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PRACTICAL SECTION FOR GROWERS

Objectives and background

Research in the arable sector has identified sulphur (S) deficiency in cereals and oilseed rape (OSR). Relatively small applications of S (10-40 kg/ha) to these crops growing on 'at risk' sites have improved yields.

There was no evidence of recent work in vegetable crops in the UK and this project aimed to provide some basic information on the responses to S applications and the extent of S deficiencies. Horticultural brassicas were chosen as the first crops to study as being closely related to OSR some response to S was anticipated.

The symptoms of S deficiency are usually seen as a yellowing of leaves, particularly the younger leaves and stunted growth.

In cereals and OSR, plant analysis is generally considered a more reliable tool for the diagnosis of S deficiency than soil testing. Measures used include total S, sulphate-S, N:S ratio and sulphate S: total S ratio. Each of these values varies with plant part and growth stage, declining with age of the plant. Sampling at a precise growth stage is therefore required.

There were no clear guidelines to transfer to the horticultural brassicas but a figure for OSR of 3.8mg g^{-1} total S at early flowering stage (GS 4.0) was found to be useful for predicting S deficiency. For cereals, grain contents of less than 1.2mg g^{-1} or an N:S ratio greater than 17:1 is considered a guide to likely deficiency, i.e. applications of S would lead to improved yields. However both these measurements come too late for corrective action and can only act as a guide for future fertiliser requirements in that field.

Before commencing an intensive research programme to identify soil and plant S requirements throughout the growth of a range of crops, it was decided to carry out some preliminary investigations. These consisted of:

- A survey to see if crops were showing signs of S deficiency
- Measurements of S in soil and plants in the main growing areas in the UK

- A response trial to see if S application can increase plant S levels

Results

Total S at harvest ranged from 2.8 to 9.0 mg g^{-1} dry weight in Brussels sprouts and from 8.3 to 19.4 mg g^{-1} in cauliflower. These levels are within the range reported for other brassicas for sprouts, but the cauliflower values are high. Crops showing visual symptoms of sulphur deficiency were sampled in Lincolnshire, Lancashire and Scotland, symptoms included upper young leaves being cupped, crinkled, thickened and brittle. Some had purple margins and in some cases there was interveinal chlorosis (yellowing). Plants could be stunted and in severe cases the buttons were poorly formed rosettes rather than buttons. These symptoms were similar to those reported for broccoli (calabrese) by Tompkins *et al* (1965).

Crop uptake was up to 120 kg/ha for sprouts and up to 168 kg/ha for cauliflower. These figures are very high compared with arable crops such as OSR 50 kg/ha, potatoes 45 kg/ha and cereals 25 kg/ha. The N:S ratio in sprouts and cauliflower was low around 3-4 rather than 17 which has been found in arable crops.

In the response trial, 0, 15, 30, 45,or 90 kg/ha S was applied to a site with < 3.0 mg kg^{-1} SO_4-S pre-planting. There were no visible signs of S deficiency in the trial and plants grew well at all rates of S application. There was no significant effect of S on total dry matter production and marketable yields. In September applying 30 kg/ha S increased the S content of the plants but this was not seen in December. At harvest the trial plants had S contents at the higher end of the range found in commercial crops.

Conclusions

1. Judging by the guidelines of S concentration from arable crops, horticultural brassica crops showed no clear sign of being deficient in S. The concentration of S found in tissue at harvest were between 2.8 and 19.4 mg g^{-1}, much higher than reported in the literature for OSR and cereals.

2. Crop requirements for S in cauliflower and sprouts are high (120 to 168 kg/ha) in comparison with OSR and cereals. Where these arable crops are at risk of S deficiency it could be hypothesised that brassicas would be at risk also.

3. In a single response trial there was no response in marketable yield to added S.

4. This work has not identified a critical concentration of S for these crops, further work is needed to establish critical soil and plant concentrations and to establish those circumstances where there could be a response to S.

5. Some crops with visual symptoms similar to those reported for S deficiency in broccoli were sampled. Some of these samples had low S content but there was no conclusive evidence that these symptoms were caused by sulphur deficiency.

6. Sulphur applied as a base dressing had a slight effect on reducing Altenaria and Powdery Mildew levels on buttons at harvest on unsprayed treatments.

7. Soil analysis on air dried and fresh soils produced different results, it is not clear what the causes or implications of this are, most work has previously been done with air dried soils.

Action points for growers

1. Growers should be aware that symptoms described in the report could be caused by S deficiency although in many crops S deficiency is characterised by yellowing of younger leaves.

2. Growers are encouraged to contact the project leader if they see such symptoms as they could provide valuable information for future work.

3. Where growers do see such symptoms and decide to treat it, they should leave an untreated area to see if there is a response.

4. Where S deficiency has been diagnosed in previous arable crops, some S could be applied to subsequent crops as an insurance measure, 20-40 kg/ha may be sufficient.

5. Soils most at risk of S deficiency are light, free-draining soils with low levels of organic matter. Areas away from heavy industry and coal fired power stations receive less atmospheric deposition, adding to the risk.

6. From one year's work it is not possible to make clear recommendations.

SCIENCE SECTION

Literature review

In 1987 Syers *et al* reviewed sulphur (S) in UK agriculture and identified that the inputs of S to agricultural land from a number of sources had already declined. McGrath *et al* updated the situation in 1996 and this section summarises parts of their review.

Atmospheric Deposition

In 1983 areas receiving 40 kg S ha^{-1} covered a large part of central and southern England, but have now almost disappeared and probably only exist close to coal-burning power stations which do not have flue gas desulphurisation equipment. Total UK emission of sulphur dioxide decreased from 6.4 million tonnes in 1970 to 4.9 million tonnes in 1980 and to 3.2 million tonnes in 1993 (DoE, 1995). International commitments will see these levels fall further. McGrath *et al* (1996) have mapped total S deposition for 1992 and shown that by that date most of the country was receiving less than 30 kg S ha^{-1}. The area which receives less than 20 kg S ha^{-1}, which is less than the requirement of most arable crops (see later), now includes most of England south of the Wash, Wales, the Scottish Borders and the whole of Scotland. Inputs in the east of Scotland, Devon, Cornwall and West Wales are now below 10 kg S ha^{-1}.

Fertiliser Usage

Syers *et al* (1987) noted that commonly used compound fertilisers no longer contained sulphur which was a contributory factor to declining soil reserves of S. However, because of the increasing occurrence of S deficiency symptoms in some susceptible arable crops (oilseed rape, multi-cut grass and cereals) S-containing fertilisers are more widely used now. In 1995 application rates of 14, 11 and 17 kg ha^{-1} were used for grass, winter wheat and oilseed rape on 3.6, 10.5 and 19.6% of the acreage in England and Wales.

Sulphur in the Soil

Leaching of S is a major pathway of S loss from agricultural systems. Both soluble organic sulphur and sulphate are lost in this way. In lysimeter studies containing a sandy loam soil under fallow conditions 53% of applied K_2SO_4 was lost by leaching in one year (McGrath *et al,* 1996). Studies have indicated that in UK soil virtually all of the indigenous sulphate was in the soil solution and consequently, susceptible to leaching. Most UK soils have a limited capacity for sulphate adsorption.

In soils, organic S forms 90-95% of the total S, most of this is unavailable to plants. Mineralisation of organic S occurs as a result of microbial activity and is much reduced below 10°C. In grassland systems 31-60 kg S ha^{-1} have been mineralised over 18 months (Sakadevan *et al,* 1993) but in arable systems, with lower organic matter levels, rates of only 2-6 kg/ha $^{-1}$ yr^{-1} have been measured (Kirchmann *et al,* 1996).

Crop Sulphur Nutrition

Crop	Part	Yield Level	Sulphur Offtake/ Uptake kg/ha S
Cereals	Grain	8 t/ha	11-17
	Straw	5 t/ha	6-9
Oilseed rape	Seed	3 t/ha	25
	Whole crop at end of flowering	(seed 3 t/ha)	45-70
Potatoes	Tubers	40 t/ha	20
Sugar beet	Roots	40 t/ha	7-23
	Tops	20 t/ha	8-16
Kale	Whole crop	10 t/ha (DM)	30-55
White Cabbage	Marketable heads	45 t/ha	30-50

Skinner (1983) presented the amounts of S uptake by major crops using data taken from the literature. Since then, many studies on oilseed rape and cereals have been undertaken in the UK. In oilseed rape uptake is 16 kg S ha^{-1} in the whole crop for each ton of seed produced in S-sufficient conditions. Thus an average crop of winter oilseed rape, producing 3 t ha^{-1} seed requires approximately 50 kg S ha^{-1}. The double-low and single-low varieties have similar S requirements (Zhao *et al*, 1993). In winter wheat the relationship between grain yield and S uptake by the whole crop is less clear. Wheat crops generally require more than 15 kg S ha^{-1} to avoid S deficiency. Breadmaking varieties have approximately 10% greater S concentrations in the grain than non-breadmaking varieties, because of the higher protein concentrations in the latter.

Little work has been done in the UK to establish the S requirement of other major crops such as potatoes, sugar beet or grain legumes or any vegetable crops. That 19.6% of oilseed rape acreage is being given S containing fertilisers suggests that horticultural brassicas should be examined.

Yield Responses

Crop	% of trials with response	Yield increase at responsive sites %
OSR	39	10-327
Barley	38	5-32
Wheat	24	4-40
Grass	25	5-134

McGrath *et al* (1996) state that S deficiency has become more common in the UK since 1987. In trials carried out since then 29% have shown positive significant responses to added sulphur (see Table above). In economic terms, at responsive sites, applications of S produced 5-15 fold returns on cost of fertiliser.

In oilseed rape glucosinolate content of rapeseed is important for its subsequent use as animal feed. The glucosinolate content has been reduced by the introduction of double-low varieties but even in these 25-30% of the S in seeds is associated with glucosinolates. Glucosinolate content is usually higher at high S than at low S sites. Addition of S fertiliser tends to increase glucosinolate content much more under S-deficient than S-sufficient conditions (Zhao *et al,* 1993). The benefit of S on seed yield and the potential adverse effect on quality of rapeseed meal are difficult to reconcile but applying more S than required by OSR crops must be avoided.

Prediction of S Deficiency

The symptoms of S deficiency are usually seen as a yellowing of leaves, particularly the younger leaves in the upper parts of the plant and stunted growth. These symptoms can be confused with N deficiency or those of other nutrients. Thus diagnosis of S deficiency needs to rely on other approaches.

Scaife and Turner (1983) grew young brassica plants (radish, turnip, Brussels sprouts and purple sprouting broccoli) in sand culture withholding S. They reported interveinal chlorosis of young leaves which cupped either concavely or convexly and eventually failed to grow. The veins stood out as a blurred, blue-green pattern against a pale green background. On the underside of the leaf these dark areas were purple or bronze, this colour could spread to the whole leaf later.

Modelling

A risk assessment model has been developed by McGrath and Zhao (1995) which combines information on atmospheric deposition and various soil characteristics. A sulphate leaching index is constructed from information on rainfall, soil type, texture and pH. Sulphur deposition, sulphate leaching index and potentially mineralisable S are combined and compared with the optimum S requirement of a crop. For oilseed rape 33% of Great Britain is at high risk of S deficiency and 22% at medium risk. The high risk areas are in south-east Scotland, the Scottish Borders, East Anglia, the Welsh Borders and south-west England. With the UK's commitment to reduce SO_2 emissions by 60% of 1980 levels by 2003, the model predicts 50% and 20% would be high and medium risk respectively. Vegetable brassica requirements have not been established to run such a prediction for these crops.

Soil testing

Soil analysis before planting has been less successful than plant tissue analysis for predicting S deficiency, however it would be more convenient for farmers as a method, for corrective applications of S could be made for that crop.

There are a number of different methods used in the literature both for extraction and measurement but these are invariably done on air dried soils. The extractants used can be split into two groups; those that extract mainly water soluble S (eg, water, $CaCl_2$, LiCl) and those that extract water soluble plus adsorbed S (e.g., KH_2PO_4, Ca $(H_2PO_4)_2$, NH_4Oac + HOAc). Apart from sulphate, different extractants also extract different amounts of soluble S, which may or may not be measured depending on the method of S determination used. Four methods of S determination are commonly used; Johnson and Nishita's reduction method, turbidimetry, ion chromatography (IC) and inductively-coupled plasma atomic emission spectrometry (ICP). Turbidimetry and IC measure only sulphate S but the other two measure any soluble organic S extracted.

In pot studies soil tests and S uptake have shown good relationships (e.g. Zhao & McGrath, 1994). In field studies soil tests have proved less reliable. using a phosphate extraction with turbidimetry, sensitive crops responded to S when the soil level was below 3 mg l^{-1} air dried soil, 3-6 mg l^{-1} was considered borderline (Withers & Sinclair, 1994). Withers *et al* (1995) used KH_2PO_4 extraction with IC measurements and correctly diagnosed fields as responsive to S or unresponsive using a critical value of 3 mg kg^{-1} in top soil in early spring. Using the same extractant but with ICP measurements <6 mg kg^{-1} is considered low, and 6-10 mg kg^{-1} borderline. These figures are all for oilseed rape, working with cereals in a total of 40 field experiments neither sulphate nor total soluble S measurements correlated well with yield (McGrath *et al,* 1995).

Availability of S in the lower layers is also important, Mahler *et al* (1993) found that 45-50 kg S ha^{-1} (equivalent to 4.5-5 mg S kg^{-1} in dry soil) in 0-75 cm profile was the critical level for oilseed rape. Soil levels also fluctuate over the seasons, extractable S in top soil tends to decrease in winter, due to leaching probably, and to increase in spring and summer as a result of mineralisation which occurs above 10°C. A measurement of extractable S at a single point in time may not give a realistic indication of the S supply to a crop throughout the growing season.

Plant Tissue Analysis

The diagnosis of S deficiency using plant analysis is widely reported for cereals and oilseed rape in particular. Different authors favour different methods i.e. total S, N:S ratio, sulphate-S and sulphate:total S ratio. Personal preferences but also crop species can determine which index is more appropriate. For example, N:S ratio has been found useful in graminaceous crops but not in OSR. In addition, concentrations of total S, sulphate S and total N change in plant tissue with crop growth so it is difficult to obtain critical values except at closely defined growth stages. Early studies suggested that ratios were more constant during plant growth (Freney *et al,* 1978) but more recent studies show that these ratios also change with growth stage (Robson *et al,* 1995).

In OSR the total S concentration in leaves at early flowering stage has shown to be the best indicator, with values less than 4 mg S g^{-1} dry matter indicating S deficiency (McGrath & Zhao, 1996). Although marginally deficient plants show high N:S ratios (>17:1), much lower values can also be associated with severe deficiency. In wheat in UK a figure of <2 mg g^{-1} total S in the upper fully developed leaves at flag leaf-anthesis stage and N:S ratio >17:1 are used as guidelines for diagnosis of S deficiency. Total S in grain and N:S ratios have been used retrospectively for diagnosis, with critical values of 1.2 mg g^{-1} and 17:1. McGrath *et al* (1995) report that these values may not be suitable for crops with extremely low or high yields. The ratio of N:S has been found to be the best diagnostic index for grassland with a ratio of 20:1 indicating S responsive crops.

There are few reports in the literature for vegetable crops. For borecole levels of 2.5 to 9 mg g^{-1} have been reported from pot trials with no indication of critical values (Schnug, 1990). Schnug also reported S deficiency symptoms in lettuce (pot grown) at 2.5 mg g^{-1}.

Plant tissue S concentrations for vegetables from nutrient culture (from Scaife & Turner, 1983)

Crop	Healthy tissue (mg g^{-1})	Tissue with symptoms (mg g^{-1})	Plant age (weeks)	Part sampled	Symptoms shown
Purple sprouting broccoli	not given	1.0	4	young leaf	severe chlorosis
Carrot	2.8	1.9	9	young leaf	pale leaves
Celery	2.7	0.9	13	mature leaves	young leaves pale
Leek	4.0	1.7	13	whole plant	leaves stiff & erect
Marrow	3.1	1.7	2	young leaf	pale
Sweetcorn	8.9	1.0	7	3rd leaf	young leaves golden colour

Scaife and Turner (1983) grew a range of vegetable crops in sand culture to induce mineral deficiencies for their book "Diagnosis of Mineral Disorders in Plants: Vegetables". They used nutrient solutions minus the appropriate element either from sowing in which case symptoms of S deficiency occurred 20 days after sowing on February 1st, or from 23 March, when symptoms appeared in 12 days. As a result all plants were fairly young when sampled, the above table shows levels of S in healthy plants and deficient plants in comparable plant parts for a range of crops.

Sulphur deficiency was reported in broccoli for the first time in America (Tompkins *et al,* 1965). In the field a wide range of symptoms were observed including dwarfing and severe stunting of plants. Leaves were constricted, twisted, blistered, thickened, necrotic and/or had interveinal chlorosis. Terminal leaves had marginal chlorosis, or necrosis or both, that was most pronounced at the tips. Normal-appearing plants were found beside dwarfed and distorted plants. Adjacent rows could show substantial differences for a hundred feet or more. Many of the affected plants were in lower, wetter field areas. The plant symptoms occurred after nitrogen had been applied by sprinkler irrigation (end August) by the end of September many of the plant symptoms had disappeared. There was no analysis of soils or plants from the field.

Soil was collected from the site and used to grow broccoli in the glasshouse. Mild interveinal chlorosis was seen on young leaves similar to field symptoms in unamended soil. The addition of ammonium sulphate at 118 kg/ha S reduced the chlorosis within 2 days. Plant analysis from the pot experiment is given below.

Treatment	Leaf	S mg g^{-1}	% N	N:S ratio
Control	Green basal leaves	1.2	4.39	36.6
Control	Chlorotic upper leaves	1.0	6.28	62.8
Ammonium sulphate added	Green upper leaves	12.3	6.02	4.9

Singh and Singh (1997) surveyed vegetable growing soils in Agra, India using a $CaCl_2$ extraction (which tends to give low readings as it extracts little organic S (Zhao and McGrath, 1994)). They measured mean levels of 10.8, 11.4 and 10.9 mg kg^{-1} in carrot, cauliflower and potato growing fields respectively, ranging from 3.0 to 24.0 mg kg^{-1} overall. They then grew carrots, cauliflower, potato and radish on a site with 8.5 mg kg^{-1} available – S with 4 rates of sulphur application; 0, 20, 40 and 80 kg/ha S over 2 years. All crops responded to added S up to 40 kg/ha increasing yield by 19.2%, 27.3%, 18.7% and 19.4%, respectively. The sulphur content of the marketable parts was 3.6, 5.7, 2.9 and 3.4 mg g^{-1} with no S added, with 40 kg/ha S added this rose to 4.7, 7.1, 3.8 and 4.6 mg g^{-1}. At 80 kg/ha S the S levels in the marketable part increased again to 5.2, 7.8, 4.2 and 5.0 mg g^{-1} respectively. They conclude that many of the soils would benefit from S applications. In these trials four crops showed yield responses to added S but with no S there were no symptoms of S deficiency reported, indicating that subclinical S deficiency occurs in carrots, cauliflower, potato and radish crops at soil levels of 8.5 mg kg^{-1} available S. No information on levels of S deposition in this region of India was presented.

In general, reliable diagnosis of S deficiency from tissue analysis, where possible, occurs near or at the end of vegetative growth. Sampling at earlier stages has been shown to be less accurate. Applications of sulphur at this stage do not generally ameliorate the deficiency in time to affect yield. However, tissue analysis can be useful to predict S fertiliser need in subsequent year. Once a site has been shown to be susceptible McGrath *et al* (1996) suggest it is reasonable to assume deficiency may occur again, if not in each year.

Introduction

In 1998 preliminary investigations consisting of a crop survey and a response trial were set up. The survey was designed to establish what the levels of S were in well grown crops of Brussels sprouts in areas identified as at risk of S deficiency. The areas selected using published maps (McGrath *et al,* 1996) were E Scotland, Lancashire, Lincolnshire, E Anglia and Cornwall. In Cornwall very few sprouts are grown so overwintered cauliflower was chosen as the crop, it has similar attributes to sprouts i.e. it is grown over a long season and reaches a high dry matter yield. In E Anglia it was difficult to find sprout growers in Norfolk so the area was extended to include Bedfordshire. Crops with "deficiency symptoms" were sampled where they occurred but were not deliberately sought out.

Lancashire was included as an area for sampling although it is not included as a high risk area for two reasons, firstly many brassica crops are grown in the area and secondly as reports of "deficiency symptoms" first came from this area.

The response trial was set up to test if a yield response to added sulphur could be measured. In addition to investigate whether applications of S could reduce disease levels fungicide treatments were withheld from half the trial.

Methods

Survey

Plant samples were collected close to harvest from 29 fields of Brussels sprouts in November/December and 9 fields of overwintered cauliflowers in April/May in Cornwall. Sprout fields were in E Scotland, Lancashire, Lincolnshire, Norfolk and Bedfordshire. A range of varieties maturing in the November/December period were sampled, the initial plan to use only one variety proved too restrictive when sampling from these diverse areas, but where possible common varieties were selected. At maturity 10 whole plants were collected at random over the field and transported back to HRI-Kirton. For cauliflowers whole plants were sampled in December and at harvest the outer leaves and stems were sampled. Here they were shredded, using a compost shredder, a subsample was dried at 70°C for 48 hours or until completely dry. Plant samples were analysed for total nitrogen, total sulphur and sulphate-sulphur. Soil samples were also taken, from near the plant samples; 0-30, 30-60 and 60-90 cm, these were frozen and then analysed for soil mineral N (NH_4-N + NO_3-N) and SO_4-S sulphate-sulphur. A water extraction on both fresh and air dried soil was used, analysis was by ICP.

Trial

Five fields at HRI-Kirton were soil sampled on 6 February 1998 0-30, 30-60 and 60-90 cm deep. These samples were analysed for mineral N and total and sulphate-sulphur. SO_4-S ranged from <1.0 to 11.2 mg/kg dry soil, the field selected contained 2.0, 2.8 and 1.0 mg/kg SO_4-S in the three soil layers.

Five levels of sulphur application as gypsum (Ca SO_4) were used 0, 15, 30, 45 and 90 kg/ha, the whole trial area also received 18 kg/ha –S as part of routine applications of P and K fertilisers. The trial was planted by hand on 21 May using module raised plants of variety Corinth. Plots consisted of six rows by 17 plants allowing four rows by 12 harvestable plants plus a pictureframe guard. Treatments with or without fungicides were established as main plots, sulphur rates were applied to subplots. The trial was arranged as a split-plot design with three replicates. The fungicide programme consisted of:

15 August	0.5 l/ha Folicur
28 August	2 l/ha Folio 575 SC
24 September	0.5 l/ha Folicur
20 October	0.5 l/ha Folicur

These sprays were applied with a tractor mounted sprayer. Details of routine husbandry carried out are given in Appendix 1.

Assessments

Twelve plants per plot for the whole trial were recorded for presence of disease e.g.: Alternaria, Ringspot, White Blister and Powdery Mildew on 1 October. On 30 October the second disease assessment was made, again 12 plants per plot were inspected but this time they were scored on a 0-3 scale for severity of individual diseases. Very similar scores were recorded on all untreated sulphur treatments and on all treated sulphur treatments, the count was therefore restricted to one replicate only.

Plant samples, 10 plants per plot, were taken on 23 September, total dry matter production and plant % S, % N and SO_4-S were measured. At harvest, 1 December, a further 10 plants were sampled as above. The remaining 40 plants were harvested for graded yield assessments, one button from the lower, middle and upper sections of each stem were taken for detailed disease assessments. The remaining buttons were graded in the following size grades; <20 mm, 20-30 mm, 30-40 mm and >40 mm. Unmarketable buttons were split into diseased or other and weights in all grades recorded. One kg of 20-30 mm graded buttons were split in half and dried at 40°C for future glucosinolate analysis.

The results were analysed by analysis of variance using Genstat V programs. Differences quoted below are significant at 5% level.

Results

Survey

Plant Sampling

Five fields of Brussels sprouts showing what was thought to be visual symptoms of sulphur deficiency were encountered during the study period. These included fields in Scotland, Lancashire and Lincolnshire. The symptoms included plants becoming stunted, leaves were straplike, thickened and a dull grey green colour sometimes tinged with purple. Buttons, where formed, were open rosettes rather than neat buttons. Plants were seen to grow away from these symptoms and produce more normal growth higher up the plant. In one field, adjacent cabbage plants showed thickened, leathery leaves and rosette formation, but small heads were later formed. A majority of these cases in Lincolnshire were reported in mid September. From the malformation of the buttons and the overall stunting of the plants it can be assumed that some loss of yield was associated with these symptoms. Although growers and advisors in Lincolnshire were unfamiliar with these symptoms, similar symptoms have been seen in Lancashire over several years (pers. comm C. Treble, F. Tyler) and sulphur deficiency had been indicated from plant analysis, as plants showed high N:S ratios in affected tissues. These symptoms are similar to those described for broccoli (calabrese) by Tompkins *et al* (1965). For convenience these symptoms will be referred to as "sulphur deficiency" for the rest of this report.

The distribution in the field did not follow similar patterns in all cases where described or investigated although in two instances quite obvious and abrupt linear patterns were seen.

Plant sulphur levels in the survey ranged from 2.8-9.0 mg g^{-1} dry weight in sprouts (average 5.73 mg g^{-1}) and from 8.3 to 13.8 mg g^{-1} in cauliflower (average 10.04 mg g^{-1}) Table 1. Sulphate – sulphur levels were high in sprouts and accounted for 71.7 to 100% of the total sulphur measured. In cauliflower this ratio was lower, from 53.5 to 70.0%. In some instances more SO_4-S was measured than total sulphur making this ratio greater than 100%. This is obviously not possible and must reflect a certain level of inaccuracy in the analytical methods. There was a strong correlation (significant as $p<0.001$) between SO_4-S and total S both for sprouts and cauliflower Fig 1. Nitrogen contents ranged from 1.93 to 3.01% in sprouts and 3.51 to 5.17% in cauliflowers. Thus the N:S ratio was quite close ranging from 2.73 to 8.85 in sprouts and 2.41 to 5.69 in cauliflower (Table 2). The N:S ratio was strongly correlated with S in the plant ($p>0.001$), due mainly to the relatively stable levels of N in plants (Fig 2).

The samples taken in Norfolk had the lowest average sulphur content 3.69-4.65 mg g^{-1}. In other areas for sprouts a range of values was found with no obvious "regional" differences. The cauliflower samples from Cornwall had consistently high S values but it is not known if this is due to the crop or the area.

Sulphur uptake for sprouts ranged from 25.1 to 119.0 kg/ha and from 88.5 to 167.7 kg/ha for cauliflower. Uptake for sprouts was generally low in Norfolk due to low S content of dried matter and in Scotland due to lower dry matter production by crops.

In the five fields sampled with visual "deficiency" symptoms the plant sulphur levels were only low in two cases (Table 3), the soil level was also low for one of these sites but was high for the field with the lowest plant S content. Only on site Lincs 7 did the sample of ten plants and associated soil cores come from plants all showing symptoms. They were taken from a single variety plot on a variety demonstration site and so all came from within a small area. On other sites samples were taken randomly across the whole field and did not necessarily contain affected plants or soil samples from those areas. On all sites, although the symptoms were still visible, new growth was healthier suggesting that the conditions causing these symptoms were no longer in place. On sites in Lincolnshire (fields 4 + 7) as well as some other fields notified to us, symptoms were first seen in early September. This may be associated with increased growth following heavy rainfall on 23 August following eight weeks with little rain. The site with the most severe symptoms, Lancs, had quite high levels of S in the plants, however the grower had applied foliar sulphur applications when the symptoms became severe.

Soils

Soil levels of soluble-S in the top 30 cm ranged from 4.5 to 21.5 mg kg^{-1} dry soil at harvest when analysed on air dried samples. The levels in the two lower layers covered the same range (Table 4). Samples analysed as fresh soil (Appendix 2) showed higher levels of soluble-S ranging from 9.1 to 49.3 mg kg^{-1} dry soil. There was no obvious relationship between levels of soluble-S measured by the two methods (Fig 3). Two of the fields (Scotland 5 and Norfolk 6) had levels of soluble-S (air dried samples) below the 6 mg kg^{-1} level at planting quoted as at risk of S deficiency for OSR (M[c]Grath *et al*, 1996), however these samples were taken at harvest.

Soil levels at harvest were lower (below 10 mg kg^{-1}) in Bedfordshire and Norfolk, in other areas more of a range was seen. In E. Scotland, where soil maps show a high degree of risk for other crops, levels ranged from 5.5 to 20.0 mg kg^{-1}, typical of all samples taken as a whole. Post planting in E Scotland (Appendix 3) soil levels tended to be higher ranging from 9.5 to 48.5 mg kg^{-1} but some of these sites did receive recent applications of fertilisers with added S (Appendix 3).

In Cornwall (Table 5) pre-planting samples, taken in July prior to planting overwintered cauliflowers, were generally low (below 10 mg kg^{-1}), and sometimes lower than at harvest.

Soil analysis for sprout crops showed that the soils contained quite large amounts of soluble-S at harvest, up to 245 kg/ha, in comparison there was up to 327 kg/ha mineral N at harvest. The mean figures were 117 and 96 kg/ha respectively.

As soil soluble-S for 0-30 cm increased so did sulphur content in plants at harvest for spouts (Fig 4). There were three sites with high soil levels (19 mg kg^{-1} or more) that fell outside the general relationship. Excluding these three sites there was a significant correlation ($p < 0.001$) which explains 46.6% of the variation ($y = 0.0295x + 0.3279$). Of the three anomalous sites one from Lancashire was a peat soil. The extraction method used extracts some soluble organic sulphur as well as SO_4-S and so may not be suitable for peat soils. One in Scotland had the lowest plant S and showed deficiency symptoms but had a high soil level. The site was waterlogged at the time of sampling which may have affected the result. There was no significant correlation for cauliflower samples (Fig 5).

Soils that contained higher levels of soluble-S in the 0-30 cm layer tended to have higher levels of soluble-S throughout, levels in the 0-30 cm were well correlated ($p<0.001$) with total amounts of soluble-S in 0-90 cm, (Fig 6). However, plant S was more closely related to soluble-S in the 0-30 cm layer than the total amount in the 0-90 cm (Fig 7).

Trial

Yield

Table 6 shows marketable yields at harvest. There were no effects of S applications on yield or weight of diseased buttons. Two plots (0 with fungicide and 90 with fungicide) at one corner of the trial were particularly badly affected by slug damage. This results in lower marketable yields although the total weight of buttons was not affected. The use of the fungicide programme had large and significant effects on yield owing to incidence of Ringspot and Alternaria in the crop. The total weight of buttons was increased at harvest using fungicides. Yields in the 20-30 mm, 30-40 mm grades and total marketable buttons were increased. Not using fungicides increased the weight of diseased buttons overall from 0.2 t/ha to 6.6 t/ha although other unmarketable waste was reduced probably as any diseased buttons with or without other damage were recorded as diseased.

Disease assessments carried out in the field (Tables 7 & 8) showed that all plants were infected with Alternaria and Ringspot in early October. By late October both leaves and buttons were infected but with fungicide applications levels of Ringspot on buttons was much reduced and levels of Ringspot on leaves and Alternaria on both were lower. There was no Powdery Mildew on treated plants by late October, earlier infection must have been on lower leaves which subsequently dropped off. White Blister was only found at low levels. There was no indication that soil applied S had any affect on the levels of disease observed in the field.

At grading 120 buttons per plot were taken for detailed disease assessments (Table 9). There were significantly more clean buttons where 45 or 90 kg/ha S had been applied. In particular, Alternaria was reduced where 90 kg/ha S was applied and Powdery Mildew was higher where 0 or 15 kg/ha S was applied. The three 0.5 l/ha applications of Folicur were not enough to control the Alternaria infection completely but on the treated plots the infection was very slight compared with untreated plots.

Plant uptake

In September total S uptake (Table 10) was increased by applying S fertiliser by up to 28%, this was accompanied by a slight but not significant increase in S content with applied S. Total uptake ranged from 74.9 kg to 96.1 kg/ha. Nitrogen uptake at this stage averaged 297.8 kg/ha with no significant effects. The N:S ratio in the whole plant was significantly higher, at 3.97, with no added S compared with other treatments. With fungicide treatment N:S ratio falls as applied S increases ($y = 4.0136 - 0.0134x$, $r^2 = 70.7\%$, *). These figures are very low compared with those quoted for other crops in the literature.

By December total plant dry weight was higher for fungicide treated plots than unsprayed plots (Table 11). In the field the unsprayed plots had lost many of their leaves while the sprayed plots still had their green leaves. This difference in dry weight is reflected in a significant treatment effect on S uptake although both treatments had the same S content. S content had fallen from 9.9 mg g^{-1} in September to 7.3 mg g^{-1} in December. At the same time the % N content had fallen from 3.4% to 2.83%. SO_4-S was also lower in December. In December there were no effects of S fertiliser application rates. Total S uptake had fallen from September to December from 86.5 kg/ha S to 72.5 kg/ha i.e. by 16.2% over the same period nitrogen uptake had fallen from 297.8 to 279.5 kg/ha N or 6.1%. Sulphur content fell more on unsprayed plots (24.4%) than on sprayed plots (8.1%) suggesting that S was lost through shedding of leaves which was more advanced on unsprayed plots, S is not readily recirculated within the plant. For nitrogen, which can be remobilised from old leaves, the loss was only 5.0% from sprayed plots and 7.3% from unsprayed plots.

Soils

Soil soluble-S concentration at harvest showed only a general trend to higher levels where more S had been applied (Table 4). Calculations suggest that plots receiving 90 kg/ha S at planting contained 50 kg/ha more S at harvest than unfertilised plots, however plant S uptake could not account for the remaining 40 kg/ha S. Zhao and McGrath (1994) have shown that adding SO_4-S to soils can increase the organic S in the soil, i.e. increase immobilisation of S. Calculating a sulphur balance from pre-planting to harvest for the zero rate treatment indicates that 120 kg/ha S became available from soil or atmospheric deposition over the period from February to December. Atmospheric deposition is between 20-40 kg/ha S (McGrath *et al,* 1996) indicating a release of 80-100 kg/ha S from soil organic matter or previous crop residue breakdown.

Table 1 Plant Samples – Brussels sprouts

Sample No./ Variety	% N	S (mg g^{-1})	SO4-S (µg g^{-1})	N:S	SO4 as % S	Total dry matter (t/ha)	N uptake (kg/ha)	S uptake (kg/ha)
Scotland								
1 Adonis	2.49	5.64	4966	4.41	88.0	11.08	275.8	62.4
2 Exodus	2.17	6.74†	6416	3.22	95.2	11.67	253.3	78.7
3 Romulus	2.76	6.24	5773	4.42	92.5	6.75	186.3	42.1
4 Adonis	2.62	5.84	5518	4.49	94.5	10.38	272.0	60.7
5 Hellemus	2.10	4.82	4594	4.36	95.3	5.78	121.5	27.9*
6 Genius	3.01	5.72	5563	5.26	97.3	11.09	334.0	63.5
7 Maximus	2.47	2.79†	2001	8.85	71.7	10.54	260.4	29.4
Lincolnshire								
1 Kundry	2.50	5.68	5193	4.40	91.4	10.65	266.3	60.5
2 4490	2.42	5.83	5130	4.15	88.0	10.28	248.7	59.9
3 Diablo	2.25	6.22	6035	3.62	97.0	11.87	267.2	73.9
4 Profline	2.66	6.02†	5666	4.42	94.1	19.77	525.9	119.0
5 Topline	2.77	5.95	5596	4.66	94.1	12.18	337.4	72.5
6 Adonis	3.12	7.05	6312	4.43	89.5	13.34	416.3	94.1
7 Brilliant	2.63	5.13†	4788	5.13	93.3	17.31	455.1	88.8
Lancashire								
1 Romulus	2.88	5.77	4958	4.99	85.9	13.23	381.1	76.4
2 Adonis	2.45	8.96	7300	2.73	81.5	12.13	297.1	108.6
3 Ariston	2.92	6.69	5309	4.36	79.4	8.04	234.8	53.8
4 Helemus	2.67	5.77	5075	4.63	88.0	12.17	324.9	70.2
5 Tavernos	2.74	5.93	4915	4.62	82.9	13.13	359.9	77.9
6 Romulus	2.90	7.20†	6298	4.03	87.5	11.71	339.6	84.3
7 Adonis	2.19	6.56	5460	3.34	83.2	8.57	187.7	56.2
Bedfordshire								
1 Diablo	2.52	5.98	5099	4.21	85.3	11.55	291.0	69.1
2 Topline	2.70	5.99	6971	4.51	116.4	12.36	333.8	74.1
3 Topline	2.52	5.15	6741	4.89	130.9	10.45	263.3	53.8*
4 JR/007	2.48	5.04	5837	4.92	115.8	14.58	361.5	73.5
5 JR/007	2.24	5.17	4632	4.33	89.6	11.41	255.7	59.0
Norfolk								
1 Ajax	1.93	4.65	4634	4.15	99.7	9.63	185.9	44.8
2 Bridge	2.47	4.13	3796	5.98	91.9	10.32	254.8	42.6
3 Helemus	2.20	3.69	3902	5.96	105.7	10.86	238.9	40.1

*these crops had been market picked for buttons before sampling so dry matter was low
†visual "deficiency symptoms" seen in these fields

Table 2 Plant Samples – Cornwall, cauliflowers

No	Variety	% N	S (mg g^{-1})	SO_4-S (µg g^{-1})	N:S ratio	SO_4 as % tot S	Dry Matter (t/ha)	N uptake (kg/ha)	S uptake (kg/ha)
	December sample								
1	Cod/Mar/Apr	4.84	12.7	7131	3.82	56.2	5.95	288.0	75.4
2	Cod/Mar/Apr	3.51	9.1	5699	3.86	62.6	5.95	208.8	54.1
3	Cod/Mar/Apr	4.31	11.9	6359	3.62	53.5	7.81	336.6	92.9
4	Medaillon	4.02	13.8	9689	2.91	70.0	5.47	219.9	75.7
5	Medaillon	5.17	13.0	8793	3.97	67.5	6.39	330.4	83.3
6	Medaillon	5.05	10.6	6908	4.76	65.1	4.89	246.9	51.9
7	Nomad	4.14	12.1	6609	3.42	54.6	6.60	273.2	79.9
8	Nomad	4.84	9.4	6255	5.15	66.5	5.41	261.8	50.9
9	Nomad	4.72	8.3	4621	5.69	55.7	3.95	186.4	32.8
	At harvest trimmings								
1	Cod/Mar/Apr	3.89	11.9	6579	3.27	55.4	11.47	446.2	136.3
2	Cod/Mar/Apr	3.49	13.3	7199	2.62	54.0	11.58	404.1	154.4
3	Cod/Mar/Apr	3.77	12.6	8002	3.00	63.7	12.10	456.2	151.9
4	Medaillon	4.77	14.4	9424	3.32	65.6	6.77	322.9	97.2
5	Medaillon	5.35	19.4	12399	2.75	63.8	8.63	461.7	167.7
6	Medaillon	5.50	14.8	9352	3.72	63.3	5.99	329.5	88.5
7	Nomad	3.96	11.2	5951	3.52	52.9	9.84	389.7	110.6
8	Nomad	3.24	13.5	8456	2.41	62.8	8.42	272.8	113.4
9	Nomad	3.72	10.9	6759	3.40	61.8	8.31	309.1	90.9

Table 3 Fields with visual symptoms of "sulphur deficiency" compared with figures from trial with 90 kg S applied

Site		Plant S mg/g	N:S ratio	Soil SO_4-S 0-30 cm
Scotland	2	6.74	3.22	13.3
Scotland	7	2.79	8.85	20.0
Lincs	4	6.02	4.42	9.4
Lincs	7	5.13	5.13	7.6
Lancs	6	7.20*	4.03	11.1
HRI-K	90	7.10	4.06	13.5

*Foliar S applied once symptoms became severe

Table 4 Sulphur 1998/9 Soils analysis results dried samples

Source	Plot	Variety	SO_4-S 0-30	µg/g 30-60	60-90	Min N kg/ha 0-90	SO_4-S kg/ha 0-90
Scotland	1	Adonis	7.2	8.4	6.5	63.6	88.8
Scotland	2	Exodus	13.3	14.2	11.8	71.9	157.2
Scotland	3	Romulus	11.1	11.8	9.5	72.9	129.5
Scotland	4	Adonis	9.0	6.9	6.7	90.6	90.6
Scotland	5	Hellemus	5.5	4.8	5.8	84.3	64.3
Scotland	6	Genius	8.8	12.1	6.1	88.7	107.7
Scotland	7	Maximus	20.0	11.0	n/a	n/a	124.0
Lincolnshire	1	Kundry	10.9	8.1	10.0	76.2	116.0
Lincolnshire	2	4490	19.8	9.0	8.1	9.1	147.9
Lincolnshire	3	Diablo	11.8	14.5	15.8	74.5	168.4
Lincolnshire	4	Profline	9.4	9.7	9.0	61.9	112.5
Lincolnshire	5	Topline	19.3	12.5	15.2	55.4	188.0
Lincolnshire	6	Adonis	10.6	10.3	9.2	63.6	120.3
Lincolnshire	7	Brilliant	7.6	5.7	5.6	52.9	75.8
Lancashire	1	Romulus	21.5	18.0	21.8	168.0	245.4
Lancashire	2	Adonis	15.5	19.2	18.0	276.8	210.4
Lancashire	3	Ariston	8.8	7.2	7.9	326.8	95.7
Lancashire	4	Helemus	8.5	8.0	13.0	88.7	118.1
Lancashire	5	Tavernos	11.0	8.6	8.1	162.8	111.1
Lancashire	6	Romulus	11.1	10.2	9.9	143.7	124.7
Lancashire	8	Adonis	11.4	9.7	10.2	33.9	125.2
Bedfordshire	1	Diablo	9.9	5.2	6.5	59.2	86.7
Bedfordshire	2	Topline	6.2	5.5	7.1	49.0	75.4
Bedfordshire	3	Topline	8.4	5.6	9.7	112.8	94.6
Bedfordshire	4	JR/007	7.0	9.3	26.1	92.8	169.7
Bedfordshire	5	JR/007	9.1	6.6	9.2	93.5	99.5
Norfolk	6	Ajax	4.5	4.3	3.4	74.2	48.8
Norfolk	7	Bridge/H	7.5	4.4	3.4	56.1	61.0
HRI Kirton	0		10.1	5.4	7.5	82.1	92.3
HRI Kirton	15		6.5	5.6	6.1	81.0	72.5
HRI Kirton	30		14.0	7.5	8.5	101.7	120.0
HRI Kirton	45		9.0	8.8	5.4	120.2	92.4
HRI Kirton	90		13.5	11.4	10.1	115.8	139.9

Table 5 Cornish Soil Analysis Results from dried samples

Sample field	Variety	At planting			At harvest		
		Soils SO_4-S (mg/kg)		SO_4-S (kg/ha)	Soils SO_4-S (mg/kg)		SO_4-S (kg/ha)
		0-30 cm	30-60 cm	0-60 cm	0-30 cm	30-60 cm	0-60 cm
1	Cod/Mar/Apr	4.99	7.44	49.72	4.06	4.62	34.72
2	Cod/Mar/Apr	6.56	3.45	40.04	15.40	4.75	80.60
3	Cod/Mar/Apr	6.72	4.53	45.00	16.69	8.46	100.60
4	Medaillon	7.79	4.45	48.96			
5	Medaillon	8.55	5.16	54.84			
6	Medaillon	7.44	5.13	50.28			
7	Nomad	10.38	10.34	82.88	6.68	6.16	51.36
8	Nomad	5.22	6.62	47.36	7.20	4.21	45.64
9	Nomad	7.56	4.08	46.56	4.90	3.42	33.28

Table 6 Marketable yield and total yield as t/ha

Sulphur rate Fungicide treated (kg/ha)	Marketable (t/ha) <20 mm	20-30 mm	30-40 mm	Total	Unmarketable Disease	Other*	Total weight
0	0.8	10.9	2.6	14.2	0.2	2.0*	16.9
15	1.1	11.5	2.5	15.0	0.2	1.6	16.8
30	1.0	11.7	2.5	15.2	0.3	2.0	17.5
45	1.0	11.4	2.4	14.8	0.1	1.8	16.7
90	0.9	10.0	2.7	13.6	0.1	3.4*	17.1
Mean	1.0	11.1	2.5	14.6	0.2	2.2	17.0
Untreated							
0	0.9	7.5	0.3	8.7	6.3	0.6	15.6
15	1.0	5.2	0.2	6.4	8.6	0.3	15.3
30	0.8	7.0	0.4	8.1	6.9	0.5	15.5
45	1.1	8.1	0.5	9.7	5.8	0.5	16.0
90	1.0	7.7	0.6	9.2	5.4	0.7	15.3
Mean	1.0	7.1	0.4	8.4	6.6	0.5	15.5
LSD 5%							
Fungicide df = 2	0.31	2.84	2.48	5.44	2.17	5.97	2.52
Fungicide x rate df = 16	0.51	2.45	0.81	3.22	1.97	1.58	1.81

*Other unmarketable buttons were mostly slug damaged buttons, 2 plots (0 with fungicide and 90 with fungicide) at one corner of the trial suffered quite serious losses

Table 7 Disease Assessments 1 October 1998
Number of plants infected out of 12

Treatment	White Blister	Alternaria	Ringspot	Powdery Mildew
Fungicide treated				
0	8.3	12.0	12.0	11.3
15	6.3	12.0	12.0	9.3
30	8.3	12.0	12.0	10.7
45	6.3	12.0	12.0	10.0
90	7.0	12.0	12.0	10.7
Untreated				
0	9.0	12.0	12.0	12.0
15	9.7	12.0	12.0	11.7
30	10.0	12.0	12.0	12.0
45	9.7	12.0	12.0	12.0
90	9.0	12.0	12.0	11.7

Table 8 Disease Assessments – 30 October 1998
Mean score per 12 plants; 1 = 1-10, 2 = 10-100, 3 = 100+ spots etc

Treatment	White Blister		Alternaria		Ringspot		Powdery Mildew	
	Leaves	Buttons	Leaves	Buttons	Leaves	Buttons	Leaves	Buttons
Fungicide treated								
0	0.08	0.00	1.33	1.08	1.92	0.33	0.00	0.00
15	0.00	0.00	1.25	1.08	1.92	0.17	0.00	0.00
30	0.25	0.00	1.17	1.00	2.00	0.17	0.00	0.00
45	0.42	0.00	1.25	0.92	1.92	0.17	0.00	0.00
90	0.08	0.00	1.17	1.00	1.83	0.42	0.00	0.00
Untreated								
0	0.17	0.17	1.75	1.33	2.42	1.58	3.00	2.50
15	0.08	0.17	1.75	1.08	2.50	1.50	3.00	2.42
30	0.08	0.08	1.58	1.25	2.25	1.58	3.00	2.42
45	0.00	0.25	1.42	1.50	2.33	1.58	2.92	2.17
90	0.08	0.17	1.67	1.58	2.67	1.58	3.00	2.66

Table 9 Button disease assessments at harvest, % of buttons affected out of 120 button sample

Sulphur Rates	Clean	Ringspot	Alternaria	White Blister	Powdery Mildew
Fungicide treated					
0	46.7	1.4	53.1	0.8	0
15	36.9	4.7	63.1	0.3	0
30	39.4	2.2	60.6	0.6	0
45	41.4	2.8	58.3	0.6	0.3
90	50.0	3.1	49.7	0.6	0
Mean	42.9	2.8	56.9	0.6	0.1
Untreated					
0	5.0	66.9	70.0	6.9	69.2
15	8.9	77.2	70.3	4.4	59.4
30	9.7	68.6	73.9	2.5	43.9
45	14.2	59.7	76.4	4.7	44.4
90	18.1	62.8	62.8	4.7	53.9
Mean	11.2	67.1	70.7	4.7	54.2
Mean					
0	25.8	34.2	61.5	3.9	34.6
15	22.9	40.1	66.7	2.4	29.7
30	24.6	35.4	67.2	1.5	21.9
45	27.8	31.2	67.4	2.6	22.4
90	34.0	32.9	56.3	2.6	26.9
Mean	27.0	34.9	63.8	2.6	27.1
LSD 5%					
Fungicide df = 2	6.84	9.29	27.07	6.06	24.96
Rate df = 16	8.01	14.10	7.84	3.83	8.54
Fungicide x rate df = 16	11.34	19.95	11.09	5.41	12.06

Table 10 Plant analysis from trial in September as percent of dry matter

	% N	% S	% SO_4-S	N:S	Total dry weight (t/ha)	Total N uptake (kg/ha)	Total S uptake (kg/ha)
Fungicide treated							
0	3.86	0.91	0.57	4.28	8.93	334.9	81.0
15	3.64	0.92	0.60	3.95	9.04	328.3	83.3
30	3.20	1.01	0.64	3.20	9.45	300.7	94.7
45	2.97	0.93	0.57	3.20	9.44	280.2	87.4
90	3.08	1.02	0.69	3.03	8.57	263.2	87.3
Mean	3.35	0.96	0.62	3.53	9.09	303.5	86.7
Untreated							
0	3.30	0.91	0.61	3.66	7.67	252.5	68.8
15	3.26	1.05	0.68	3.10	9.34	304.7	98.5
30	3.57	1.08	0.71	3.31	9.10	323.3	97.6
45	3.58	0.98	0.66	3.68	8.19	294.7	80.3
90	3.49	1.06	0.73	3.31	8.19	285.0	85.8
Mean	3.44	1.02	0.68	3.41	8.50	292.1	86.2
Mean							
0	3.58	0.91	0.59	3.97	8.30	298.7	74.9
15	3.45	0.99	0.64	3.53	9.19	316.5	90.9
30	3.39	1.04	0.68	3.26	9.27	312.0	96.1
45	3.28	0.95	0.62	3.44	8.82	287.5	83.9
90	3.29	1.04	0.71	3.17	8.38	274.1	86.5
Mean	3.40	0.99	0.65	3.47	8.79	297.8	86.5
LSD 5% Fungicides	0.37	0.11	0.10	0.26	1.53	45.8	19.5
Rate	0.44	0.13	0.12	0.44	0.94	47.4	10.0
F x R	0.62	0.19	0.17	0.63	1.33	67.1	14.1

Table 11 Plant analysis from trial in December as percent of dry matter

	% N	% S	% SO_4-S	SO_4-S as % of S	N:S	Total dry weight (t/ha)	Total N uptake (kg/ha)	Total S uptake (kg/ha)
Fungicide treated								
0	2.80	0.71	0.56	78.9	3.97	10.69	297.6	76.6
15	2.51	0.77	0.59	76.6	3.26	10.28	258.6	78.9
30	2.72	0.74	0.60	81.1	3.70	10.50	284.9	77.2
45	2.56	0.75	0.57	76.0	3.45	11.82	301.7	89.3
90	2.68	0.69	0.68	98.6	3.92	11.19	298.9	76.7
Mean	2.65	0.73	0.60	82.2	3.66	10.89	288.3	79.7
<u>Untreated</u>								
0	3.07	0.68	0.55	80.9	4.50	9.31	287.2	63.7
15	3.07	0.72	0.54	75.0	4.27	8.97	276.7	64.5
30	2.94	0.74	0.62	83.8	3.98	9.06	266.5	67.4
45	2.98	0.76	0.61	80.3	3.94	9.12	270.5	69.5
90	3.00	0.73	0.60	82.2	4.20	8.42	253.0	61.0
Mean	3.01	0.73	0.58	79.5	4.18	8.98	270.8	65.2
<u>Mean</u>								
0	2.94	0.70	0.56	80.0	4.24	10.00	292.4	70.2
15	2.79	0.74	0.56	75.7	3.77	9.62	267.6	71.7
30	2.83	0.74	0.61	82.4	3.84	9.78	275.7	72.3
45	2.77	0.75	0.59	78.7	3.70	10.47	286.1	79.4
90	2.84	0.71	0.64	90.1	4.06	9.81	275.9	68.9
Mean	2.83	0.73	0.59	80.8	3.92	9.94	279.5	72.5
LSD 5% Fungicide	0.45	0.08	0.12	-	1.04	1.11	27.8	13.9
Rate	0.24	0.07	0.07	-	0.53	1.09	38.2	11.6
F x R	0.34	0.10	0.09	-	0.75	1.54	54.1	16.5

Discussion

Plant sulphur levels ranged from 2.8 to 9.0 mg g^{-1} in sprouts and from 8.3 to 19.4 mg g^{-1} in cauliflower. These levels fall within the range of figures given in the literature for other brassicas although some values for cauliflower are high. McGrath & Zhao (1996) gave values of 4-4.5 mg g^{-1} at harvest for OSR (whole plants) as sufficient, Schnug (1990) measured borecole in pot trials and found 2.5-9 mg g^{-1}, Tompkins *et al* (1965) measured 1.0-1.2 mg g^{-1} in leaves of broccoli grown in pot trials in deficient plants, after ammonium sulphate application deficiency symptoms disappeared in 2 days, upper leaves then had 12.3 mg g^{-1} S. Singh and Singh (1997) found 5.7-7.8 mg g^{-1} S in marketable cauliflower from field trials with application rates of S up to 80 kg/ha.

Plants from fields with visual symptoms of "sulphur deficiency" contained 2.79 - 7.2 mg g^{-1} S, these levels are high compared with figures given in the literature for deficient plant leaves e.g. <4 mg g^{-1} in OSR in leaves at early flowering stage (McGrath & Zhao, 1996), 1.0 mg g^{-1} in chlorotic young leaves of purple sprouting broccoli (Scaife and Turner, 1983), 1.0 and 1.2 mg g^{-1} in chlorotic upper leaves and green basal leaves respectively for broccoli grown in pots (Tompkins *et al*, 1965). However, plant samples taken in the survey were generally taken randomly across fields from crops showing visual symptoms and consist of whole plants rather than affected leaves. Both factors would tend to increase S contents. Also in one instance a foliar spray of S had been applied following the development of symptoms. In the one case where samples came from plants with symptoms the S content was 5.13 mg g^{-1}, one of the lowest levels measured.

The levels of S found in the survey and in the literature for vegetable brassicas are high compared with those found in wheat and grassland. A critical value of <2 mg g^{-1} in flag leaf at anthesis is given for wheat (McGrath & Zhao 1996) and an N:S ratio of 17:1 in grain. An N:S ratio of 20:1 in grassland is given for responsive crops. It is not possible from this field work or literature review to give critical plant concentrations for cauliflower or sprouts.

The S uptake for sprouts and cauliflower was high, especially when compared with current deposition rates. Cereals and OSR which take up 25 and 50 kg/ha respectively have been shown to be responsive to S applications, crops which take up, up to 120 and 168 kg/ha respectively should also be likely to respond to S applications, but this hypothesis needs to be confirmed in further experiments.

Soil analysis was originally carried out on fresh soil, however these results were higher than expected and showed no relationship with analysis based on dry soil. It is not obvious why drying the soil sample should reduce the amount of soluble-S measured however as the methods quoted in the literature use air dried soil it is probably more appropriate to use this method. Pot studies have shown good relationships between soil tests on air dried soil and plant S uptake (Zhao & M^c^Grath, 1994).

Soil levels of soluble-S at harvest ranged from 4.5 to 21.5 mg kg^{-1} dry soil. Plant S content at harvest was correlated with soil soluble-S at harvest, when three high soil levels were excluded. One of these sites was a peat soil and the extraction method used may not be suitable for such soils, organic matter content on one of the other two sites could also account for anomalous results. The remaining site was waterlogged at sampling, which may also affect the results.

In the trial applying some S fertiliser increased S uptake in September even though 18 kg/ha S had been applied as part of routine fertiliser applications. Applying S also increased the S content in September but not in December. At harvest it appears that even applying 90 kg/ha S did not affect the level of S in the whole plant suggesting that luxury S uptake may not be very great.

Applications of S did not greatly affect soil levels of soluble-S at harvest and uptake by the plants could not account for the difference in S levels. Calculations for the unfertilised plots suggested that 80-100 kg/ha S could have been released from soil organic matter or previous crop residue breakdown. Nitrogen mineralisation over the same period was 170 kg/ha. This suggests that mineralisation of S could be a more important source of S for crops than previously assumed. Net mineralisation of 31-60 kg/ha S over 18 months have been reported for grassland sites (Sakadevan *et al*

(1993)). Soil measurements of available S and transformations in the soil are not well documented. Further investigations in these areas may be appropriate.

Conclusions

1. Sulphur concentrations in whole plants of horticultural brassicas at harvest are higher than those reported in the literature for arable crops. The critical concentrations applicable for OSR or cereals may not be applicable. Applicable critical levels still need to be determined.

2. Sulphur uptake by cauliflower and sprouts are high suggesting that where they are grown in areas where cereals and OSR are considered to be at risk of S deficiency, they could also be at risk, but this conclusion needs to be tested in further response trials.

3. Some crops showing visual symptoms ascribed to S deficiency have been sampled but although some of these samples had low S content there was no clear evidence that these symptoms were caused by sulphur deficiency.

4. Sulphur applied in a replicated trial increased S content in sprouts in September but not in December, there were no significant effects of applying S on total dry matter and marketable yields.

5. Sulphur applied as a base dressing had a slight effect on reducing Altenaria and Powdery Mildew levels on buttons at harvest on unsprayed treatments.

6. Soil analysis on air dried and fresh soils produced different results, it is not clear what the causes or implications of this are, most work has previously been done with air dried soils.

7. A target level for soil analysis prior to planting or for plant analysis at an early stage would be useful for growers, this will require further research.

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Appendix 1 Husbandry Details

Soil texture and site:	Coarse silty marine aluvial, Snargate series
Previous cropping:	1997 Winter wheat 1996
Soil analysis:	See HRI Kirton in Appendix 2
Cultivations:	Ploughed January 1998 Worked with Kuhn power harrow pre-planting
Fertiliser:	62.5 kg/ha K as sulphate of potash 25 kg/ha P as triple super phosphate applied 17 February 100 kg/ha N as ammonium nitrate at planting 100 kg/ha N top dressing 15 July as above
Plants:	cv Corinth sown 4 March 1998 planted 21 May
Herbicide:	Chlorthal dimethyl as 6 kg/ha Dacthal plus propachlor at 9 l/ha in 450 l water
Insecticides:	Pirimicarb as 420 g/ha Aphox plus cypermethrin as 250 ml Toppel in 600 l water on 12 June, 24 July, 7 August, 19 August, 24 September Demeton-s-methyl as 560 ml/ha Metaphor in 650 l water on 12 September Heptenophos as 840 ml/ha Hostaquick in 650 l water on 5 November
Fungicides:	As per treatments

Appendix 2 Soil Analysis Results fresh samples

	Fresh samples		SO_4-S mg/kg			Min N kg/ha	SO_4-S kg/ha
Source	Plot	Variety	0-30 cm	30-60 cm	60-90 cm	0-90 cm	0-90 cm
Scotland	1	Adonis	14.54	11.46	9.97	63.6	143.88
Scotland	2	Exodus	35.84	16.95	19.32	71.88	288.44
Scotland	3	Romulus	15.49	18.46	16.02	72.92	199.88
Scotland	4	Adonis	28.66	31.48	18.97	90.6	316.44
Scotland	5	Hellemus	13.48	14.07	18.52	84.28	184.28
Scotland	6	Genius	13.24	12.13	18.4	88.72	175.08
Scotland	7	Maximus	n/a	n/a	n/a	n/a	n/a
Lincolnshire	1	Kundry	16.22	13.25	14.33	76.16	175.2
Lincolnshire	2	4490	19.8	29.03	30.26	53.96	316.36
Lincolnshire	3	Diablo	18.43	29.72	23.92	74.48	288.28
Lincolnshire	4	Profline	13.6	13.67	13.12	61.92	161.56
Lincolnshire	5	Topline	13.22	10.9	13.79	55.36	151.64
Lincolnshire	6	Adonis	12.95	9.27	11.28	63.6	134
Lincolnshire	7	Brilliant	13.29	10.97	14.88	52.92	156.56
Lancashire	1	Romulus	49.31	107.27	25.04	168	726.48
Lancashire	2	Adonis	14.83	13.9	37.52	276.8	265
Lancashire	3	Ariston	31.51	21.55	19.99	326.8	292.2
Lancashire	4	Helemus	14.03	21.59	17.92	88.72	214.16
Lancashire	5	Tavernos	33.09	22.45	25.35	162.8	323.56
Lancashire	6	Romulus	29.04	23.73	25.45	143.68	312.88
Lancashire	8	Adonis	31.88	39.68	37.2	33.88	435.04
Bedfordshire	1	Diablo	9.13	17.12	14.05	59.24	161.2
Bedfordshire	2	Topline	17.15	16.07	15.75	49.0	195.88
Bedfordshire	3	Topline	26.13	33.29	31.38	112.8	363.20
Bedfordshire	4	JR/007	27.79	23.75	22.19	92.8	294.92
Bedfordshire	5	JR/007	20.08	27.55	26.29	93.5	295.68
Norfolk	1	Ajax	21.7	7.35	11.88	74.16	163.72
Norfolk	2/3	Bridge./H	13.31	9.04	12.71	56.12	140.24
HRI-K	0		11.05	12.06	22.25	82.12	181.44
HRI-K	15		15.42	18.79	21.72	81	223.72
HRI-K	30		18.37	14.02	21.44	101.68	215.32
HRI-K	45		18.33	16.26	17.7	120.16	209.16
HRI-K	90		16.98	23.86	15.3	115.84	224.56

Appendix 3

Scottish soil analysis results from post planting (from air dried samples) and S applied at planting

Source	Plot	Post planting Soils SO_4-S (mg/kg)		SO_4-S kg/ha	Sulphur applied
		0-30 cm	30-60 cm	0-60 cm	kg/ha
Scotland	1	45.5	30.5	304.0	19
Scotland	2	28.0	27.0	220.0	40
Scotland	3	15.5	7.5	92.0	40
Scotland	4	35.5	27.5	252.0	23.75
Scotland	5	15.5	9.0	98.0	35
Scotland	6	9.5	72.5	328.0	53
Scotland	7	48.5	46.0	378.0	

Appendix 4

Fig 1 Plant SO_4-S for both crops

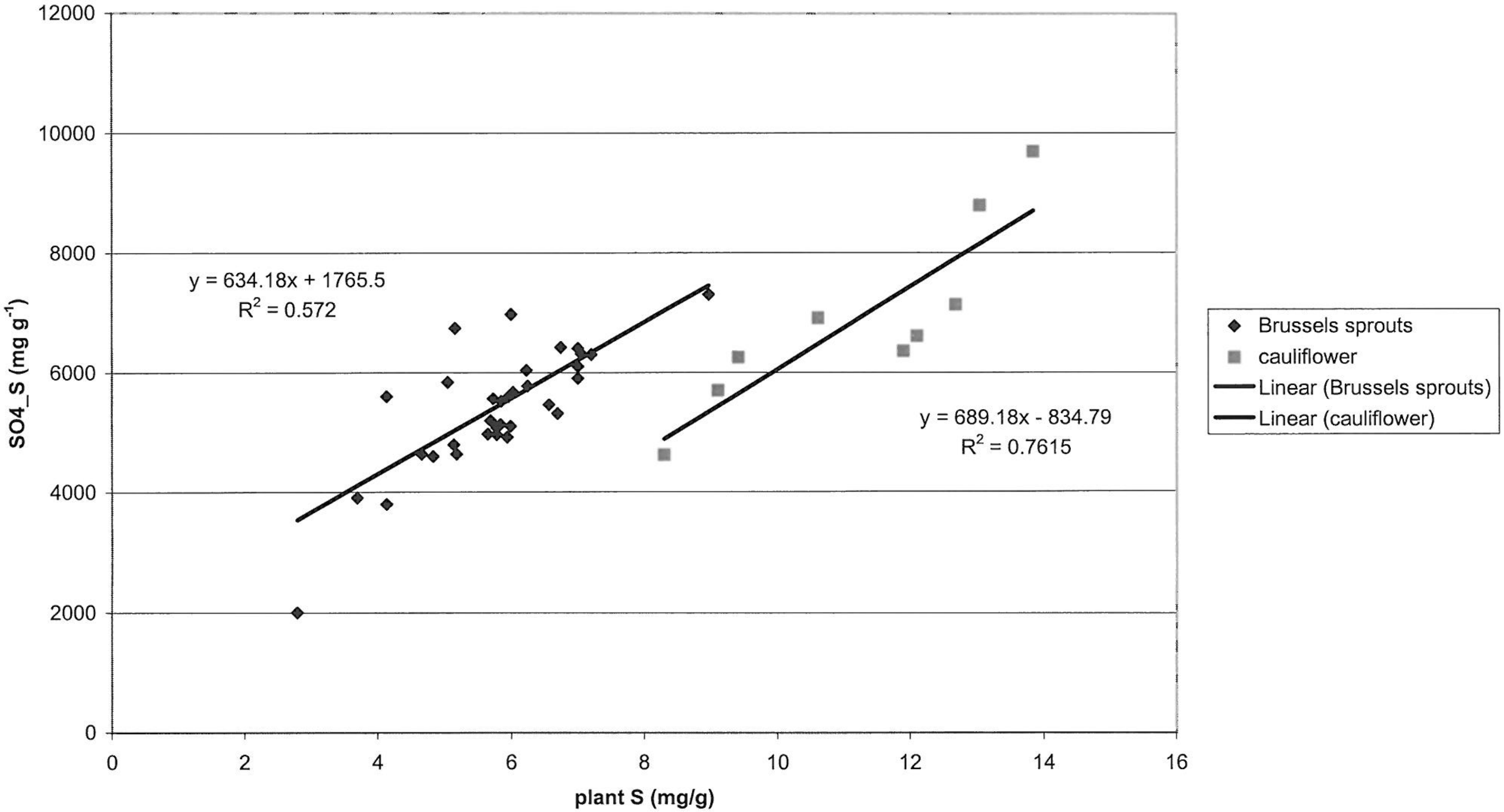

Fig 2 Sulphur; relationship between plant S and plant %N and N:S ratios

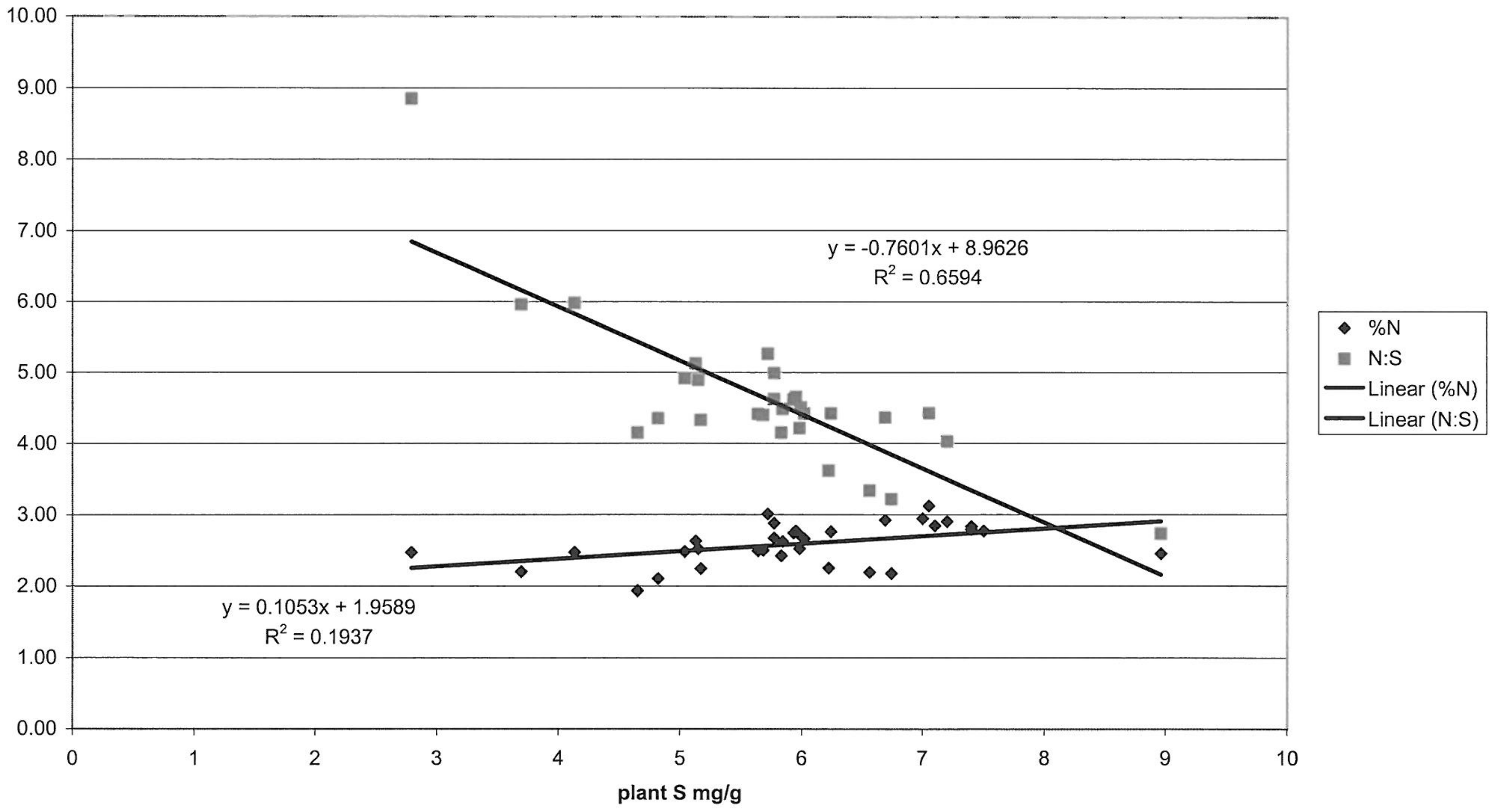

Fig 3 Soil soluble-S mg/kg ; fresh and dry samples by layers

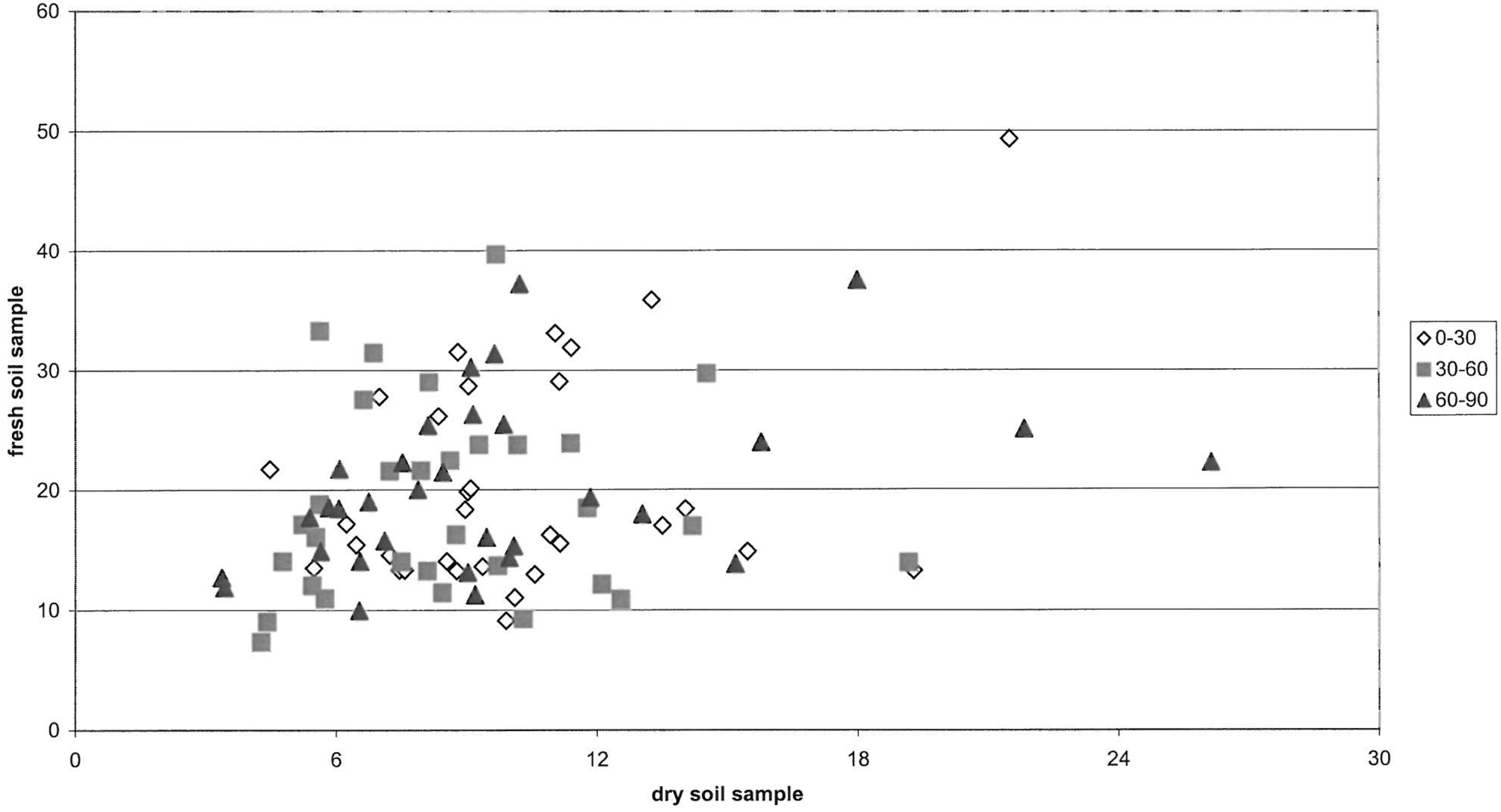

Fig 4 sprouts; soil SO4-S in 0-30 cm v plant S content

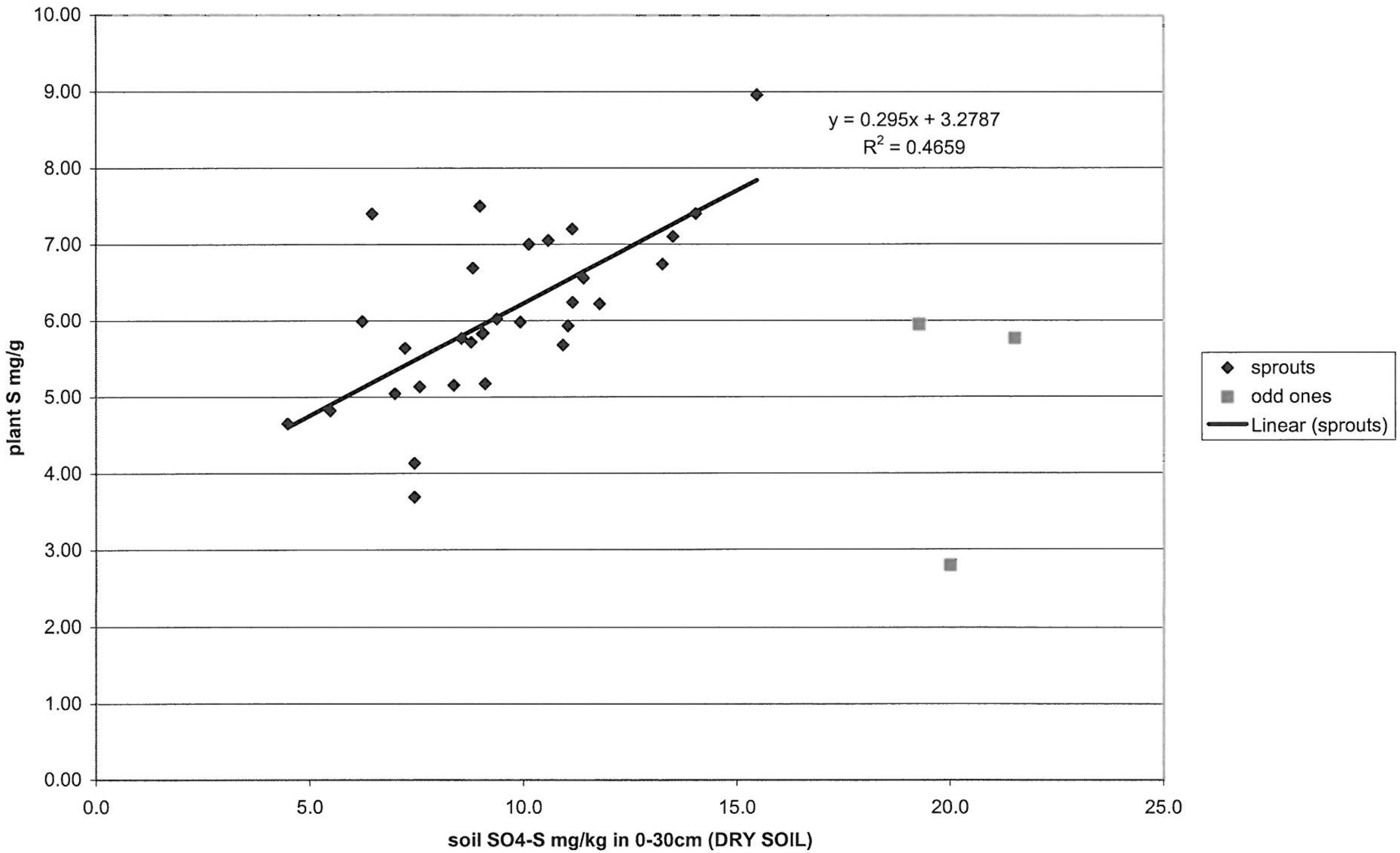

Fig 5 Cauliflower at harvest, trimmings

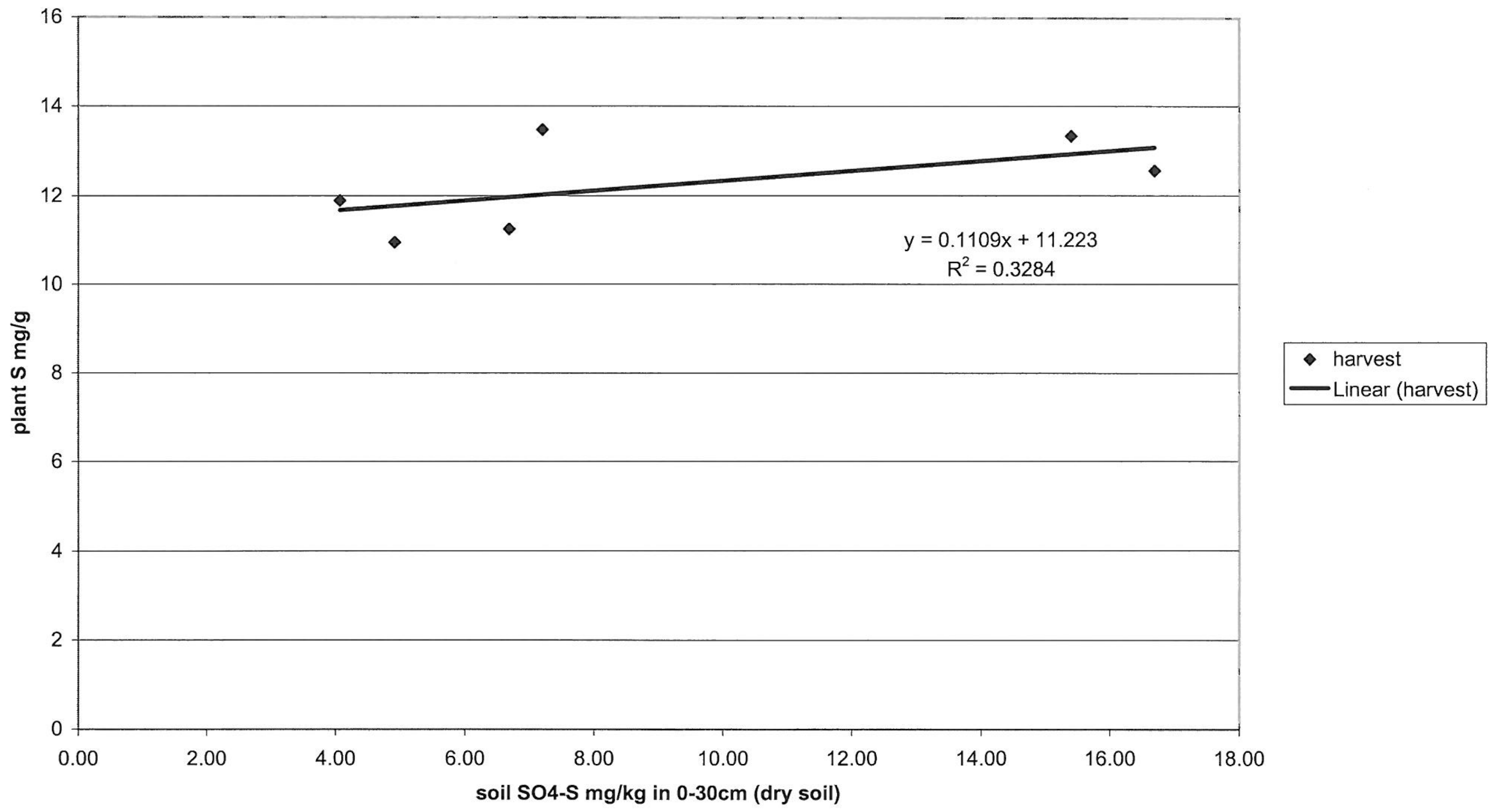

Fig 6 Soil SO4-S in 0-30cm v total soil SO4-S, dry soils

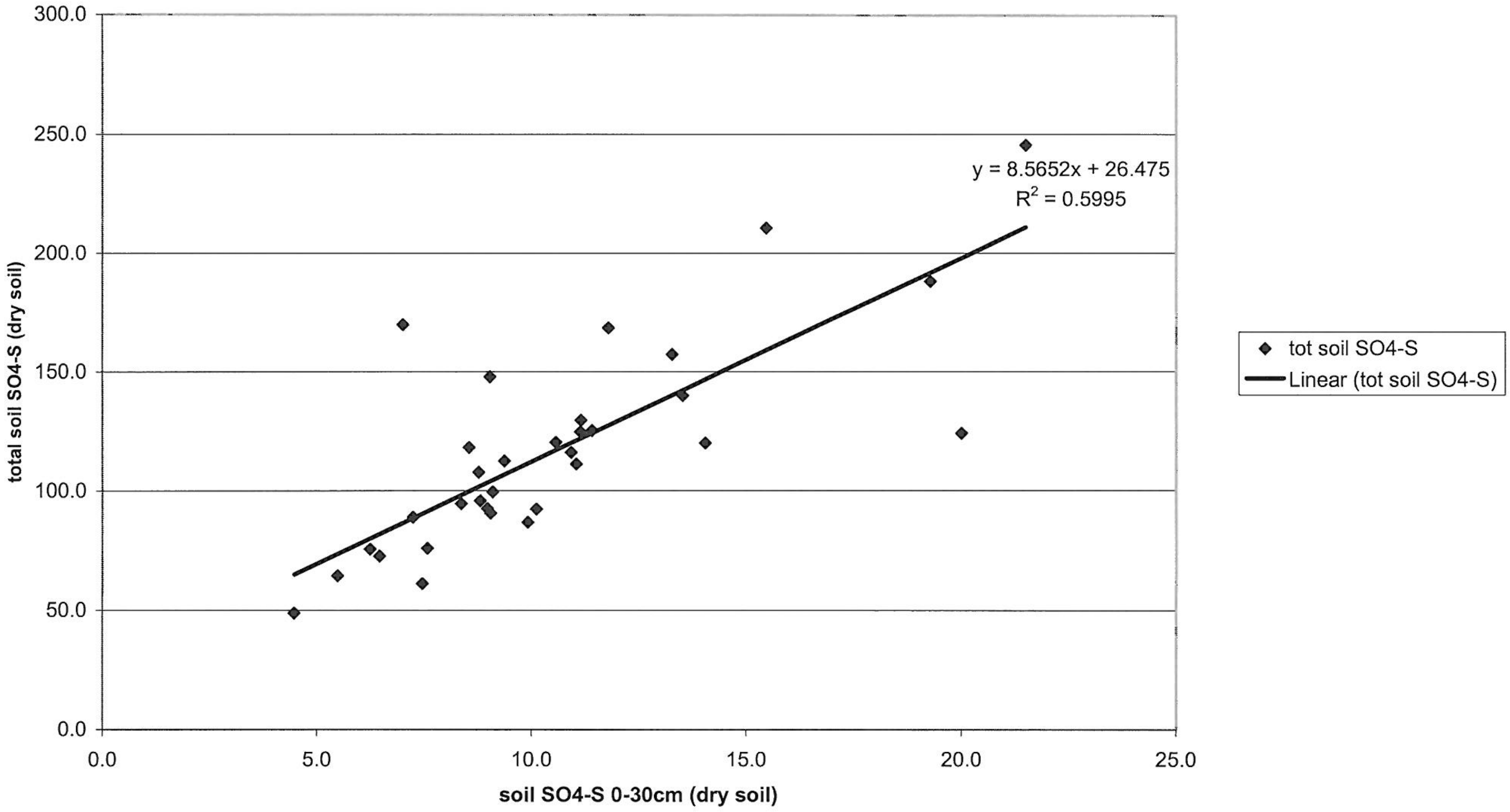

Fig 7 Sulphur in plant v soil S04-S in 0-90cm (kg/ha)