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AMOUNT AND FORM OF SULPHUR FERTILISER REQUIRED TO PREVENT SULPHUR DEFICIENCY IN SPRING OILSEED RAPE

by

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ABSTRACT

Sulphur (S) requirements for preventing S deficiency in spring oilseed rape were tested at eleven sites over a three year period. In 1995 and 1996, seedbed dressings of 0, 10, 20, 40 and 80 kg/ha (S), applied as potassium sulphate, were compared with elemental sulphur in the seedbed and foliar sprays of Epsom salts, both applied at 20 and 40 kg/ha S, at three sites each season. Additional foliar spray treatments of magnesium chloride, applying the same amounts of magnesium as the two rates of Epsom salts, were also applied to test for any magnesium response. In both years, two sites were selected on sandy and shallow chalk soils with moderate to high risk of S deficiency, with a third site on heavy loam representing marginal deficiency risk. In 1997, the experiment design was simplified, to test only seedbed dressings of 0, 10, 20 and 40 kg/ha S applied as potassium sulphate, but with five sites instead on sandy or shallow chalk soils. The cultivar Starlight was used at all sites.

Significant (10% probability level) yield responses of 7-30% were obtained from S application at five sites on sandy or shallow chalk soils out of the eleven sites in total. Finely divided elemental S, incorporated as a seedbed dressing, was as effective as seedbed applied potassium sulphate at the two S-responsive sites in 1995 and 1996, when different forms of S were compared. Foliar spraying with Epsom salts at the 6-7 leaf stage was, however, a less effective method of applying S to prevent deficiency and, at three sites, reduced yield as a result of crop scorch or stress, particularly at the higher rate tested.

Yield responsive sites were mostly associated with total S concentrations below 0.4% (on a dry matter basis) in the leaves at flowering and extractable total S (Inductively Coupled Plasma Atomic Emission Spectrometry determination) contents in the soil shortly before drilling of less than 7 mg/kg in the top 30 cm layer or as an average over the 0-90 cm depth. These results suggest that the soil and leaf analysis guidelines previously developed for predicting or diagnosing S deficiency in winter oilseed rape are also appropriate for the spring sown crop.

An application rate of 20 kg/ha S was generally sufficient for preventing S deficiency in this series of experiments, but 30 kg/ha S may be needed for very deficient sites with otherwise good yield potential. Symptoms of S deficiency were only observed at two sites, of which one was the most yield responsive site in this experiment. At the second site, however, mineralisation of soil S later in the season and a moderate yield potential may largely account for the small, non-significant yield response (+5%) to S application.

OBJECTIVES

- To determine the susceptibility of spring sown oilseed rape to sulphur deficiency.
- To establish the most suitable form and rate of sulphur application to prevent sulphur deficiency on soils with low or marginal sulphur status.

INTRODUCTION

Sulphur deficiency in susceptible crops has become more widespread over the last decade, mainly as a result of a continuing decline in atmospheric S inputs (McGrath *et al* 1996). Before 1992, only 2-3% of the total oilseed rape area in the United Kingdom (UK) was spring sown (Agricultural Census data), and studies since the mid 1980's on the sulphur (S) requirement of the crop had only been done on winter oilseed rape. During this period, a number of studies showed yield increases, ranging from 10 to 267%, from applications of S fertiliser to winter oilseed rape grown on S deficient sites (Withers 1989; Zhao *et al* 1993; Walker & Booth 1994; Withers & O'Donnell 1994; Withers *et al* 1995; McGrath & Zhao 1996). Crop surveys in 1991 and 1992 had suggested that 20% of winter oilseed rape grown in England was potentially deficient in S (Withers, unpublished). Light textured, freely draining soil types in areas of low atmospheric S deposition had been identified as those most likely to be S deficient but the diagnostic and predictive guidelines, together with treatment recommendations, for S deficiency in oilseed rape were based on the autumn sown crop (McGrath *et al* 1996).

The introduction of the interim Oilseeds Scheme in 1992, and its subsequent incorporation into the Arable Area Payment Scheme, resulted in a dramatic expansion in the area of spring sown oilseed rate between 1991 and 1993. The proportion of the UK oilseed rape area which was spring sown increased from 8% to 30% between 1992 and 1994, but then declined to 15% in 1996 and 1997 (Agricultural Census data). Although the spring sown area subsequently declined, due to increases in rape seed commodity prices and the resulting improvement in profitability of winter oilseed rape, the spring sown crop still represents a significant proportion of the total oilseed rape area. Little, if any information was available about the susceptibility of spring oilseed rape to S deficiency, or the actual amount and most suitable form of sulphur fertiliser required for optimum yield response under UK conditions.

This report presents results of field experiments in the 1995 to 1997 seasons, which investigated the amount of S required for spring oilseed rape grown in soils with moderate or marginal deficiency risk. In 1995 and 1996, the suitability of different forms of S application for preventing S deficiency were also tested.

MATERIALS AND METHODS

Sites

Sulphur treatments were tested at 3 sites in both 1995 and 1996 and, to increase the chances of obtaining yield responses to applied S, at 5 sites in 1997. All the sites were selected as having a moderate to high risk of sulphur deficiency, located on on sandy or shallow chalk soil types, apart from the 2 heavy loam sites in 1995 and 1996, where only a marginal deficiency risk was expected.

One site (Bridgets, 1995) had to be re-drilled, as the first drilling failed despite initial crop emergence. At two other sites (Elgin, 1995 and Forres, 1996), pest or wind damage respectively had a significant effect on crop growth in one replicate block of plots and those replicates were therefore omitted from the subsequent data analyses.

Site location, soil type and management details for the test crop are given in Table 1.

Table 1. Site details.

					Test Crop			
Year	Site location	Grid reference	Soil series	Soil description	Sowing date	Fertiliser N (kg/ha)	Harvest method	Harvest date
1995	Bridgets, Hampshire	SU341518	Andover	Shallow silty clay loam over chalk	22 March[1]	120	Dessicated	1 September
	Elgin, Morayshire	NJ185624	Corby	Deep sandy loam	26 April	100	Swathed	26 September
	Rothamsted, Hertfordshire	TL132134	Batcombe	Silty clay loam over clay	3 April	104	Dessicated	18 August
1996	Bridgets, Hampshire	SU341518	Andover	Shallow silty clay loam over chalk	5 April	150	Dessicated	9 September
	Forres, Morayshire	NJ006577	Dryburn	Deep sandy loam	30 April	98	Swathed	23 September
	Rothamsted, Hertfordshire	TL132134	Batcombe	Silty clay loam over clay	3 April	100	Direct combined	30 August
1997	Bridgets, Hampshire	SU341518	Andover	Shallow silty clay loam over chalk	20 March	150	Direct cut	2 September
	Crailing, Roxburghshire	NT683237	Hobkirk	Deep sandy loam	8 April	144	Dessicated	14 September
	Forres, Morayshire	NJ077591	Orton	Deep sandy loam	15 April	110	Dessicated	19 September
	Raynham, Norfolk	TF912288	Lynn	Loamy sand over coarse sand	13 March	120	Direct cut	2 September
	Woburn, Bedfordshire	SP964360	Cottenham	Sandy loam over loamy sand	18 April	100	Direct cut	2 September

[1] Redrilled 2nd May [2] Clay enriched subsoil

Treatments

The range of treatments used in the first two seasons tested both rate and form of S application (Table 2). Magnesium chloride treatments were also included, to test whether any apparent responses to foliar applied Epsom salts could have been caused by magnesium, rather than S effects. In 1997, however, the experiment design was simplified, to test only seedbed dressings of 0, 10, 20 and 40 kg/ha S, applied as potassium sulphate.

Table 2. Experiment treatments, 1995 and 1996 seasons.

Sulphur Form	Application method	Sulphur Rate kg/ha S
Untreated		Nil
Untreated		Nil
Potassium Sulphate	Seedbed	10
		20
		40
		80
Elemental Sulphur	Seedbed	20
		40
Epsom Salts	Foliar spray	20 (15.4 kg/ha Mg)
		40 (30.8 kg/ha Mg)
Additional treatments:		
Magnesium Chloride	Foliar spray	Nil (15.4 kg/ha Mg)
		Nil (30.8 kg/ha Mg)

A full randomised block design, with four replications, was used at each site in 1995 and 1996. In 1997, there were five replicates of each treatment.

Potassium sulphate (18% S, 50% K_20) dressings were spread manually but elemental S, applied as Thiovit (80% S), was sprayed onto the soil shortly before drilling. Epsom salts (13% S, 10% Mg) treatments were applied as 5% w/v foliar sprays plus non-ionic wetter over two timings, with half of the total S rate applied at GS1.6-1.7 and the remainder one week later. At each timing, spray applications were repeated to achieve the required S rates of 10 or 20 kg/ha. The same approach was used for applying the magnesium chloride (25.5% Mg) foliar treatments, using a 2% w/v solution. Each foliar spray application was allowed to dry before the next spray was applied to the same set of plots. Inputs of potassium in the potassium sulphate fertiliser were balanced by additions of potassium chloride fertiliser as thoroughly incorporated seedbed dressings, to ensure all plots received the same amount of potassium (111 kg/ha K_2O).

Site Husbandry

Plots were drilled with the cultivar Starlight (Anon 1994) at all sites, which were located within commercial field crops of spring oilseed rape. The amount of fertiliser N applied varied between sites (Table 1) and the crops received other agronomic inputs according to good commercial practice. Total plot size ranged from 42 to 72m^2 between sites.

Assessments

The amount of plant-available S in the soil was measured at 30, 60 and 90 cm depths just before seedbed treatments were applied in the spring, when nine cores were taken at each depth from each block in the first two years and from three blocks in the third year. After bulking soil cores, the block samples were air dried prior to extraction with 0.016M potassium dihydrogen phosphate (Scott 1981). In each year, the total amount of S in the extract was measured by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES). In 1997, also for the two Rothamsted sites in 1995 and 1996, inorganic sulphate-S (SO_4.S) in the filtered extract was measured using an ion chromatograph (IC) with conductivity detection (Dionex). The results of both determinations were expressed as mg/kg of air dried soil. Soil bulk density at each depth was assumed to be 1.3 g/cm^3 at all sites, for calculating the amount of S (as kg/ha) in the soil profile at 30, 60 and 90 cm depths. In 1997, preliminary site samples were also taken when initially selecting sites in late winter, to check actual soil S status.

Plant populations were recorded at GS 1.4-1.6, after full crop establishment, the crops were also scored for visual symptoms of S deficiency at this stage and again at early flowering. At early flowering, samples of young, fully expanded leaves from each of the untreated control and potassium sulphate-treated plots were taken at each site for determination of N, S and SO_4-S content (Withers & O'Donnell 1994). Total N was determined either by Dumas combustion technique, using a Leco N analyser or titrimetrically, after a Kjeldahl digestion with a copper catalyst. Total S was determined by ICP-AES after digestion with either nitric and perchloric acids (Zhao *et al.* 1994) or nitric and hydrochloric acids (aqua regia). SO_4-S was determined either by ICP-AES after water extraction or turbidometrically, after hydrochloric acid digest and addition of barium chloride; both methods, however, overestimate SO_4-S in plant tissues.

Plots were harvested by plot combine to measure seed yield, corrected to 91% dry matter. Rapeseed samples were analysed for total S, using the same methods as for leaf samples, and for oil concentration, using nuclear magnetic resonance.

Statistical analysis

The data were subjected to analysis of variance, to test for statistical significance.

RESULTS

Soil sulphur content

Extractable total S contents ranged from 3.4 - 12.4 mg/kg at 0-30cm and 2.2 - 24.6 mg/kg at 60-90cm depth (Table 3). Values for extractable sulphate-S, where determined, varied between 2.0 - 9.8 mg/kg at 0-30cm and 2.2-23.7 mg/kg at 60-90cm. The majority of sites showed similar or lower extractable S levels at 30-60 and 60-90cm, compared to 0-30cm, except for Elgin, Rothamsted in both 1995 and 1996 and also Raynham, where higher contents were measured at 60-90cm depth.

Table 3. Concentrations (mg/kg, block means) of extractable total S, ICP-AES and extractable sulphate-S (in brackets) at different depths (cms) in the soil and corresponding soil sulphur contents (kg/ha), prior to seedbed treatment applications.

Year	Site	Extractable total S, ICP-AES (extractable sulphate-S, IC) (mg/kg)			Total S (sulphate-S) content (kg/ha)			
		0-30	30-60	60-90	0-30	30-60	60-90	0-90
1995	Bridgets	4.2	1.8	2.2	16.8	7.2	8.8	32.8
	Elgin	8.9	5.2	13.5	35.6	20.8	54.0	110.4
	Rothamsted	(9.8)	(12.4)	(23.7)	(39.2)	(49.6)	(94.8)	(183.6)
1996	Bridgets	6.6	4.4	5.5	26.4	17.6	22.0	66.0
	Forres	10.0	8.9	9.5	40.0	35.6	38.0	113.6
	Rothamsted	12.4	10.0	18.7	49.6	40.0	74.8	164.4
		(8.1)	(6.9)	(15.1)	(32.4)	(27.6)	(60.4)	(120.4)
1997	Bridgets	5.2	3.4	3.4	20.8	13.6	13.6	48.0
		(3.5)	(1.9)	(2.5)	(14.0)	(7.6)	(10.0)	(31.6)
	Crailing	4.7	5.9	4.8	18.8	23.6	19.2	61.6
		(2.0)	(2.0)	(2.6)	(8.0)	(8.0)	(10.4)	(26.4)
	Forres	6.4	6.7	6.8	25.6	26.8	27.2	79.6
	Raynham	9.8	11.4	24.6	39.2	45.6	98.4	183.2
		(6.7)	(6.0)	(14.7)	(26.8)	(24.0)	(58.8)	(109.6)
	Woburn	3.4	2.5	3.0	13.6	10.0	12.0	35.6
		(2.1)	(1.9)	(2.2)	(8.4)	(7.6)	(8.8)	(24.8)

Leaf analysis

Leaf total S concentrations in the untreated crop at early flowering ranged from 0.29 to 1.27% (DM basis) between sites, with N:S ratios varying from 3.1 to 20.9 (Table 4). SO_4-S : S ratios also showed a wide range, from 0.25 to 0.89.

Table 4. Leaf nitrogen and sulphur composition (DM basis) at early flowering in untreated plots.

Year	Site	N %	S	SO_4-S	N : S ratio	SO_4-S : S ratio
1995	Bridgets	3.44	0.29	0.10	11.9	0.34
	Elgin	4.62	1.13	0.95	4.1	0.84
	Rothamsted	-	0.82	-	-	-
1996	Bridgets	4.92	0.40	0.15	12.3	0.38
	Forres	2.74	0.87	0.77	3.1	0.89
	Rothamsted	-	1.27	-	-	-
1997	Bridgets	6.18	0.63	0.40	9.8	0.63
	Crailing	6.68	0.32	0.08	20.9	0.25
	Forres	5.69	0.48	0.29	11.9	0.60
	Raynham	4.07	1.07	0.92	3.8	0.86
	Woburn	5.17	0.34	-	15.2	-

Total S and SO_4-S leaf concentrations both increased with increasing S rate, applied as potassium sulphate, at all sites except Elgin (Table 5).

Table 5. Effect of sulphur rate, applied as potassium sulphate, on leaf sulphur composition (%, DM basis) at early flowering.

Year	Site	Analysis	Sulphur rate (kg/ha S)				
			Nil[1]	10	20	40	80
1995	Bridgets	Total S	0.29	0.32	0.30	0.49	0.54
		SO_4 - S	0.10	0.17	0.15	0.31	0.36
	Elgin	Total S	1.13	1.06	1.25	1.13	1.17
		SO_4 - S	0.95	0.87	1.00	0.85	0.93
	Rothamsted	Total S	0.82	0.78	0.88	1.10	1.30
		SO_4 - S	-	-	-	-	-
1996	Bridgets	Total S	0.40	0.49	0.61	0.66	0.81
		SO_4 - S	0.15	0.23	0.33	0.40	0.54
	Forres	Total S	0.87	0.97	1.01	1.27	1.69
		SO_4 - S	0.77	0.89	0.93	1.21	1.64
	Rothamsted	Total S	1.27	1.22	1.18	1.31	1.52
		SO_4 - S	-	-	-	-	-
1997	Bridgets	Total S	0.63	0.99	1.17	1.46	-
		SO_4 - S	0.40	0.76	0.94	1.22	-
	Crailing	Total S	0.32	0.46	0.58	0.72	-
		SO_4 - S	0.08	0.19	0.31	0.47	-
	Forres	Total S	0.48	0.62	0.70	0.77	-
		SO_4 - S	0.29	0.44	0.54	0.63	-
	Raynham	Total S	1.07	1.22	1.35	1.45	-
		SO_4 - S	0.92	1.06	1.22	1.33	-
	Woburn	Total S	0.34	0.65	1.03	1.36	-
		SO_4 - S	-	-	-	-	-

[1] mean of two untreated controls

Seed yield

Mean seed yields for the potassium sulphate treatments, averaged over the 10-80 (10-40 only in 1997) kg/ha S rates, showed significant (*P* <0.05) yield responses at Bridgets (+11%), Forres (+7%) and Crailing (+28%) in 1997 (Table 6a). Although the mean response (+13%) to applied S was not significant (*P*=0.158) at Bridgets in 1995, where redrilling and an extremely dry season resulted in low yields, some yield differences between individual S rates were almost significant (*P*=0.054). The 9% yield response at Bridgets in 1996 was almost significant at the 10% probability level (*P*=0.108). Crailing, which gave the largest yield increase to applied S, was the only site which also showed significant treatment differences between nil and other individual rates of S applied as potassium sulphate.

The slight apparent increases in mean yield for the potassium sulphate treatments at Forres in 1996 (+3% P=0.52) and Woburn (+4%; P=0.21) were not, however, statistically significant. At Elgin, the mean yield from this form of S application was 7% less than the untreated yield.

At Rothamsted, the apparent yield difference between the nil and S treated means was not significant in 1995 and was associated with variable yields between replicates (CV=24.1%). The equivalent site in 1996 was unresponsive to S applied as potassium sulphate.

Table 6a. Effect of sulphur rate applied as potassium sulphate, on seed yield (t/ha @ 91% DM).

Year	Site	Sulphur rate (kg/ha S)					S-treated
		Nil[1]	10	20	40	80	mean[2]
1995	Bridgets	0.33	0.30	0.38	0.41	0.40	0.37
	Elgin	1.65	1.54	1.75	1.36	1.49	1.54
	Rothamsted	0.54	0.58	0.62	0.58	0.64	0.60
1996	Bridgets	2.96	3.33	3.19	3.21	3.21	3.23
	Forres	2.28	2.47	2.23	2.21	2.44	2.34
	Rothamsted	2.84	2.59	2.81	2.85	2.69	2.74
1997	Bridgets	1.33	1.39	1.48	1.54	-	1.47
	Crailing	2.20	2.65	2.87	2.91	-	2.81
	Forres	2.32	2.43	2.57	2.47	-	2.49
	Raynham	2.09	2.00	1.99	2.14	-	2.04
	Woburn	1.95	2.05	1.99	2.01	-	2.02

[1] mean of two untreated controls
[2] mean of 10-40 (1997 only) or 10 - 80 kg/ha S rates

No yield benefits were obtained from the other forms of S application which were tested at each site in 1995 and 1996, except for a 10% response to elemental S at Bridgets in 1996 (Table 6b). However, foliar applied Epsom salts reduced yield significantly (P=0.003) at Rothamsted in 1995, compared with S applied as potassium sulphate or elemental S, although no scorch symptoms were observed. This form of foliar applied S also caused a moderate but significant (P=0.004) yield reduction (mean of -12% compared to the equivalent sulphate-S rates) in 1996 at Bridgets, where some crop scorch was evident, particularly at the higher rate which caused a greater yield loss. Yield was also reduced slightly by the higher rate of Epsom salts at Rothamsted in 1996.

Table 6b. Mean effect of applied form of sulphur on seed yield (t/ha @ 91% DM).

Year	Site	Untreated (Nil S)[1]	Potassium sulphate[2]	Elemental sulphur[2]	Epsom salts[2]	Magnesium chloride[3]
1995	Bridgets	0.33	0.40	0.37	0.36	0.32
	Elgin	1.65	1.56	1.36	1.38	1.44
	Rothamsted	0.54	0.60	0.68	0.51	0.60
1996	Bridgets	2.96	3.20	3.27	2.82	2.61
	Forres	2.28	2.22	2.25	2.22	2.20
	Rothamsted	2.84	2.83	2.77	2.83	2.87

[1] mean of two untreated controls
[2] mean of 20 and 40 kg/ha S rates
[3] mean of two magnesium rates equivalent to the Epsom salts treatments

Seed oil concentration

Effects of S application rate on seed oil concentration were mostly slight and rarely statistically significant (Table 7a). Seed oil concentration was unaffected by S rate at Rothamsted in both 1995 and 1996, Bridgets in 1997 and at Raynham. In contrast, seed oil concentration showed a small but significant mean increase with S application at Crailing, the most S deficient and yield responsive site. At the majority of sites, however, increasing rates of sulphur tended to reduce seed oil concentration slightly, with an average decrease in concentration across all sites (excluding Crailing) of 0.2% per 20 kg/ha S applied over 0-40 kg/ha range. The mean decrease in oil concentration from S application was only significant ($P<0.05$) at Bridgets in 1996. Overall, however, maximum changes in seed oil concentration from S application were within ± 1% (DM basis) across all sites.

Table 7a. Effect of sulphur rate, applied as potassium sulphate, on seed oil concentration (%, DM basis).

Year	Site	Sulphur rate (kg/ha S)					S-treated
		Nil	10	20	40	80	mean
1995	Bridgets	40.5	39.9	40.4	39.1	40.0	39.8
	Elgin	40.9	41.4	40.7	40.8	40.5	40.9
	Rothamsted	39.5	39.5	39.3	39.6	39.7	39.5
1996	Bridgets	48.6	48.2	48.4	48.0	47.9	48.1
	Forres	47.2	47.3	46.9	46.9	47.0	47.0
	Rothamsted	44.8	44.8	44.8	44.6	44.8	44.7
1997	Bridgets	45.4	45.4	45.3	45.4	-	45.4
	Crailing	40.7	41.7	41.6	41.1	-	41.5
	Forres	46.3	46.3	46.2	45.3	-	45.9
	Raynham	45.7	45.4	45.2	45.5	-	45.4
	Woburn	43.0	42.9	43.0	42.5	-	42.8

The form of S application did not have any significant effect on seed oil concentration at any site in 1995 or 1996, apart from a small but significant ($P<0.001$) decrease in oil content with the foliar spray treatments at Bridgets in 1996, as a result of leaf scorching.

Table 7b. Mean effect of applied form of sulphur on seed oil concentration (%, DM basis).

Year	Site	Untreated (Nil S)	Potassium sulphate	Elemental sulphur	Epsom salts	Magnesium chloride
1995	Bridgets	40.5	39.7	40.4	40.3	40.6
	Elgin	40.9	40.7	40.8	40.6	40.3
	Rothamsted	39.5	39.4	39.3	39.2	39.5
1996	Bridgets	48.6	48.2	48.2	47.7	47.9
	Forres	47.2	46.9	46.2	46.4	46.0
	Rothamsted	44.8	44.7	44.9	44.6	44.5

Seed sulphur concentration

At all sites except Rothamsted in 1995 and 1996, S concentrations in the harvested rapeseed increased (significantly, apart from Elgin and Forres in 1997) with increasing rate of S, applied as potassium sulphate, with sig (Table 8a).

The smallest effects were obtained at sites with adequate soil S reserves, whereas the largest response in seed S concentration to applied S occurred at Crailing, the most deficient site.

Table 8a. Effect of sulphur rate, applied as potassium sulphate, on seed sulphur concentration (%, DM basis).

Year	Site	Sulphur rate (kg/ha S)					S-treated
		Nil	10	20	40	80	mean
1995	Bridgets	0.47	0.59	0.58	0.65	0.67	0.62
	Elgin	0.52	0.53	0.53	0.54	0.55	0.54
	Rothamsted	0.76	0.70	0.72	0.75	0.77	0.74
1996	Bridgets	0.28	0.31	0.33	0.36	0.38	0.34
	Forres	0.33	0.35	0.36	0.35	0.35	0.35
	Rothamsted	0.49	0.49	0.49	0.50	0.48	0.49
1997	Bridgets	0.38	0.41	0.45	0.43	-	0.43
	Crailing	0.32	0.36	0.38	0.42	-	0.39
	Forres	0.33	0.34	0.36	0.37	-	0.36
	Raynham	0.41	0.43	0.43	0.44	-	0.43
	Woburn	0.36	0.40	0.42	0.44	-	0.42

The three forms of S, where tested, showed similar effectiveness in increasing seed S concentration at the sites which had lower soil S status (Bridgets in both years, Elgin and Forres in 1996) (Table8b).

Table 8b. Mean effect of applied form of sulphur on seed sulphur concentration (%, DM basis).

Year	Site	Untreated (Nil S)	Potassium sulphate	Elemental sulphur	Epsom salts	Magnesium chloride
1995	Bridgets	0.47	0.61	0.61	0.58	0.50
	Elgin	0.52	0.54	0.53	0.54	0.53
	Rothamsted	0.76	0.74	0.72	0.76	0.73
1996	Bridgets	0.28	0.34	0.35	0.36	0.29
	Forres	0.33	0.35	0.32	0.31	0.32
	Rothamsted	0.49	0.50	0.50	0.49	0.48

Sulphur off-take in harvested seed

Effects of S application on seed S off-take depended largely on responses in seed yield, rather than seed S concentration (Tables 9a,b). Small but significant ($P<0.05$) increases in S off-take, ranging from +1 to +5 kg/ha between nil and 40 kg/ha S applied as potassium sulphate, were obtained at Bridgets each year and at Crailing, Forres and Woburn in 1997. Sulphur off-take was also increased by applying S in elemental form at Bridgets in 1995 and 1996. Average off-takes, meaned across all sites, were 3.4 or 3.8 kg S/tonne seed (@91%DM) respectively at nil or 20 kg/ha S (applied as potassium sulphate).

Table 9a. Effect of sulphur rate, applied as potassium sulphate, on sulphur off-take in harvested seed (kg/ha S).

Year	Site	Sulphur rate (kg/ha S)					S-treated
		Nil	10	20	40	80	mean
1995	Bridgets	1.4	1.6	2.0	2.4	2.4	2.1
	Elgin	7.9	7.4	8.6	6.7	7.4	7.5
	Rothamsted	3.5	3.7	4.1	4.0	4.3	4.0
1996	Bridgets	7.5	9.4	9.6	10.4	11.0	10.1
	Forres	6.9	7.8	7.2	7.1	7.4	7.4
	Rothamsted	12.6	11.5	12.6	12.9	11.8	12.2
1997	Bridgets	4.6	5.2	6.1	6.0	-	5.8
	Crailing	6.4	8.7	10.0	11.2	-	10.0
	Forres	6.9	7.6	8.5	8.3	-	8.1
	Raynham	7.8	7.8	7.8	8.6	-	8.0
	Woburn	6.4	7.4	7.7	8.1	-	7.7

Table 9b. Mean effect of applied form of sulphur on sulphur off-take in harvested seed (kg/ha S).

Year	Site	Untreated (Nil S)	Potassium sulphate	Elemental sulphur	Epsom salts	Magnesium chloride
1995	Bridgets	1.4	2.2	2.0	1.8	1.4
	Elgin	7.9	7.7	6.6	6.8	6.9
	Rothamsted	3.5	4.0	4.4	3.5	4.0
1996	Bridgets	7.5	10.0	10.3	9.2	6.9
	Forres	6.9	7.1	6.5	6.2	6.4
	Rothamsted	12.6	12.8	12.6	12.7	12.6

DISCUSSION

Soil and leaf analysis for prediction of yield response

Previous HGCA-funded work on winter oilseed rape showed that extractable sulphate-S (by IC) is on average 50, 60 and 70% of extractable total -S (by ICP-AES) at 30, 60 and 90 cm soil depths respectively (Withers *et al*, 1995); also that field responsive sites were often associated with extractable sulphate -S and total -S soil concentrations (either to 30 cm or averaged over the profile) of <4 and <8 mg/kg respectively. Using the 8 mg/kg critical limit for extractable total -S, the results in Table 3 suggested that all three shallow chalk sites at Bridgets, also Crailing and Woburn in 1997, were potentially deficient in sulphur. On the same basis, the Elgin and Forres sites in Morayshire were apparently borderline for sulphur deficiency, whereas the two sites at Rothamsted had adequate supplies of sulphur in the soil profile, with the highest concentrations of extractable S at 60-90 cm depth. Similarly, soil analysis also indicated that Raynham had an adequate sulphur status, particularly in the lower subsoil (60-90 cm depth); this latter site had, however, been selected because preliminary sampling had indicated a marginal sulphur status, with extractable total-S concentrations of 7.9, 6.0 and 11.7 mg/kg in the 0-30, 30-60 and 60-90 cm depths respectively.

Regression analysis of the limited dataset showed that extractable sulphate-S in the soil was approximately 70% of the total extractable S, with little difference between sampling depths. There were, however, insufficient analytical data for extractable sulphate-S in this series of experiments to assess whether this determination was a better predictor of S deficiency risk than total extractable S.

Sampling at a precise growth stage is required to overcome the problem of varying critical values for potential diagnostic indices such as total-S, N:S ratio, sulphate and sulphate:total S ratio in plant material. For winter oilseed rape, a number of field experiment studies in the UK, as summarised by McGrath *et al* (1996), have consistently demonstrated that the total S concentration in the leaves at early flowering stage is the best indicator for S deficiency, with values less than 0.4% (DM basis) indicating a deficiency. Leaf N:S ratio, however, has been shown to be less useful, because it is linearly correlated with seed yield and consequently lacks a clear critical value (McGrath & Zhao, 1996). Although marginally S deficient crops of winter oilseed rape have often shown N:S ratios >17:1, McGrath & Zhao (1996) found that much lower values can also be associated with severe S deficiency, probably because of the effect of S deficiency on N uptake and assimilation. Use of the sulphate:total S ratio has been criticised by Scaife & Burns (1986), on the basis that the numerator (sulphate-S) is the major variable in the denominator, which decreases the sensitivity of the index and it also doubles the amount of analytical work compared to measurement of total S or sulphate alone.

If the critical leaf S concentration of 0.4% for deficiency in the autumn sown crop is assumed to be equally applicable to spring oilseed rape at early flowering, the results in Table 4 for the untreated crop suggested: a deficiency of S at Bridgets in 1995, Crailing and Woburn; marginal crop S status at Bridgets in 1996 and Forres in 1997; an adequate S content in the crop at all the other sites. Leaf N:S ratios in the untreated crop were less than 17:1 at all sites, except Crailing. Linear regression showed that the total S concentration in the leaves of the untreated crop at flowering was significantly ($P<0.001$) correlated with total extractable S at 0-30 cm soil depth, with no improvement in the correlation where total extractable S was averaged over

0-60 cm or 0-90 cm depths (Fig. 1). This finding is similar to that obtained by Withers *et al* (1995), who found that calculation of the mean extractable total-S, also SO_4-S over 0-90 cm soil depth gave only a slight improvement in the regression relationships with leaf S concentrations, compared to using 0-30 cm soil values, for winter oilseed rape.

A threshold leaf S concentration of 0.4% in the spring oilseed rape crops was associated with an extractable total-S concentration in the soil of 5 mg/kg in the top 30 cm or an average of 4 mg/kg in the 0-60 or 0-90 cm depths, based on the linear regressions. The smaller set of paired values just showed a significant (P=0.05) correlation between leaf total S and extractable sulphate-S at 0-30 cm soil depth (R^2(adj)=57.5%).

Five sites gave significant yield responses, based on a 10% probability level. Three out of these five sites were distinguished by low (≤ 0.4%) total S concentrations in young, fully expanded leaves at early to mid flowering. The other two sites had concentrations of 0.5% (Forres, 1997) or 0.6% (Bridgets, 1997) (Fig. 1). Yield responsive sites also contained the smallest concentrations (≤7 mg/kg extractable total S) in the soil at 0-30 cm depth (Fig. 1(a)).

This study has confirmed that leaf analysis for total S at early flowering provides a useful guide to crop S status, and hence S fertiliser requirements for future crops grown under similar conditions, for spring as well as winter oilseed rape. Leaf total S was significantly (P<0.001) correlated with leaf SO_4-S (R^2(adj)=98.7%) in the untreated crop while leaf SO_4-S: total S ratios increased significantly (P=0.004) with total extractable S in the soil (R^2(adj)=74.6%), which suggests that leaf SO_4-S might also have some potential use as a diagnostic index.

Previous field experiments have shown 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. The high leaf S concentrations obtained in the untreated crop at the two Rothamsted sites, also at Elgin and Raynham, suggest that the depth and degree of root growth in these spring sown crops were sufficient to enable crop uptake of S from the lower subsoil layer (60-90 cm depth).

So far, reliable diagnosis of S deficiency in oilseed rape using tissue analysis has only been obtained by leaf sampling at the end of the vegetative growth stage (McGrath *et al*, 1996). Diagnosis at this stage is, however, too late to prevent at least some yield loss in the current crop, even if treated with S at the same time. In Australia, Hocking *et al* (1996) found that the yield of oilseed rape was decreased by 15% when S application (as potassium sulphate) was delayed until flowering, compared with S application at stem extension. Previous studies have shown that S analysis of tissue samples taken at an earlier growth stage is a less accurate guide to crop S status, but current research work under UK conditions is re-examining this possible approach to earlier prediction of S deficiency.

Yield response and sulphur requirement

Balanced supplies of N and S are critical for crop yield, fertiliser efficiency and environmental protection, as increasing N supply increases crop demand for S and consequently exacerbates S deficiency (Walker & Booth 1994; McGrath *et al* 1996). Only limited data are available from previous experimental work on the sulphur requirement of spring-sown oilseed rape. In the 1970s, when atmospheric S deposition was much greater than now, Holmes & Ainsley (1977)

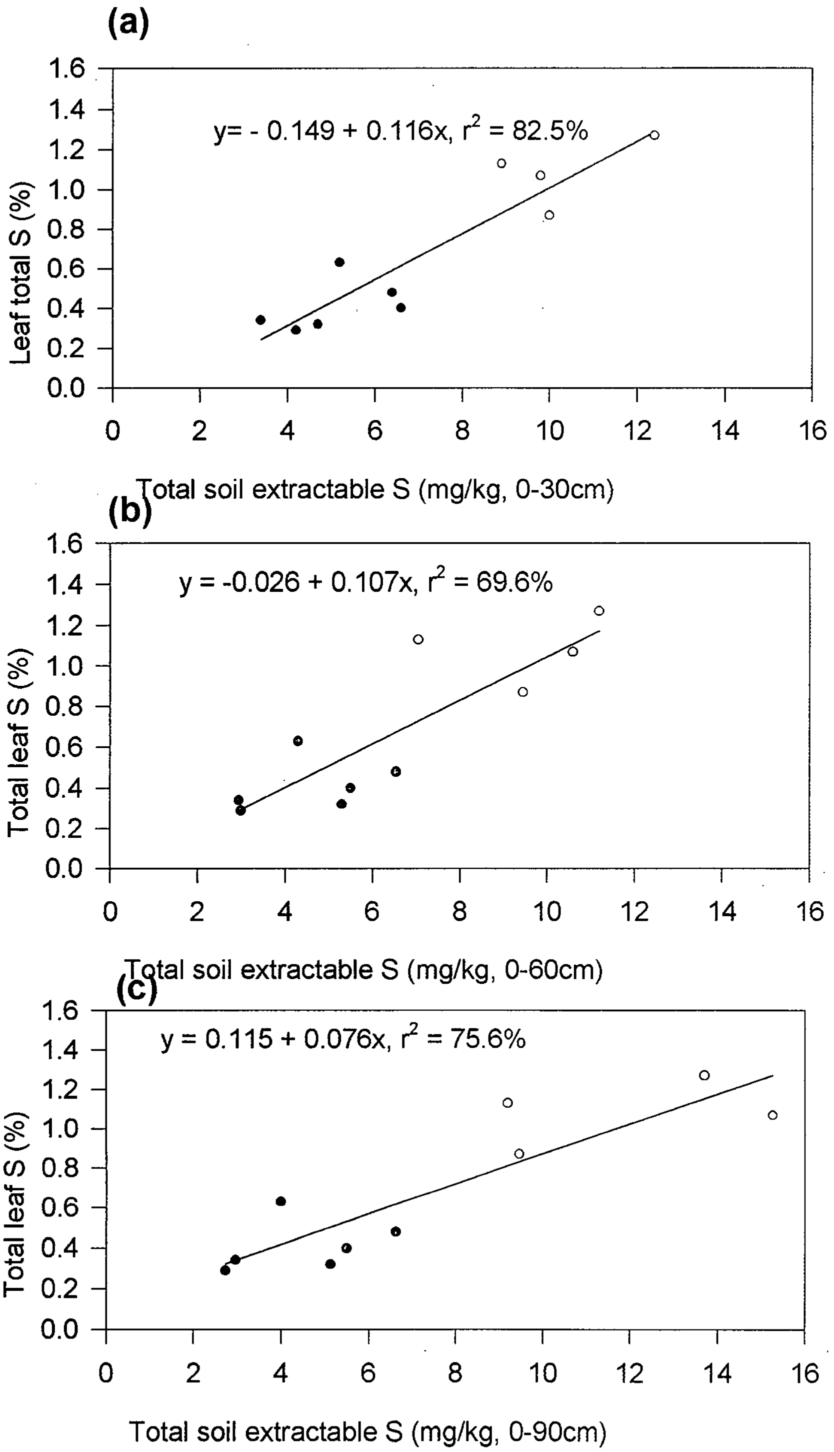

Figure 1. Relationship between leaf S concentration in the untreated crop at flowering and extractable total-S (ICP-AES) in the soil, expressed as a) concentration in top, 0-30 cm layer, b) average concentration for 0-60 cm depth and c) average concentration for 0-90 cm profile. (● denotes yield responsive sites).

found no yield response in spring oilseed rape to S at fourteen sites in the UK which compared application rates of nil and 37 kg/ha S, applied as single superphosphate at sowing. In some parts of Canada, sulphur deficiency was identified in summer rape and summer turnip rape over thirty years ago, when yield responses to applied sulphate-S, ranging 7 to 635% in the most extreme case, were obtained across a number of sites (Wetter *et al* 1970; Nyborg & Bentley 1971; Nyborg *et al* 1974). These experiments showed very little yield response above 20 kg/ha S, even in conditions of extreme S deficiency, for maximum yield levels of 1.5 - 2.0 t/ha. However, other experiments at that time showed no real response, possibly because S was applied in elemental rather than water-soluble form and, under the prevailing conditions, may not have been oxidised rapidly enough to become available for plant uptake (Anderson & Kusch 1968). More recent experiments in Canada have also shown very high yield responses to S applications on deficient soils (Nuttall *et al* 1987). Experiments in Sweden during 1989 to 1993, testing S rates from 0-30 kg/ha applied as calcium sulphate, gave yield responses ranging from nil to 0.2 t/ha (+8%) (Kjellquist & Gruvaeus 1995).

The optimum rate of S application depends on the crop grown, its yield potential, the N supply and potentially also the chemical form of S fertiliser used (McGrath *et al* 1996). For winter oilseed rape, the recommended rate for an average crop is 20-30 kg/ha S, applied as soluble sulphate-S at the start of spring growth, although 10-20 kg/ha may be sufficient on sandy soils if yield potential is restricted by summer drought (McGrath & Zhao 1996; Withers & O'Donnell 1994). In Scotland, S treatment recommendations have been the same for both autumn and spring sown oilseed rape (Anon 1985). The results from this series of experiments suggest that an application rate of 20 kg/ha S is adequate to prevent S deficiency in spring oilseed rape, except possibly on very deficient sites, because of its lower yield potential compared to the autumn sown crop. Several studies have shown that fertiliser S which is not used by crops is highly susceptible to leaching (McGrath *et al* 1996).

Sulphur form

Elemental S is not available to crops until it has been microbially oxidised to sulphate and the oxidisation process occurs more rapidly with decreasing particle size (McGrath *et al* 1996). The main factors affecting oxidisation are the presence of suitable micro-organisms; effective surface of the elemental S particles; soil physical and chemical conditions (temperature, moisture status, aeration, pH). The elemental S must also be well dispersed within the soil to promote oxidisation. The very fine particle size (typically 5-8μm) of the micronised elemental S (Thiovit) treatments which were tested in both 1995 and 1996, combined with seedbed incorporation early in the season, would be expected to produce rapid oxidisation. The yield responses obtained from elemental S applications at Bridgets, both in 1995 and particularly 1996, also the increases in seed S concentrations from this S form at the Bridgets and Morayshire sites in both seasons, suggest that the S was oxidised rapidly enough for effective crop utilisation. A spray application is, however, the only practical method for applying finely divided elemental S, due to its physical nature and the low product (80% S) rate which would be required. Flowers of sulphur, which has a larger particle size (≤100μm), may be an alternative option for seedbed incorporated elemental S but would need further investigation, as Withers & O'Donnell (1994) found that this S form was less effective than potassium sulphate when applied as a spring top dressing to winter oilseed rape. Experiments in Canada have also shown mostly similar effectiveness in yield response of oilseed rape to elemental S and sulphate -S fertiliser (applied as ammonium sulphate), provided the elemental S applications were suitably timed and placed optimally in the soil (Nuttall *et al* 1993).

Elemental S will, however, have a greater acidifying effect on the soil, compared to other S forms.

Field trials in Germany on winter oilseed rape showed that foliar applications of magnesium sulphate (Epsom salts) at flowering were as effective yield-wise as any other method of S application (Chalmers *et al* 1992); application rates of 10-12 kg/ha S were optimal and did not appear to cause any crop scorch. However, in severe S deficiency situations, maximum yield response is most likely to be achieved from earlier (e.g. rosette stage) rather than later applications (Janzen & Bettany 1984). Foliar sprays of ammonium sulphate or ammonium thiosulphate have also been used successfully to control severe S deficiency (Rollier & Ferrif 1969). An application rate of 77 kg/ha magnesium sulphate will supply 10 kg/ha S which, depending on the time of application, would provide most of the S required to prevent or correct S deficiency, unless the soil was very deficient. However, this rate requires a very high volume spray to obtain a 5% w/v solution for low scorch risk and for practical on-farm spraying purposes, would be more suitably applied as split foliar sprays, each supplying 5 kg/ha S. This form of S application is, however, agronomically less convenient than using solid or liquid S - containing fertilisers and foliar spraying with Epsom salts is more suited to applying S as a corrective measure to offset yield loss, where a deficiency is identified later in the season.

Seed quality

Seed oil content decreased slightly at the majority of sites in this experiment, but increased at the most S deficient site, with S application. Holmes (1980) summarised a range of experimental data which showed that severe S deficiency, if left untreated, reduced seed oil content but that S application, where it had only a small or no effect on seed yield, tended to depress oil content, usually by relatively small amounts. Holmes (1980) concluded that severe S deficiency impedes oil synthesis, whereas applying sufficient S for maximum potential crop growth and yield also slightly increases the synthesis of products other than fats in the seed. Recent studies have also shown that the oil content of rapeseed is increased significantly by S application at severely deficient sites (McGrath & Zhao 1996; Hocking *et al* 1996), but that applied S usually has a small negative effect on oil content at marginally deficient sites (Withers & O'Donnell 1994).

Seed total S, rather than glucosinolate contents were determined in this experiment, to estimate the amounts of S residues which would be initially left after harvest as a result of S application. The effects of applied S on seed glucosinolate contents in winter oilseed rape have been summarised by Walker & Booth (1994), Bilsborrow *et al* (1995), McGrath *et al* (1996) and Zhao *et al* (1997). Similar effects presumably occur in the spring sown crop. Both references also emphasised the importance of applying no more S than the crop requires for seed yield response, to minimise the adverse effect on rapeseed meal quality.

The N:S ratio and total S concentration in grain have been advocated as suitable indicators of S deficiency in wheat (Randall *et al* 1981). Seed N concentrations were not determined in this study, but Zhao *et al* (1997) found that the relationship between yield response to S and N:S ratio in rapeseed was not sufficiently reliable for use in diagnosing S deficiency in winter oilseed rape.

Sulphur deficiency is most likely to occur in areas of the UK with light textured soils and low atmospheric inputs of S i.e. eastern Scotland, Scottish borders, East Anglia, South and South West England, Shropshire and South Wales. McGrath & Zhao (1995) have developed a risk assessment model which predicts that a total of 33 and 22% of the UK land area is currently at high and medium risk respectively of S deficiency for oilseed rape. The model also predicts that by 2003, continuing reductions in sulphur dioxide emissions will increase the high risk area to 50%, with 20% of the UK area in the medium risk category. Survey data have shown a large increase in fertiliser S use on oilseed rape in Great Britain over recent years, from 8% of the crop area receiving S fertiliser in 1993 to 30% in 1996, because of the increasing risk of S deficiency (Burnhill *et al* 1997).

CONCLUSIONS

1. Yield responses of 7-30% were obtained at 5 out of 11 sites on sandy or shallow chalk soils testing the form and/or rate of S application for preventing S deficiency in spring oilseed rape.

2. Finely divided elemental S, incorporated as a seedbed dressing, was as effective as seedbed applied potassium sulphate at the 2 S-responsive sites in 1995 and 1996, when different forms of S were compared. Foliar spraying with Epsom salts at the 6-7 leaf stage was, however, a less effective method of applying S to prevent deficiency and, at 3 sites, reduced yield as a result of crop scorch or stress, particularly at the higher rate tested.

3. Yield responsive sites were mostly associated with total S concentrations ≤ 0.4% in the leaves at flowering and all had extractable total S (ICP-AES determination) contents in the soil shortly before drilling of less than 7 mg/kg in either the top 30 cm layer or as an average over 0-90 cm depth.

4. Symptoms of S deficiency were only observed at 2 responsive sites, including the most yield responsive site and were evident at both sites from an early stage of crop growth. Mineralisation of soil S later in the season and moderate yield potential may, however, largely account for the subsequent small, non-significant response (+4%) in seed yield which was obtained at the second of these two sites.

5. Soil analysis in early spring was a useful method for predicting sulphur deficiency. Sampling to 90 cm depth is necessary, to adequately determine available S within potential rooting depth.

6. Effects of S application on seed oil concentration were consistent with those previously observed in winter oilseed rape.

7. Only a small proportion of applied S was removed in the harvested rapeseed at yield responsive sites, however, most or all of the residual S is likely to be lost by leaching over the following winter.

8. An application rate of 20 kg/ha S was generally sufficient for preventing S deficiency at yield responsive sites in this series of experiments, although 30 kg/ha S may be needed for very deficient sites with otherwise good yield potential.

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