DM were obtained at Raynham and Wimborne where fertilizer S was applied. At Raynham, this was due to increased seed yield but at Wimborne, seed, straw and chaff DM were all substantially increased. Statistically significant effects of applied S were, however, absent due to the large variability between individual quadrats within plots. The apparent significant reductions in seed and straw yields at Great Tew must be treated with caution because of the very poor crop growth at this site. Seed yields as measured by the combine were up to 60% below those based on whole crop samples just before harvest, reflecting the extent of combine losses.

Sulphur concentrations in seed, straw and chaff were all increased upon application of S (Table 4), particularly at Sessay, Raynham and Wimborne. At Great Tew and Shifnal, statistically significant effects were confined to straw and chaff. Significant increases in total S uptake at harvest were obtained at all these ADAS sites except Great Tew, where the S fertilizer treatment increased S uptake only in the chaff. Seed S uptake was increased at Sessay, Raynham and Wimborne and represented 60% of total S uptake.

Large increases in straw S uptake were recorded at Raynham and Shifnal, whilst chaff S content was increased two-fold at Sessay and Shifnal. Total S uptake at harvest did not exceed 55 kg/ha. The crops at Raynham and Wimborne continued to take up S after flowering but at other sites there was a substantial decline in crop S content between flowering and harvest. With the exception of Great Tew, which was a very poor crop, the apparent recovery of the fertilizer S applied ranged from 24-46%. The largest recovery was at Raynham, which produced the largest seed yield response of these five sites.

TABLE 4

Effect of sulphur fertilizer on (a) above-ground dry matter, (b) crop sulphur concentration and (c) crop sulphur uptake at harvest at ADAS sites in 1993.

Site	Nil S				40 kg S/ha			
	Seed	Straw	Chaff	Total	Seed	Straw	Chaff	Total
	(a) Above ground dry matter (t/ha)							
Sessay	4.18	6.99	4.73	15.90	4.53	6.70	5.10	16.33
Raynham	2.59	5.59	2.26	10.44	4.03	6.65	2.28	12.96
Great Tew	1.20	2.34	0.90	4.44	0.98[a]	1.74[a]	0.95	3.67
Shifnal	2.92[1]	4.55	1.99	9.46	2.75[1]	4.49	2.04	9.28
Wimborne	2.87	3.70	1.87	8.44	4.31[a]	5.08	2.38	11.77
	(b) Crop sulphur concentration (mg/g)							
Sessay	3.00	0.62	0.62[2]		3.72[c]	1.10[b]	1.10[b]	
Raynham	2.60	0.95	1.25		4.70[d]	1.70[c]	1.67[b]	
Great Tew	3.00	1.87	2.75		3.10	2.90[b]	4.05[c]	
Shifnal	2.45[1]	1.42	2.20		2.70[1]	3.05[d]	4.85[c]	
Wimborne	2.37	0.72	0.92		3.65[d]	0.97[c]	1.20	
	(c) Crop sulphur uptake (kg/ha)							
Sessay	12.5	4.4	3.0	19.9	16.8[b]	7.3[b]	5.6[b]	29.7[c]
Raynham	7.1	5.4	2.9	15.4	18.9[b]	11.2[c]	3.8	33.9[b]
Great Tew	3.6	4.4	2.5	10.5	3.0	5.1	3.8[a]	11.9
Shifnal	7.1[1]	6.7	4.5	18.3	7.4[1]	13.8[b]	9.9[c]	31.1[b]
Wimborne	6.8	2.8	1.7	11.3	15.9[b]	4.9[a]	2.9[a]	23.7[b]

[1]Values based on combine yields.
[2]Not measured but assumed to be the same as in straw.
Statistically significant effects compared to the nil S treatment are denoted by [a]0.1, [b]0.05, [c]0.01, [d]0.001.

The offtake of S in combined grain measured at 10 of the sites ranged from 2.6-13.2 kg/ha on nil S treated plots and from 7.0-17.2 kg/ha on S treated plots. In addition to the effects of applied S at the ADAS sites, grain S offtake was significantly increased at Flodden and Woburn in 1992 but not at Cockle Park, Bridgets or Rothamsted in 1992. Fertilizer S increased the concentration of N in the grain by only very small amounts (2 mg/g) at 8 of these 8 sites. At Raynham and Wimborne, grain N offtake (as measured off the combine) was increased by 25 and 16 kg/ha, respectively but there were no effects of S fertilizer on grain N offtake at other sites.

Soil sulphur content

Comparable concentrations of KH_2PO_4 extractable inorganic SO_4-S (measured by IC) and extractable total S (measured by ICP-AES) for each of the sites are shown in Table 5. The average amount of extractable organic S (measured as the difference between IC and ICP-AES) at 30, 60 and 90 cm depth was 50%, 40% and 30%, respectively of total S, but there was considerable variation between sites, especially in the topsoil. There were noticeably smaller concentrations of extractable organic S at Rothamsted in both years compared to most other sites. The amount of extractable inorganic SO_4-S (measured by IC) in the soil at the Fochabers site in 1992 was not measured but can be estimated at 3.5 mg/kg based on 1992 data.

The amounts (kg/ha) of S in the soil profile to 90 cm at different times during the growing season were very variable (Table 6). Comparison of soil S content (kg/ha) between 1992 and 1993 cannot be made because of the differences in the method of extraction. There were no large differences in extractable soil S content at any depth between crop emergence (GS 0,8) and the start of spring growth (GS 1,2), except at Etal where 14 kg S/ha was applied to all plots prior to sampling. Comparison of soil S contents in nil S treated plots at flowering (GS 4,3) with those in spring (GS 1,2) indicated a depletion of soil S reserves at most sites although this was not consistent. At Flodden and Etal in Northumberland there was an apparent net mineralization of S over this period. At sites where it was measured, soil S content at flowering was increased on S fertilized plots except at Bridgets in 1992 and Woburn in 1993.

Deposition of sulphur from the atmosphere

The amounts (kg/ha) of wet and/or dry deposition of S are shown in Table 7. Amounts of dry deposition at Sessay, Raynham, Great Tew, Shifnal and Wimborne were 14.0, 5.3, 4.8, 8.5 and 4.7, respectively. Total deposition of S was <20 kg/ha/year at all sites in 1993, with lowest amounts falling in Scotland and northern England. Larger amounts of S were deposited in rainfall than as sulphur dioxide, except at Rothamsted and Woburn. Concentrations of SO_4-S in rainfall were lower in 1993 compared to 1992, but fluctuated widely (maximum range of 0.19 to 22.3 mg/l) in both years depending on the volume sampled. Similarly, there was large variation in the concentrations of sulphur dioxide deposited at each site.

TABLE 5

A comparison of concentrations (mg/kg) of extractable sulphate-S (IC) and extractable total S (ICP-AES) at different depths in the soil prior to treatment application.

Year	Site	IC			ICP-AES			IC:ICP-AES		
		30	60	90	30	60	90	30	60	90
1992	Cockle Park	4.7	7.2	10.2	12.8	12.4	13.7	0.39	0.59	0.76
	Flodden	2.7	3.9	4.1	7.8	7.5	6.5	0.35	0.52	0.64
	Fochabers	3.4	3.2	2.9	9.7	7.4	4.1	0.36	0.49	0.73
	Bridgets	4.2	5.1	PM[1]	12.8	10.2	PM	0.33	0.54	PM
	Rothamsted	6.8	8.5	10.3	10.3	11.7	12.8	0.67	0.75	0.81
	Woburn	2.9	1.9	2.2	6.0	4.1	4.7	0.48	0.46	0.48
1993	Etal	2.9	2.8	5.8	5.4	7.3	8.0	0.50	0.39	0.72
	Fochabers	ND[2]	ND	ND	10.2	9.7	7.5	ND	ND	ND
	Bridgets	5.0	5.0	PM	7.6	5.4	PM	0.65	0.92	PM
	Rothamsted	10.3	71.7	153.2	13.3	76.2	162.3	0.80	0.96	0.94
	Woburn	5.0	3.9	4.4	10.6	8.7	6.9	0.46	0.46	0.66
	Sessay	3.7	4.7	6.7	7.2	8.9	8.8	0.52	0.54	0.75
	Raynham	2.2	2.2	1.9	4.7	4.0	3.5	0.48	0.53	0.55
	Great Tew	5.2	PM	PM	8.6	PM	PM	0.62	PM	PM
	Shifnal	3.1	2.4	3.2	5.7	4.6	4.6	0.55	0.52	0.68
	Blandford	3.0	2.1	1.5	6.4	3.6	2.8	0.46	0.57	0.53

[1]PM denotes that the underlying parent material was too hard to sample
[2]denotes not determined

TABLE 6

Cumulative soil sulphur content (kg/ha) at different depths in the soil during the growing season.

Year	Site	Cumulative S (kg/ha)											
		GS O, 8			GS 1, 2			GS 4, 3					
								Nil S			40 kg S/ha		
		30	60	90	30	60	90	30	60	90	30	60	90
1992[1]	Cockle Park	18.3	56.5	104.5	15.7	55.5	108.7	9.6	40.8	96.5	28.7	58.2	108.4
	Flodden	11.6	28.9	46.6	12.1	28.9	49.2	22.3	45.2	60.7	53.2[a]	72.2	103.3
	Fochabers	10.2	19.8	29.1	9.9	18.3	26.1	6.6	11.7	18.0	35.7[b]	48.9[d]	70.5[d]
	Bridgets	15.7	28.3	40.9	13.4	30.2	47.0	14.4	30.3	46.2	13.4	28.6	43.8
	Rothamsted	28.6	55.6	103.5	34.1	64.7	108.0	13.0	40.7	79.3	25.5[c]	51.1	94.8
	Woburn	9.4	20.6	31.7	16.0	24.9	34.3	8.5	15.0	23.9	9.4	21.1	33.0
1993[2]	Etal	22.4	50.0	82.8	48.0	76.9	111.1	51.7	102.5	157.7	64.6	115.4	165.0
	Fochabers	30.6	59.7	82.2	ND	ND	ND	38.1	59.4	ND	48.9	74.7[b]	ND
	Bridgets	28.7	49.3	69.9	27.6	42.1	56.6	ND	ND	ND	ND	ND	ND
	Rothamsted	68.1	265.7	785.2	66.6	340.9	1023.0	ND	ND	ND	ND	ND	ND
	Woburn	ND[3]	ND	ND	49.9	90.6	120.0	41.9	82.1	116.2	41.4	78.8	109.9
	Sessay	28.9	68.2	104.9	32.0	77.4	116.7	27.1	65.3	98.8	42.6	85.4	122.9
	Raynham	21.7	44.2	65.1	19.6	35.7	50.6	ND	ND	ND	ND	ND	ND
	Great Tew	26.6	ND	ND	27.9	ND	ND	33.4	ND	ND	40.5[c]	ND	ND
	Shifnal	19.7	43.7	70.4	26.7	49.2	71.6	26.7	50.2	80.8	39.3[c]	67.7	97.8
	Wimborne	30.1	50.5	70.1	21.9	39.0	53.9	20.9	34.2	49.1	50.6[b]	67.2	85.8

[1]Measured as inorganic SO_4-S by ion chromatography. (IC). [2]Measured as total S by inductively coupled plasma atomic emission spectroscopy (ICP-AES).
[3]ND denotes not determined. Statistically significant effects compared to the nil S treatment are denoted by [a]0.1, [b]0.05, [c]0.01, [d]0.001.

TABLE 7

Wet and/or dry deposition of S from the atmosphere at selected sites in 1992 and 1993

Site	Mean concentration of SO_4-S in rainfall (mg/l)		Deposition of S (kg/ha)			
			Wet		Dry	Total
	1992	1993	1992	1993	1993	1993
Cockle Park	2.32	1.33	14.3	8.9	6.8	15.7
Flodden/Etal	2.43	1.59	12.4	8.1	5.2	13.3
Fochabers	1.41	0.93	7.2	5.0	4.3	9.3
Bridgets	1.50	0.97	12.3	10.5	6.4	16.9
Rothamsted	1.18	1.20	8.6	7.9	9.7	17.6
Woburn	1.20	1.14	8.5	6.4	8.9	15.3

Prediction of yield response

Yield responsive sites were clearly distinguished by low (<4 mg/g) total S concentrations in young fully expanded leaves at flowering (Fig. 1). A leaf total S concentration of 4.0 mg/g was obtained at Sessay but plant analysis was not carried out at the other sites showing deficiency symptoms but no yield response. Although not measured at all sites, leaf N:S ratio and SO_4-S concentrations were high (≥ 18:1) and low (≤ 1.1 mg/g), respectively at yield responsive sites, confirming their S-deficient status. A high N:S ratio in leaves from Sessay reflected the comparatively large amount of N applied at this site (Table 1). Analysis of the S and N content of whole plants in the spring or in the seed at harvest did not clearly distinguish S-deficient sites (Table 8). Analysis of whole plants at the flowering stage was more useful with S-deficient crops showing generally smaller total S concentrations and higher N:S ratios than sites which did not show a yield response or deficiency symptoms.

Yield responsive sites also contained the smallest concentrations (≤3 mg/kg) of SO_4-S in the top 30 cm as measured by IC (Fig. 1), although the low concentration of SO_4-S at Shifnal suggests this site should have given a yield response (Table 5). These sites generally contained lower amounts of cumulative extractable SO_4-S and S in the top 60 and 90 cm (Fig 1). Extractable SO_4-S by IC could not distinguish sites which showed S deficiency symptoms from sites which were apparently well supplied with S (Cockle Park, Bridgets in 1992 and Rothamsted in both years). Although the dataset was somewhat limited, there was a significant relationship between extractable SO_4-S in the soil and the

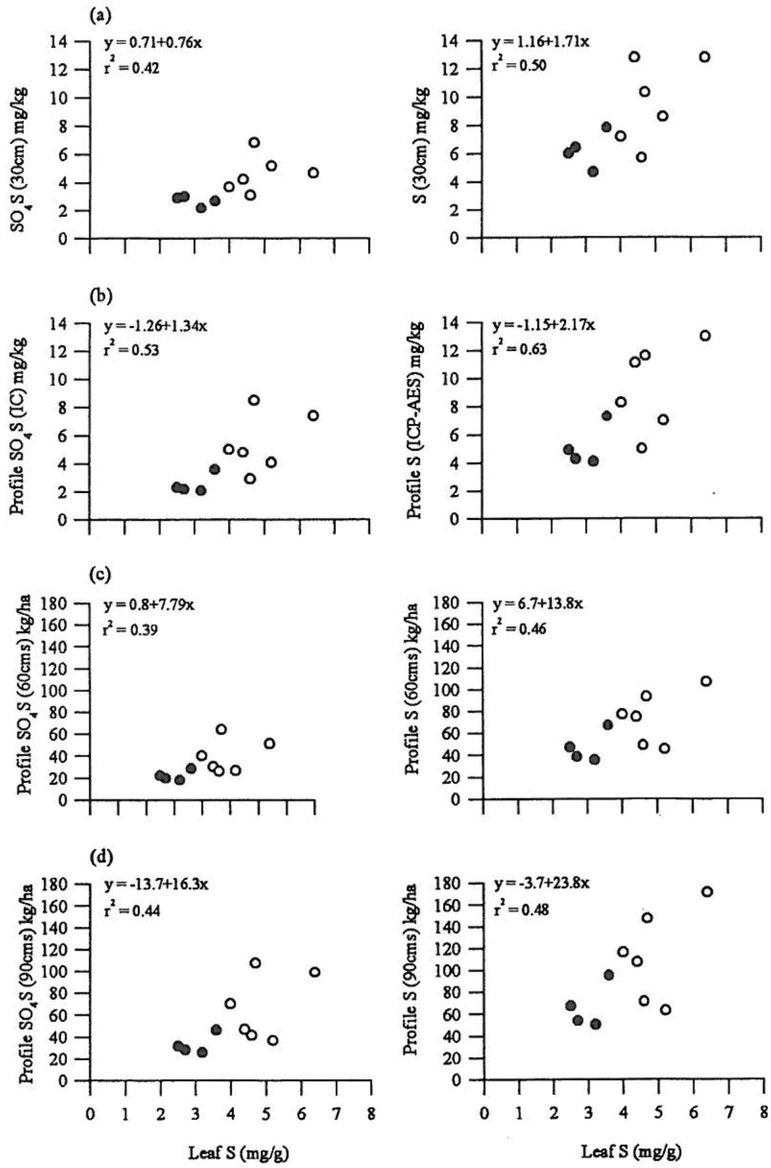

Figure 1. Relationship between leaf sulphur concentration and extractable SO_4-S (IC) and extractable S (ICP-AES) expressed as a) concentration in the top 30 cm and b) concentration averaged to 90 cm, c) cumulative content to 60 cm and d) cumulative content to 90 cm. • denotes yield responsive sites. Data for Fochabers in 1992 and 1993 is excluded.

TABLE 8

Crop nitrogen and sulphur composition on nil treated plots at selected sites.

Year	Site	Spring (whole plants)			Summer (whole plants)			Summer (2nd & 3rd leaves)					Seed[1]		
		N	S	N : S	N	S	N : S	N	S	N : S	SO_4S	SO_4S :	N	S	N : S
		mg/kg		ratio	mg/kg		ratio	mg/kg		ratio	mg/k	ratio	mg/kg		ratio
1992	Cockle Park	ND[2]	ND	ND	ND	ND	ND	ND	6.4	ND	ND	ND	28.2	3.1	9.0
	Flodden	ND	ND	ND	ND	ND	ND	ND	3.6	ND	ND	ND	32.7	3.8	8.5
	Fochabers	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Bridgets	47.6	6.1	7.8	35.6	3.4	10.8	ND	4.4	ND	ND	ND	30.7	3.6	8.6
	Rothamsted	24.7	4.4	5.7	42.2	4.8	8.9	ND	4.7	ND	ND	ND	32.1	3.9	8.4
	Woburn	26.2	5.5	4.8	28.5	1.5	19.4	ND	2.5	ND	ND	ND	23.8	4.1	5.8
1993	Fochabers	ND	ND	ND	40.0	2.3	17.6	66.6	2.7	24.5	0.7	0.25	ND	ND	ND
	Bridgets	47.2	6.7	7.1	31.6	2.0	15.6	ND	ND	ND	ND	ND	ND	ND	ND
	Rothamsted	45.7	7.8	5.9	23.4	4.9	4.8	ND	ND	ND	ND	ND	ND	ND	ND
	Sessay	48.7	5.0	9.9	39.0	2.2	18.5	65.9	4.0	18.0	1.7	0.41	35.3	3.0	11.8
	Raynham	43.9	3.9	11.3	37.0	3.3	12.0	59.8	3.2	18.8	1.1	0.35	30.4	2.6	11.9
	Great Tew	55.1	9.5	5.8	33.9	4.8	7.1	49.0	5.2	9.3	4.0	0.76	27.1	3.0	9.2
	Shifnal	42.7	6.0	7.2	33.5	4.0	8.5	56.6	4.6	12.3	2.9	0.64	27.6	2.4	11.3
	Wimborne	49.6	3.9	10.1	28.3	2.2	12.8	49.1	2.7	18.1	1.0	0.36	28.4	2.4	12.0

[1]Combine sample. [2]ND denotes not determined. Sites at Etal and Woburn in 1993 are excluded.

concentration of S in leaves at flowering (Fig. 1). A threshold leaf S concentration of 4 mg/g was associated with a soil SO_4-S concentration of 3.7 mg/g in the top 30 cm or of 4.1 mg/g averaged over 90 cm, which is consistent with the amounts of soil S at yield responsive sites.

The relationship between yield response and extractable S in the soil to 30 cm as measured by ICP-AES was less clear, although small values were obtained at most of the S-deficient sites (e.g. Woburn in 1992, Raynham and Wimborne). Sites at Bridgets, Great Tew and Shifnal contained less extractable S (ICP-AES) and Fochabers in 1993 contained more extractable S (ICP-AES) than expected. However, when averaged over the soil profile to either 60 or 90 cm, extractable S (ICP-AES) was slightly better correlated to leaf S concentration than extractable SO_4-S (IC) content at these depths (Fig 1). At a threshold leaf S concentration of 4 mg/g, extractable S in the top 30 cms and averaged over the soil profile to 90 cm was 8.0 and 7.5, respectively. With the exception of Fochabers, yield responsive sites were all below this level of extractable S. The sites at Bridgets 1993 and Sessay, which showed deficiency symptoms, also contained < 8 mg/kg extractable S in the soil.

DISCUSSION

Seed yield responses were larger and more frequent than in previous experimental series (Withers & O'Donnell 1994) which demonstrates the increasing importance of S deficiency in winter oilseed rape production. The majority of yield responsive sites were located in areas (Scotland, northern and south-west England) and on soil types (sandy and shallow chalk soils) where S deficiency has previously been seen. However, the large increases in seed yield obtained at Woburn in 1992 and Raynham in 1993 indicate that sandy soils in eastern England are now also at risk of S deficiency, which agrees with the results of recent surveys of the winter oilseed rape crop in England (Withers, unpublished). Measured amounts of S deposited from the atmosphere were <20 kg/ha/year at these sites confirming national estimates (Campbell *et al.* 1990).

Sites which showed deficiency symptoms but no yield response were probably borderline with respect to crop S supply. The appearance of symptoms at Sessay despite the relatively large amount of dry deposition of S from the atmosphere at this site was probably an effect of the large amount of N applied (300 kg/ha), since the interaction between crop N and S supply is well known to influence the expression of S deficiency

(Zhao *et al.* 1993). The lack of a yield response at sites showing visual symptoms is probably due to uptake of S mineralized late in the growing season.

The large variation in the uptake of S up to stem extension at the different sites was due as much to differences in crop growth over the winter as to differences in the availability of soil S. Sulphur treatments generally produced significant increases in crop S contents at flowering but there was still a wide range in S uptake between sites at this growth stage. At non yield responsive sites there was an apparent reduction in crop S content between flowering and harvest, whilst at Raynham and Wimborne, crop uptake increased over this period. The loss of nutrients in senescing tissue after the flowering stage has been indicated by previous work (Gregory *et al.* 1979; Barraclough 1989), and the increase in S uptake at S-deficient sites may be an indication of delayed maturity. There were also large increases in seed GLS concentrations at harvest at S deficient sites although this was not consistent. For example, at Woburn in 1992 there was a comparatively small increase in GLS although this maybe a reflection of the method of GLS determination since the glucose release method is considered to be less accurate than the XRF method on immature seed. Large increases in seed GLS at S deficient sites have been recorded previously (Zhao *et al.* 1993; Withers & O'Donnell, 1994) but other factors influence the final GLS concentration in the seed apart for crop S supply (Milford & Evans 1991). The large increase in GLS at Bridgets in 1993 provides further evidence that this site was probably borderline with respect to S deficiency. Cockle Park, Bridgets in 1992 and Rothamsted showed only small increases in either crop S content or seed GLS content when fertilizer was applied, confirming the results of leaf analysis that these sites were well supplied with S.

The clear relationship between yield response and concentrations of S in newly expanded leaves at flowering has been shown, albeit less convincingly, in previous work (Zhao *et al.* 1991; Withers & O'Donnell 1994) but leaf analysis at this stage comes too late to take preventative action. Although topsoil analysis has previously been considered to be unreliable in predicting S deficiency (Syers *et al.* 1987; Hoque *et al.* 1987), there was surprisingly good agreement between yield response, leaf S content and extractable SO_4-S in the soil either to 30 cm depth or averaged over the soil profile to 90 cm. This may be because the atmosphere is becoming a less important source of S to crops with the result that S deficiency has become more widespread and severe and yield responses more frequent. The suggested threshold concentration of 3-4 mg/g, above which crops do not give a yield increase to applied S, is currently used in Scotland to indicate probable yield response (Chalmers *et al.* 1992). Yield responses in cereals have also been obtained at similar concentrations of SO_4-S in the soil in work outside the UK (Jones 1986; Withers & Sinclair 1994).

The determination of SO_4-S in soil is not considered very reliable and in these experiments repeatability was not always satisfactory. This determination could not distinguish sites which showed transient deficiency symptoms and values for S deficient sites were perhaps too close to those of sites well supplied with S for this technique to be relied upon in advisory work without further experimentation. Available soil S measured by ICP-AES, which includes an estimate of plant-available organic S, is analytically more reliable and considered to be more appropriate as an estimate of soil S supply (Vendrell *et al.* 1990; Zhao & McGrath, 1994). Extractable S (ICP-AES) was slightly better correlated to leaf S concentrations than extractable S (IC) but was less consistent in terms of defining yield responsive sites. In particular the site at Fochabers contained more extractable S than the threshold concentration of 8 mg/kg suggested by regression with leaf analysis.

Calculation of extractable SO_4-S and S to 90 cms depth slightly improved the regression relationships with leaf S concentrations (Fig. 1). The inclusion of measured soil bulk density in the calculation of profile S content did not improve the regression relationships. However the majority of these sites were of uniform soil texture throughout the soil profile. Previous field experiments have clearly demonstrated that subsoils can be a significant source of S for crop uptake (Hue & Cope 1987; Mahler *et al.* 1993; Zhao & McGrath 1994), although Barraclough (1989) found that most of the nutrient uptake by a high yielding winter oilseed rape crop occurred within the top 40 cm of the soil profile. Good relationships between phosphate-extractable SO_4-S or S in the soil and S uptake by crops have been obtained in pot experiments (Warman & Sampson 1992; Zhao & McGrath, 1994) and the results of these field experiments suggest that soil analysis can be useful in diagnosing S deficiency at potentially S deficient sites. However, soil analysis may not always be reliable. It is not known why Shifnal did not respond to S fertilizer since soil S status was low when measured by both IC and ICP-AES. Crop S concentrations were outside the deficiency range indicating that atmospheric deposition may have been significant at this site. Sites with shallow soils over hard parent materials (Great Tew) may also be difficult to evaluate.

CONCLUSIONS

1. Sulphur deficiency reduced seed yield in winter oilseed rape by up to 74% at 5 of the 16 sites evaluating crop response to S fertilizer.

2. Large increases in seed GLS concentrations were obtained at most S deficient sites.

3. Crops which are borderline with respect to S supply may show transient deficiency symptoms during stem extension without significantly reducing yield.

4. Yield increases from applied S fertilizer were associated with leaf S concentrations below 4.0 mg/g in young fully expanded leaves at flowering.

5. Yield responsive sites received small amounts of S from the atmosphere and were generally but not exclusively associated with low concentrations of extractable SO_4-S (< 4 mg/kg) or extractable S (< 8 mg/kg) in the soil.

6. Soil analysis was a useful if not totally reliable guide to S fertilizer need by winter oilseed rape at sites susceptible to S deficiency.

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