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SULPHUR NUTRITION OF CEREALS IN BRITAIN: YIELD RESPONSES AND PREDICTION OF LIKELY DEFICIENCY

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SULPHUR NUTRITION OF CEREALS IN BRITAIN: YIELD RESPONSES AND PREDICTION OF LIKELY DEFICIENCY

by
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ABSTRACT

Shortage of sulphur has become a problem for arable crops in some areas of the U.K., mainly as a result of decreased inputs from atmospheric deposition. The aims of this project were to assess those areas in Britain where cereals are at the most risk of S deficiency, to investigate the change in S status of wheat grain during the past decade, and to identify sites giving a response to S fertiliser and relate that response to atmospheric inputs, soil S and crop S status.

A qualitative computer model using soil, atmospheric deposition and meteorological data predicts that currently 11% of the British land area is at high risk of S deficiency for cereals, and a further 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. These areas are characterized by small inputs of S from the atmosphere, low content of soil organic matter and light soil texture. The SO_2 emissions in the U.K. are set to decrease to 40% of the 1980 level by 2003. The model predicts that such decreases would increase the medium and high risk areas to 27 and 22%, respectively.

The concentrations of S in British wheat grain have decreased considerably during the past decade. Grain samples with low S concentrations were located mainly in Scotland, northern England, and the west and southwest of England, whereas samples from central England tended to have higher S concentrations. Breadmaking varieties had significantly higher grain N and S concentrations than other varieties, but little difference was found between varieties in grain N:S ratio. For the varieties Mercia in both 1992 and 1993 and Hereward in 1993, grain S concentration correlated better with loaf volume than grain N concentration.

The effects of S application at a rate of 40 kg/ha on grain yield were tested at 21 and 19 sites around Great Britain in the 1992/93 and 1993/94 seasons, respectively. Yield responses were obtained at three sites at a significance level of $p<0.05$ in both 1992/93 and 1993/94 seasons, and at two further sites at $p<0.10$ in 1992/93. The yield increases due to S application ranged from 4.2 to 18.4%. The responsive sites were located in Scotland, Scottish Borders, East Anglia and Southwest England. The geographical distribution of the responsive sites agreed well with the model prediction and therefore validated the modelling approach. In contrast, soil extractable S in spring was not a good indicator of S supply. Also, there was no clear relationship between either grain S concentration or N:S ratio with yield responses.

CONTENTS

1. INTRODUCTION

Sulphur is often referred to as the fourth major nutrient for agricultural crops, following N, P and K (Syers *et al.*, 1987). Much effort has been put into research on the N requirements of cereals and the major effects this element has on the quality of cereals for various end uses. By comparison, less research has been carried out on S nutrition of cereal crops in the U.K. In the past, the inputs of S from atmospheric deposition and fertilisers were more than sufficient to meet the requirement of crops in the U.K. In fact, most concern was focused on the harmful effects of acidic deposition on natural ecosystems. Historically, anthropogenic sulphur dioxide (SO_2) emissions in both western Europe and North America increased gradually from the early part of this century to a peak in early 1970's, and since then have been decreasing due to the adoption of pollution control measures (Whelpdale, 1992). For example, SO_2 emissions in the U.K. have decreased from 6.4 million tonnes in 1970 to under 3.2 million tonnes in 1993 (Fig. 1), and further large decreases are expected (DoE, 1995). Based on the data supplied by the Warren Spring Laboratory, it is estimated that 77 and 20% of the British land area currently receives less than 20 and 10 kg S/ha, respectively, from atmospheric deposition. These inputs are smaller than the amount required by most crops. Meanwhile, traditional S-containing fertilisers, such as ammonium sulphate and single superphosphate, are no longer widely used, whereas the use of N fertilisers has increased considerably (Chalmers *et al.*, 1990). The increased consumption of S-free, high-analysis fertilisers is one of the major causes of S deficiency. As S inputs decrease, the S supply in the soil becomes a more critical component of the crop's demand. There has been a growing concern that the pool of available S in soil may have been depleted, particularly in light soils with little organic matter, thus accentuating S deficiency.

In the U.K., S deficiency was first reported in multiple-cut grassland (Scott *et al.*, 1983; Syers *et al.*, 1987). Widespread deficiency of S also occurs in the field crop of winter oilseed rape (Zhao *et al.*, 1993; Withers and O'Donnell, 1994; McGrath and Zhao, in press). Cereals require smaller amounts of S and, up to 1991, few experiments showed yield responses to S addition (Withers and Sinclair, 1994). However, a sufficient supply of S is important in maintaining the baking quality of breadmaking wheat, because the sulphydryl and disulphide groups of cysteine and cystine in grain storage proteins are essential to the viscoelasticity of the dough and its nutritional value (Randall and Wrigley, 1986).

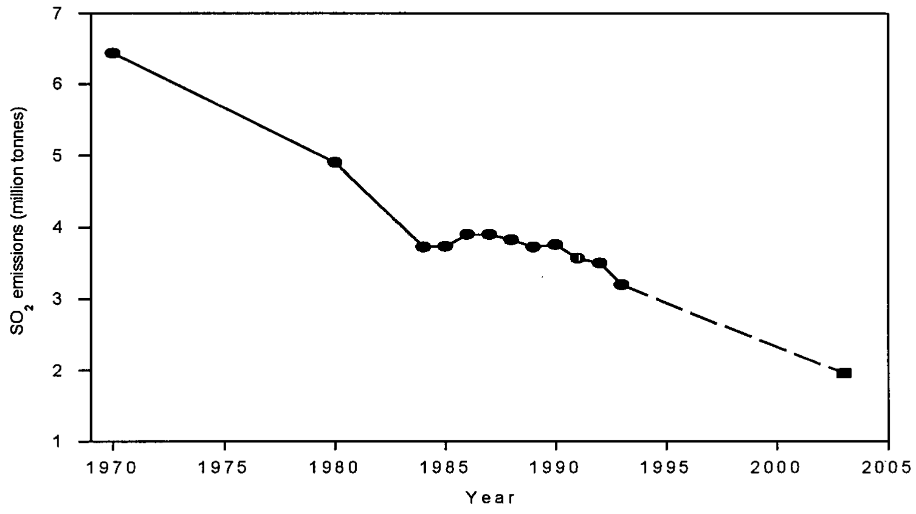


Figure 1. Total SO_2 emissions in the U.K. (DoE, 1995).

Since S deficiency in cereals is a recent development in the U.K., there has been a great deal of interest in both the farming and fertiliser industries in predicting the occurrence and extent of S deficiency, as well as the future trends. This project was initiated in 1992 with the following objectives for the first three years:

1). To assess those areas and soils in Britain that are at the most risk of S deficiency using computer-based techniques, and to use this as a practical tool to predict when other areas will become deficient over the next ten years.

2). To compare the change in S status of wheat grain between 1981/82 (Byers *et al.*, 1987b) and 1992/3, with the aim of assessing if crop S levels are declining as the atmosphere has become cleaner.

3). To identify sites giving a response to S fertiliser and relate that response to atmospheric inputs, soil S and crop S status.

The project was originally proposed for five years, with additional objectives to study the dynamics of S uptake and distribution in cereals and the effects of S on quality and crop composition. Reacting to the knowledge gained from the research done in the first three years, we have now reshaped the project from the end of year three and started a new HGCA project (0018/1/94) with strong emphasis on breadmaking quality of wheat. This report covers the results obtained from the first three years research.

2. MATERIALS AND METHODS

2.1. Assessing the risk of S deficiency in cereals using computer-based techniques

Although simple methods of soil testing, such as extraction with phosphate solution, perform satisfactorily in predicting dry matter responses and S uptake by wheat in greenhouse studies (Zhao & McGrath, 1994a) and oilseed rape in field experiments (Withers *et al.*, 1994), they are not considered totally reliable (Syers *et al.*, 1987). This is because the amount of available S in soil fluctuates with time and because inputs of S from the atmosphere, mineralization of organic S and losses of S due to leaching all vary. Therefore, a measurement of extractable S at a single point in time cannot give a realistic indication of the S supply to a crop throughout the growing season. Plant analysis is a more reliable indicator of S fertiliser need but comes too late to treat the current crop. Clearly, atmospheric S inputs, potential mineralization of organic S and potential leaching losses of S need to be considered in predicting the risk of S deficiency. In this study, we have used a qualitative model, which takes into account the above factors and uses the existing information on soil properties, atmospheric deposition and rainfall, to assess the risk of S deficiency in cereals in Britain and to predict the future trends.

2.1.1. Data sets

Soil information was obtained from the National Soil Inventory (McGrath and Loveland, 1992) and from the Macaulay Land Use Research Institute. In total, 5665 data points with grid references were used for soils in England and Wales and 636 points for soils in Scotland. The data points for England and Wales were distributed on regular 5x5 km grids, whereas for Scotland the distribution of the data points was irregular. Soil properties for England and Wales were recorded for the top 15 cm depth, whereas for Scotland they were based on the top mineral horizon (A), which varies widely in depth, but for arable land is usually between 15-20 cm.

Total inputs of S from atmospheric deposition in 1990 were obtained from the Warren Spring Laboratory. The total S inputs included both dry and wet deposition and the latter also included marine-derived S (U.K. Review Group on Acid Rain, 1990). The data were based on 20x20 km grids over mainland Britain.

Mean annual rainfall at 143 meteorological stations, averaged for the period of 1971-1990, was retrieved from the BBSRC Meteorological Data System. The data were then interpolated into a 5x5 km field using non-linear optimal technique of kriging (Webster and Oliver, 1990).

2.1.2. Design of a risk index for sulphate leaching

Leaching losses of sulphate can represent a large proportion of the S inputs (Bristow and Garwood, 1984; McGrath and Goulding, 1990). Potential sulphate leaching is determined by factors such as soil type, texture, sulphate adsorption capacity and rainfall. Most U.K. soils, particularly those in agricultural use, have limited sulphate adsorption capacities (Syers *et al.*, 1987). This is because sulphate adsorption decreases sharply as pH increases, with little adsorption at pHs above 6.0 (Scott, 1976; Curtin and Syers, 1990), and most arable soils are maintained at pH≥6.5. Each of these factors was given scores between 1 (low risk) and 3 or 4 (high risk), as appropriate (Table 1). The risk index for sulphate leaching for each soil was then derived from summation of all four individual scores, which ranged from 5 to 13. Based on the frequency distribution of the risk index (Fig. 2) and after assessing the possible combinations of risk factors, three classes of leaching risk, i.e. low, medium and high, were chosen representing total scores of ≤8, 9-10 and ≥11, respectively.

Table 1. Design of the risk index of sulphate leaching.

Score	Soil type (Major soil group)	Texture	Soil pH	Annual rainfall (mm)
1	Raw gley, Pelosols, Surface water gley, Groundwater gley	Clayey	< 4.0	< 600
2	Terrestrial raw soil, Podzolic, Peat	Fine loamy, Fine silty	4.0 - 6.0	600 - 800
3	Lithomorphic, Brown earth, Man-made	Coarse silty, Coarse loamy	> 6.0	800 - 1000
4	-	Sandy, Peaty	-	> 1000

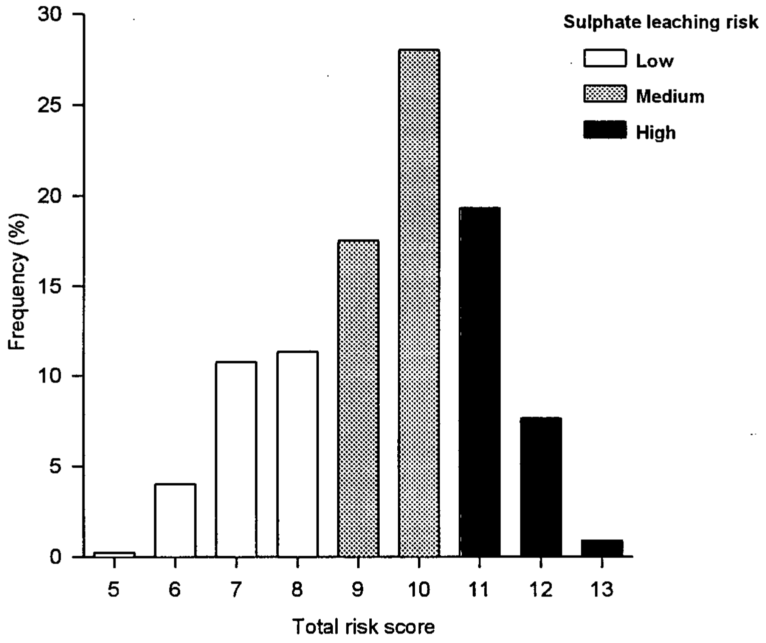


Figure 2: Frequency distribution of sulphate leaching risk index.

2.1.3. Design of a risk index for S deficiency in cereals

Normal cereal crops require about 20-30 kg S/ha (Syers *et al.*, 1987). Plants take up S mainly in the form of sulphate from soil solution, in addition to direct adsorption of SO_2 by leaves. The sulphate pool in soils is replenished by the inputs of S from the atmosphere and from mineralization of organic S. The mineralization potential of soil organic S is affected by the quantity and forms of organic S, climatic factors such as temperature and moisture, and cultivation (Freney, 1986). Although not widely confirmed, some studies have shown that the mineralization potential of organic S is closely related to the contents of soil organic C and S (Nelson, 1964; Nguyen and Goh, 1992; Sakadevan *et al.*, 1993). Hoeft and Fox (1986) and Murphy (1990) have shown that soil texture and organic C content are the two most important factors influencing the yield responses of grass to S addition. In incubation studies Tabatabai and Al-Khafaji (1980) found that 3.5-13.3% of organic S was mineralized in six months at 20°C. Under field conditions the amount of mineralization is likely to be much smaller. Very little is known about S mineralization rates in U.K. soils. No information was available about the contents of organic and inorganic S in the soil data sets used here. In this study, the potentially mineralizable S in the top 15 cm of soil was assumed to be 2% of the total organic S, which was estimated from the total organic C content using a typical C:S ratio of 80 for U.K. soils (McLaren and Swift, 1977; Zhao and McGrath, 1994a) and a dry soil bulk density of 1.33 g/cm^3:

$$\text{Potentially mineralizable S (kg S/ha)} = \text{Organic C (g/kg)} / 80 * 0.02 * 2000$$

The risk of S deficiency in cereals was generated for the location of each soil data point by considering total inputs of S from the atmosphere, potentially mineralizable S and sulphate leaching risk (Table 2). The value of atmospheric S deposition at the data point nearest to the soil data point was used if grid references did not coincide. The risk index was classified into low, medium or high categories, based on a typical S uptake of 20-30 kg/ha by cereal crops.

The U.K. is committed to reducing SO_2 emissions by 60% of the 1980 level by the year 2003 (DoE, 1995), which is approximately half of the level in 1990. The scenario of the risk of S deficiency in 2003 was therefore predicted using the same model, but with different S deposition data. It was assumed that the marine-derived component in the total deposition of S would remain unchanged, but that the component of non marine-derived S would decrease in proportion to the reduction in SO_2 emissions.

Data manipulations were carried out using programs written in FORTRAN 77. Results of the risk assessment were interpolated and mapped to cover the entire British land area using default routines of Unimap 2000 (Uniras/AS, 1989).

Table 2. Design of the risk index of S deficiency in cereals, based on the balance between S inputs and leaching risk.

Atmospheric S deposition + Potentially mineralizable S (kg/ha)	Sulphate leaching risk	Risk of S deficiency
< 10	All classes	High
10 - 20	Medium or High	High
	Low	Medium
20 - 30	High	High
	Medium	Medium
	Low	Low
30 - 40	High	Medium
	Medium or Low	Low
> 40	All classes	Low

2.2. Sulphur status of British wheat grain and its relationship with parameters of breadmaking quality

Wheat grain samples from the HGCA quality survey were used in this study. In 1992 and 1993, 400 and 393 grain samples, respectively, were collected. The variety of each sample was also recorded. These samples were selected at random from each region in approximate proportion to the amount of wheat being grown in that area. Within each region the number of samples of each variety collected was also related to the area of that variety grown (HGCA, 1993; 1994). Therefore these surveys can be considered as representative of the wheat growing area each year. Milling and baking quality was assessed by the Flour Milling and Baking Research Association at Chorleywood. Quality parameters used in this report include protein content, Hagberg falling number, and sodium dodecyl sulphate (SDS) sedimentation volume for all samples, and loaf volume (Chorleywood Bread Process; CBP) for breadmaking varieties.

Samples of ground wholemeal were dried at 80°C overnight prior to chemical analysis. Ground wholemeal weighing 0.600 g was digested with $HClO_4$-HNO_3 according to the method of Zhao *et al.* (1994). Sulphur in the digested solution was determined by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES). The total N concentration was calculated by dividing the crude protein content determined by Near Infrared Reflectance (NIR) by a factor of 5.7 (Osborne *et al.*, 1982). This method agreed closely with a combustion method (Foss-Heraeus Macro-N) on 25 selected samples with the following regression equation: $N_{combustion} = 1.0 + 0.96N_{NIR}$ (R^2=0.92; N concentration in mg g^{-1}). Both N and S concentrations are expressed on a dry matter basis.

Analysis of variance and regression were performed using Genstat 5 software (Genstat 5 Committee, 1993). Where necessary, the data were logarithmically transformed prior to statistical analysis. The exact locations of the collection sites were recorded for 381 and 387 samples from the 1992 and 1993 surveys, respectively. National grid references were obtained and transformed into easting and northing coordinates for these samples. Results were mapped using the Unimap 2000 program (Uniras/AS, 1989). Results from 1992 and 1993 surveys were also compared to those of 1981 and 1982 surveys reported by Byers *et al.* (1987b).

2.3. Responses of winter cereals to S fertiliser

Responses of winter wheat and barley to S fertiliser were tested at 21 and 19 sites around Britain in the 1992/93 and 1993/94 seasons, respectively. A paired plot design was used for all field experiments, consisting of two treatments, i.e. nil and 40 kg/ha of S. The treatments were replicated five times in 1992/93 and six times in 1993/94, respectively. Plot area was 4x20 m^2. A locally recommended variety was used for each site. Sulphur was applied as potassium sulphate in early spring and potassium chloride was used to balance the application of K in the plots receiving no S. Both treatments received the same rate of N, which was determined according to the local conditions. Soil samples were taken from the depths 0-30, 30-60 and 60-90 cm in early March prior to S application for the measurement of available S using ICP-AES. Sulphur uptake by the crop was determined at maturity. Grain yields were estimated by sampling four 1 m^2 quadrates from each plot in 1992/93 and by plot combine in 1993/94. Grain specific weight, thousand grain weight and Hagberg falling number were determined. Grain N concentration was determined by the Macro-N combustion method and grain S by $HNO_3/HClO_4$ digestion and ICP-AES measurement (Zhao *et al.*, 1994).

Atmospheric SO_2 concentrations were monitored on a monthly basis by installing diffusion tubes in the experimental fields. Sulphur dioxide molecules which diffused into the tubes were adsorbed by stainless steel meshes containing a mixture of KOH and glycerol. Sulphur was extracted with H_2O_2 and determined by ion chromatography (Dionex).

3. RESULTS AND DISCUSSION

3.1. Assessing the risk of S deficiency in cereals using computer-based techniques

The soil data used reflect the soil properties at the time of sampling, i.e. during the late 1970's to the early 1980's (McGrath and Loveland, 1992). However, soil type (major soil group) and texture are unlikely to change, and the changes in soil organic C and pH are likely to be small (Skinner *et al.*, 1992). More recent data of atmospheric S deposition were not available during the course of this study, but preliminary results showed that the changes in total S deposition between 1990-92 were small (Stedman *et al.*, 1993). Therefore, the results of this risk assessment can be considered to be appropriate to the current situation.

The low, medium and high classes of sulphate leaching risk represent 26, 46 and 28%, respectively, of the British land area (Fig. 2). The distribution of the three classes is shown in Fig. 3. The high leaching risk class is mainly distributed in the western part of the country because of the high average rainfall, whereas the low leaching risk class is mainly associated with heavy soils in the eastern part of England, particularly in the broad area from the Wash to Oxfordshire where the soil parent materials are predominantly Jurassic clays.

The map of the current risk of S deficiency in cereals is shown in Fig. 4. Overall, 11% of the British land area is at high risk of S deficiency if cereals are grown, and a further 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. These areas are characterized by low inputs of S from the atmosphere, low content of soil organic matter and light soil texture, and are also among the major cereal growing areas in Britain. The medium risk areas are more scattered, whereas broad areas in western Scotland, Wales, north-west England and the central Midlands are in the low risk category. The low risk areas are in fact largely associated with hilly lands having high contents of organic matter in the topsoils.

If the target for reduced SO_2 emissions is met by 2003, the high and medium risk areas are predicted to increase to 23 and 27%, respectively (Fig. 5), to cover most cereal growing areas.

The major factors influencing the supply of S have been considered in the model. Some other factors could not be taken into account due to the lack of information, and these include any S reserve in the subsoil, crop rotation and the use of animal manures. In some

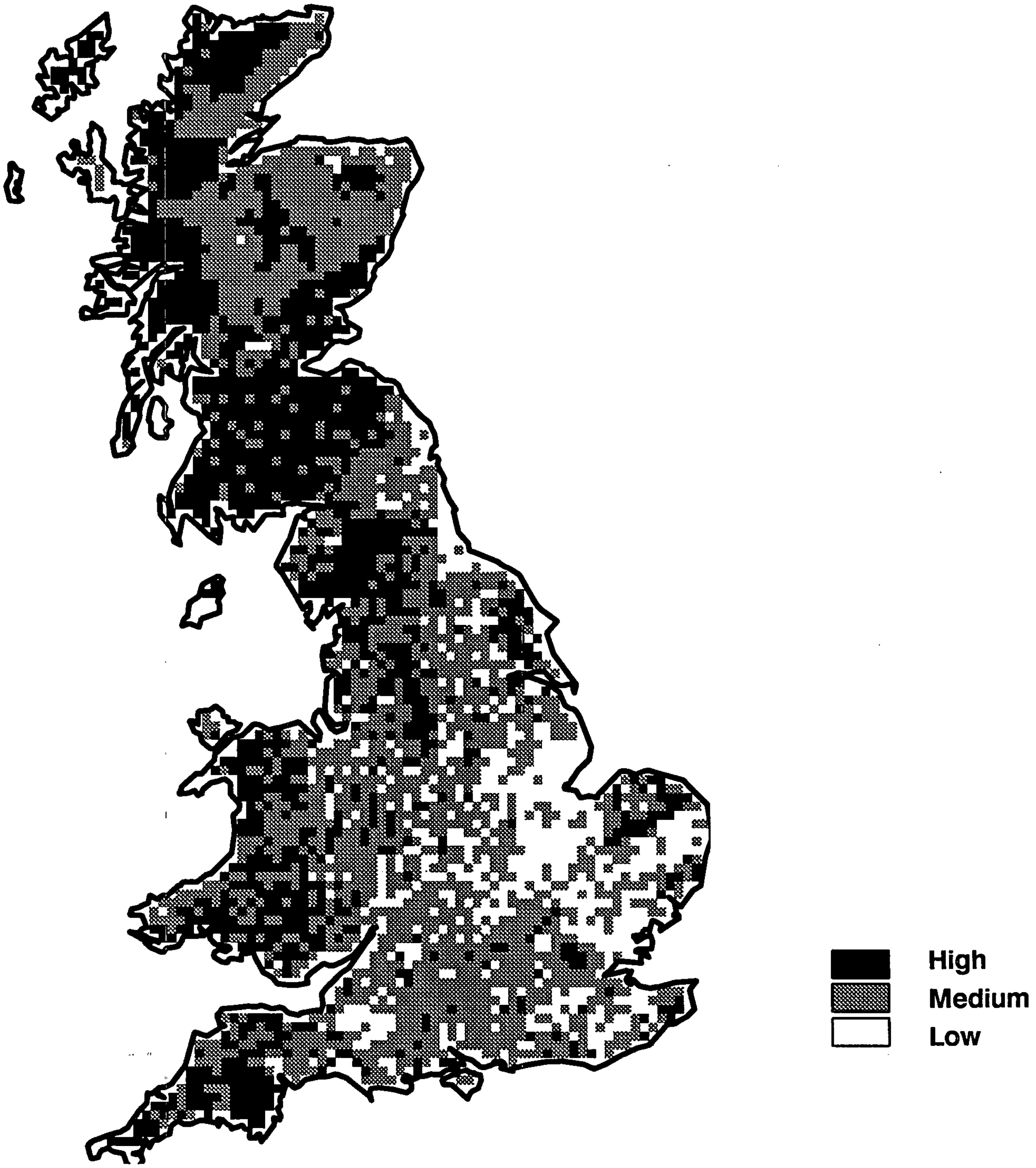


Figure 3. Risk of sulphate leaching.

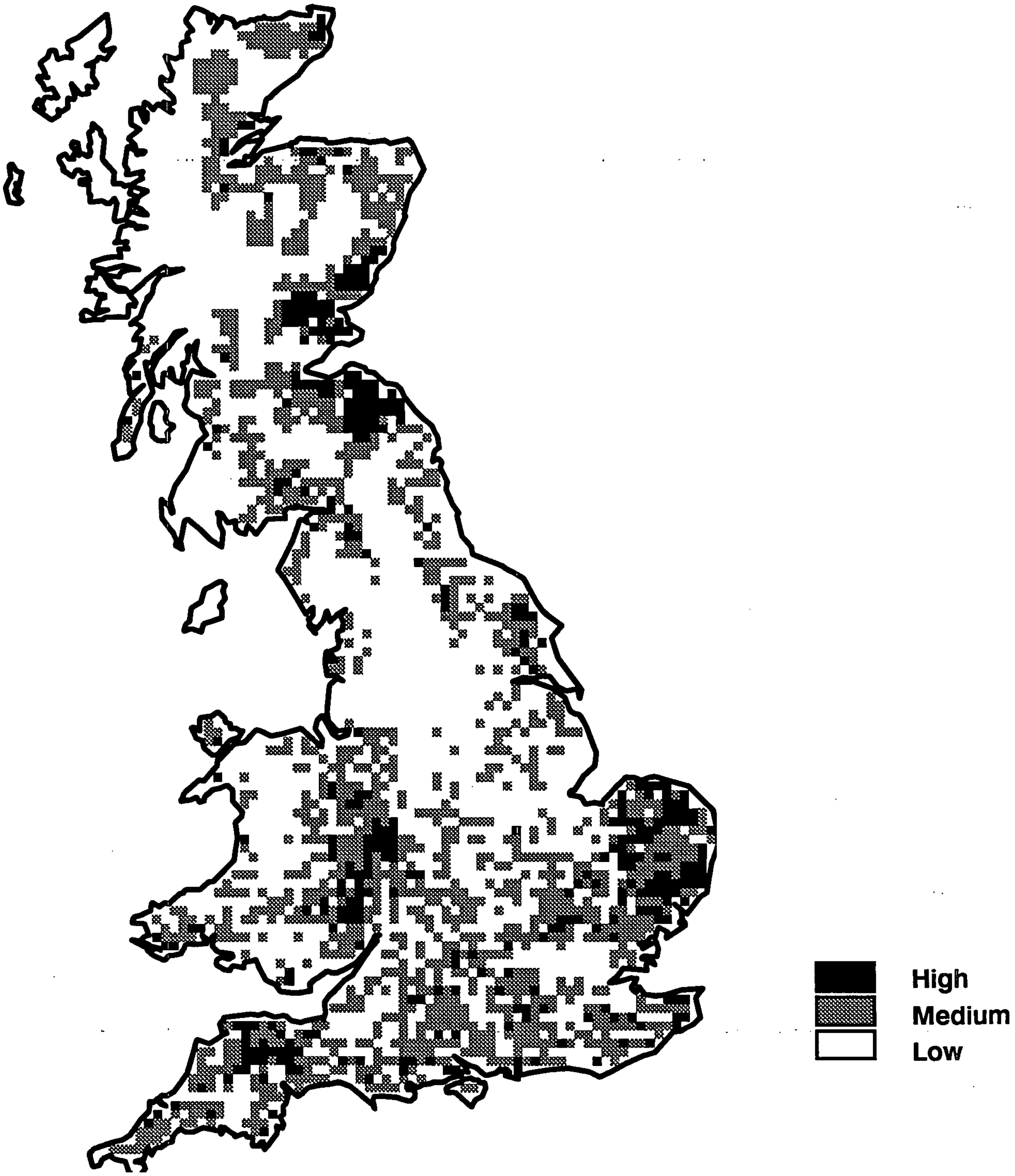


Figure 4. Current risk of sulphur deficiency in cereals.

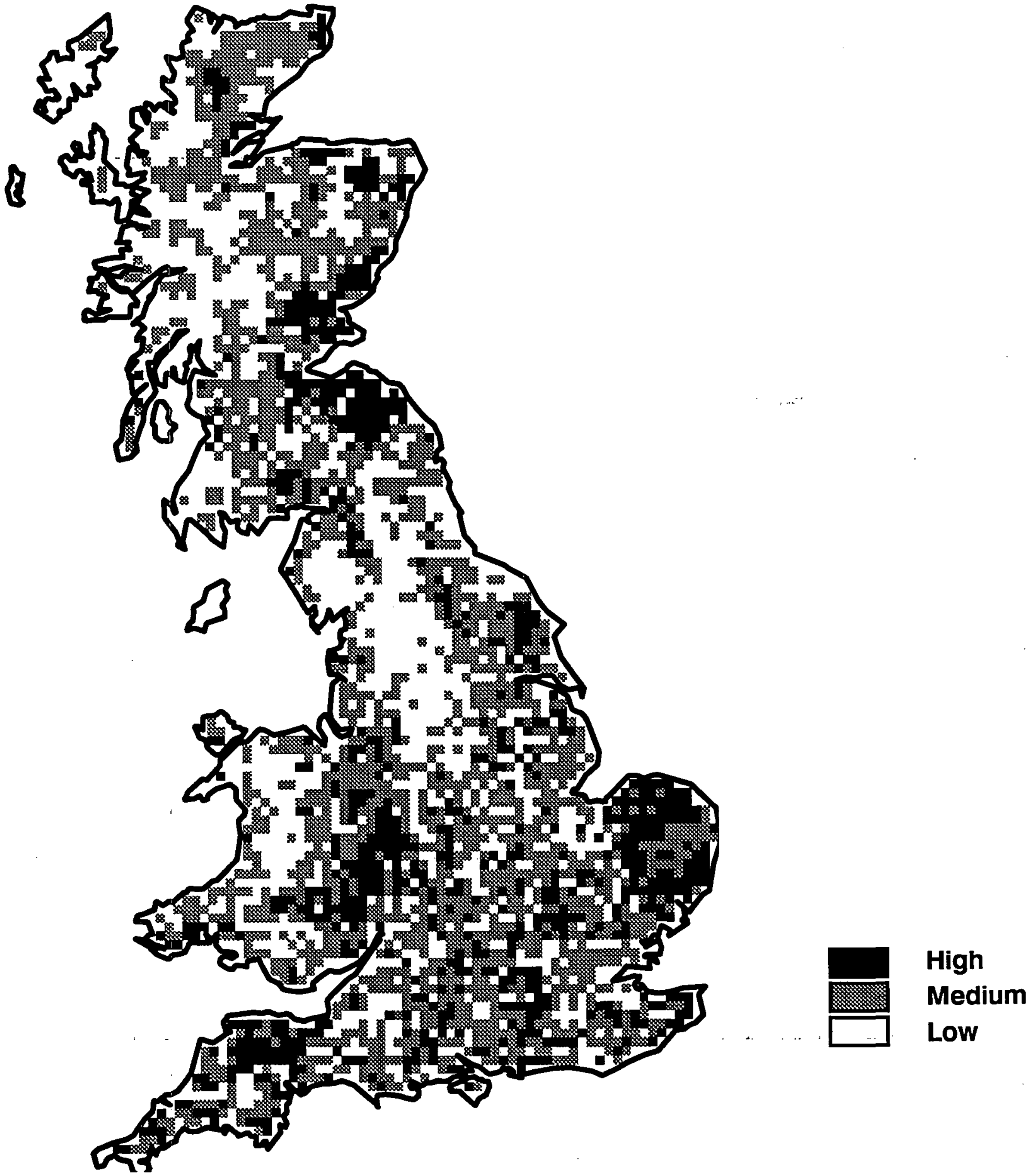


Figure 5. Risk of sulphur deficiency in cereals in 2003.

cases the amount of adsorbed sulphate in subsoils can be much larger than in the topsoils and can contribute significantly to crop S uptake (Zhao and McGrath, 1994b). Cereals grown immediately after grass in a rotation may be at lower risk of S deficiency because of the build-up of more easily mineralizable organic matter. Animal manures can contain appreciable amount of S. For example, an application of 50 m^3/ha of cow slurry to land would add about 20 kg/ha of S (Withers and Sinclair, 1994). Frequent applications of animal manures will therefore decrease the risk of S deficiency.

Since much more soil data were used for England and Wales than for Scotland, the prediction is more reliable for the former than the latter. Although large arrays of soil and atmospheric deposition data have been used, it must not be forgotten that each soil data point does not necessarily reflect the soil properties of the whole area of each grid cell in the maps. Soils vary widely at all scales both within and between individual fields and landscapes (McGrath and Loveland, 1992). However, this study was intended to be a relatively large scale risk assessment for the whole country. Farmers growing cereal crops in those high risk areas should be aware of the likely shortage of S and look for additional confirmatory information, such as the appearance of visual symptoms of S deficiency in crops, plant tissue analysis and soil testing.

3.2. Sulphur status of British wheat grain and its relationship with parameters of breadmaking quality

The concentration of S in grain and the N:S ratio have been used to diagnose the occurrence of S deficiency in wheat and the values of 1.2 mg g^{-1} and 17, respectively, are usually considered as critical values (Randall *et al.*, 1981; Moss *et al.*, 1981; Randall and Wrigley, 1986; Byers *et al.*, 1987a; 1987b). A survey of the S status of British wheat grain collected by the HGCA in 1981 and 1982 showed that none of the samples was S-deficient, but the regional pattern of grain S concentration corresponded closely with the estimated S inputs from the atmosphere (Byers *et al.*, 1987b). Grain S concentration and N:S ratio for the 1992 and 1993 surveys are reported here and compared to those of the previous surveys (Byers *et al.*, 1987b).

3.2.1 Varietal differences

A total of 30 and 33 wheat varieties were recorded in the 1992 and 1993 surveys, respectively, most of which were winter sown. In both years significant varietal differences in grain N and S concentrations were found (Table 3), with Mercia having the largest and Riband the smallest mean S concentration. Regression analysis showed that between 20 and 30% of the variations in grain N and S concentrations were accounted for by variety alone. In contrast, varietal differences in grain N:S ratio were much smaller and were significant only in the 1993 survey (Table 3).

The HGCA classifies wheat varieties into three groups: group 1 is for hard wheat favourable for breadmaking; group 2 includes other hard wheat suitable for animal feed and incorporation in some grists; and group 3 is for the soft wheat varieties suitable for biscuit-making and inclusion in other grists and animal feed (HGCA, 1993; 1994). In both years there were significant differences between the three groups in grain N and S concentrations, with group 1 having the largest and group 3 the smallest N and S concentrations (Table 4). Differences between groups 2 and 3 were generally small. The three groups, however, did not differ significantly in grain N:S ratio in both years (Table 4). The concentrations of S and N correlated closely in grain (Fig 6a and 6b). The N and S relationship appeared very similar in all varieties and all three HGCA groups. Thus, inclusion of variety or group in the regression model improved the fitting of the model only slightly. Therefore all varieties were pooled to give an overall regression equation for each year:

1992 $N = 3.56 + 13.21\ S \quad (n=400,\ R^2=0.663)$

1993 $N = 1.65 + 14.30\ S \quad (n=393,\ R^2=0.675)$.

It is perhaps surprising that this similarity in the N and S relationship between different groups occurred, in view of the fact that breadmaking varieties are qualitatively different from non-breadmaking varieties in their spectrum of storage proteins (Payne *et al.*, 1987; Shewry *et al.*, 1994).

Fig 6 also shows the samples most likely to be deficient in S, i.e. those distributed in zone I with total S concentrations smaller than 1.2 mg g^{-1} and N:S ratios greater than 17. In both years there were 10 samples belonging to this category, of which 9 were of the group 3 varieties. The group 3 varieties happen to be those grown in Scotland in areas which have low S inputs. In contrast, most of the group 1 samples occur in zone II, indicating that they contain sufficient S. This could be partly due to the fact that the breadmaking wheat is more often grown on better quality land which is less prone to S deficiency.

Table 3. Variety means (±SE) of wheat grain N and S concentrations and N:S ratio in the 1992 and 1993 surveys*

Variety	HGCA group	Number of samples	N (mg g^{-1})	S (mg g^{-1})	N:S ratio
			1992		
Apollo	3	25	21.7 (0.46)	1.40 (0.029)	15.6 (0.31)
Beaver	3	55	22.5 (0.31)	1.42 (0.020)	16.0 (0.21)
Galahad	3	7	22.1 (0.86)	1.40 (0.055)	15.7 (0.59)
Haven	2	41	21.5 (0.36)	1.39 (0.023)	15.4 (0.24)
Hereward	1	33	23.8 (0.40)	1.46 (0.026)	16.3 (0.27)
Mercia	1	61	24.9 (0.29)	1.58 (0.019)	15.8 (0.20)
Riband	3	112	20.8 (0.22)	1.34 (0.014)	15.6 (0.15)
Slejpner	2	20	22.6 (0.51)	1.48 (0.033)	15.4 (0.35)
Soissons	1	5	23.1 (1.02)	1.42 (0.066)	16.3 (0.70)
F ratio			7.57	5.80	0.99[a]
p<			0.001	0.001	0.48
			1993		
Apollo	3	13	20.6 (0.50)	1.34 (0.028)	15.4 (0.28)
Avalon	1	7	21.8 (0.68)	1.39 (0.039)	15.7 (0.38)
Axona	1	7	21.7 (0.68)	1.40 (0.039)	15.5 (0.38)
Admiral	3	15	19.4 (0.46)	1.24 (0.026)	15.6 (0.26)
Beaver	3	54	19.2 (0.25)	1.21 (0.014)	15.9 (0.14)
Estica	2	7	20.6 (0.68)	1.22 (0.039)	16.9 (0.38)
Galahad	3	5	19.3 (0.80)	1.21 (0.046)	15.9 (0.45)
Haven	2	23	18.0 (0.38)	1.24 (0.021)	15.1 (0.21)
Hereward	1	35	21.0 (0.30)	1.31 (0.017)	16.0 (0.17)
Hussar	2	6	19.0 (0.73)	1.24 (0.042)	15.4 (0.41)
Hunter	3	13	20.8 (0.50)	1.27 (0.028)	16.5 (0.28)
Mercia	1	32	21.1 (0.32)	1.41 (0.018)	15.0 (0.18)
Riband	3	116	18.4 (0.17)	1.20 (0.010)	15.4 (0.09)
Slejpner	2	14	19.9 (0.48)	1.29 (0.027)	15.4 (0.27)
Soissons	1	15	22.2 (0.46)	1.39 (0.026)	16.0 (0.26)
Spark	1	5	21.7 (0.80)	1.39 (0.046)	15.6 (0.45)
F ratio			6.67	7.00	3.18[a]
p<			0.001	0.001	0.001

* Data for the varieties with less than 5 samples are not shown.

[a] Log-normalised prior to analysis of variance.

Table 4. Group means (±SE) of grain N and S concentrations and N:S ratio in the 1992 and 1993 surveys

HGCA group	Number of samples	N (mg g^{-1})	S (mg g^{-1})	N:S ratio
		1992		
1	118	24.5 (0.22)	1.53 (0.014)	16.0 (0.14)
2	69	22.0 (0.29)	1.42 (0.019)	15.5 (0.19)
3	213	21.4 (0.17)	1.37 (0.011)	15.8 (0.11)
F ratio		42.91	31.16	2.20[a]
p<		0.001	0.001	0.09
		1993		
1	112	21.4 (0.18)	1.36 (0.010)	15.7 (0.10)
2	60	19.3 (0.25)	1.25 (0.014)	15.5 (0.14)
3	221	19.0 (0.13)	1.22 (0.007)	15.6 (0.07)
F ratio		62.13	69.41	1.19[a]
p<		0.001	0.001	0.31

[a] Log-normalised prior to analysis of variance.

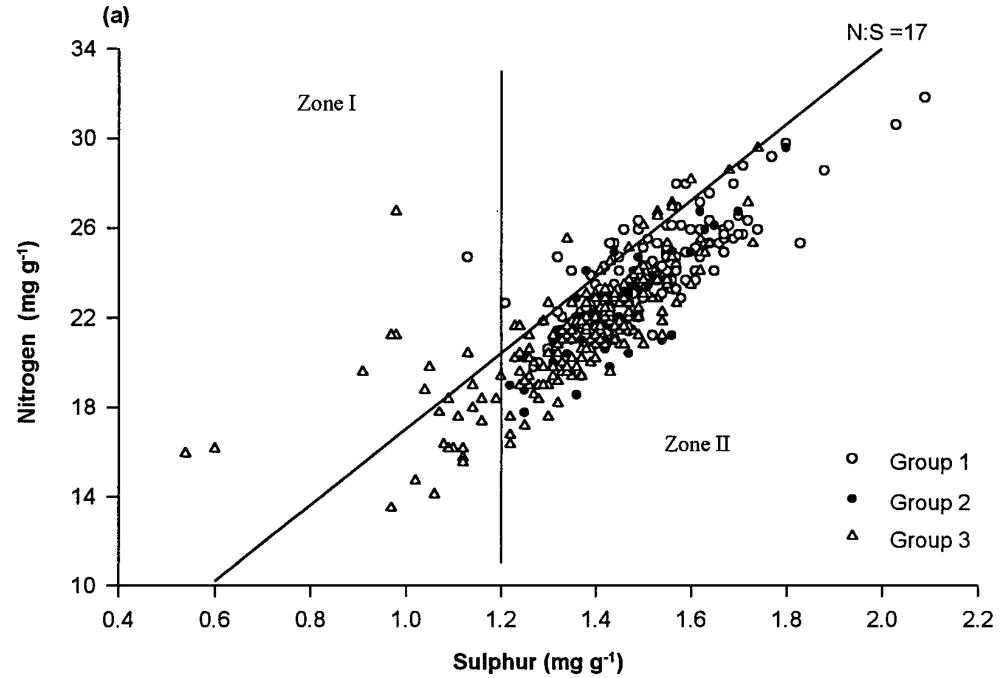


Figure 6a. Relationship between grain N and S concentrations in 1992 .

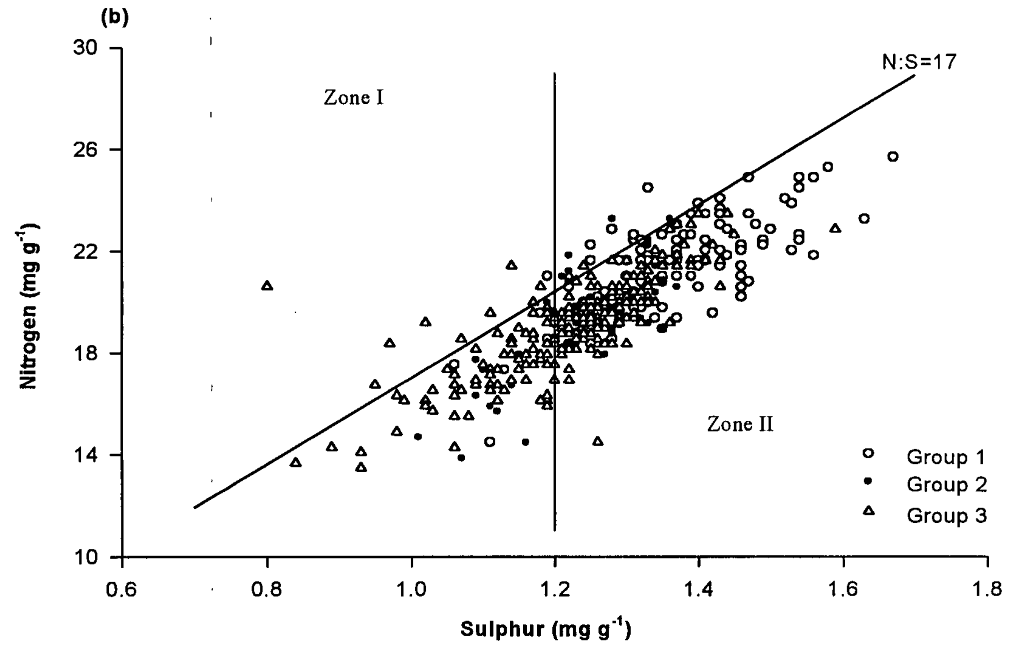


Figure 6b. Relationship between grain N and S concentrations in 1993.

3.2.2. *Changes of sulphur status in wheat grain from 1981-82 to 1992-93*

The ranges and means of N and S concentrations and N:S ratio for the 1992 and 1993 surveys, as well as those for 1981 and 1982 (Byers *et al.*, 1987b), are shown in Table 5. Mean and minimum S concentrations in grain were much smaller in 1992-93 than in 1981-82, whereas the ranges and means of grain N concentration were similar in 1981 and 1993 and in 1982 and 1992. Consequently, the ranges and means of the grain N:S ratio were considerably larger in 1992-93 than those in 1981-82.

The frequency distributions of grain N concentrations (Fig 7a) were identical between 1982 and 1992, with greater proportions of samples having larger N concentrations than in the 1981 and 1993 surveys. Thus there is no evidence of any significant trend in N concentration between the samples from 1981-82 and 1992-93, despite changes in the varieties grown.

Table 5. Ranges and means of grain N and S concentrations and N:S ratio

	1993	1992	1982[a]	1981[a]
Number of samples	393	400	238	170
N (mg g^{-1})				
Range	13.5-25.7	13.5-31.8	15.7-29.0	13.5-27.9
Mean	19.7	22.4	22.6	19.6
S (mg g^{-1})				
Range	0.80-1.67	0.54-2.09	1.33-2.14	1.30-2.03
Mean	1.26	1.43	1.72	1.71
N:S ratio				
Range	11.5-25.9	13.3-29.6	10.7-15.0	8.8-14.5
Mean	15.6	15.8	13.1	11.5

[a] Data from Byers *et al.* (1987b).

In contrast, grain S concentrations were distributed towards a much smaller value in the more recent sampling (Fig 7b). In 1981 and 1982 no samples contained less than 1.2

mg g^{-1} total S (the critical value for deficiency), whereas in 1992 and 1993 7% and 26% of the samples had a S concentration below 1.2 mg g^{-1}, respectively. Although S concentrations were smaller in 1993 than in 1992, the frequency distributions of N:S ratio in grain were similar in the two years (Fig 7c). Grain N:S ratio is sometimes considered to be a more reliable indicator for S deficiency than S concentration (Randall *et al.*, 1981; Byers *et al.* 1987a). Approximately 10% and 7% of the samples in 1992 and 1993, respectively, had a grain N:S ratio greater than the critical value of 17, whereas in 1981 and 1982 none of the samples had an N:S ratio greater than 17. In both 1992 and 1993, 2.5% of the samples satisfied both criteria of S deficiency.

The average grain yield of wheat in the UK has increased by approximately 15% from the 1981-82 level (HGCA, 1993). This yield increase may have caused a growth-dilution effect on grain S concentration, but the effect would be too small to account for the overall decrease in grain S status. In fact, yield increases brought about by, for example, larger application rates of N fertiliser, can have a positive effect on the concentrations of S in grain if S is in plentiful supply (McGrath, 1985). Thus, the decreased S concentrations in 1992-93 compared to 1981-82 can only be attributed to two main reasons: changes in varieties and/or decreased S inputs. During the period from 1981-82 to 1992-93 most varieties have been superseded, and too few varieties in insufficient numbers in both periods existed for a direct comparison of their S status to be made. However, a smaller proportion of the samples were of potential breadmaking varieties in 1992-93 than in 1981-82. The potential breadmaking varieties refer to those with the rank of breadmaking quality of A and B according to the National Institute of Agricultural Botany (NIAB, 1981; 1992; Payne *et al.*, 1987). These varieties represented 51 and 57% of all samples in the 1981 and 1982 surveys, respectively, and their proportions dropped to 31% in both 1992 and 1993 surveys, reflecting a decrease in the area of breadmaking wheat grown. Since the breadmaking varieties generally have larger grain S concentrations, the decrease in their proportion would shift the distribution of grain S towards smaller values.

However, changes in varieties only partly explain the decrease in grain S status from 1981-82 to 1992-93, because grain S concentrations of the potential breadmaking varieties themselves were still smaller in 1992-93 than in 1981-82 (Fig. 8). Also, the increased N:S ratios in 1992-93 compared to 1981-82 were very unlikely to be due to the changes in varieties, because there was little difference between the breadmaking and non-breadmaking varieties in the grain N:S ratio. These results strongly suggest that decreased S inputs have contributed significantly to the decreased S status in British wheat. This is not surprising since S deposition from the atmosphere has decreased substantially during the past decade (U.K. Review Group on Acid Rain, 1990; Stedman *et al.*, 1993). Crops must therefore rely more on the S supply in the soil, and it is thought that soil S reserves may have been depleted to a certain extent (Syers *et al.*, 1987).

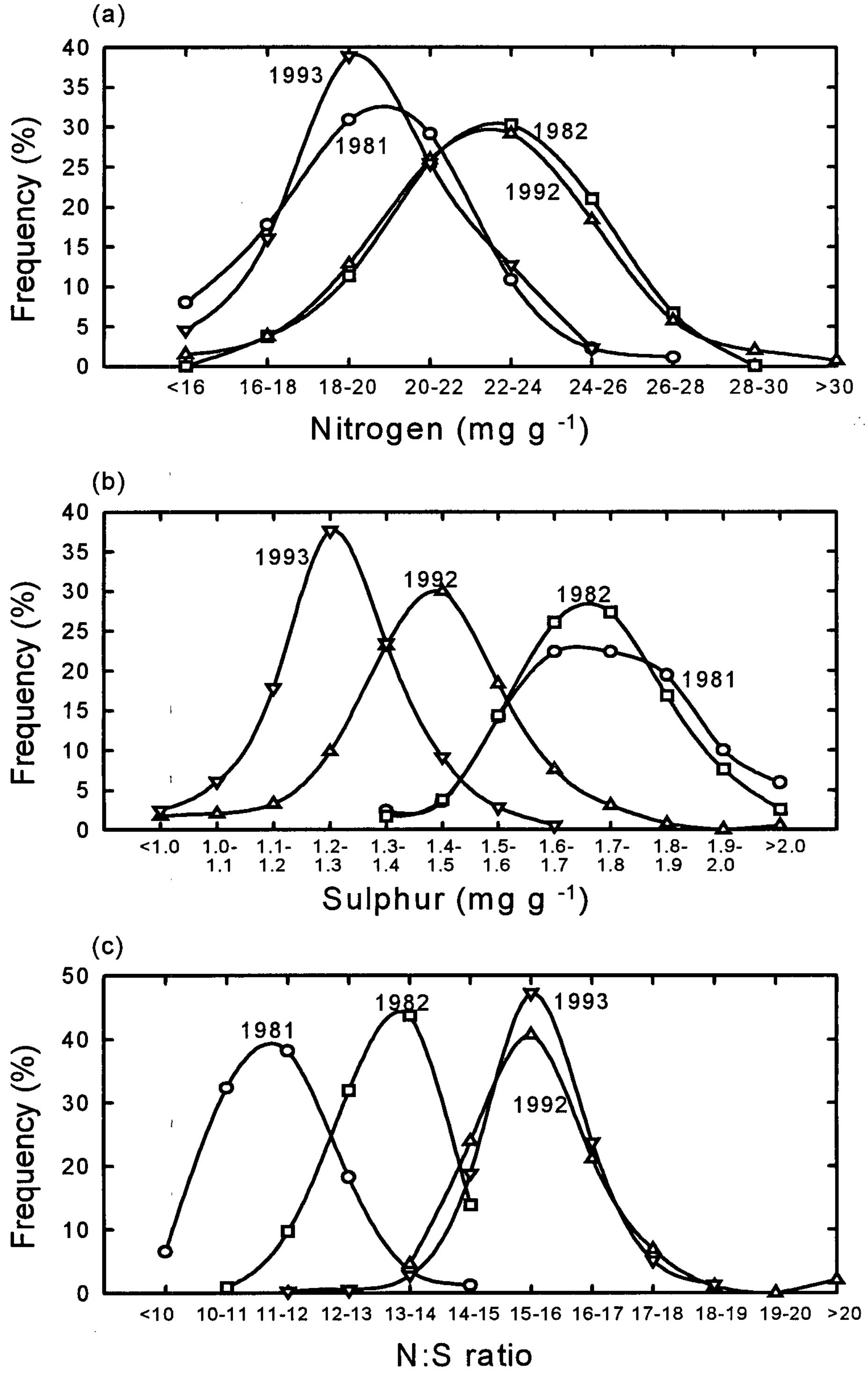


Figure 7. Frequency distributions of (a) grain N, (b) grain S and (c) grain N:S ratio in 1981, 1982, 1992 and 1993.

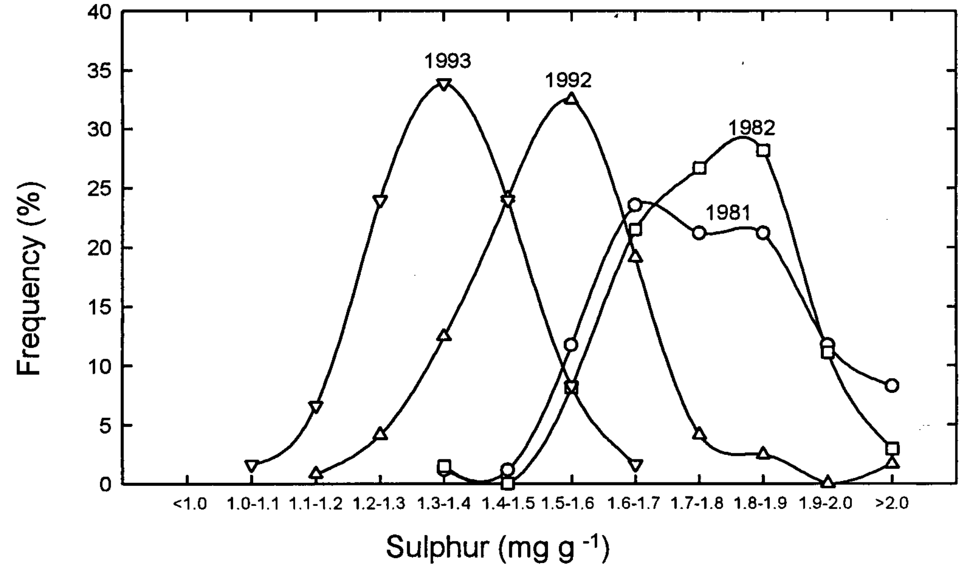
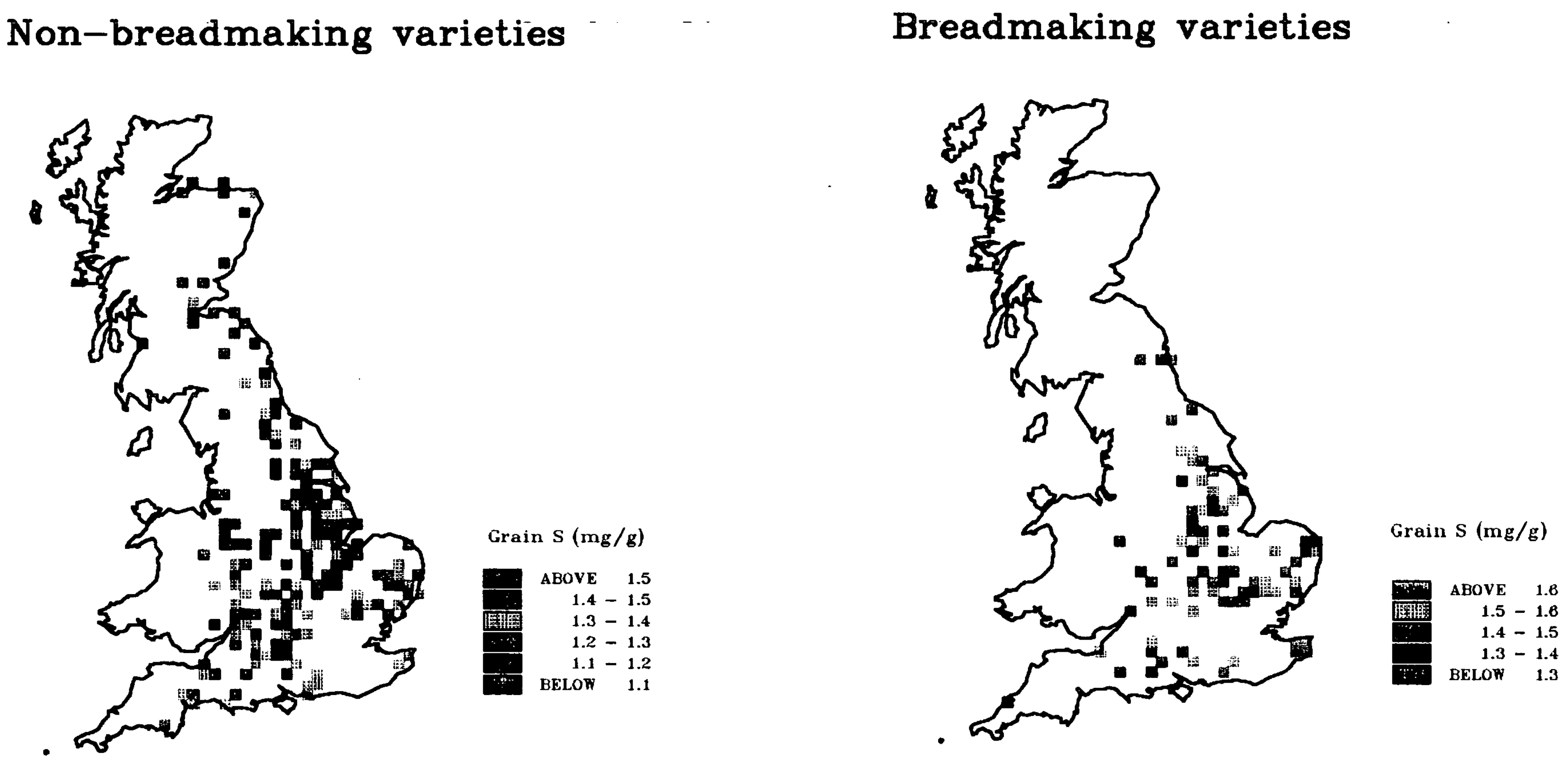


Figure 8. Frequency distributions of grain S concentrations among the samples of potential breadmaking varieties in 1981, 1982, 1992 and 1993.

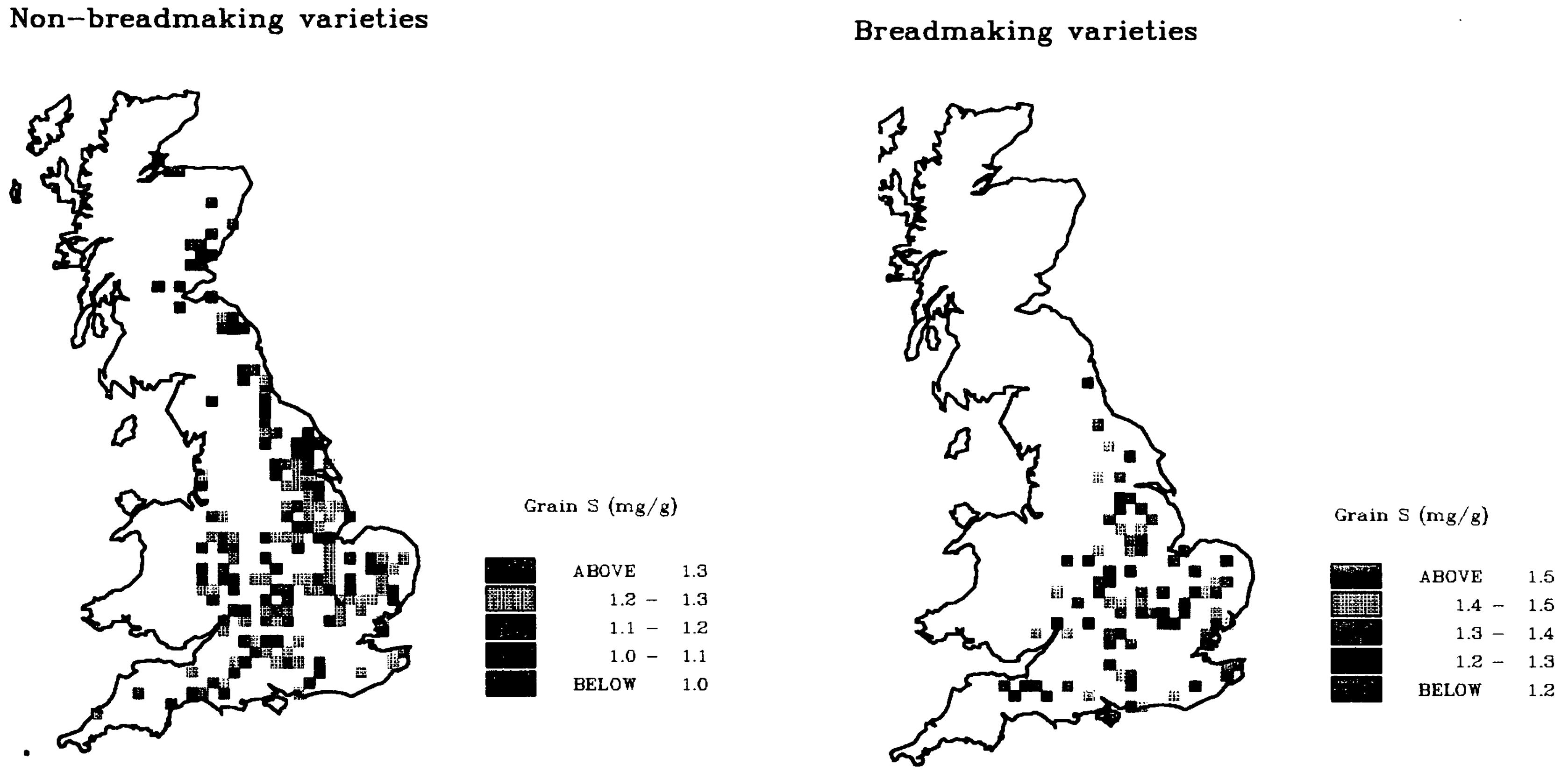
3.2.3. The Geographical distribution

Figs 9 and 10 show the geographical distributions of grain S concentrations for 1992 and 1993, respectively. Each map square is based on a 15x15 km grid and the value represents the mean of all data occurring within that square. Since breadmaking varieties (HGCA group 1) had significantly higher S concentrations than the varieties of other two groups, the data were mapped separately. The patterns of geographical distributions of grain S concentrations were not as strong as those for the 1982 survey (see Byers *et al.*, 1987b), probably because the regional differences in S inputs were much weaker in the 1990s than they were in the early 1980s. Nevertheless, it is still apparent that the samples from Scotland, northern England, and the west and southwest of England, where S deposition is low, contained the smallest S concentrations. In contrast, the largest S concentrations occurred mainly in the areas near to or down-wind of the industrial conurbations of central England.


Non-breadmaking varieties

Breadmaking varieties

Figure 9. Grain S concentrations in the 1992 survey.


Non–breadmaking varieties

Breadmaking varieties

Figure 10. Grain S concentrations in the 1993 survey.

3.2.4. Correlations with quality parameters.

In both surveys grain S concentration correlated closely with protein content and the relationships were similar in all three groups of varieties (see Fig. 6 for the relationship between grain N and S).

The SDS sedimentation volume is often used as a quality parameter for breadmaking and has been shown to correlate well with loaf volume (Axford *et al.*, 1979), although some recent studies showed that SDS volume alone did not always truly reflect the baking potential of flour (Bhandari and Pritchard, 1994). There were significant correlations between grain S concentration and SDS volume in both 1992 (r=0.41) and 1993 (r=0.52), when all varieties were included. The correlations became very weak if the three groups of varieties were treated separately (see Fig. 11 for the 1993 survey; results for the 1992 survey not shown). For group 1 samples (breadmaking varieties) the SDS volume and grain S concentration were virtually independent of each other. Therefore, the overall significant correlation between grain S and SDS volume is a result of systematic differences between the groups of varieties.

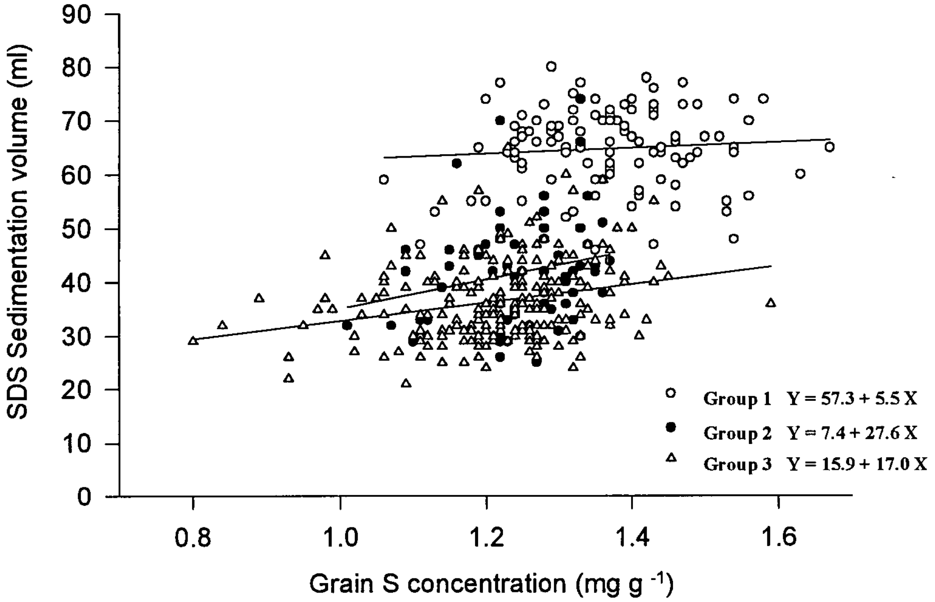


Figure 11. Relationship between SDS sedimentation volume and grain S concentration in the 1993 survey.

Loaf volume is the most objective measurement of breadmaking performance of flour. Figs. 12-14 show the relationships between the concentrations of N or S in wholemeal and CBP loaf volume for the 1992 and 1993 surveys, respectively. Only Mercia and Hereward had sufficient number of samples to enable the relationships to be examined. For samples of Hereward in 1992, there were no significant correlations between loaf volume and either grain N or S concentrations. For Hereward in 1993 and Mercia in both years, grain N accounted for 8.3-29.9% and grain S for 19.7-36.9% of the variations in loaf volume. Even though the degree of correlation was generally low, because samples were collected from different areas with varying growth conditions, it is clear that grain S correlated more strongly with loaf volume than grain N. This is possibly due to the fact that grain S concentration is a reflection of both quantity and quality of protein in flour, whereas grain N only reflects the quantity. Under the conditions of marginal S nutrition, as now prevail in some areas of the UK, grain S concentration would be expected to have greater influence on baking performance. This theory will be tested more vigorously in the new project (0018/1/94).

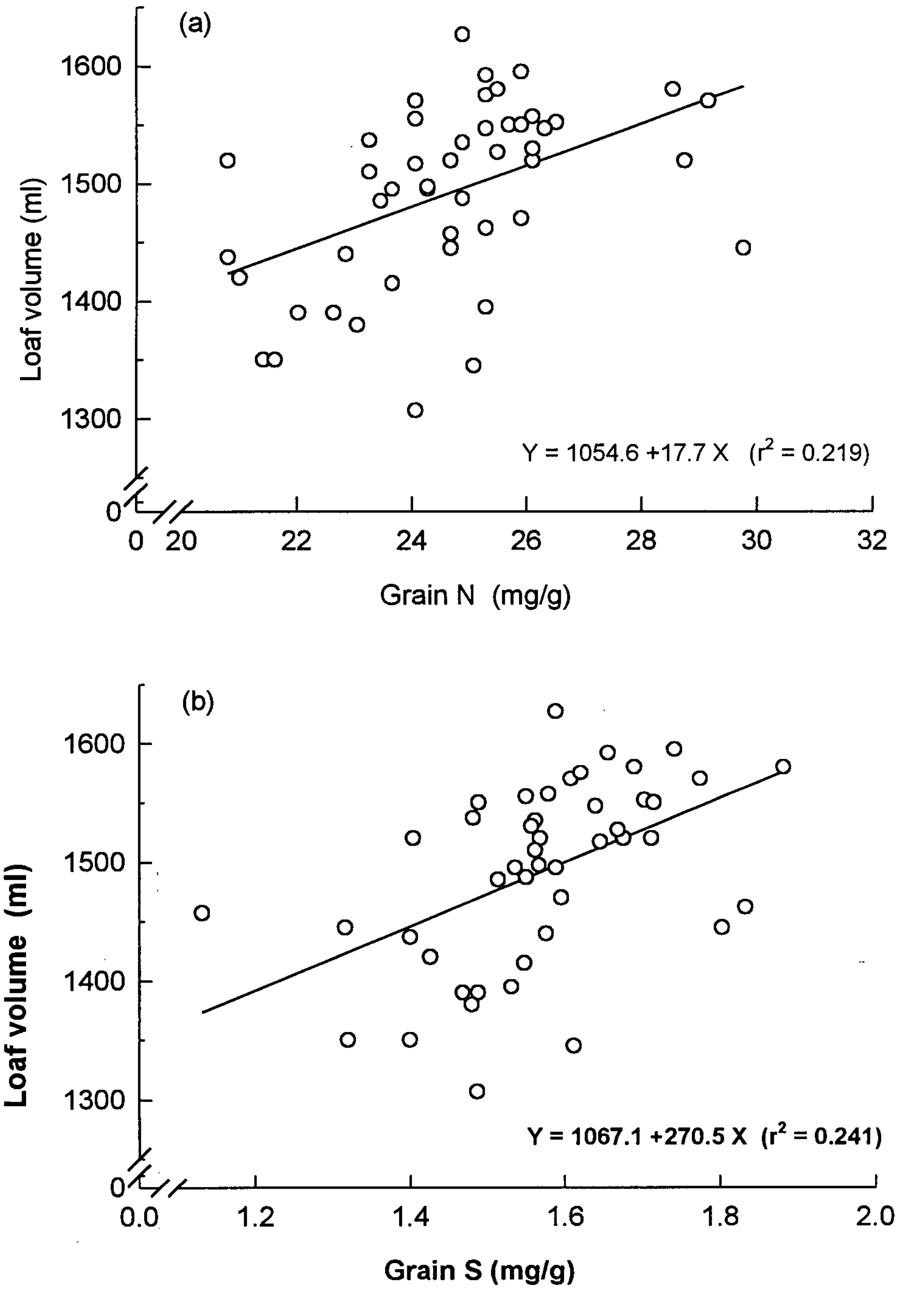


Figure 12. Relationships between loaf volume and (a) grain N and (b) grain S concentrations for Mercia in 1992.

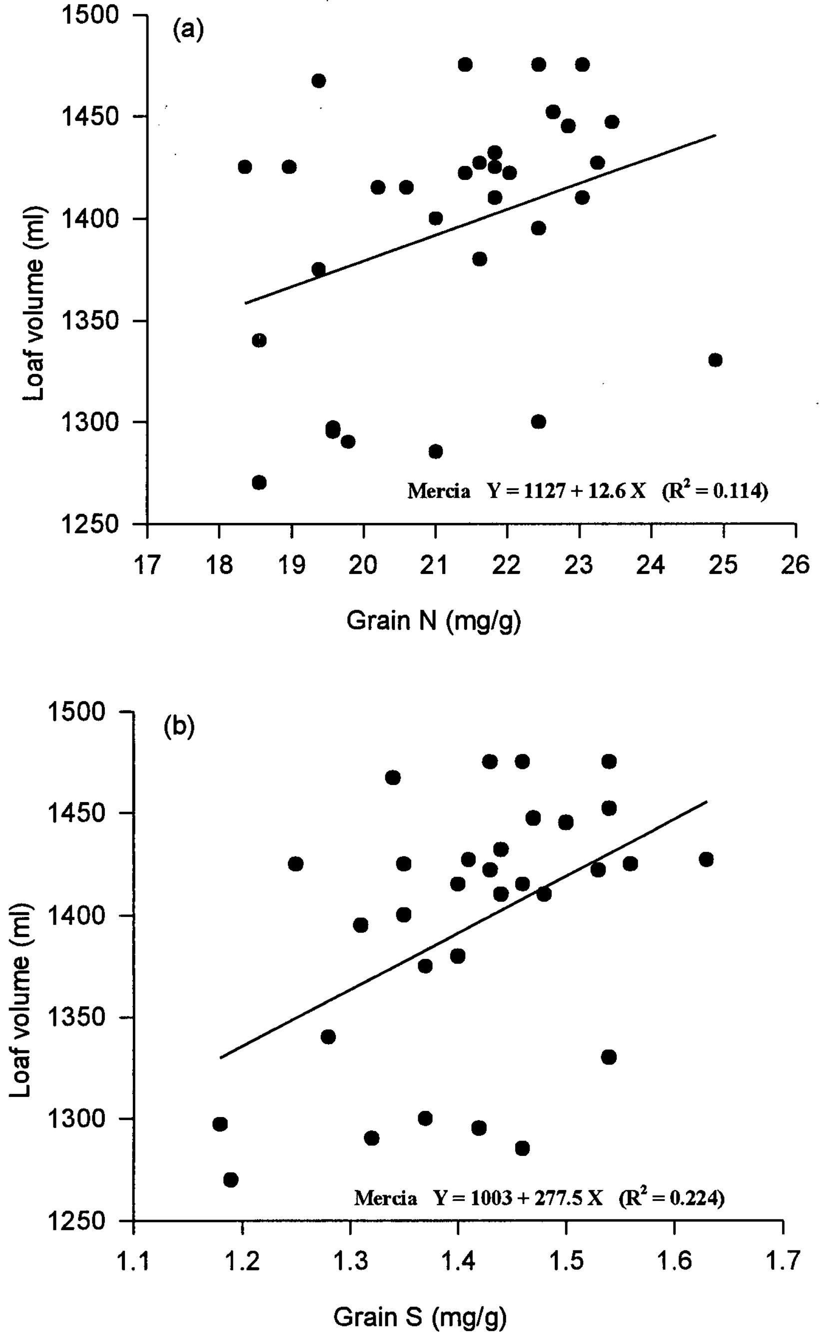


Figure 13. Relationships between loaf volume and (a) grain N and (b) grain S concentrations for Mercia in 1993.

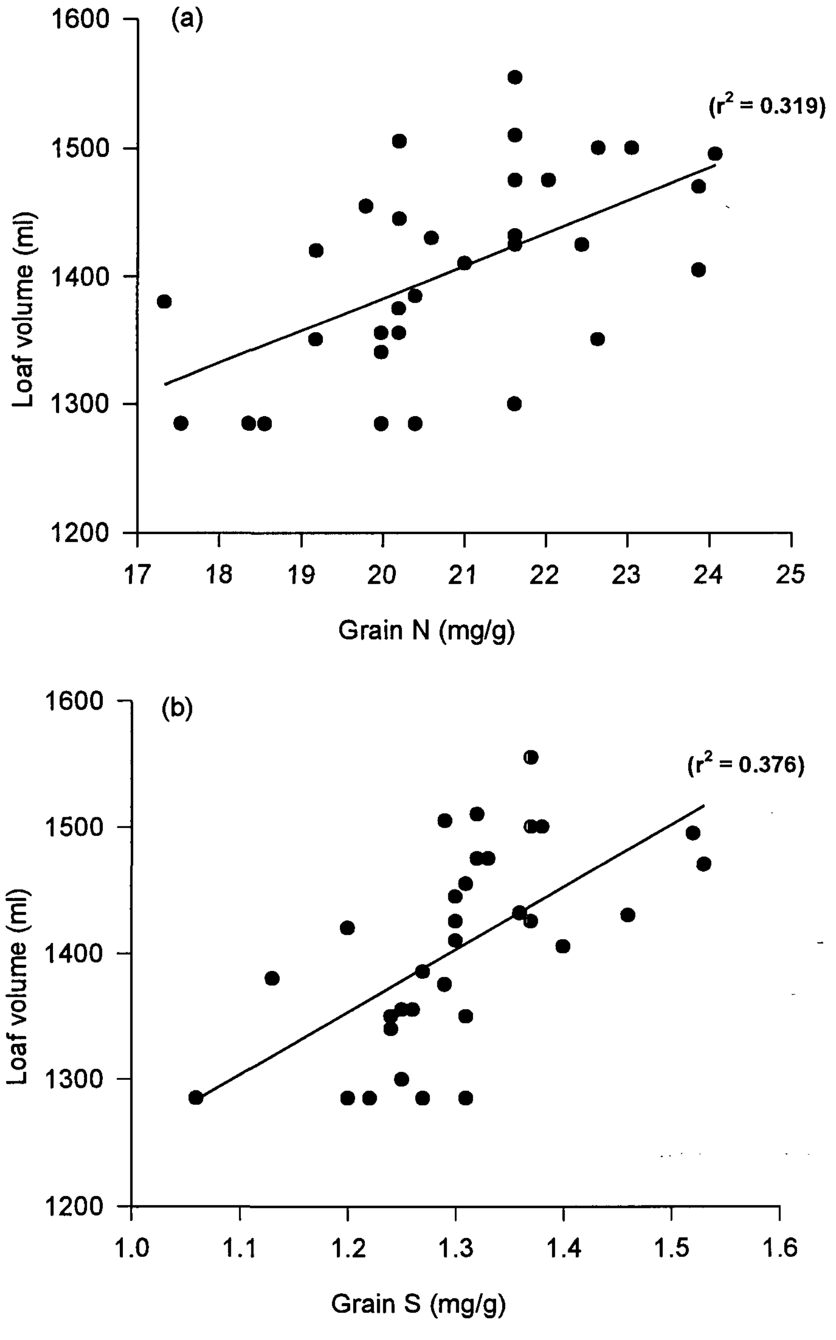


Figure 14. Relationships between loaf volume and (a) grain N and (b) grain S concentrations for Hereward in 1993.

3.3. Yield responses to S fertiliser

Changes in soil extractable S, plant S concentration and crop S uptake during growing season in all field experiments are presented in the report of a related HGCA project (0029/1/93). Estimated dry deposition of S at the experimental sites and soil extractable S in spring are shown in Appendices 1 and 2. Deposition velocities of 5.0 and 6.7 mm s^{-1} are used in the calculation for the winter months (Oct-Mar.) and summer months (April-Sept.), respectively (U.K. Review Group on Acid Rain, 1987). There is a degree of uncertainty about the dry deposition data, because of the limited precision of diffusion tube measurement. Nevertheless, the results generally agree with those reported by the Acid Precipitation Monitoring Network, and show low inputs in the sites in Scotland and southwest England and high inputs in the sites from the Midlands to North Yorkshire. Soil extractable S in the top 30 cm ranged from 4.2 to 29.1 mg/kg in 1992/93 and from 3.2 to 12.2 in 1993/94. Most of the experimental sites had extractable S in the range of 5-10 mg/kg and showed a uniform distribution to 90 cm in the soil profile.

In the 1992/93 season, yield assessment could not be made at two sites, Woburn (winter wheat) and Penygarn, Gwent (winter barley). At the other 18 sites with winter wheat, yield responses were obtained at three sites at a significance level of $p<0.05$ and at two sites at $p<0.10$ (Table 6; Appendix 3). The yield increases due to S application ranged from 4.2 to 18.4%. In the 1993/94 season, significant ($p<0.05$) yield responses to S were obtained at three sites, with yield increases in the range of 5.4-8.9% (Table 6; Appendix 4), although symptoms of S deficiency were observed at ten sites. The responsive sites were located in Scotland, Scottish Borders, East Anglia and Southwest of England. This geographical pattern agrees very well with the model prediction (in Section 1). The results from field experiments thus validate the modelling approach. Soil extractable S in spring was not a good indicator of S supply.

Woburn is classified as a site having a high risk of S deficiency. Large yield responses in winter oilseed rape have been reported (McGrath and Zhao, in press). In the 1993/94 season, S deficiency symptoms were seen in the S_0 plots at this site and dry matter production prior to anthesis was significantly increased by S addition. However, the increase in final grain yield was not significant, mainly because a prolonged dry period after anthesis stopped the filling of grain at an early stage due to the crops with S using up all the available water. As a result, the harvest index was significantly decreased by S application.

Table 6. The responsive sites in 1992/93 and 1993/94.

Site	Risk index	Yield response		% increase in grain S
		%	Sig. $p<$	
1992/93				
Langston, Devon	Medium	18.3	0.05	5.6
Shifnal, Salop	High	4.0	0.05	14.9
Elrick, Kincardineshire	High	14.2	0.05	2.6
Ednam, Kelso	High	6.8	0.079	7.1
Stetchworth, Suffolk	High	3.6	0.061	6.5
1993/94				
Bridgets, Hants	Medium	5.4	0.05	18.3
Wimborne, Dorset	High	6.1	0.05	7.3
Fakenham, Norfolk	High	8.9	0.05	55.8

At Clipburn, Cumbria, grain yield of winter barley was decreased, though not significantly, by S addition in both seasons. This site was low in soil extractable S and dry deposition inputs, and symptoms of S deficiency were clearly visible. Crop growth prior anthesis was markedly improved by the use of S fertiliser. It is possible that S addition may have induced Cu deficiency, which resulted in yield losses. The interaction between Cu and S nutrition has not been reported widely and needs to be investigated further.

In 1992/93 one site (Garblies, Morayshire) showed significant yield depression due to S application. The reason for the yield loss at this low S site is unclear.

Total S uptake at harvest ranged from 7.3 to 26.4 kg/ha in the S_0 treatment (Appendices 3 and 4). Application of S increased total S uptake significantly ($p<0.05$) at 12 and 13 sites in 1992/93 and 1993/94, respectively. The magnitude of the increases was small, a mean of 3.7 and 5.6 kg/ha in two respective seasons. This indicates a low (9-14%) utilization efficiency of fertiliser S. Lack of responses at the other sites may be due to slow movement of fertiliser S to the active rooting zone.

Application of S fertiliser increased the concentration of S in grain significantly ($p<0.05$) at 9 sites in 1992/93 and 13 sites in 1993/94. The increments ranged from 5.3 to 15.6% (mean 9.9%) in 1992/93 and from 4.0 to 55.8% (mean 17.8%) in 1993/94. The 1993/94 season was more responsive to the S treatment in terms of total S uptake and grain S concentration than the previous season. Whether the increased grain S concentration in these experiments would benefit baking performance of flour has not been tested.

Application of S had no significant effect on the concentration of N in grain at all sites in 1992/93 and increased grain N significantly ($p<0.001$) only at one site in 1993/94. Grain N:S ratio was generally decreased by S.

Neither grain S concentration nor N:S ratio, alone or combined, could indicate S responsive sites, although there was a tendency that the chance of a yield response due to S addition increased as grain S concentration in the S_0 treatment decreased. The rather variable relationships between yield response and grain S concentration or N:S ratio may be due to different varieties used at different sites. Whether diagnostic criteria should be different for different varieties needs to be studied. The mechanism and the factors influencing S translocation to grain are poorly understood. Sulphur and N availability, weather conditions and variety all probably interact, and the interactions between these need to be studied further.

Hagberg falling number was not significantly affected by S at most sites with either breadmaking or non-breadmaking varieties. In a few cases in 1993/94 the effect of S on the Hagberg falling number was registered as significant. But these results were small and inconsistent. The effect of S on grain specific weight was small, but significant decreases were obtained at two sites in both seasons. Altogether there were eight sites in the two seasons showing significant negative effect of S application on the thousand grain weight. This compares to only one site showing significant positive effect. The decreases in thousand grain weight occurred even when grain yield was increased by S. It thus appears the effect of S was mainly on increasing the number of ears and/or the number of grains per ear.

4. CONCLUSIONS

1). Sulphur deficiency in cereals is a recent development. A qualitative model was developed to assess the risk of S deficiency in cereals in Britain using soil, atmospheric deposition and meteorological data. The model predicts that currently 11% of the British land area is at high risk and a further 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. These areas are characterized by low inputs of S from the atmosphere, small content of soil organic matter and light soil texture. The SO_2 emissions in the U.K. are set to decrease to 40% of the 1980 level. The model predicts that such decreases would increase the medium and high risk areas to 27 and 22%, respectively. This means that 50% of land would be at risk, and this area includes nearly all of the cereal growing regions in Britain.

2). The concentration of S in British wheat grain has decreased considerably during the past decade. The changes are mainly due to decreased S inputs from atmospheric deposition. Grain samples with small S concentrations were located mainly in Scotland, northern England, and the west and southwest of England, whereas samples from central England tended to have larger S concentrations. Overall, as S inputs have decreased, the geographical pattern of grain S concentration has become weaker in 1992-93 than in 1982.

3). Breadmaking varieties had significantly greater grain N and S concentrations than other varieties, but little differences were found between varieties in grain N:S ratio. For the varieties Mercia in both 1992 and 1993 and Hereward in 1993, grain S concentration correlated better with loaf volume than grain N concentration.

4). The effects of S application at a rate of 40 kg/ha on grain yield were tested at 21 and 19 sites around Great Britain in the 1992/93 and 1993/94 seasons. Yield responses were obtained at three sites at a significance level of $p<0.05$ in both 1992/93 and 1993/94 seasons, and at two further sites at $p<0.10$ in 1992/93. The yield increases due to S application ranged from 4.2 to 18.4%. The responsive sites were located in Scotland, Scottish Borders, East Anglia and southwest England.

5) The geographical distribution of the responsive sites agreed well with the model prediction and therefore validated the modelling approach. In contrast, soil extractable S in spring was not a good indicator of S supply. Also, there was no clear relationship between either grain S concentration or N:S ratio with yield responses.

5. REFERENCES

AXFORD, D. W. E., McDERMOTT, E. E. AND REDMAN, D. 1979. Note on the sodium dodecyl sulfate test of breadmaking quality: comparison with Pelshenke and Zeleny tests. *Cereal Chem.* **56,** 582-584.

BHANDARI, D. G. AND PRITCHARD, P. E. 1995. Improvement of methods for measuring the quality of breadmaking wheat. *Project Report No. 99.* Home-Grown Cereals Authority, London.

BRISTOW, A. W. AND GARWOOD, E. A. 1984. Deposition of sulphur from the atmosphere and the sulphur balance in four soils under grass. *J. Agric. Sci.* **103,** 463-468.

BYERS, M., FRANKLIN, J. AND SMITH, S. J. 1987a. The nitrogen and sulphur nutrition of wheat and its effect on the composition and baking quality of the grain. *Asp. Appl. Biol.* **15**, 337-344.

BYERS, M., MCGRATH, S. P. AND WEBSTER, R. 1987b. A survey of the sulphur content of wheat grown in Britain. *J. Sci. Food Agric.* **38,** 151-160.

CHALMERS, A., KERSHAW, C. AND LEECH, P. 1990. Fertilizer use on farm crops in Great Britain: results from the survey of fertilizer practice, 1969-88. *Outlook Agric.* **19,** 269-278.

CURTIN, D. AND SYERS, J. K. 1990. Extractability and adsorption of sulphate in soils. *J. Soil Sci.* **41,** 305-312.

DoE (DEPARTMENT OF ENVIRONMENT) 1995. *Digest of Environmental Statistics No. 17.* HMSO, London.

FRENEY, J. R. 1986. Forms and reactions of the organic sulphur compounds in soils. In: *Sulfur in Agriculture* (ed. M. A. Tabatabai), American Society of Agronomy, Madison. pp. 207-232.

GENSTAT 5 COMMITTEE 1993. *Genstat 5 Release 3 Reference Manual.* Clarendon Press, Oxford.

HGCA. 1993 *Cereals Statistics 1992.* Home-Grown Cereals Authority, London.

HGCA. 1994 *Cereals Statistics 1993.* Home-Grown Cereals Authority, London.

HOEFT, R. G. AND FOX, R. H. 1986. Plant response to sulfur in the midwest and northeastern United States. In: *Sulfur in Agriculture* (ed. M. A. Tabatabai), American Society of Agronomy, Madison. pp. 345-356.

McGRATH, S. P. 1985. The effects of increasing yields on the macro- and micro-element concentrations and offtakes in the grain of winter wheat. *J. Sci. Food Agric.* **36,** 1073-1083.

McGRATH, S. P. AND GOULDING, K. T. W. 1990. Deposition of sulphur and nitrogen from the atmosphere. *J. Sci. Food Agric.* **53,** 426-427.

McGRATH, S. P. AND LOVELAND, P. J. 1992. *The Soil Geochemical Atlas of England and Wales.* Blackie Academic and Professional, London.

McGRATH, S. P. AND ZHAO, F. J. (in press). Sulphur uptake, yield responses and the interactions between nitrogen and sulphur in winter oilseed rape (*Brassica napus*). *J. Agric. Sci.*

McLAREN, R. G. AND SWIFT, R. S. 1977. Changes in soil organic sulphur fractions due to long term cultivation of soils. *J. Soil Sci.* **28**, 445-453.

MOSS, H. J., WRIGLEY, C. W., MACRITCHIE, F. AND RANDALL, P. J. 1981. Sulfur and nitrogen fertilizer effects on wheat. II. Influence on grain quality. *Aust. J. Agric. Res.* **32,** 213-226.

MURPHY, M. D. 1990. Fifteen years of sulphur research in Ireland. *Sulphur in Agriculture* **14,** 10-12.

NELSON, L. E. 1964. Status and transformation of sulfur in Mississipi soil. *Soil Sci.* **97,** 300-306.

NGUYEN, M. L. AND GOH, K. M. 1992. Sulphur mineralization and release of soluble organic sulphur from camp and non-camp soils of grazed pastures receiving long-term superphosphate applications. *Biol. Fert. Soils* **14,** 272-279.

NIAB 1981 *Classified List of Cereal Varieties 1981/82.* National Institute of Agricultural Botany, Cambridge.

NIAB 1992 *Classified List of Cereal Varieties 1992/93.* National Institute of Agricultural Botany, Cambridge.

OSBORNE, B. G., DOUGLAS, S., FEARN, T. AND WILLIS, K. H. 1982. The development of universal calibrations for measurement of protein and moisture in UK home-grown wheat by near-infrared reflectance analysis. *J. Sci. Food Agric.* **33,** 736-740.

PAYNE, P. I., NIGHTINGALE, M. A., KRATTIGER, A. F. AND HOLT, L. M. 1987 The relationship between HMW glutenin subunit composition and the bread-making quality of

British-grown wheat varieties. *J. Sci. Food Agric.* **40,** 51-65.

RANDALL, P. J., SPENCER, K. AND FRENEY, J. R. 1981. Sulfur and nitrogen fertilizer effects on wheat. I. Concentrations of sulfur and nitrogen and the nitrogen to sulfur ratio in grain, in relation to the yield response. *Aust. J. Agric. Res.* **32,** 203-212.

RANDALL, P. J. AND WRIGLEY, C. W. 1986. Effects of sulfur supply on the yield, composition, and quality of grain from cereals, oilseeds, and legumes. *Adv. Cereal Sci. Tech.* **8,** 171-206.

SAKADEVAN, K., HEDLEY, M. J. AND MACKAY, J. D. 1993. Sulphur cycling in New Zealand hill country pastures. I. Laboratory sulphur, nitrogen and carbon mineralization studies. *J. Soil Sci.* **44,** 73-83.

SCOTT, N. M. 1976. Sulphate contents and sorption in Scottish soils. *J. Sci. Food Agric.* **27,** 367-372.

SCOTT, N. M., WATSON, M. E., CALDWELL, K. S. AND INKSON, R. H. E. 1983. Responses of grassland to the application of sulphur at two sites in the north-east of Scotland. *J. Sci. Food Agric.* **34,** 354-361.

SHEWRY, P. R., TATHAM, A. S., HALFORD, N. G., BARKER, J. H. A., HANNAPPEL, H., GALLOIS, P., THOMAS, M. AND KREIS, M. 1994. Opportunities for manipulating the seed protein composition of wheat and barley in order to improve quality. *Transgenic Res.* **3,** 3-12.

SKINNER, R. J., CHURCH, B. M. AND KERSHAW, C. D. 1992. Recent trends in soil pH and nutrient status in England and Wales. *Soil Use Manag.* **8,** 16-20.

STEDMAN, J. R., CAMPBELL, G. W. AND SMITH, R. I. 1993. *Acid deposition in the United Kingdom 1992, LR959.* Warren Spring Laboratory, Stevenage.

SYERS, J. K., SKINNER, R. J. AND CURTIN, D. 1987. *Soil and fertiliser sulphur in U.K. agriculture.* Proceedings of the Fertiliser Society, No. 264. London.

TABATABAI, M. A. AND AL-KHAFAJI, A. A. 1980. Comparison of nitrogen and sulfur mineralization in soils. *Soil Sci. Soc. Am. J.* **44,** 1000-1006.

U.K. REVIEW GROUP ON ACID RAIN. 1987. *Acid deposition in the United Kingdom 1981-1985, Second Report.* Warren Spring Laboratory, Stevenage.

U.K. REVIEW GROUP ON ACID RAIN. 1990. *Acid deposition in the United Kingdom 1986-1988, Third Report.* Warren Spring Laboratory, Stevenage.

UNIRAS/AS. 1989. *Unimap 2000 Users Manual.* Uniras/AS, Søbory, Denmark.

WEBSTER, R. AND OLIVER, M. A. 1990. *Statistical Methods in Soil and Land Resource Survey.* Oxford University Press, Oxford.

WHELPDALE, D. M. 1992. An overview of the atmospheric sulphur cycle. In: *Sulphur Cycling on the Continents, SCOPE 48* (eds. R. W. Howarth, J. W. B. Stewart and M. V. Ivanov). John Wiley & Sons, Chichester, England. pp. 5-26.

WITHERS, P. J. A. AND O'DONNELL, F. M. 1994. The response of double-low winter oilseed rape to fertiliser sulphur *J. Sci. Food Agric.* **66**, 93-101.

WITHERS, P. J. A. AND SINCLAIR, A. H. 1994. Sulphur nutrition of cereals in the UK: effects on yield and grain quality. *Research Review No. 30.* Home-Grown Cereals Authority, London.

WITHERS, P. J. A., EVANS, E. J., BILSBORROW, P. E, MILFORD, G. F. J., McGRATH, S. P., ZHAO, F. AND WALKER, K. C. 1994. Development and prediction of sulphur deficiency in winter oilseed rape. *Project Report No. OS11.* Home-Grown Cereals Authority, London.

ZHAO, F. J., EVANS, E. J., BILSBORROW, P. E. AND SYERS, J. K. 1993. Influence of sulphur and nitrogen on seed yield and quality of low glucosinolate oilseed rape (*Brassica napus* L). *J. Sci. Food Agric.* **63,** 29-37.

ZHAO, F. AND McGRATH, S. P. 1994a. Extractable sulphate and organic sulphur in soils and their availability to plants. *Plant and Soil* **164**, 243-250.

ZHAO, F. AND McGRATH, S. P. 1994b. Comparison of sulphur uptake by oilseed rape and the soil sulphur status of two adjacent fields with different soil series. *Soil Use Manag.* **10,** 47-50.

ZHAO, F., MCGRATH, S. P. AND CROSLAND, A. R. 1994. Comparison of three wet digestion methods for the determination of plant sulphur by inductively coupled plasma atomic emission spectroscopy (ICP-AES). *Comm. Soil Sci. Plant Anal.* **25,** 407-418.

6. APPENDICES

Appendix 1. Deposition of S and soil extractable S in spring at the experimental sites in 1992/93.

Site	Grid reference	Dry deposition (kg S/ha/year)	Soil extractable S (mg/kg)		
			0-30 cm	30-60 cm	60-90 cm
Langston, Devon	SX649483	2.8	10.0	14.4	-
Shifnal, Salop	SJ761079	12.3	4.9	4.0	3.8
Stetchworth, Suffolk	TL669605	11.4	6.1	6.1	6.9
Ednam, Kelso	NT743375	4.1	7.0	9.1	7.7
Elrick, Kincardineshire	NJ828060	4.2	13.4	13.8	-
Witchampton, Dorset	ST974093	5.3	7.9	7.4	3.3
Adisham, Sussex	TQ210549	17.0	8.6	-	-
Flodden, Scottish Borders	NT863375	8.8	29.1	28.8	10.7
Gupton, Dyfed	SR897989	11.4	7.6	5.6	7.0
Lewes, Kent	TQ358094	9.4	4.2	-	-
Raynham, Norfolk	TF904237	7.9	4.9	4.8	6.2
Sessay, North Yorkshire	SE448765	23.1	5.8	8.8	9.5
Garblies, Morayshire	NH915554	4.9	6.7	6.0	5.9
Ross on Wye, Herefordshire	SO631289	6.5	7.0	7.8	6.8
Great Tew, Oxon	SP410223	8.5	9.7	-	-
Woodmancote, Glocestershire	SP003089	10.8	11.9	-	-
Bridgets, Hants	SU341518	9.0	6.3	2.8	2.7
Devizes, Wiltshire	SU044668	11.2	8.5	3.8	3.9
Penrith, Cumbria	NY600262	6.4	5.8	3.0	5.0
Penygarn, Gwent	SO517098	11.7	6.4	11.7	12.8
Woburn, Bedfordshire	SP964360	12.8	8.0	7.6	7.0

Appendix 2. Deposition of S and soil extractable S in spring at the experimental sites in 1993/94.

Site	Grid reference	Dry deposition (kg S/ha/year)	Soil extractable S (mg/kg)		
			0-30 cm	30-60 cm	60-90 cm
Bicton, Dyfed	SM838073	8.7	7.3	10.2	10.0
Bridgets, Hants	SU341518	11.3	6.3	7.2	7.5
Mileoak, Sussex	TQ246089	14.7	11.9	-	-
Clipburn, Penrith, Cumbria	NY590265	8.3	3.2	2.2	3.1
Sidmouth, Devon	SY082883	7.6	5.4	5.5	4.7
Wimborne, Dorset	ST964123	6.1	7.3	3.4	2.1
East Leach, Gloucestershire	SP194076	11.6	6.9	-	-
Fakenham, Norfolk	TF905293	7.6	9.6	7.8	6.5
Hempstead, Norfolk	TG109362	10.1	7.5	5.6	5.5
Kennington, Kent	TQ005451	15.3	5.9	6.4	5.9
Kildrummie, Scotland	NH880560	7.3	6.1	11.6	13.2
Bush Penicuik, Scotland	NT230590	11.8	9.3	11.4	-
Scottish Borders	NT863375	9.1			
Plas, Gwent	SM459615	11.0	11.4	14.4	14.3
Ross on Wye, Herefordshire	SO631289	10.2	3.2	3.7	4.0
Sessay, North Yorkshire	SE448765	18.9	9.5	11.2	12.3
Shifnal, Salop	SJ776076	13.1	7.0	6.4	5.4
Lydeard St Lawrence, Somerset	ST122321	7.2	8.1	6.5	5.2
Stetchworth, Suffolk	TL630598	7.7	12.2	11.5	13.0
Woburn, Bedfordshire	SP964360	7.9	4.7	4.4	3.6

Appendix 3. Responses to S in the 1992/93 field experiments.

Langston, Devon. Winter wheat: Beaver

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	4.92	13.0	22.0	1.62	13.6	72	63.4	24.3
40	5.82	17.7	21.2	1.71	12.3	71	64.3	26.0
SED	0.22	1.044	0.64	0.026	0.33	4.43	0.67	0.61
Sig.	*	*	NS	*	*	NS	NS	*

Shifnal, Salop. Winter wheat: Riband

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	8.43	12.1	14.6	1.14	12.8	226	77.3	49.8
40	8.77	16.2	14.5	1.31	11.0	229	76.6	47.1
SED	0.11	0.622	0.16	0.020	0.16	12.6	0.11	0.35
Sig.	*	**	NS	***	***	NS	**	**

Stetchworth, Suffolk. Winter wheat: Beaver

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	7.83	12.4	17.9	1.23	14.5	192	N/A	43.3
40	8.11	15.0	18.0	1.31	13.8	231		44.4
SED	0.11	0.263	0.42	0.025	0.13	28.4		0.98
Sig.	p=0.061	***	NS	*	**	NS		NS

Ednam, Kelso. Winter wheat: Riband.

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	8.74	12.8	14.7	1.12	13.1	171	75.7	40.7
40	9.33	15.3	15.2	1.20	12.7	159	75.9	43.3
SED	0.25	0.94	0.27	0.032	0.19	14.5	0.36	1.59
Sig.	p=0.079	p=0.054	NS	p=0.071	p=0.090	NS	NS	NS

Elrick, Kincardineshire. Winter wheat: Riband.

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	6.22	14.3	16.0	1.16	13.9	238	70.5	29.5
40	7.10	16.4	15.5	1.19	13.0	218	70.7	31.0
SED	0.24	1.046	0.39	0.028	0.12	10.3	0.67	0.83
Sig.	*	NS	NS	NS	**	NS	NS	NS

Witchampton, Dorset. Winter wheat: Riband

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	8.10	13.2	17.4	1.31	13.3	173	75.4	46.7
40	8.48	17.8	16.8	1.43	11.8	173	74.8	44.3
SED	0.28	1.43	0.36	0.031	0.46	19.2	0.27	0.88
Sig.	NS	*	NS	*	*	NS	NS	p=0.055

Adisham, Sussex. Winter wheat: Beaver

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	8.92	17.6	17.8	1.30	13.7	188	80.5	42.4
40	9.01	19.3	17.6	1.36	13.0	186	80.7	42.7
SED	0.23	0.369	0.33	0.037	0.31	9.2	0.18	0.74
Sig.	NS	**	NS	NS	p=0.086	NS	NS	NS

Borders. Winter wheat: Mercia

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	9.04	26.4	20.6	1.47	14.0	300	79.0	39.1
40	8.73	31.4	20.5	1.48	13.9	302	78.9	39.5
SED	0.41	2.80	0.32	0.033	0.26	9.3	0.82	1.70
Sig.	NS	NS	NS	NS	NS	NS	NS	NS

Gupton, Dyfed. Winter wheat: Galahad

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	4.90	18.3	22.1	1.56	14.2	237	71.2	29.6
40	5.18	20.4	21.4	1.57	13.6	243	71.3	31.4
SED	0.27	0.776	0.72	0.081	0.27	24.1	0.53	2.00
Sig.	NS	p=0.051	NS	NS	NS	NS	NS	NS

Lewes, Kent. Winter wheat: Hereward

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	5.46	8.3	18.1	1.22	14.9	217	78.7	33.5
40	5.30	10.2	18.3	1.39	13.2	219	77.4	30.2
SED	0.11	0.20	0.90	0.030	0.54	18.5	0.69	0.87
Sig.	NS	***	NS	**	*	NS	NS	*

Raynham, Norfolk. Winter wheat: Haven

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	10.05	13.8	15.4	1.19	12.9	213	N/A	43.8
40	10.10	17.8	15.6	1.34	11.7	222		44.0
SED	0.10	0.25	0.55	0.028	0.27	20.2		1.42
Sig.	NS	***	NS	**	*	NS		NS

Sessay, North Yorkshire. Winter wheat: Haven

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	6.65	14.2	19.9	1.53	13.1	248	77.2	33.9
40	6.27	17.3	20.5	1.60	12.8	257	75.3	30.8
SED	0.70	0.77	1.26	0.13	0.66	46.4	1.60	2.43
Sig.	NS	*	NS	NS	NS	NS	NS	NS

Garblies, Morayshire. Winter wheat: Riband.

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	9.13	14.9	16.8	1.13	14.9	190	76.7	38.5
40	8.73	21.8	16.5	1.19	13.9	180	75.9	35.0
SED	0.08	0.378	0.26	0.014	0.33	28.5	0.34	1.76
Sig.	**	***	NS	**	*	NS	p=0.075	NS

Ross-on-Wye, Herefordshire. Winter wheat: Mercia

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	7.51	17.2	22.3	1.51	14.8	286	79.8	32.5
40	7.42	19.8	22.2	1.55	14.3	288	80.4	30.0
SED	0.22	1.04	0.05	0.03	0.36	9.6	0.34	1.71
Sig.	NS	p=0.068	NS	NS	NS	NS	NS	NS

Great Tew, Oxon. Winter wheat: Riband

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	9.72	20.3	18.6	1.39	13.3	143	72.7	44.4
40	9.62	25.8	18.4	1.47	12.5	119	71.5	44.5
SED	0.57	1.37	0.37	0.017	0.17	13.3	0.88	0.85
Sig.	NS	*	NS	**	**	NS	NS	NS

Woodmancote, Gloucestershire. Winter wheat: Estica

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	10.08	16.7	19.5	1.22	16.0	158	79.6	43.1
40	9.69	19.6	19.1	1.29	14.9	156	79.4	38.7
SED	0.23	1.056	0.44	0.027	0.19	13.9	0.12	1.88
Sig.	NS	p=0.051	NS	p=0.062	**	NS	NS	p=0.079

Bridgets, Hants. Winter wheat: Admiral

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	6.71	10.4	17.1	1.22	14.1	234	74.7	34.8
40	6.86	13.2	17.0	1.41	12.1	226	74.3	33.3
SED	0.32	0.51	0.29	0.035	0.22	11.3	0.22	1.23
Sig.	NS	**	NS	**	***	NS	NS	NS

Devizes, Wiltshire. Winter wheat: Hereward

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	8.13	23.2	22.5	1.53	14.7	180	80.4	36.1
40	8.41	26.2	22.3	1.55	14.4	138	79.6	35.7
SED	0.42	0.83	0.21	0.030	0.28	28.2	0.94	0.75
Sig.	NS	*	NS	NS	NS	NS	NS	NS

Penrith, Cumbria, Winter Barley: Marinka

Treatment	Grain yield (t/ha)	S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	4.28	7.4	21.3	1.36	15.7	N/A	71.7	40.2
40	3.73	7.8	20.9	1.54	13.6		71.4	38.8
SED	0.42	0.24	1.35	0.093	0.18		0.41	1.79
Sig.	NS	NS	NS	NS	***		NS	NS

Note: Grain yields are based on 85% dry matter. Grain N and S concentrations are based on dry matter.
Significant level: NS not significant; * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

Appendix 4. Responses to S in the 1993/94 field experiments.

Bicton, St Ishmaels, Dyfed. Winter wheat: Beaver

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	9.43	18.3	16.7	1.11	15.0	62	69.7	45.4
40	9.61	19.1	17.0	1.20	14.1	62	69.8	45.7
SED	0.180	0.620	0.486	0.028	0.198	moulded	0.296	0.702
Sig.	NS	NS	NS	**	***	samples	NS	NS

Bridgets, Hants. Winter wheat: Hunter

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	8.83	14.5	19.1	1.15	16.7	295	79.2	42.0
40	9.31	20.0	18.5	1.36	13.6	289	77.8	37.9
SED	0.212	2.10	0.316	0.032	0.331	10.18	0.244	0.767
Sig.	*	*	p=0.07	***	***	NS	***	***

Mileoak, West Sussex. Winter wheat: Soissons

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	8.85	14.4	19.2	1.39	13.8	331	81.5	41.6
40	9.07	19.3	19.2	1.49	12.9	332	81.6	41.1
SED	0.175	1.054	0.354	0.028	0.307	7.02	0.141	0.445
Sig.	NS	**	NS	**	*	NS	NS	NS

Clipburn, Cumbria, Winter barely: Firefly

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	3.40	8.2						
40	2.97	16.3						
SED	0.28	0.837						
Sig.	NS	***						

Sidmouth, Devon. Winter wheat: Spark

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	6.66	10.2	16.8	1.12	15.0	271	78.9	36.2
40	6.82	11.9	16.5	1.21	13.7	280	77.7	32.2
SED	0.271	0.421	0.425	0.028	0.434	18.1	0.139	0.766
Sig.	NS	**	NS	*	NS	NS	***	***

Wimborne, Dorset. Winter wheat: Riband.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	9.87	21.1	17.2	1.24	13.9	N/A	75.5	46.7
40	10.47	30.9	17.4	1.33	13.0		75.4	45.9
SED	0.253	1.202	0.357	0.021	0.257		0.158	0.531
Sig.	*	***	NS	**	*		NS	NS

East Leach, Gloucestershire. Winter wheat: Hussar.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	6.81	9.4	16.9	1.05	16.1	321	78.0	36.2
40	6.79	13.7	19.1	1.23	15.6	334	77.8	35.2
SED	0.154	0.664	0.421	0.038	0.504	4.32	0.227	0.752
Sig.	NS	***	***	***	NS	*	NS	NS

Fakenham, Norfolk. Winter wheat: Haven.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	4.82	7.3	22.3	1.04	21.4	277	73.0	43.2
40	5.25	12.8	21.9	1.62	13.6	218	73.1	40.8
SED	0.168	0.538	0.471	0.043	0.559	8.25	0.148	0.349
Sig.	*	***	NS	***	***	***	NS	***

Hempstead, Norfolk. Winter wheat: Riband.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	6.21	10.7	18.8	1.10	17.1	303	74.3	40.5
40	5.96	13.1	19.1	1.34	14.2	294	73.8	39.7
SED	0.192	0.635	0.302	0.072	1.031	13.13	0.251	0.447
Sig.	NS	*	NS	*	*	NS	p=0.09	NS

Kennington, Kent. Winter wheat: Soissons.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	7.54	12.8	16.8	1.24	13.6	308	78.7	37.9
40	7.66	16.1	16.5	1.29	12.8	307	78.4	36.5
SED	0.159	0.919	0.148	0.013	0.170	5.55	0.171	0.448
Sig.	NS	**	NS	**	***	NS	p=0.06	*

Kildrummie, Scotland. Winter wheat: Riband.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	7.58	9.62	13.4	0.88	15.4	208	73.7	42.2
40	7.48	9.86	14.0	1.00	14.1	234	73.6	41.6
SED	0.405	0.693	0.874	0.040	0.658	11.07	0.579	1.252
Sig.	NS	NS	NS	*	p=0.09	*	NS	NS

Bush Penicuik, Scotland. Winter wheat: Riband.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	7.52	10.8	19.6	1.21	16.2	131	77.1	43.8
40	7.76	10.9	19.1	1.22	15.7	165	76.7	45.1
SED	0.212	0.346	0.346	0.038	0.387	17.08	0.247	1.062
Sig.	NS	NS	NS	NS	NS	P=0.08	NS	NS

Plas, Gwynedd, Wales. Winter wheat: Zodiac.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	8.50	23.4	19.6	1.25	15.8	289	78.9	38.1
40	8.50	26.6	19.5	1.25	15.6	284	78.6	38.1
SED	0.176	2.07	0.253	0.049	0.811	3.74	0.268	0.841
Sig.	NS	NS	NS	NS	NS	NS	NS	NS

Ross on Wye, Herefordshire. Winter wheat: Mercia.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	6.36	19.5	24.5	1.38	17.8	321	77.7	28.2
40	6.16	22.2	24.2	1.52	16.0	320	77.8	28.0
SED	0.147	1.211	0.286	0.067	0.805	3.69	0.385	1.516
Sig.	NS	P= .053	NS	P= .060	*	NS	NS	NS

Sessay, North Yorkshire. Winter wheat: Riband.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	6.08	11.8	19.5	1.12	17.5	318	79.4	40.5
40	6.29	14.6	18.7	1.19	15.8	307	79.0	39.1
SED	0.167	0.969	0.400	0.046	0.425	3.73	0.378	0.747
Sig.	NS	*	NS	NS	*	*	NS	NS

Shifnal, Salop. Winter wheat: Hereward.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	6.51	10.0	20.7	1.29	16.0	271	82.7	42.0
40	6.37	17.4	20.5	1.53	13.4	278	82.2	39.0
SED	0.461	1.44	0.481	0.034	0.47	23.4	0.350	1.273
Sig.	NS	***	NS	***	***	NS	NS	*

Lydeard St Lawrence, Somerset. Winter wheat: 70% Soissons, 30% Estica.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	6.62	11.7	20.7	1.16	18.1	268	80.8	38.5
40	6.86	15.2	20.5	1.40	14.7	258	80.7	37.8
SED	0.175	0.631	0.251	0.050	0.863	9.19	0.107	0.98
Sig.	NS	***	NS	***	**	NS	NS	NS

Stetchworth, Suffolk. Winter wheat: Soissons.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	9.33	13.3	21.1	1.27	16.7	320	81.8	39.8
40	9.26	16.6	21.0	1.34	15.8	317	81.7	40.2
SED	0.076	1.194	0.176	0.034	0.461	3.54	0.079	0.388
Sig.	NS	p= .051	NS	p= .095	NS	NS	NS	NS

Woburn , Bedfordshire. Winter wheat: Hereward.

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	5.08	9.4	24.8	1.41	17.7	360	77.0	30.2
40	5.27	23.4	25.8	1.81	14.3	357	76.2	26.9
SED	0.255	1.37	0.436	0.036	0.319	3.49	0.174	0.999
Sig.	NS	***	NS	***	***	NS	NS	*

Scottish Borders. Winter wheat: .

Treatment	Grain yield (t/ha)	Total S uptake (kg/ha)	Grain N (mg/g)	Grain S (mg/g)	N:S ratio	Hagberg falling no.	Specific wt. (kg/hl)	1000 grain wt. (g)
0	9.29	17.0	20.2	1.28	15.8	300	82.3	41.7
40	9.10	18.1	20.1	1.31	15.4	305	82.2	40.1
SED	0.102	1.474	0.267	0.027	0.242	4.08	0.102	0.651
Sig.	NS	NS	NS	NS	NS	NS	NS	p=.054

Note: Grain yields are based on 85% dry matter. Grain N and S concentrations are based on dry matter.
Significant level: NS not significant; * $p<0.05$; ** $p<0.01$; *** $p<0.001$.