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Decision support for sulphur applications to cereals

by

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Contents

Abstract

Yield response to the application of sulphur fertilisers has become more widespread in cereals. Without sulphur fertiliser, yield losses in winter wheat can be up to 30% in the most responsive situations (approximately £240/ha at current prices) but average 6% (approximately £48/ha). This represents a total potential loss of £83million across England in winter wheat alone (with similar levels of yield loss in other cereals). On the other hand, a typical application of 20 kg S/ha costs about £10/ha, which would be a waste if crop yield does not respond to sulphur fertiliser. A number of factors interact to influence the soil sulphur supply and a crop's ability to explore the available sulphur pool in the soil. These factors need to be considered together to guide the decision on sulphur applications.

Two hundred and four field trials on sulphur responses in cereals were collated as part of the project. A subset of 88 trials with winter wheat was chosen for further statistical analysis, based on a number of selection criteria. Within this subset of trials, 26% showed a significant and positive response to sulphur application. The data were analysed to determine the key factors affecting yield response to sulphur.

Site factors including soil type and over-winter rainfall were found to be important, whereas the influence of sulphur deposition was relatively small. This is likely to be due to a combination of decreased overall sulphur deposition coupled with the relatively small range of deposition rates now experienced in rural areas of the UK. A new matrix scoring system was developed based on the relative contribution of over-winter rainfall, soil type and sulphur deposition to guide cereal growers on sulphur applications to cereals.

Summary

Objectives

1. To update and develop further an existing model of the national status of yield responsiveness to sulphur fertilisers in cereals.
2. To collate and review experimental data, both published and unpublished, on sulphur responses in cereals.
3. To analyse experimental data to identify the key factors that are driving crop yield response to sulphur fertiliser.
4. To develop a decision support framework for predicting yield response to sulphur application in cereals. A matrix system will be devised to help farmers and consultants decide whether sulphur should be applied on a field by field basis.

Methods

1. In a previous project funded by HGCA, a simple risk assessment model for predicting the national status of cereal crop yield responsiveness to sulphur was developed (McGrath et al. 1995, HGCA Project Report No. 115). This model used large national databases for soils, rainfall and atmospheric sulphur deposition. The sulphur deposition data used in that work are out of date by more than 10 years now. During that time a dramatic decrease in sulphur deposition has occurred. This project has updated the national databases to improve our understanding of how the national status of cereal crop yield responsiveness to sulphur has changed.

2. Two HGCA-funded projects on various aspects of the sulphur nutrition of cereals have been carried out by Rothamsted research since 2000. One on malting barley (Zhao et al. 2005, HGCA Project Report No. 369), and the other on the development of diagnostics (Blake-Kalff et al, 2004, HGCA Project Report No. 327). In addition, sulphur response trials have been conducted by TAG (Arable Research Centre and Morley). In total, over 204 field trials on cereal yield response to sulphur were available. Some of the trial results have been published, but many have not. These data were collated, together with important information such as geographical location, soil type, soil analysis data, weather, cropping history and variety.

3. A statistical analysis of the relationships between locations, soil type and weather and sulphur responses in winter wheat was undertaken in order to identify the key factors that influence sulphur responses. It is clear that a number of factors interact to influence soil sulphur supply and a crop's ability to explore the available sulphur pool in the soil. Section 3 of this report aims to identify these key factors, which include soil type, sulphur deposition and weather pattern (particularly winter rainfall). The key factors were weighted according to their relative importance in determining sulphur supply to crops.

4. A decision matrix framework was developed based on the analysis carried out in Section 4. For an individual field crop the overall responsiveness in three categories (high, medium and low) was estimated using soil type, over-winter rainfall and sulphur deposition information This matrix system approach is simple to use, and can be used to guide the decision on sulphur applications to cereal crops on a field-by-field basis early in the growing season.

Key results and conclusions

- Based on an analysis of field trials data and an update of the national risk model, a robust estimate of the percentage of wheat crops where significant yield responses to the application of sulphur is approximately 30%.
- Yield response to sulphur seems more pronounced in wheat crops than in barley.
- In all of the trials with wheat an overall average of 6% yield response was observed (rising to 27% response where ONLY significantly positive yield responses were considered)
- Actual yield response observed in an individual field trial was driven by the interactions between soil type, over-winter rainfall and estimated sulphur deposition. Other factors used within the analysis (nitrogen fertiliser rate, crop cultivar) were not significant.
- The project highlights two areas for targeted research in the future: the influence of crop rotation on sulphur supply for cereal crops and the role of organic manuring on building up sulphur reserves in the soil.

Implications

The latest survey of fertiliser practice (Anon 2005) shows that 41% of the cereal crop area in the UK (this equates to 1.19 million ha) was treated with sulphur fertilisers at an average rate of 22 kg S/ha in 2005. This is equivalent to a total amount 26.4 thousand tonnes of sulphur being used. Using an assumed price of £0.5 per kg S, the total cost of sulphur fertilisers is estimated at £13.2 million for cereals per year. What is not clear from the survey is whether the sulphur fertiliser is being applied in the appropriate responsive areas. A 25% improvement of sulphur use, *i.e.* through better targeting of sulphur applications, means a potential saving of £3.3 million on fertilisers.

Using a figure of 30% of the wheat grown (a total of 560 thousand ha) being at risk of yield loss if sulphur fertilisers are not used, an average wheat yield of 8 t/ha and an estimate of 27% yield response to sulphur applications, the estimated potential yield increase due to sulphur is presently 1.2 million tonnes of wheat. This amounts to a value of over £120 million in extra wheat yield at the current price of £100/tonne. In addition to this, effects on quality are also important for the market, but these are more difficult to quantify.

The decision support framework created by this project allows cereals growers to make a realistic assessment of the crop yield responses to sulphur application for individual situations. This will help them to decide on the sulphur application strategy early in the growing season.

Detailed technical report

Background

There is no doubt that yield response to sulphur application has become widespread in UK crops, most prominently in oilseed rape and to a lesser extent cereals (McGrath et al. 2002; Zhao et al., 2002). For oilseed rape, the potential yield response to sulphur application is so high that a blanket application of sulphur to all crops is now warranted. However, this is not the case for cereals, particularly in light of the current economic conditions in farming and the need to reduce input costs. It is important that cereal growers are able to make correct decisions on the applications of sulphur fertilisers, to avoid potential yield losses or to avoid unnecessary applications of sulphur where not warranted. However, this is not an easy task.

A number of projects, funded or co-funded by HGCA, have been conducted to investigate various aspects of sulphur nutrition of cereals since the early 1990s. These projects highlight the extent of crop yield responses to sulphur application (McGrath et al. 1995. HGCA Project Report No. 115), the impacts of sulphur on yield and breadmaking quality of wheat (McGrath et al. 1999. HGCA Project Report No. 197) and barley (Zhao et al. 2005, HGCA Project Report No. 369), the efficiency of different forms of sulphur fertilisers (Riley et al. 2000. HGCA Project Report No. 222), and soil analysis and crop diagnosis methods for predicting yield responses to sulphur application (Withers et al. 1997. HGCA Project Report No. 142; Blake-Kalff et al. 2000. HGCA Project Report No. 327). It seems that although in some cases it can be useful (Zhao et al. 2005, HGCA Project Report No. 369) soil analysis does not always provide a reliable indicator for crop yield responses to sulphur (Withers et al. 1997. HGCA Project Report No. 142). Plant diagnostic methods are more successful, but the results obtained are often too late to guide the decision on sulphur application for the current crop (Blake-Kalff et al. 2004. HGCA Project Report No. 327).

It is believed that the decision on sulphur application should be made taking into account all of the key factors affecting sulphur supply to crops and the ability of a crop to explore the available sulphur pool in soil. The key factors are likely to include soil type, weather conditions (especially winter rainfall), atmospheric deposition of sulphur, past use of manures or other sulphur-containing fertilisers, and cropping history. Data are available from a large number of field trials that have already been conducted. Approximately 200 field trials have been conducted in the HGCA funded projects listed above. In addition, TAG (including its predecessors ARC and Morley) has conducted a number of commercially funded sulphur response trials on cereals. Here we evaluate these data in this report, and develop a decision matrix system for assessing the potential yield responses to sulphur application in cereals.

In a previous project carried out in 1992-1994 (McGrath et al. 1995. HGCA Project Report No. 115), a model for the national status of yield response to sulphur application was developed, using national databases for soil, atmospheric deposition and weather. The model predicted that cereal crops grown on 11% of the British land area were highly responsive to sulphur application and this would increase to 27% by 2003 if atmospheric deposition was to decrease to meet the national targets on air pollution control. In fact, SO_2 emissions and atmospheric deposition of sulphur decreased much more rapidly than expected, especially since 1998. New data on atmospheric deposition are now available; there is a need to update the model prediction to gain a better picture of the current nationwide situation with regard to yield responsiveness to sulphur. Also, we see the need to extend the model, taking into account of the research done over the last decade and, specifically, integrating the matrix scoring system into the risk assessment model.

1. Updating existing national status model

A model that assesses the national status of cereal crops responsiveness to sulphur fertilisers was published in 1995 (McGrath & Zhao, 1995). This model was based on soils, rainfall and sulphur deposition databases dating from 1990. While the distribution of soil types can be considered static, in the period between 1990 and the current time sulphur deposition has changed considerably (Bower et al., 2005). In addition an improved historic rainfall database for the UK land surface has become available (Perry & Hollis, 2005).

1.1 Updated databases

The model described in McGrath & Zhao (1995) was updated using new datasets where available. The existing database for soils, originally obtained from the National Soil Inventory (McGrath & Loveland, 1992) (for England and Wales) and Macaulay Land Use Research Institute (for Scotland), was used. The soils database for England and Wales was sampled on a regular 5km x 5km grid. The soils information for Scotland is based on a sparser grid (10 x 10 km) with a large number of missing samples in upland and isolated areas, and a small number of additional samples not aligned to the 10km grid. An updated database for sulphur deposition averages for 2000 to 2004 across England, Wales and Scotland interpolated at a 5 km x 5 km resolution was obtained directly from the Atmospheric Sciences unit at CEH Edinburgh. A complete database of historic UK climate data (including the rainfall data used here) interpolated at a 1 km gird square resolution was available from the meteorological office website - http://www.metoffice.gov.uk/climate/uk/averages/index.html. The rainfall data were aggregated to the same 5 km x 5 km grid as the soil and sulphur deposition databases before use.

It should be noted that, although within the remit of the HGCA, Northern Ireland is not included in either the existing or revised model because of the lack of readily available sulphur deposition and soils information.

The changes in sulphur deposition are shown in Figure 1. The datasets from 1990 and 2000-2004 are both based on the interpolation of measured sulphur deposition from a network of sampling sites (details in Bower et al. 2005). Differences in the appearance of the maps for 1990 and 2000-2004 stem from small differences in the way the data are collated and presented; the dataset from 1990 was interpolated on a 20 km square resolution whereas the most recent dataset is interpolated on a 5 km x 5 km resolution. The original 1990 dataset was based on a single year's deposition data whereas the most recent dataset is an average of the five year period. Between 1990 and 2000-2004 there has been a considerable overall decrease in the deposition of sulphur; the average deposition rate has fallen from 16 kg/ha/yr to 10 kg/ha/yr. Importantly, as a result of sulphur deposition falling to a greater extent in areas where it had previously been high, the range of values of sulphur deposition observed over the UK has decreased; while the range of sulphur deposition observed had previously been 5 to 52 kg/ha/yr it is currently 3 to 31 kg/ha/yr.

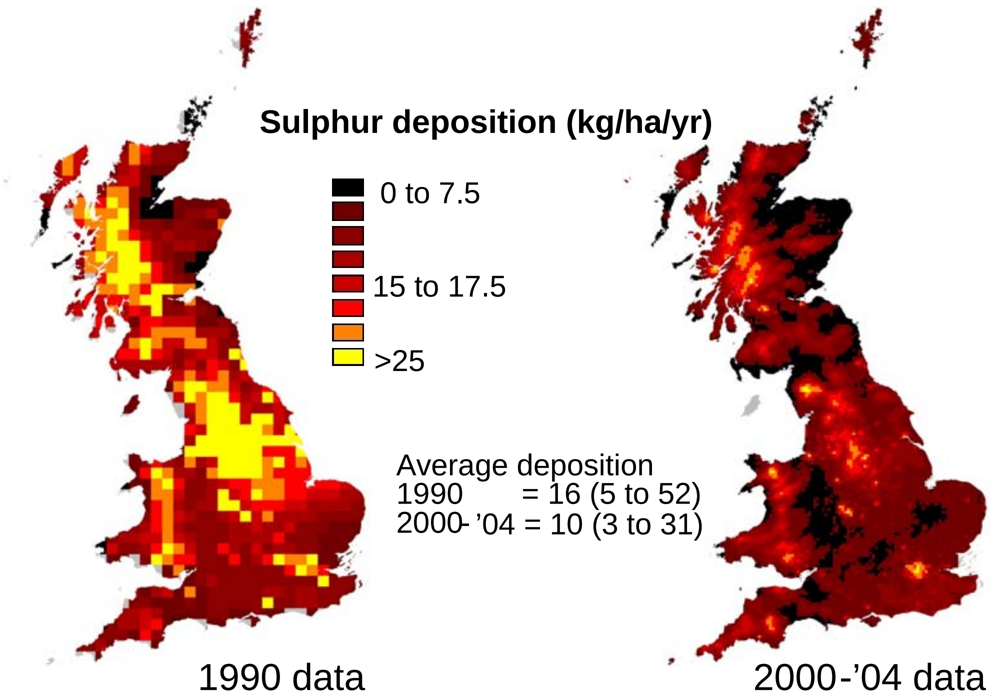

Figure 1: Changes in sulphur deposition from 1990 to 2004. See text for description of data sources.

Initially the model was revised only on the basis of updated information in the underlying databases (rainfall and sulphur deposition). Figure 2 shows estimates of yield responsiveness to sulphur fertilisers in cereal crops mapped across the UK land area. Table 1 provides a breakdown of the relative proportion on the land area assessed (England, Wales and Scotland) that are in each broad category of responsiveness. Where cereal crops are grown on land sited in the highest responsiveness category, yield response to sulphur applications is likely. Sulphur responsiveness is considered possible for crops growth on land placed in the intermediate category. A complete description of the development of these categories is given in McGrath & Zhao (1995).

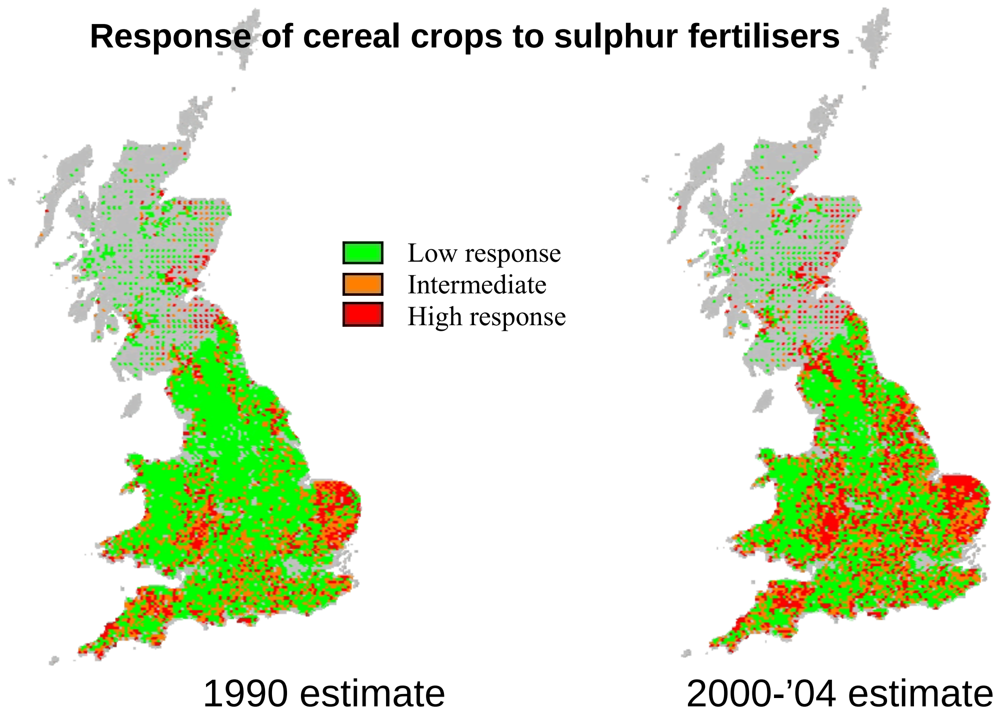

Figure 2: Estimates of the yield responses to sulphur fertilisers for cereal crops grown across the UK land area.

Over the period 1990 to 2000-2004 the percentage of the land area most responsive to sulphur application has almost doubled: from 12% to 23%. If high and intermediate areas are combined the figure has risen from 33% to 47%. This rise is entirely a result of the changes in sulphur deposition observed between 1990 and 2000-2004.

Table 1: The percentage of the UK land area estimated to be in three categories of responsiveness to sulphur fertilisation in cereals crops grown there.

	1990	2000-2004
Low response	67	52
Intermediate response	21	25
High response	12	23

1.2 Revised model to account for land use distribution.

From the maps of sulphur responsiveness (Figure 2) there is a suggestion that these estimates may under-emphasize the true level of crop yield responsiveness to sulphur. This is because the previous model of McGrath & Zhao (1995) estimated the status of the entire land area whereas only certain areas of the country are predominantly used for arable agriculture. There are large area of ‘low’ responsiveness to sulphur fertilisers in Wales, Northern England and Scotland where there is relatively little arable agriculture.

The existing model was modified to take into account the distribution of land use by incorporating an additional source of data made available as a result of the Countryside Survey 2000 (Haines-Young et al. 2000). Figure 3 shows the distribution of arable agricultural land use across the UK. Complete details of the methodology used and downloadable datasets for the distribution of land use across the UK (the Land Cover Map 2000) are available from http://www.cs2000.org.uk/. Data from this source are provided at a resolution of 1 km x 1 km. These data were aggregated to the 5 km x 5 km grid used for the assessment model.

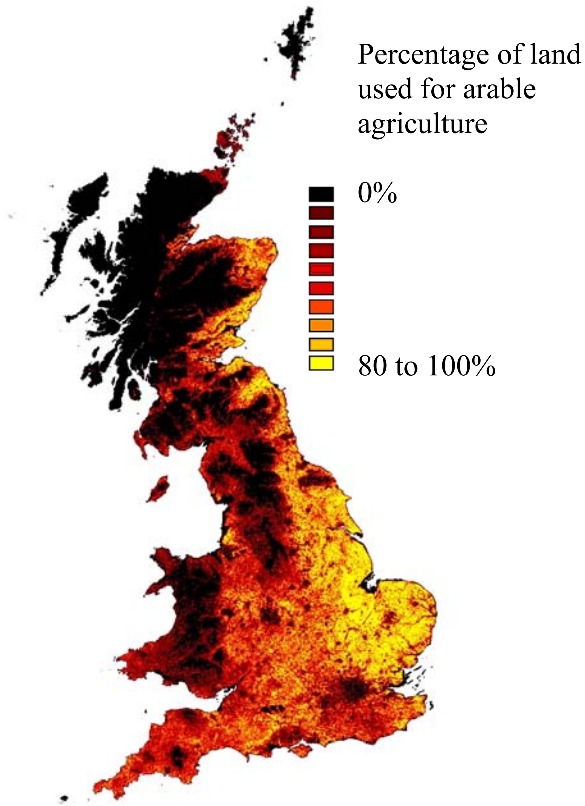

Figure 3: The distribution of arable land across England, Wales and Scotland (see text for description of the source of the data).

Table 2 gives the percentage of arable land in each of three responsiveness categories in cereal crops. When only arable land, rather than the whole land area, is accounted for, the percentage of land in high responsiveness category rises from 23% to 30%.

Table 2: The percentage of arable land estimated to be in three categories of yield response to sulphur fertilisers in cereals crops grown there.

	1990	2000-2004
Low response	59	40
Intermediate response	25	30
High response	16	30

1.3 Discussion

Updating of the original national status model reveals the extent to which decreasing atmospheric sulphur deposition has increased the area of cereal crops that is likely to respond to sulphur fertilisers. By accounting for the distribution of arable land use a better estimate of the percentage of cereal production is likely to respond to sulphur fertilisers. The status model integrates information about rainfall, soil type and sulphur deposition, thus the estimates of 30% of cereal production being highly responsive and a further 30% responding to a lesser extend provides a good baseline figure for the national status. The variability in responsiveness to sulphur fertilisers that the model predicts, with an estimated 40% likely to show little or yield response to sulphur fertilisers, while 30% is predicted to show high levels of response reinforces the need for decision support to help target sulphur fertiliser usage.

2. Review of experimental datasets

Initially a collection of 204 available field trials was collated; these included field trials on spring barley (24), winter barley (35) and winter wheat (123). A number of these field trials were excluded from the analysis based on a number of criteria (see Section 2.1). All results and calculations presented here are based on the results of the remaining field trials.

2.1 Criteria for selection of field trials data

A set of criteria were created to select field trial data appropriate for this analysis and any datasets that did not meet the criteria A-D below were excluded from the analysis.

<u>A. Field trials harvested in the period 2000 to 2005.</u>

Since 2000 sulphur emissions from the UK and the rate of atmospheric sulphur depositions have largely stabilised. In the period prior to 2000 sulphur emission and deposition had been in rapid decline. Figure 4 illustrates this trend and shows how the changing rate of sulphur deposition (data on long term trends in emissions and deposition are available in Bower et al. 2005) was associated with changes in the yield response to sulphur fertilisers observed in field trials. Data from field trials after 2000 form the bulk of the available data; by restricting the dataset in this way, any changes that are associated with rapid declines in SO_2 emissions and hence sulphur deposition can be discounted. In addition, since sulphur deposition and SO_2 emissions appear to have stabilised at the post-2000 level, any results and conclusions drawn will be most relevant to farmer decision making in the near future.

<u>B. Discount data where foliar applications of sulphur were used.</u>

Previous experimental work by Rothamsted Research has shown that while late (applied at GS61 of the crop or later) foliar applications of sulphur can be useful for boosting grain sulphur concentrations, such applications did not reliably prevent loss of crop yield . Where field trials only contained foliar applications the whole field trial was excluded. Where field trials used other forms of sulphur then those treatments were included.

C. Discount field trials without effective (zero sulphur treatment) controls.

The available field trials included some that had not been designed to test for significant crop yield responses to sulphur fertiliser applications. Although sulphur was applied in these cases, no exactly comparable 'control' treatment was included in the design of the field trial.

D. Discount field trials where yield in control plots (-S treatment) were less than 3 t/ha.

Field trials with average yield in the control treatment less than 3t/ha were considered to be unrepresentative of winter wheat production in the UK. Such trials were excluded from the analysis.

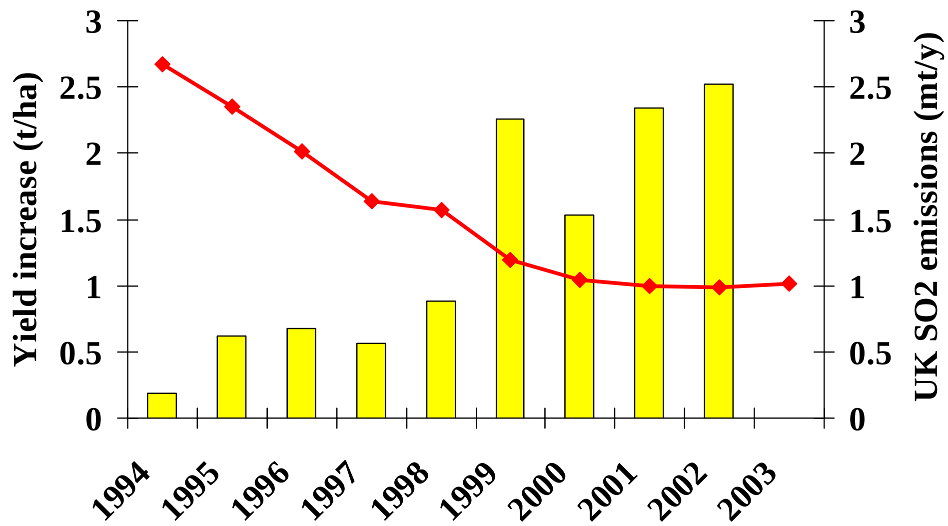

Figure 4: Yield responses over time of winter wheat grown at Rothamsted's farm at Woburn. Decreasing SO_2 emissions are associated with increasing yield response to sulphur fertiliser. The line indicates UK SO_2 emissions (million tonnes per year). The bars indicate the recorded yield response to sulphur application.

2.2 Summary of datasets and overall response to sulphur fertilisers

Table 3 shows a summary of the field trial data collated for this project following the above screening process. The 88 winter wheat trials (from 21 different trials sites – see Figure 5) provide the bulk of the data and these were used in the analysis of factors that influence yield response. The combined dataset for spring barley and winter barley was considerably smaller, and an initial examination revealed that many more of these trials could not be used for a complete analysis of factors influencing yield response. This limited number of field trials together with the fact that the available data indicated that barley crops show a lesser response to sulphur application meant that the complete analysis was confined to the larger winter wheat field trials dataset. Data for winter barley and spring barley are for reference only and were not subject to the same screening process, neither were they included in the analysis presented in Section 2 and Section 3.

Table 3: Summary of overall crop yield responses observed in collated datasets.

	Number of trials	Average Yield response	Range of yield responses
Spring Barley	20	4%	-21% to + 26%
Winter Barley	33	3%	-4% to + 23%
Winter Wheat	88	6%	-8% to +113%

2.3 Detailed summary of winter wheat trial database

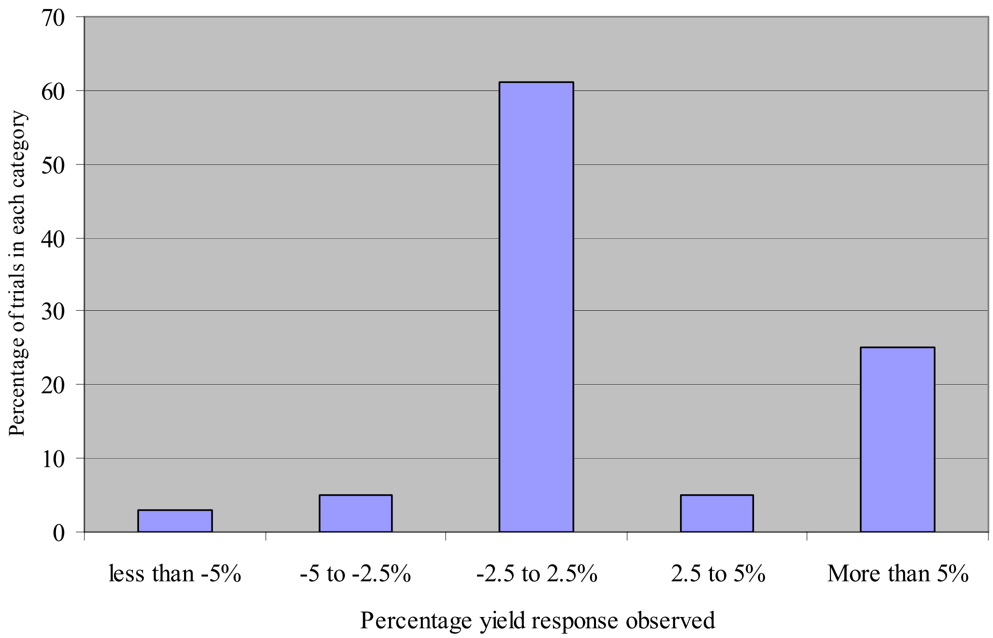

Figure 5: The frequency distribution of crop yield responses observed in the database of selected field trials.

A detailed breakdown of the frequency distribution of crop yield responses observed highlights the potentially misleading nature of average response over all the field trials (Table 3). The average figure of 6% yield response to sulphur application disguises the fact there is a sub-set of the field trials where responses were very large. Figure 5 shows the percentage of field trials falling into different categories of responsiveness to sulphur fertiliser application. The dataset exhibits a characteristic 'skewed' distribution. Although two thirds of trials showed little or no yield response to sulphur fertiliser application, in the remaining field trials where responses were observed they were consistently large. To illustrate this point, although the overall average yield response for all winter wheat trials was just 6% (i.e. including non-responsive and "negative" trials), but when only the field trials in the category of 'greater than 5% yield response' are considered the average response is 27%.

Of the 88 field trials 23 showed a significant and positive response to sulphur fertilisers and in addition 2 field trials showed a significant and negative yield response. There is no clear reason for the negative yield responses. However, this number of statistically significant negative results is not unexpected because statistically one might expect 2.2 out of 88 field trials to indicate a 'false negative' result by chance at the 5% probability level, given the two sided nature of parametric statistics used to make the comparisons. In contrast, the number of significant positive response (n=23) was much larger than the chance number of 2.2.

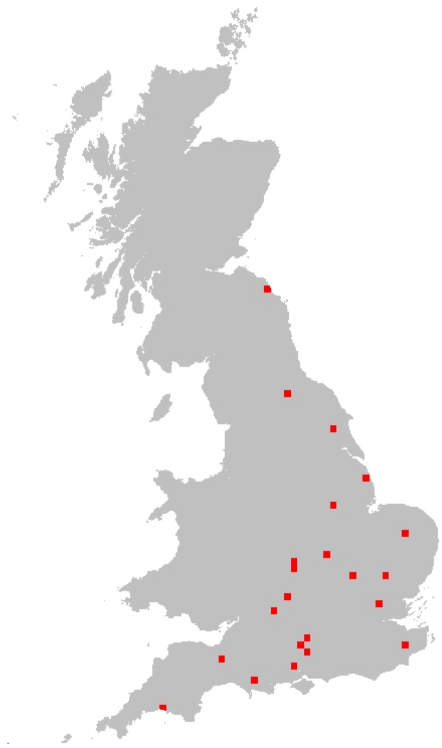

Figure 6: Locations of field trial sites.

These 88 field trials were located at 21 sites in England (see Figure 6). One of the difficulties of any analysis of this nature, conducted on a collation of existing experimental datasets, is that different numbers of field trials were conducted at each of the sites and in each of the years. Table 4 summarises the years in which field trials were conducted at each of the 21 sites. For reference, the average yield response observed across all sites in each year and the average across all years at each field trial site are both provided. However, because the trials were not performed systematically at all sites and years, direct comparison of yield responses between sites or years is not recommended.

Table 4: List of field trials sites and the number of field trials datasets collated for each site for the period 2000 to 2005.

SITE NAME	2000	2001	2002	2003	2004	2005	TOTAL	Average Yield response
Trerulefoot					1	1	2	-1%
Taunton			1	1	1	1	4	-1%
Kingston Maurwart			1				1	-4%
Berwick-upon-tweed			1		1	1	3	-2%
Cirencester	2	1	3	2	2	3	13	2%
Burford			1	2			3	12%
Croft-on-tees			2	1	1	1	5	2%
Wimbourne	1		1	1	1	1	5	4%
Warwick			2	1	1		4	2%
Tufton					1	1	2	17%
ADAS Bridgets		1					1	6%
Basingstoke LNF				2			2	19%
Kettering				2	1		3	-1%
Caythorpe		1	1	1	1	3	7	-1%
Bainton		1	1	2	2	1	7	2%
Biggleswade				2			2	0%
Great Carlton		1	2	3	2	3	11	0%
Chelmsford						1	1	-2%
Woburn	2	2	2				6	59%
Morley				1		2	3	0%
Wye	1		1		1		3	-1%
TOTAL	6	7	19	21	16	19	88	
Average yield response	7%	27%	8%	4%	4%	-1%		

2.4 Treatment factors contained within winter wheat trials database

The database of winter wheat trials that was created contained a large number of experiments that had been designed and carried out for different reasons. Each experiment within the database contained at least one simple comparison of a zero rate of sulphur application (control treatment) in contrast to a sulphur application rate of between 4.4 and 228 kg S/ha. Late (at GS61 or later) applications of sulphur fertilisers were excluded and in the rest of the trials sulphur was applied during the spring at the same time as the nitrogen fertiliser application (between early March and late April). The majority of the experiments also contained a comparison of additional agronomic factors such as crop cultivar and/or form of sulphur fertiliser. The statistical design of the experiments was relatively consistent. All field trials used a randomized block design and the number of blocks for all but a single experiment was either 3 or 4 (the majority used 3 replicates or blocks). One single experiment contained 2 replicates.

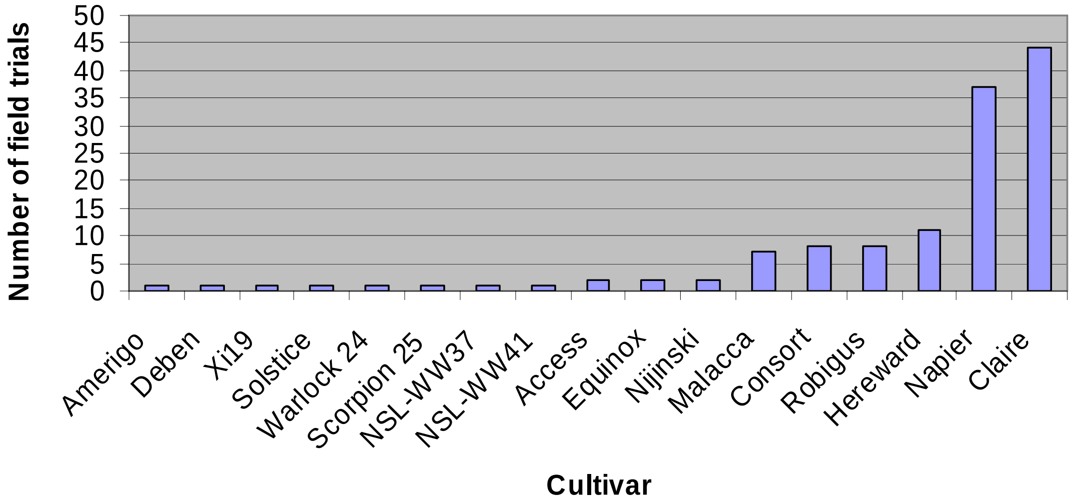

Figure 7: The winter wheat cultivars present in the database of 88 field trials and the number of field trials in which each was used.

Figure 7 shows the range of winter wheat cultivars that were used in the field trials and the number of field trials in which each cultivar was used. Similarly, Figure 8 shows the forms of sulphur that were used in the field trials and the number of field trials in which each was used. These figures give the number of trials (of the 88 used for the analysis) where different cultivars and sulphur fertilisers were used, however; since a large number of trials contained more than one cultivar and/or sulphur fertiliser treatment the total number obtained by summing each treatment from the graphs is more than 88. It is clear that the cultivars Napier and Claire predominate, as does the use of "Double Top" as the source of sulphur. These two facts rule out direct comparisons of the performance of particular cultivars or forms of sulphur fertiliser.

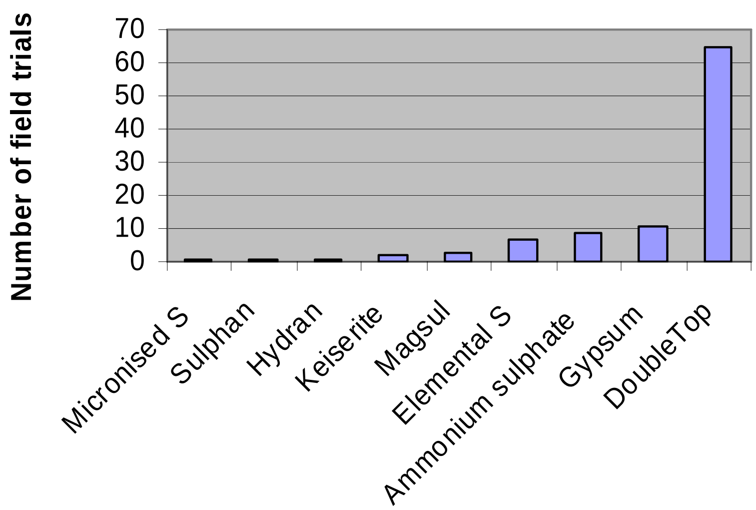

Figure 8: The forms of sulphur fertiliser used in the database of 88 field trials and the number of field trials in which each was used.

2.5 Discussion

The percentage of winter wheat field trials which responded significantly and positively to sulphur fertiliser applications was 26% (Figure 5). This value is similar to the estimate of 30% of cereal crops being highly responsive that was given by the updated national status model (Table 2). The agreement of these two approaches reinforces the value of using a figure of 30% as a realistic estimate of the percentage of winter wheat crops likely to respond significantly to sulphur fertilisers in the UK.

The dataset exhibits a very characteristic statistically skewed distribution of responses and this must lead to caution when interpreting any average values. While the overall average of yield response was only 6%, most of this response is driven by much higher levels of response in a subset of the data (the 26% of trials where yield responses were significant and positive). The nature of the database of field trials collated from previous studies makes it difficult to carry out a simple comparison of means between factors such as cultivar and form of sulphur fertiliser. Table 4 shows how non-systematic the coverage of field trials over sites and years is. Because of this unevenness, means of experimental factors cannot be directly compared. One example is the average yield response observed for the Hereward cultivar of 24% (compared to the overall average of 6%). One might conclude that this cultivar is particularly responsive to sulphur. In fact, the average is elevated because this cultivar was used (but not exclusively) in the four most responsive field trials within the database, all undertaken at a single site (Woburn) with particularly light soil.

As discussed in the following Section, any analysis of the factors that drive crop yield response to sulphur must attempt to account for the non-orthogonal nature of the matrix of sites and years. Such an analysis, described in the next section, is made possible only by the collation of such a large database that contains a large number of comparisons between plus and minus sulphur plots.

3. Analysis of factors influencing crop yield response.

Because of the nature of the dataset where sites and years are not systematically organised and where there are different treatments within individual field trials, an ANOVA approach is not possible. Therefore, a regression approach was adopted to describe the influences of site factors. There are clear indications of complex interactions between numbers of factors both experimental treatments and site factors such as rainfall and soil type. Because of this, a multivariate regression approach has been adopted (McCullagh & Nelder 1989). A statistical model was constructed which describes the influence of individual factors, and the interactions between factors, on the crop yield response observed. To maximise the use of the data available, the analysis was carried out using all the individual plot values; in this way large experiments with high levels of replication and low standard errors are given more weight than smaller experiment and/or those with higher standard errors. Within the combined dataset of 88 field trials there were 1282 individual data values of which 509 were from control (zero sulphur applied) plots.

3.1 Estimation of site factors

In addition to the experimental data collated in Section 2, the levels of site factors (over-winter rainfall and atmospheric sulphur deposition) acting on each of the field trials were estimated.

Atmospheric sulphur deposition was estimated from the dataset of average deposition from 2000 to 2004 shown in Figure 1. Atmospheric sulphur deposition levels occurring in the database of field trials sites ranged from 6.7 to 13.1 kg S/ha/year (Figure 9). This range is much narrower than that observed over the whole of England, Scotland and Wales of 3 to 31 kg S/ha/year. The higher end of the range of sulphur depositions experienced within the UK is not represented within the dataset of field trials, and this may have implications for the analysis. However, it is worth emphasising that the range 6-13 kg S/ha/year is typical of that prevailing in the major rural wheat-growing areas.

The total over-winter rainfall for each field trial was estimated using a database obtained from the meteorological office (Perry & Hollis, 1980). Over-winter rainfall was calculated as the total of November, December, January and February monthly rainfall. The levels of over-winter rainfall estimated for the field trials within the dataset are shown in Figure 10.

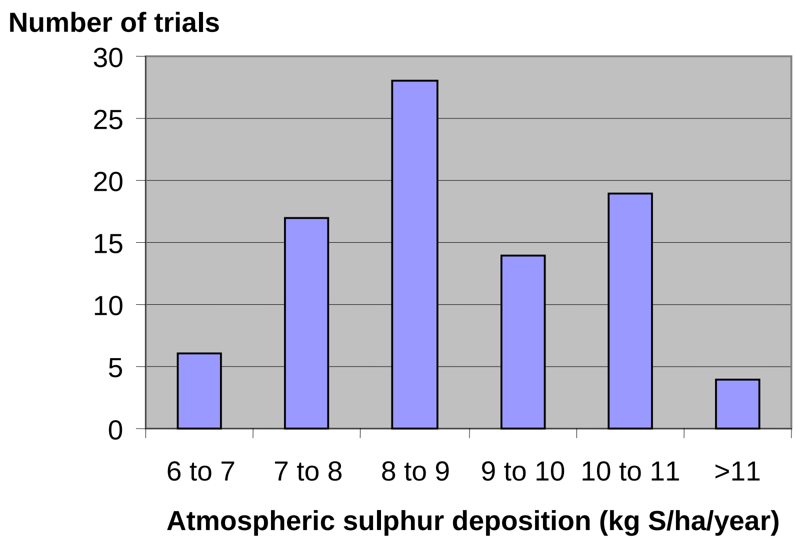

Figure 9: The distribution of atmospheric sulphur deposition estimated for the field trials in the database.

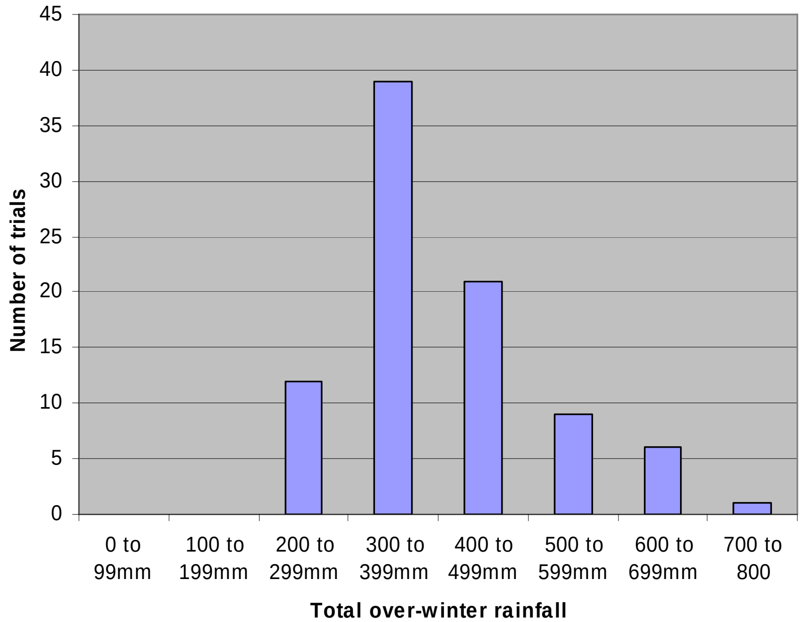

Figure 10: The distribution of total over-winter rainfall estimated for the field trials in the database.

3.2 Comparison of treatments within experiments

Crop yields were expressed as percentage yield response compared with the average value of the equivalent control (zero sulphur applied) plots. The field trials within the database each contain a number of treatments. The treatments included in the field trials were:

- Nitrogen rate (kg N/ha)
- Sulphur rate (kg S/ha)
- Crop cultivar
- Form of sulphur applied
- Timing of sulphur application

In order to undertake an analysis of the combined database of field trials the effect of these treatments must first be described and accounted for. The purpose of this initial analysis of experimental treatments is not to compare particular treatments or to illustrate their relative effects but rather to decide if they should be included or not in a fuller analysis of the external site factors that affect yield response to sulphur.

3.2.1 Application rates of nitrogen and sulphur fertilisers

The effect of the application rate of sulphur was statistically significant ($P<0.001$) and the percentage variance accounted for is 9.4%. There is no indication from the data that crop yield responses exhibit any kind of dose-response to increasing rates of sulphur fertiliser application. When the same regression analysis is repeated but with the control (0 kgS/ha) plots excluded the effect of sulphur rate (from 4.6 to 240 kg S/ha) on yield response is non-significant and there is no increase in yield response with increasing sulphur application rate (Figure 11). This is not surprising because cereals require relatively small amounts of sulphur (~20 kg S/ha).

The effect of the application rate of nitrogen was small but statistically significant (P<0.001). One might expect that higher nitrogen rates could be associated with a greater yield response to the application of sulphur, although the relationship is 'noisy' and the percentage variance accounted for by the model is only 5.4%. In fact this overall regression in isolation is not a good test of the importance of nitrogen rate in determining the response to sulphur fertilisers. Even though the motivation for the original experimental design was to test for responses to nitrogen, there are very few data points outside the range 200 to 250 kg N/ha, and the regression response is therefore highly weighted by a few data points.

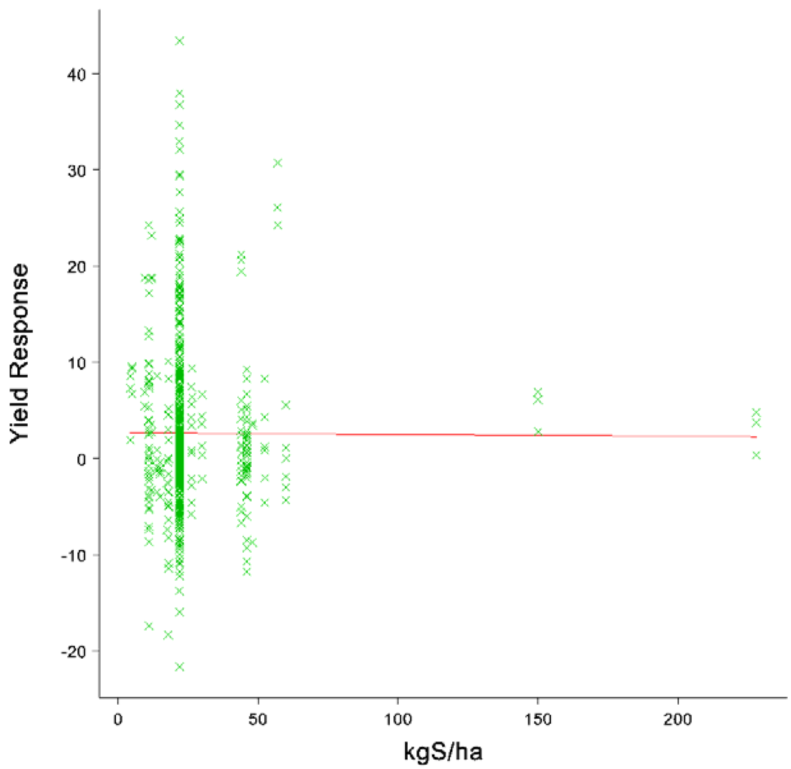

Figure 11: A regression plots of crop yield response against the dose of S applied (kg S/ha) across all 88 experiments. Crosses represent individual data points (plot values) and the line is the best regression fit. (n=641).

As the basis for a statistical model of the complete dataset a multiple regression of the effects of nitrogen and sulphur rates is presented in Table 5. From the regression coefficients it is possible to see the relative effects of nitrogen rate (response slope =0.015% per kg N/ha) and sulphur rate (response slope = 2.325% per kg S/ha) on crop yield response. Figure 12 shows observed versus expected values and the variability in crop yield responses when using this model which includes only experimental treatment factors.

Table 5: A multiple linear regression model to describe the effect of nitrogen and sulphur fertiliser on the crop yield response (percentage change compared to the equivalent control). The percentage variance accounted for by the complete model is 11%.

	slope	s.e.	t (n=1282)	t probability
S rate kg S/ha	2.325	0.187	12.46	<0.01
N rate kg N/ha	0.015	0.004	4.36	<0.001
S rate x N rate	-0.011	0.001	-11.42	<0.001

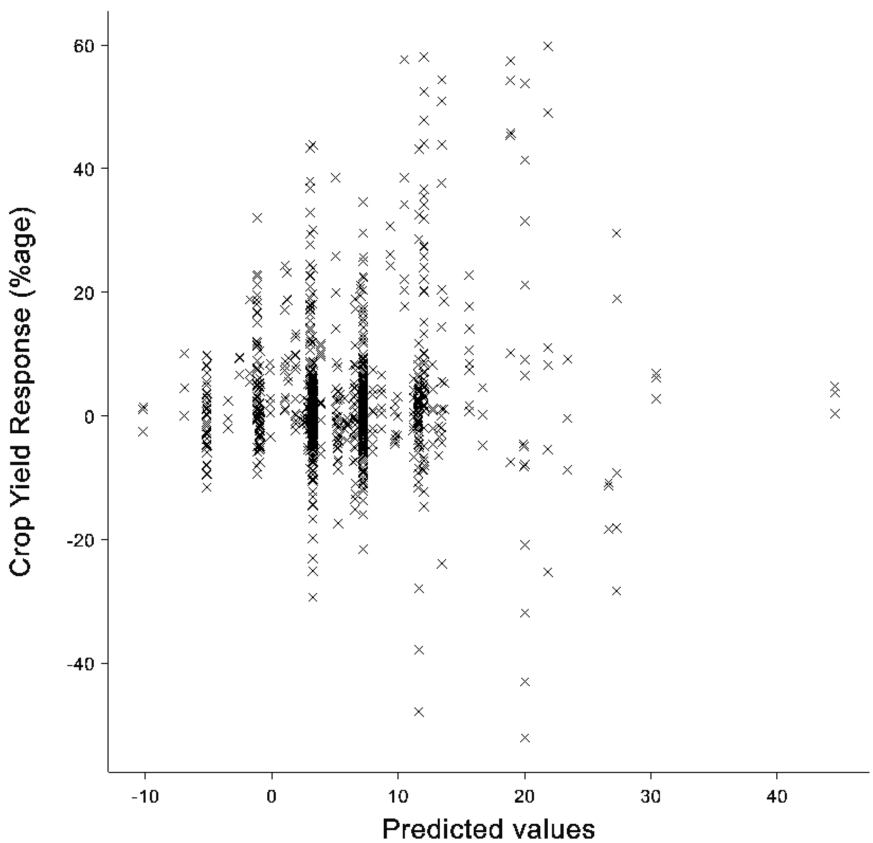

Figure 12: Plot of observed crop yield response (%) against predicted values for a linear regression model (Table 5) using only experimental treatments to describe the crop yield loss observed. The percentage variance accounted for by the model is 11%.

3.2.2 Crop cultivar

When a term for crop cultivar was added to the statistical model described in Table 5 there were indications that two cultivars had a statistically significant influence on the yield response to sulphur: cv. Amerigo (P=0.006) and cv. Nijinski (P=0.029). However, these cultivars were not representative of the database as a whole; Amergio was only present in a single field trials and Nijinski in two field trials (Figure 7). For the crop cultivars that are represented in larger numbers in the database (Claire P= 0.924, Napier P=0.431, Hereward P=0.434, Robigus P=0.099 & Malacca P=0.076) there was no statistically significant change in the yield response observed. Any statistical significance of particular cultivars that occur at such a low frequency in the dataset is considered to be an artefact of other factors influencing yield response at those particular sites. This emphasises the general point that one should not put much weight on replicate data for any small group of selected trial/site/variety results. It was concluded that overall the choice of crop cultivar had no apparent effect on the response of yield to sulphur.

3.2.3 Form of Sulphur applied and timing of application

The timing of application of the sulphur fertiliser had no effect on the crop yield response to sulphur. In the database of field trials the timing of application had been categorised depending on whether the sulphur was applied at the time of the first, second or third dose of nitrogen fertiliser. Adding a term for the timing of application to the model described in Table 5 gave no improvement in the fit of the model (percentage variance accounted for remained 11%) and none of the terms were statistically significant (T1 $P=0.730$, T2 $P=0.453$ & T3 $P=0.573$).

When a term for the form of sulphur applied was added to the model of crop yield response to sulphur application (given in Table 5) there was a significant improvement in regression model obtained. The percentage variance accounted for increased from 11% to 38.8%. When the fertiliser was applied as gypsum (used in 11 of the 88 trials) then the yield responses were significantly higher. However, on closer examination of the pattern of usage of gypsum in the database, it is clear that this significant response is most likely to be a result of its use for two series of experiments carried out at the Rothamsted's Woburn farm, which is a highly responsive site. It is therefore likely that the apparent effect of sulphur form is actually derived from an effect of this site.

3.3. Key factors driving crop yield responses to sulphur application

The model described in Table 5 provides a baseline for the analysis of the external influences that drive the crop yield response to sulphur fertiliser application. It is clear that across the dataset there are no clear driving factors that have been captured by the experimental treatments applied, apart from the application of sulphur fertiliser itself and an interaction with the rate of nitrogen fertiliser used. The message of the initial summary of the dataset (cf. Figure 5) that yield responses to sulphur fertiliser are very variable and not immediately predictable for individual field trials is reinforced. A simple statistical description of the complete dataset (based on some 1282 individual plots values) can only describe 11% of the variation in yield response observed on the basis of the rates of sulphur and nitrogen fertiliser applied.

In a further analysis of the dataset of compiled field trials, the role of site factors as opposed to experimental treatments in driving the crop yield response was explored. The site factors investigated include soil type, rainfall and sulphur deposition. In Section 3.3.1 the results of an analysis combining all the factors to describe yield response is presented; in Sections 3.3.2 to 3.3.4 the influence of individual site factors (rainfall, sulphur deposition and soil type) are explored independently.

3.3.1 A complete generalised linear model (GLM) to account for variability in the crop yield response to sulphur application.

A GLM regression model was created that described 64.8% of the variability in crop yield response to sulphur. The model combines the influence of 3 site factors;

Deposition – Total sulphur deposition kg S/ha/year (see Section 3.3.2)

Soil – The lightest soil category (1 – ‘sandy’) is distinguished from all other soil types combined (see Section 3.3.3).

Rainfall – Total over-winter rainfall (mm) is used (see Section 3.3.4)

Table 6 shows the statistics and parameter estimates of the minimal regression model after the effects of treatment factors have been accounted for. Figure 13 shows the relationship between observed data and values predicted from the model in Table 6. Because of the regression technique used it is not easy to directly interpret the parameter estimate from the model; for this reason Equation 1 explains how percentage yield response can be predicted from the three factors. The description of the dataset provided by this model of site factors is much greater than a similar regression model using only experimental treatment factors (Table 5 and Figure 12).

Table 6: Generalised linear model describing the influence of site factors of on the crop yield response to sulphur observed. Percentage variance accounted for is 64.8%. Parameter estimates for ‘other soils’ area relative to those estimated for light soils and cannot be used directly (refer to Equation 1).

	Parameter estimate	Standard error of parameter estimate	t statistic (n=766)	t probability
Light (Sandy) soils				
Constant	-3979.0	272.0	-14.64	<0.001
Rainfall	12.720	0.821	15.50	<0.001
Sulphur deposition	468.3	35.8	14.73	<0.001
Rainfall x Deposition	-1.466	0.094	-15.61	<0.001
Other soils				
Constant	3964.0	272	14.56	<0.001
Rainfall	-12.682	0.822	-15.43	<0.001
Sulphur deposition	-467.4	31.8	-14.96	<0.001
Rainfall * deposition	1.4649	0.0941	15.57	<0.001

It is clear that the model is made more complex by the number of significant interaction terms. The term for soil category interacts strongly with the influence of both rainfall and sulphur deposition. Figure 14 shows the relationships between total over-winter rainfall and crop yield response for the categories of soil texture other than sandy.

In Sandy Soils:
Yield response = -3979 + 12.7xRainfall + 468.3xDeposition – 1.466xRainfallxDeposition

In all other soils:
Yield Response = -15 + 0.04xRainfall - 0.9xDeposition + 0.0011xRainfallxDeposition

Equation 1: A statistical model to predict percentage yield response from over-winter rainfall (mm) and sulphur deposition (kg S/ha/year).

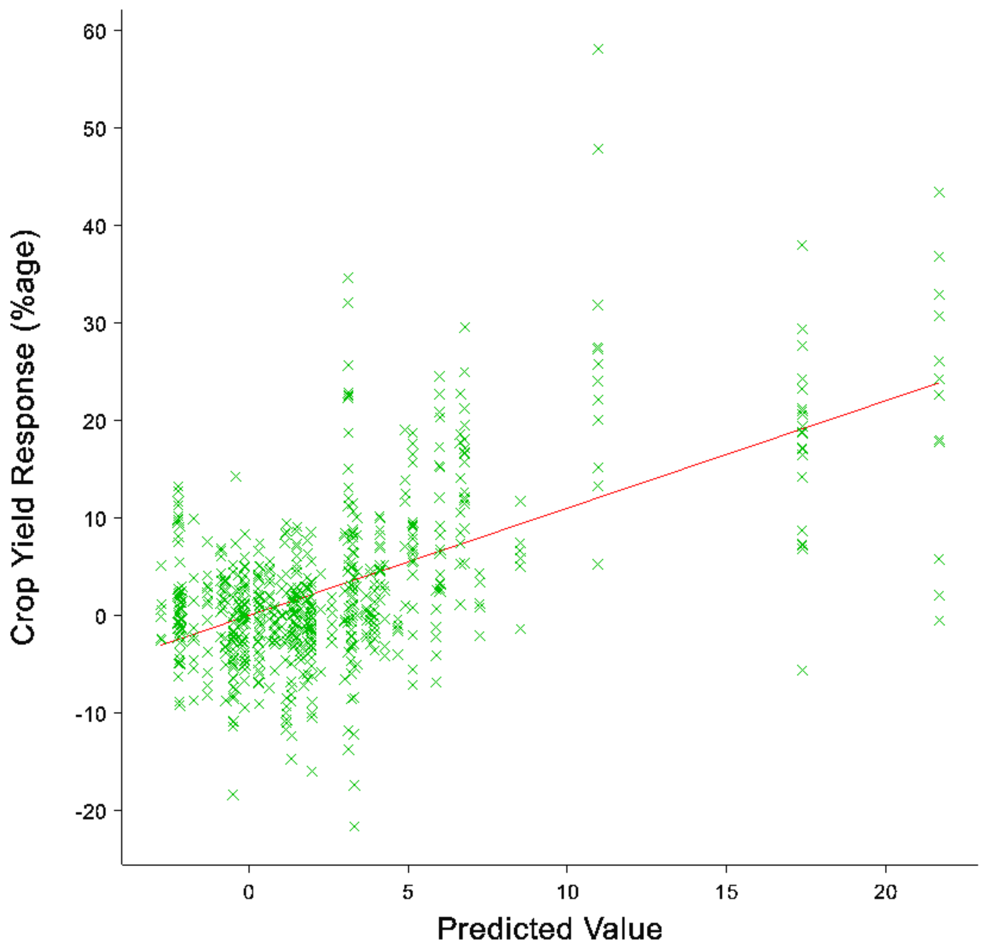

Figure 13: Plot of observed crop yield response against predicted values for GLM model in Table 6. The percentage variance accounted for by the model is 64.8%.

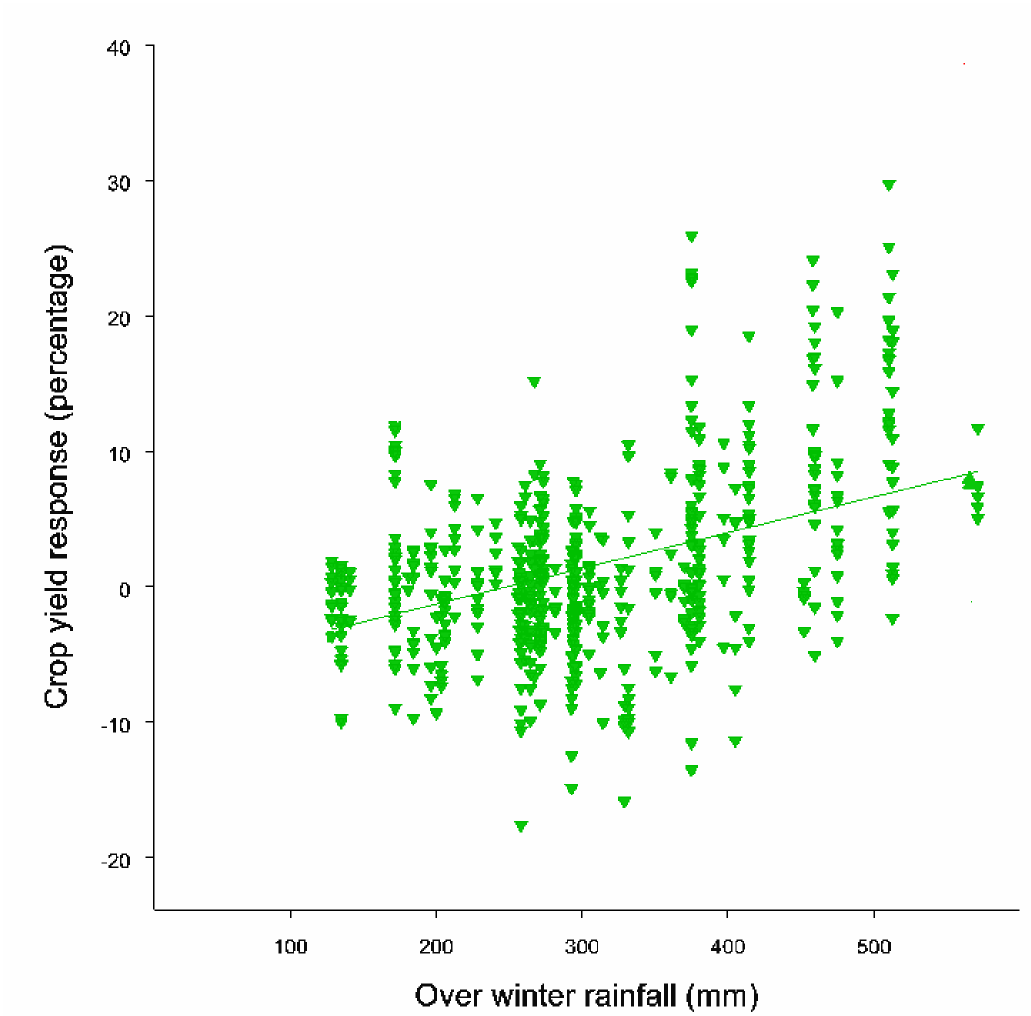

Figure 14: The influence of over-winter rainfall on crop yield response on non-sandy soils. Green triangles are individual plot data points and the line is the predicted values from the models described in Table 6.

3.3.2 Sulphur deposition

When a regression of estimated sulphur deposition against crop yield response over all trials and treatments was carried out the correlation proved significant. The overall relationship between sulphur deposition and yield response was as we would expect, higher yield responses were observed where sulphur deposition was lower. Although a simple regression of sulphur deposition against yield response was highly significant ($P < 0.001$), the percentage of the variance in the dataset accounted for by such a model (irrespective of other treatment and external factors) was just 1.2%.

3.3.3 Soil type

A description of soil type was available for all the farm locations at which each field trial was sited which enabled the soil to be allocated to one of 7 soil texture classes (see Table 7). For a sub-set of field trials more detailed soil records (including some soil analyses) were available for the specific field trial, but the number was insufficient to allow a full analysis of other more detailed soil characteristics to be carried out in parallel. Figure 15 shows the number of individual field trials in each soil texture group (numbered 1 to 7). There were no examples of ‘Peaty’ soils within the dataset.

Table 7: Groups and classes of soil texture. Adapted from Avery and Bascombe (1974).

Assigned code	Texture group	Class
1	Sandy	Coarse sand, loamy coarse sand, medium sand, loamy medium sand, fine sand, loamy fine sand
2	Coarse loamy	Sandy loam, sandy silt loam
3	Fine loamy	Sandy clay loam, clay loam
4	Coarse silty	Silt loam
5	Fine silty	Silty clay loam
6	Clayey	Sandy clay, silty clay, clay
7	Peaty	Peaty

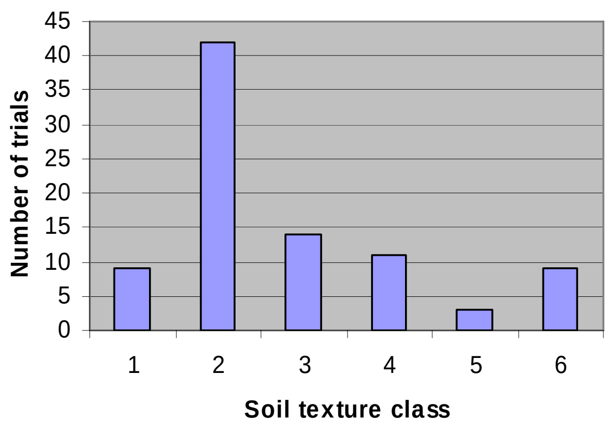

Figure 15: The number of field trials with different soil texture classes. (Refer to Table 7 for details of how the classes are derived).

The influence of soil type was statistically significant ($P<0.001$). This was tested by combining the model presented in Table 5 with a term for soil texture class. The percentage variance accounted by this more complex model for rose from 11.1% to 35.8%. Figure 16 shows the average crop yield response (irrespective of other treatment and external factors) observed for each of the 6 soil classes. In fact only the lightest soil texture group differed significantly from the other soil types and there was as much explanatory power from sub-dividing the soil types into class 1 (the sandy soils) and all the other soil types combined (classes 2 to 6). A model sub-dividing the sites into the lightest soil texture class (class 1: sandy soils) and other soils (all other classes) gave a percentage variance accounted for of 35.7%. Sub-dividing the dataset into these two categories (sandy soils and others) provides further evidence of the impact of sandy soils on the yield response to sulphur observed. A simple t-test comparing the average yield response on sandy soils compared to the average response on other soils was highly significant (P<0.001).

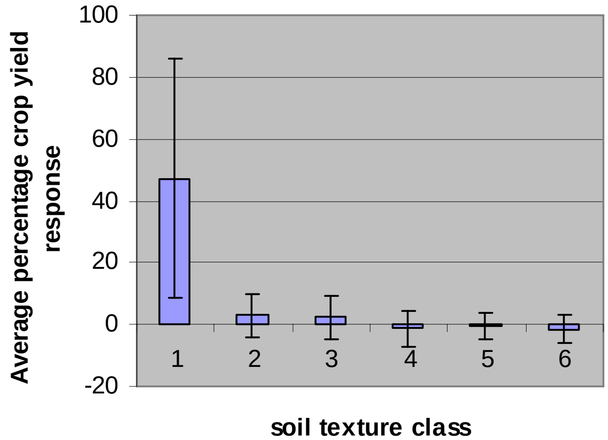

Figure 16: The average percentage yield response observed for data obtained from 6 different soil texture classes. Error bars are standard deviation of the mean.

3.3.4 Over-winter rainfall

The original national status model of McGrath & Zhao (1995) used a value for total annual rainfall to estimate the risk of leaching sulphur from the soil. A number of approaches to describing the rainfall that occurred at each site were explored as part of the present project. It was concluded that the most appropriate variable was over-winter rainfall (sum of November to February). A regression of total over-winter rainfall and yield response provides an explanation of 33.6% variation in the data. The statistics and parameter estimates for this regression are given in Table 8. It is clear from this analysis how significant the interaction between soil type and rainfall appears. The relationship between rainfall and yield response is positive (higher rainfall results in higher yield response) in all soil types apart of the lightest sandy soil (category 1).

Table 8: A simple linear regression model to describe the effect of estimated over-winter rainfall on the crop yield response (% change compared to the equivalent control). The percentage variance accounted for by the complete model is 33.6%.

	Parameter estimate	Standard error of parameter estimate	t statistic	t probability
Light (sandy) soils				
Constant	47.11	2.86	16.46	<.001
Rainfall	-0.04337	0.00789	-5.50	<.001
Other Soils				
Constant	-50.55	3.30	-15.32	<.001
Rainfall	0.05766	0.00937	6.15	<.001

3.4 Discussion

Individual field experiments show a very variable response to the application of sulphur fertilisers. This variability was not as a result of differences in experimental design or of the treatments applied. Section 3.2 illustrates that the best statistical model of the combined dataset for all 88 trials (some 1282 individual plot values) can only explain 11% of the variation observed in the yield response on the basis of experimental treatments. This finding reinforces the view that yield responses of winter wheat to sulphur is dependent more on the site factors (soil type, rainfall, sulphur deposition, etc) than on the experimental factors (nitrogen or sulphur rates, form and timing of sulphur fertilisers).

The variability in crop yield responses observed can be largely explained by a model that includes the influences of site factors including over-winter rainfall, sulphur deposition and soil type. When these factors are considered individually they have some explanatory power. Sulphur deposition provides the least explanation of variation in yield response whereas a model that includes either soil type or over-winter rainfall provides better descriptions (increasing the percentage variance accounted for to 35.7% and 33.6% respectively). Only a regression model that accounts for all the factors and their interactions provides an effective description of this dataset, with 64.8% of the variance accounted for (Table 6).

The analysis confirms that some agronomic factors such as crop cultivar and sulphur application date (with the same, appropriate windows as nitrogen fertiliser application) are not important when compared with the influence of site factors. The significance of all three site factors is an important finding and confirms the predictions of previous work. However, the relative contribution of these three factors does differ somewhat from previous findings (McGrath and Zhao, 1995). The influence of sulphur deposition is now found to be less important than that of soil type and winter rainfall. This is likely to be due to a combination of decreased overall sulphur deposition coupled with the relatively small range of deposition rates now experienced in rural areas of the UK (Figure 1 and Figure 9).

The contribution of soil type seems pre-eminent but in fact only the very lightest soils are clearly distinguished from the range of other soil types observed. There is a trend of smaller yield responses with increasingly heavy soil textures but it is much less marked. The influence of rainfall is significant but there is an important interaction with soil type. It is only on soil types other than the lightest (sandy) that the tendency for higher over-winter rainfall to result in increased yield responses to sulphur application shows clearly (Figure 14). This is thought to be due to increased leaching of sulphate. On sandy soils, the relationship with over-winter rainfall is not seen, as these soils are so easily leached, and have small sulphur reserves and are therefore intrinsically responsive.

Using this non-systematic set of field trials we were not able to test the influence of other key agronomic factors that could potentially influence crop yield response, namely previous cropping and manuring history. There were not enough field trials where the cropping history and manuring history were available in enough detail. Agronomic factors such as these are best explored using targeted field experimentation rather than a meta-analysis of existing field trials.

4. Development of decision support framework

Using the analysis presented in Section 3 as a basis we have created a simple matrix system to estimate the responsiveness of individual wheat crops to sulphur fertiliser. The analysis presented in Section 3 provides an important guide in the creation of a decision support framework. It is not appropriate however to adopt the precise quantitative relationships revealed in the regression analysis. The dataset on which it is based is not systematic across sites and years and the coverage of the full range of site factors is not exhaustive.

Using the analysis in Section 3 together with previous work on the creation of a model to estimate the national status (McGrath & Zhao 1995) of sulphur responsiveness in cereals, we have devised a simple matrix system to help growers and their advisors to understand the potential yield responsiveness to sulphur fertilisers which they might experience.

4.1 Categorisation of site factors influencing yield response

Each of the three site factors was categorised to simplify the creation of a decision support framework and to allow a simple matrix to be created where the likely responsiveness can be looked up for individual situations. The categories were developed on the basis of the analysis carried out in Section 3 but also guided both by expert opinion and previous studies on the sulphur nutrition of cereal crops.

1. Soil type

The analysis has demonstrated the need to consider sandy soils in a separate distinct category to all other soil texture types. A further separation is made between Medium and Heavy soils on the basis of the trend observed in the analysis of lower yield response in heavier soils (Figure 16). The division between clay and other soils is made on the basis of previous expert knowledge of the characteristics of soils in these two categories. Refer to Table 7 for more detail of the soil categories (numbered 1 to 7).

- Sandy: Sandy soils (category 1)
- Medium: Loamy and coarse silty soils (category 2, 3 & 4)
- Heavy: Clayey and fine silty soils (category 5 & 6 – includes peaty soils 7)

2. Over-winter rainfall

- Low: Less than 175mm
- Medium: 175mm to 375mm
- High: More than 375mm

3. Sulphur deposition

Reflecting the findings of the analysis, very little account was taken of the estimated sulphur deposition in constructing the matrix. However, some account was taken of situations where high deposition rates might be experienced. Although not within the range of sulphur depositions within the dataset (Figure 9), a rate of 15 kg S/ha/year was included as a cut-off. This value is based on our knowledge of the sulphur requirement of wheat.

- Low: Less than 15kg S/ha/year
- High: More than 15kg S/ha/year

4.2 Matrix system to estimate yield responsiveness

The categories created above give rise to a 3 x 3 x 2 matrix (soil type x over-winter rainfall x sulphur deposition). The likely crop responsiveness to sulphur for each cell of the matrix was estimated using three broad categories (High, Intermediate and Low). These estimates are based on the findings of our analysis. For example, crops grown on sandy soils were demonstrated to be highly responsive in all situations.

Table 9: A simple matrix system to estimate the likely responsiveness of wheat crops to sulphur fertilisers.

a) High sulphur deposition sites (≥15 kg S/ha/year)				
		Over-winter Rainfall		
	Soil texture	Low	Medium	High
	Sandy	High	High	High
	Loamy and coarse silty	Low	Intermediate	Intermediate
	Clay, fine silty or peaty	Low	Low	Low
b) Low sulphur deposition sites (<15kg S/ha/year)				
		Over-winter Rainfall		
	Soil texture	Low	Medium	High
	Sandy	High	High	High
	Loamy and coarse silty	Low	High	High
	Clay, fine silty or peaty	Low	Low	Intermediate

4.3 Revised national status maps

By using the matrix presented in Table combined with the databases of soil type, rainfall and sulphur deposition collated in Section 1.1 an updated model of the national status was created (Figure 17). This revised model updates and improves the estimates presented in McGrath and Zhao (1995) by including the findings of this recent analysis. The percentage of arable land in each of the broad risk categories estimated in this way provides an evaluation of the appropriateness of the decision matrix created. Table 7 presents the percentage of arable land that is predicted to be in three broad categories of yield responsiveness to sulphur. In the revised model, 26% of arable land is estimated to be in the category of high responsiveness to sulphur. This percentage is the same as the percentage of winter wheat crops showing a significant and positive response to sulphur applications discussed in Section 2.

Table 7: The percentage of arable land estimated to be in three categories of crop yield response to sulphur fertilisers in cereals crops grown there.

	Revised status model	Original status model (see Section 1.1)
Low responsiveness	35	40
Intermediate responsiveness	39	30
High responsiveness	26	30

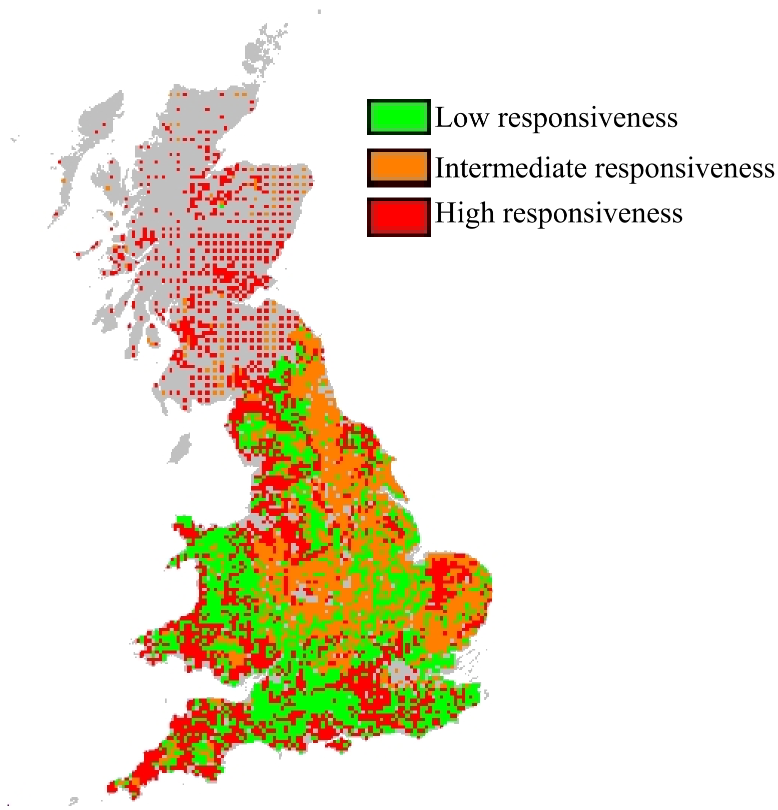

Figure 17: Estimates of the crop yield responses to sulphur fertilisers for cereal crops grown across the UK land area according to the new matrix system presented in Table 9.

4.4 Discussion

The matrix system presented is simple and captures our understanding of the key factors driving variation in crop responsiveness to sulphur. Over-winter rainfall and soil texture are variables that are both readily available to growers and advisors. Maps of sulphur deposition should allow growers and advisors to obtain information about the approximate sulphur deposition status of their local area, especially as they only have to define if they are in an area of particularly high deposition (>15 kg S/ha/year) or not.

Revision and refinement of the decision matrix system should be undertaken before it is disseminated to end-users. Perhaps the best approach to this would be by expert review; experienced scientists, farmers and advisors providing feedback about the realism of the advice given by the matrix in specific cases and the overall level of responsiveness predicted. As with any decision support approach, the dissemination of the information will be the key to maximising its uptake. The dissemination is made easier by the flexibility of this approach. The matrix can be presented as a simple paper-based system (to include a map of estimated sulphur deposition) or developed into a step-by-step computer based application.

The revision of the national status model for sulphur response of cereal crops provides useful confirmation of the validity of the decision matrix system. The overall level of yield responsiveness predicted is appropriate and the regional distribution of responsive and non-responsive crops is in accord with our understanding of the current status. When referring to the national model findings presented as a map (Figure 17) it is important to be aware of its limitations. Although the model is based on a very large set of databases for soil types, rainfall and sulphur deposition, it must be remembered that each data point on the map is 5 km x 5 km, within which substantial variation in soil properties is expected. For this reason the map is not intended to be used by growers or advisors to make decision about individual field, rather it provides a much larger scale overview of the national and regional status of crop responsiveness to sulphur, and the matrix is more appropriate to use when making local decisions.

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APPENDIX 1: Crop values, growing areas and other prices used in calculations in this report.

	Value used	Source
Average wheat yield	8 t/ha	1
Wheat grain price	£100/t	2
UK Wheat production area	1,868,300 ha	1
UK Cereal production area	2,924,800 ha	1
Cost of S as "Double Top"	£150/t	3
Cost of S application	£10/ha for 20 kg S	4

1. Defra statistics – http://statistics.defra.gov.uk/esg/
2. Current market price at time of writing
3. Information supplied by local distributor
4. Calculated from cost of "Double Top" and offsetting difference with normal nitrogen application costs.