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Optimising sulphur management to maximise oilseed rape yields and farm profitability (OPTI-S)

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1. Abstract

Sulphur (S) is an essential plant nutrient that has important effects on both the yield and quality of crops. The aim of this project was to develop improved guidance for farmers on S management.

(i) Optimum S rates for oilseed rape

Sulphur response field experiments were carried out at ten sites cropped with winter oilseed rape over four harvest years (2014 to 2017). Data from a further eight S response experiments carried out between 2011 and 2013 are included in the data set giving a total of 18 site years of data collected between 2011 and 2017. Ten of the eighteen S response experiments showed a yield response to S fertiliser of between 0.1 and 4.4 t/ha and economic optimum S rates at these sites varied between 30 and 79 kg SO_3/ha. There was no relationship between the optimum S rate and yield at the optimum rate and therefore no evidence to suggest that higher yielding oilseed rape required higher fertiliser S rates. The optimum S rate was insensitive to typical changes in fertiliser and crop price.

Leaf tissue testing for malate: sulphate, S content and N:S ratio and seed analysis for S and N:S ratio were able to identify differences between some, but not all, of the S sufficient/deficient sites. All of the ten sites which showed a yield response to S were light or medium textured i.e. loamy sand, sandy loam and sandy clay loam soils. Soil texture and over-winter rainfall was a better predictor of S deficiency than soil analysis or tissue testing.

At the majority of sites there was no effect of S fertiliser on seed oil or protein content. Sulphur fertiliser increased glucosinolate concentrations at eight of the ten S deficient sites, but had no effect on glucosinolate concentrations at any of the eight S sufficient sites and glucosinolate concentrations were below the current limit of 20 µg/g at all sites.

We recommend updating the guidance for S application to oilseed rape to include soil texture and winter rainfall in assessing the risk of S deficiency and increasing the current S recommendations to 50-80 kg SO_3/ha. The wording in the AHDB Sulphur information sheet should be revised to highlight potential uncertainly in diagnosing S deficiency based on visual symptoms and tissue analysis.

(ii) Sulphur supply from organic materials

At five of the S response field experiments additional organic material treatments were included to quantify the S supply from organic materials. Four of these sites showed a yield response to S fertiliser and a yield increase from the organic material treatments which indicates that organic materials supply crop available S that can contribute towards crop S fertiliser requirement. Based on the results of this project, we recommend updating the guidance on S availability from organic materials to increase the S use efficiency from autumn applications of organic materials (from 5-10% to 15% for livestock manures and from 10-20% to 25% for biosolids) to oilseed rape and grassland. This change reflects the S uptake by these crops in the period between application and the start of over-winter drainage (and subsequent reduction in S leaching losses). We also recommend

increasing the S use efficiency figures for spring applied slurry (from 35% to 45%) and biosolids (from 20% to 35%) for all crops.

This work has produced a robust evidence base to support S recommendations to oilseed rape and led to a better understanding of the crop available S supply from organic materials.

2. . Introduction

2.1. Sulphur fertiliser

Sulphur (S) is an essential plant nutrient that has important effects on both the yield and quality of crops. Sulphur deficiency in crops has become more widespread since the 1990s due to the substantial decrease in atmospheric S deposition, a change in the use of fertilisers towards 'high content straight' fertilisers that contain little or no S, and increased crop yields. Deficiency manifests as a yellowing of the youngest leaves and paler flowers in oilseed rape, although there can be losses of yield and quality without visual symptoms. As levels of atmospheric S deposition have declined, so S deficiency has become more widespread. Cereals, oilseed rape and multi-cut silage have all shown significant yield responses to applied S. Cussans *et al*. (2007) reviewed 88 experiments on winter wheat and found that a quarter of experiments responded significantly to S fertiliser application and the average yield response was 27%. Oilseed rape is among the most responsive crops to S due to its high S requirement and a high yielding oilseed crop (5 t/ha) will typically take up 250 kg SO_3/ha. Notably, oilseed rape has a much higher S requirement than cereals, and insufficient use of S has been suggested as a factor that may be linked to the "yield plateau" constraint seen in oilseed rape (Knight *et al*., 2012). Multi-cut grass for silage has also been shown to be highly susceptible to S deficiency, with typical yield increases in the range of 5-30% (Brown *et al.*, 2000; Zhao *et al*., 2002). Other crops, in particular brassica vegetable crops, are known to have a high demand for S, although there is limited available data on typical yield responses or optimum S application rates.

Sulphur deficiency not only affects yields, but also impacts on crop quality. Optimum S supply has been shown to improve the bread making quality of wheat, by increasing loaf volume (Zhao *et al.,* 1999a; Zhao *et al*., 1999b) and decreasing the acrylamide-forming potential of wheat (Curtis *et al*., 2014). Experiments have also shown that the application of S fertiliser at deficient sites can improve the quality of oilseed rape through a reduction in seed chlorophyll content (Knight and Bingham, 2006) and for malting barley, malting quality and beer flavour can be improved (Zhao *et al*., 2006). Grass that is low in S is nutritionally inferior for animals, and the application of S fertiliser has been shown to increase soluble sugars and true protein in silage (Brown *et al.,* 2000). However, excessive S supply may reduce oilseed rape quality by increasing concentrations of glucosinolates (Schnug, 1989). Also excessive levels of S in grass have been shown to have an adverse effect on animal health by either reducing the absorption of copper in the animal, and/or reducing the uptake of selenium by grass.

Fertiliser S is now routinely recommended for susceptible crops in areas of high risk of S deficiency. Susceptibility to S deficiency is greatest on light sandy or shallow calcareous soils that are low in organic matter and in high rainfall areas (Cussans *et al*., 2007). Since the early 1990s, the proportion of land in Great Britain receiving S fertiliser has increased from 3-6% to 56-63% of the cereal area and from 8% to 70% of the oilseed rape area, with average field application rates currently 56 kg SO_3/ha for winter wheat and 84 kg SO_3/ha for oilseed rape (Benford, 2017). In contrast, the grassland

area receiving S fertiliser (less than 10%) and average field application rate (*c.*35 kg SO_3/ha) have remained largely unchanged since 1993 (Benford, 2017).

2.2. Sulphur requirements of oilseed rape

Fertiliser S recommendations for oilseed rape were first included in the 6th Edition (1994) of Defra's "Fertiliser Recommendations (RB209)". The recommended S rate (50-75 kg SO_3/ha) was based on a limited number of experiments carried out in the early 1990s. Table 1 summarises details of S experiments on oilseed rape; review of these shows that the earlier research on oilseed rape and S tended to focus on glucosinolates (Withers, 1992; Milford *et al*., 1994), and later research on diagnosis of S deficiency (Withers, 1995; Blake-Kalff *et al*., 2000, 2004; Carver, 2005), rather than dose responses in terms of yield. There are only two AHDB funded projects (Withers, 1992; Blake-Kalff et al., 2000) and one other project (McGrath and Zhao, 1996) on winter oilseed rape that included sufficient rates of S to give dose-response information. Of these experiments, only two (Withers 1992; McGrath and Zhao, 1996) gave a significant yield response to S (and in both these experiments, a yield response was recorded at one site only).

When Defra's "Fertiliser Manual (RB209)" was reviewed in 2008 comment was sought from the farming industry with regards to fertiliser S recommendations. The consensus view was that current recommendations for oilseed rape were adequate and that there were no new data which would justify increasing oilseed rape S recommendations, although comment was made that they should probably be towards the higher end of the 50-75 kg SO_3/ha range quoted (Keith Goulding, pers. comm.).

Since the original S recommendations were provided in the early 1990s, farm oilseed rape yields have increased from 3.0 t/ha in 1990 to 3.5 t/ha in 2017[1]. Furthermore, the average gross output yield reported in the AHDB recommended list has increased from 4.0 t/ha in 1990 to 5.4 t/ha in 2017[2], representing the improvement in genetic yield potential of new varieties. It is likely that an increase in genetic yield potential of >1 t/ha will increase the crop's requirement for S.

The work carried out in this project addressed the need to understand whether current fertiliser S recommendations are appropriate for modern high yielding oilseed rape varieties and the results to date were included in the 2016 RB209 review and revision (Roques *et al.,* 2016).

[1] Based on linear regression of Defra national yield data; https://www.gov.uk/government/organisations/department-for-environment-food-rural-affairs
[2] Based on linear regression of AHDB Recommended List data; www.ahdb.org.uk

Table 1. Summary of oilseed rape sulphur experiments

Reference	AHDB report	Winter/ Spring	Date of exp	SO_3 rates (kg/ha)	Number of exp	SO_3 rate to achieve max yield
Withers (1992)	OS2	WOSR	1992	0,25,50,75,125,200 50,125 50	5 5 5	25-125
Milford *et al.,* (1994)	OS8	WOSR	1994	0,125,250	4	
Withers (1995)	OS11	WOSR		100 or 125	16	
McGrath and Zhao (1996)	N/A	WOSR	1991, 1992, 1994	0,25,50,100	3	50
Chalmers *et al*. (1998)	OS34	SOSR	1995-1997	0, 25, 50, 100, 200 0, 25. 50, 100	6 5	50
Blake-Kalff *et al.,* (2000)	PR217	WOSR	1997, 1998	0,12,25,50,100,200	2	*No effect of S*
Riley *et al*., (2000)	PR222		1998, 1999	0,75	2	
Blake-Kalff *et al.,* (2004)	PR327	WOSR SOSR	2000-2003	0,50,200	3	
Carver (2005)	PR374	WOSR	2002, 2003, 2004	0,110	28	

2.3. Organic manures as a source of sulphur fertiliser

Organic manures contain useful quantities of S, as well as other plant nutrients and organic matter. They are used on around 65% of farms in Britain, being applied to an estimated 23% of the arable area, 48% of the temporary grassland area (<5 years old) and 31% of the permanent grassland area (> 5 years old) (Benford, 2017). However, until recently there has been little data on the crop availability of S from organic manures.

AHDB Cereals and Oilseeds project 3606 (Sagoo *et al*., 2013) quantified the S supply from organic materials to winter wheat crops and showed that the S contained in organic manures can make a significant contribution to crop S requirements, with spring applications the most effective in supplying S. The results from this work provided the scientific evidence base to update guidance for farmers on S supply from applications of organic materials which was published in ADHB Sulphur

information sheet 28 ‘Sulphur for cereals and oilseed rape’ and included in the 2016 RB209 review and revision (Williams *et al.,* 2016).

‘Typical’ figures for the total S content of different organic materials are given in AHDB’s Nutrient Management Guide (RB209). However, only a portion of the total S content is in the crop available SO_4 form. AHDB Cereals and Oilseeds project 3606 measured the total and extractable S content of organic materials Extractable S was determined by extraction with 0.016M KH_2PO_4 followed by analysis via ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy), which gives total S in the extract and includes SO_4 and some dissolved organic S. It is likely that any dissolved organic S extracted represents the more labile pool of organic S in the organic material, which can become available to plants through mineralisation to SO_4. Studies on grassland soils have shown that soil testing methods which include a fraction of organic S along with extractable S correlated best with the availability of S to herbage (Blair *et al*., 1991), and the organic S extracted was directly related to the mineralisable organic S (Watkinson *et al*., 1991). AHDB Cereals and Oilseeds project 3606 showed that extractable S contents can vary significantly between organic material types (from *c*.15% of total S for cattle FYM up to *c*.60% of total S for broiler litter) and that for spring organic material applications, extractable S applied can be directly related to grain S offtake and the fertiliser S replacement value of the organic material for winter wheat.

There was a need for additional work to quantify the S supply from organic materials to other crop types, notably oilseed rape which has a higher S requirement than winter wheat. Organic material applications that supply the S requirement of a winter wheat crop may not supply the full S requirement of an oilseed rape crop. Furthermore, as AHDB Cereals and Oilseeds project 3606 showed the ‘extractable’ S content of organic materials to be a good indicator of crop S availability, additional laboratory analysis of a range of organic materials was required to provide robust ‘typical/standard’ figures for ‘extractable’ S.

2.4. Project aims and objectives

The overall aim of this project was to develop improved guidance for farmers on S management. The specific project objectives were:

- Objective 1 (Work Package 1). To determine optimum S rates for oilseed rape.
- Objective 2 (Work Package 2). To quantify the S supply from organic materials to oilseed rape.
- Objective 3 (Work Package 3). To characterise manure total and extractable S content.

3. Optimum sulphur rates for oilseed rape

3.1. Introduction

The overall aim of this work package was to determine economic optimum S rates for oilseed rape. Sulphur response field experiments were carried out at ten sites cropped with winter oilseed rape over four harvest years (2014 to 2017). Data from a further eight S response experiments carried out between 2011 and 2013 (part of a previous project funded by CF Fertilisers and Monsanto) were included in the dataset, giving a total of 18 site years of S response data between 2011 and 2017.

3.2. Methodology

3.2.1. Field sites

The 18 field sites were located on commercial farms on a range of soil types across the country (Table 2 and Figure 1). This report provides detailed results from the ten sulphur response experiments between 2014 and 2017 and summary results from the 2011 to 2013 experiments.

Table 2. Field sites

Project	Harvest year	Site number	Site name	Site abbreviation	County	Soil type[1]
CF Fertilisers & Monsanto	2011	1	Towthorpe	TW	N. Yorks.	SCL
		2	Perrystone	PS	Herefords.	SL
		3	Fincham	FI	Norfolk	SCL
	2012	4	Towthorpe	TW	N. Yorks.	SCL
		5	Perryston	PS	Herefords.	SL
		6	Fincham	FI	Norfolk	SCL
	2013	7	Perryston	PS	Herefords.	SL
		8	Terrington	TT	Norfolk	ZCL
Current project (OPTI-S)	2014	9	Frostenden	FR	Suffolk	LS
		10	Woburn	WB	Beds.	SL
	2015	11	Gleadthorpe	GT	Notts.	SL
		12	Perrystone	PS	Herefords.	SL
	2016	13	Letton	LT	Norfolk	LS
		14	Newark	NW	Notts.	C
		15	Boxworth	BX	Cambs.	C
	2017	16	Gleadthorpe	GT	Notts.	SL
		17	Perrystone	PS	Herefords.	CL
		18	Rothamsted	RT	Herts.	CL

[1]. C = Clay; LS = loamy sand; CL = Medium clay loam; SCL = Sandy clay loam; SL = Sandy loam; ZCL = Silty clay loam

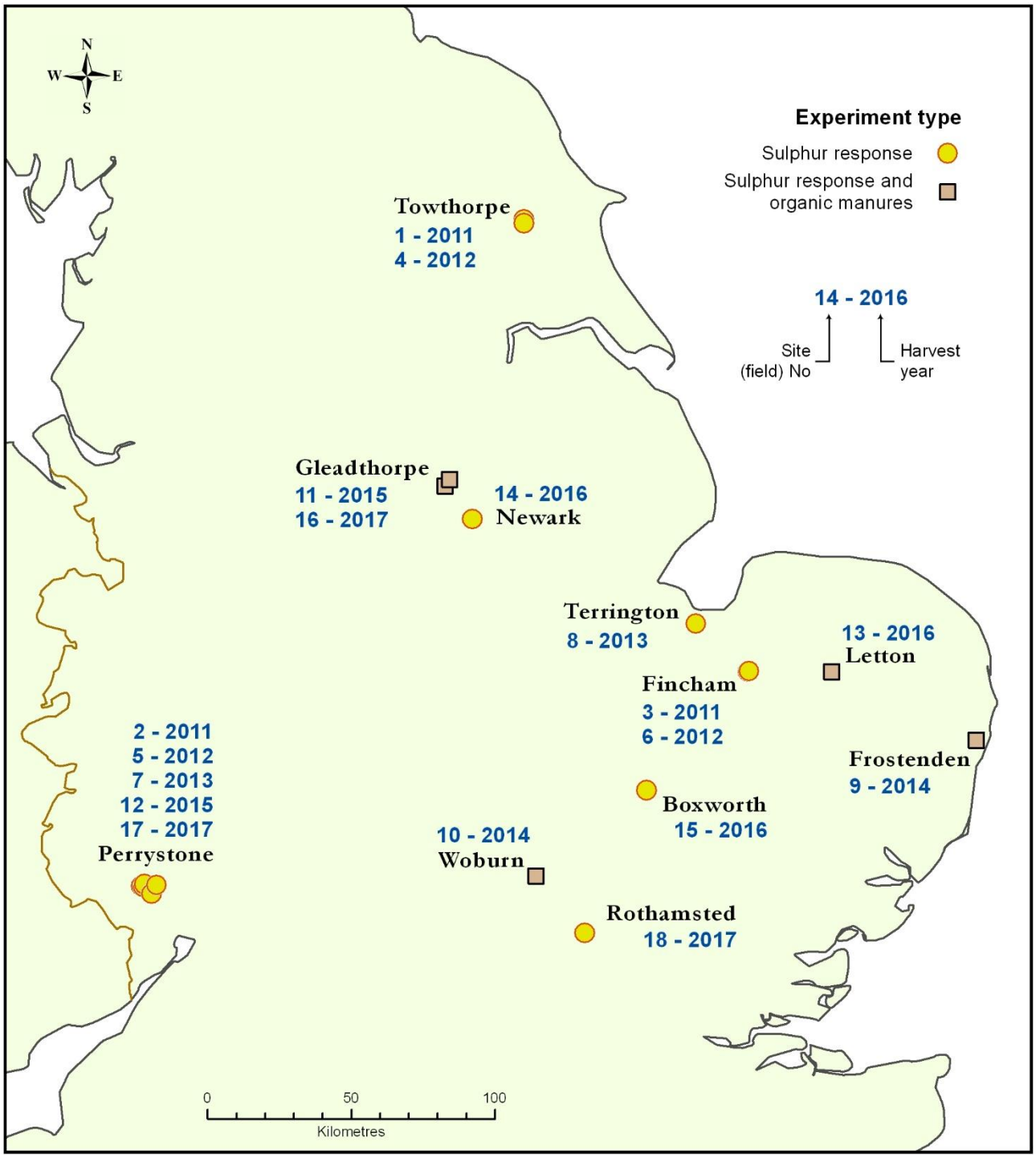


Figure 1. Location of field sites

3.2.2. Experimental treatments and design

At each site, manufactured S fertiliser was applied as ammonium sulphate at six rates (0, 30, 60, 90, 120 and 150 kg SO_3/ha[3]), each treatment was replicated 3 times and arranged in a randomised block design. At each site (apart from Gleadthorpe in 2015) the fertiliser S rates were applied at two N rates (balanced for the N in the ammonium sulphate) to investigate whether applying more N to target a greater yield also increased the S requirement. At Gleadthorpe in 2015 the fertiliser S rates

[3] The S response treatments at Towthorpe in 2011 included additional higher S rates (0, 30, 60, 120, 180, 240, 300 kg SO_3/ha).

were applied at one N rate only. The Soil Nitrogen Supply (SNS) Index was estimated by SMN and crop sampling (section 3.1.3) and N fertiliser rates based on recommendations in the Fertiliser Manual (RB209 8th Edition) and sufficient to achieve target yields of 3.5 t/ha (N rate 1) and 5.0 t/ha (N rate 2) (Table 3).

Table 3. Fertiliser N rates and oilseed rape varieties

Harvest year	No.	Name	N rate 1	N rate 2	Variety
2011	1	Towthorpe	220	310	DK Expower & MLCH175
	2	Perrystone	182	272	DK Expower
	3	Fincham	190	280	DK Cabernet
2012	4	Towthorpe	100	190	DK Expower
	5	Perryston	212	302	DK Expower & DK Extrovert
	6	Fincham	53	143	DK Expower
2013	7	Perryston	113	203	DK Expower & DK Extrovert
	8	Terrington	190	280	Catana
2014	9	Frostenden	190	280	DK Expower
	10	Woburn	220	310	DK Expower
2015	11	Gleadthorpe	250		DK Extrovert
	12	Perrystone	160	250	DK Expower & DK Extrovert
2016	13	Letton	120	210	Tactic
	14	Newark	190	280	DK Extrovert
	15	Boxworth	120	210	Charger
2017	16	Gleadthorpe	120	210	DK Extrovert
	17	Perrystone	190	280	SY Harnas
	18	Rothamsted	220	310	Elgar

Sulphur fertiliser was applied with the first N application in late February/ early March (pre GS 3,3; Sylvester-Bradley and Makepeace, 1984). Nitrogen fertiliser was applied in either two or three splits depending on the quantity required and in accordance with guidance in RB209 (8th Edition).

Four of the 18 experiments compared S response of two oilseed rape varieties at the same site at two N rates (i.e. six S rates x two N rates x two oilseed rape varieties) to assess whether there was an effect of variety on sulphur response (Table 3).

3.2.3. Measurements

Topsoil samples (0-15 cm) were taken from each site at the start of the experiment and analysed for pH, extractable P (Olsen's method), extractable K and Mg, and extractable S (0.016M KH_2PO_4 extraction; Zhao and McGrath, 1994), soil texture (percentage sand, silt and clay) and organic carbon (Modified Walkley Black method). Soil profile (0–90 cm in three depths: 0–30 cm, 30–60 cm and 60–

90 cm) samples were taken from the zero S control treatment in January for extractable S and mineral N determination (including an estimate of mineralisable N 'additionally available N' (AAN) in the 0-30 cm depth). At the same time, above ground N content of the crop was measured by cutting and weighing a 1m^2 area of crop and analysing a subsample for dry matter and total N content. Soil nitrogen supply (SNS) Index was calculated as the sum of SMN, AAN and crop N.

Leaf samples were taken from the zero S control treatments twice during the growing season, at target growth stage 3,6 (late green bud) (typically early to mid-April) and then again approximately two weeks later, and analysed for total N and S and malate: sulphate ratio.

Where present, visual symptoms of S deficiency were recorded throughout the growing season. All plots were assessed for symptoms of S deficiency at around GS 3,7 (by scoring the 'greenness' of leaves on a scale of 1-5; for which a score of 5 represented dark green) and at mid-flowering (by scoring the 'yellowness' of flowers on a scale 1-5; for which a score of 5 represented dark yellow). These assessments give a subjective score to assess visual differences between treatments at one site, but are not compared between sites.

Oilseed rape seed yields (fresh weight) were determined at harvest using a small plot combine. Seed samples were taken and analysed for dry matter, total N, total S, oil content, protein content and glucosinolates[4]. Seed yield (91% DM), gross output[5] and seed S offtake (kg SO_3/ha) were calculated. **All yield data is presented as gross output yields**. Total S in plant tissue was determined by nitric/hydrochloric acid digest and analysis by ICP-OES; total N in plant tissue was determined by the Dumas combustion method; and oil, protein and glucosinolates were determined by NIR analysis.

3.2.4. Field experiment data analysis

Analysis of variance (ANOVA) was used to evaluate the effect of fertiliser S and N rates and variety on seed and gross output yields, seed SO_3 offtake, seed glucosinolates, protein and oil content.

Where there was a yield response to S, a response curve was fitted to the gross output yield and seed SO_3 offtake data. The economic optimum S rate was calculated for gross output yield based on a breakeven ratio (BER) of 0.5 which is the 'average' BER over the period 2011-2017. The economic optimum S rate is the point at which the additional yield from applying more S fertiliser no longer covers the cost of the fertiliser. This is represented as the BER of crop yield (kg) needed to pay for 1 kg of SO_3 and is calculated as:

[4] Glucosinolate analysis was performed on seed from all treatments in 2014 and 2015, but only on seed from the 60 and 150 kg SO_3/ha treatments in 2016 and 2017.

[5] Gross output yields were calculated by adjusting the seed yield according to the premium paid for oil; +/- 1.5% for every 1% of oil content above/below 40%.

$$Breakeven\ ratio = \frac{Cost\ of\ S\ (pence\ per\ kg\ SO_3)}{Value\ of\ oilseed\ rape\ (pence\ per\ kg)}$$

The price of S was calculated based on the mean price of two separate N and S containing fertilisers. In each case the value of N in the fertiliser was calculated based on the price of ammonium nitrate fertiliser (in p/kg N); the difference between the product price for the N and S fertiliser and the value of the N in the fertiliser is considered to be the S value and calculated as p/kg SO_3. A BER of 0.5 is equivalent to oilseed rape at £300/t and sulphur at £0.15 p/kg SO_3.

As a general principle, the economic optimum S rate is expected to be relatively insensitive to changes in the value of oilseed rape seed or the cost of S fertiliser. However, in order to assess the impact of economic changes, the optimum S rate was also calculated based on a BER of 0.2 and 0.9, representing the range of BERs calculated over the period 2011 to 2017.

3.3. Results

3.3.1. Yield response (gross output yields)

Ten of the 18 S response experiments showed a yield response to S fertiliser; the increases in yields were statistically significant (P<0.05) at nine of the ten sites[6]. Yield increases ranged from 0.1 to 4.4 t/ha (Table 4). The largest yield increases were recorded at Frostenden and Woburn in 2014 where application of S fertiliser increased yields from 1.0 t/ha on the zero S control up to 5.4 t/ha at Frostenden, and from 2.4 and 1.3 t/ha on the zero S control treatments for the lower (220 kg/ha N) and higher (310 kg/ha N) N rates, respectively, up to 5.6 t/ha at Woburn, representing some of the largest S response yield increases measured in the UK. Mean treatment yields (for each S and N rate) for the 2014 to 2017 experiments are given in Table 11 to Table 20.

Table 4. Summary of yield increases achieved from application of sulphur fertiliser

Harvest year	Site	Yield increase (t/ha)[1]	Yield at optimum (t/ha)[2]	Economic optimum S rate (kg SO_3/ha)[3]
2011	Towthorpe	0.7	3.7	*77*
	Perrystone	0.9	4.9	*42*
	Fincham	0.4	2.8	*64*
2012	Towthorpe	*None*	4.1	*
	Perryston	0.1	4.4	*30*
	Fincham	*None*	3.9	*
2013	Perryston	0.5	2.8	*69*
	Terrington	*None*	5.2	*
2014	Frostenden	4.4	5.4	*79*
	Woburn	3.8	5.6	*62*
2015	Gleadthorpe	1.0	5.7	*30*
	Perrystone	0.6	5.8	*35*
2016	Letton	0.6	4.6	*30*
	Newark	*None*	4.7	*
	Boxworth	*None*	2.3	*
2017	Gleadthorpe	*None*	4.7	*
	Perrystone	*None*	4.6	*
	Rothamsted	*None*	5.5	*

1. Gross output yield at optimum SO_3 rate minus yield from zero S control treatment.
2. Gross output yield at optimum SO_3 rate or mean site yield where no response to S.
3. Economic optimum fertilizer SO_3 rate based on gross output yield (i.e. taking into account oil content) and a break-even ratio of 0.5.

[6] The 1.0 t/ha yield increase at Gleadthrope in 2015 was not statistically significant (P=0.172), reflecting the yield variability between treatment replicates.

Mean site yields (calculated as the yield at the optimum SO_3 rate where sites showed a yield response to S, and average site yield where there was no yield response to S) varied between 2.3 and 5.8 t/ha and gave an overall mean of 4.5 t/ha (Table 4). There was no evidence that higher yielding sites were either more likely to respond to S or show a larger yield response to S. The average yield of the ten sites which responded to S (4.6 t/ha) was close to the average yield from the eight sites which showed no yield response to S (4.4 t/ha). For the ten sites which responded to S fertiliser, regression analysis showed no relationship between the yield at the optimum SO_3 rate and the size of the yield increase (P>0.05).

At each site (apart from Gleadthorpe in 2015) the fertiliser S rates were applied at two N rates. The higher N application rate (additional 90 kg N/ha) significantly (P<0.05) increased yields at five of the sites (Fincham, 2011; Towthorpe, 2012; Fincham, 2012; Perrystone, 2013 and Terrington 2013) by a mean of 0.18 t/ha (range 0.13-0.22 t/ha).

There was a significant (P<0.05) interaction effect between S and N on yields at the Woburn (2014) site only (Table 12). At this site, yields were lower from the zero S control at the higher N rate (*c*.1 t/ha) compared to the lower N rate (*c*.2.5 t/ha), which is likely to be due to inhibition of N incorporation due to lack of sulphur at this very S deficient site (McGrath and Zhao, 1996).

Four experiments compared S response of two oilseed rape varieties (DK Expower and MLCH175 at Towthorpe in 2011; DK Expower and DK Extrovert at Perrystone in 2012, 2013 and 2015) at two N rates (i.e. six S rates x two N rates x two oilseed rape varieties). There was no consistent effect of variety on yields. Although, there was a significant effect (P<0.05) of variety at Perrystone in 2012 and 2013, the effect was not consistent between years. In 2012, yields at both N rates were higher from DK Extrovert. In 2013, yields were higher from DK Expower at the lower N rate, but there was no difference in yields between the varieties at the higher N rate. There was no effect (P>0.05) of variety on yields at Towthorpe in 2011 or Perrystone in 2015.

3.3.2. Economic optimum SO_3 rate

At the ten sites which showed a yield response to S, the economic optimum S rates varied between 30 and 79 kg SO_3/ha (Table 4); five sites had economic optima less than 50 kg SO_3/ha, just below the current RB209 recommended range of 50-75 kg SO_3/ha, three sites had optima within the current RB209 recommended range and two sites had optima between 75 and 80 kg SO_3/ha, just above the current RB209 recommended range. Based on these results, we recommend a minor revision to oilseed rape S recommendations to 50-**80** kg SO_3/ha.

Table 5 shows the effect of variation in BER on economic optimum yields. At three of the sites (Perrystone in 2012, Gleadthorpe in 2015 and Letton in 2016), the increase in yields was achieved at the first S rate and the optimum is therefore assumed to be at the first rate tested (i.e. 30 kg SO_3/ha) and it was not possible to test the effect of varying the BER at these three sites. At the other seven sites, reducing the BER from 0.5 to 0.2 increased the optimum by a mean of 6 kg SO_3/ha and

increasing the BER from 0.5 to 0.9 reduces the optimum by a mean of 7 kg SO_3/ha. However, as the BER for S response is low, the economic optimum rate is always close to the maximum yield and the change to optimum rates from reducing or increasing BER at these seven sites was estimated to have <0.06 t/ha impact on yields. Therefore, we suggest that S fertiliser recommendations do not need to take into account potential variations to BER.

Table 5. Impact of breakeven ratio (BER) on economic optimum S rates

Harvest year	Site	Economic optimum S rate (kg SO_3/ha)		
		BER = 0.2	BER = 0.5	BER = 0.9
2011	Towthorpe	80	77	74
2011	Perrystone	43	42	41
2011	Fincham	78	64	55
2012	Perryston	*	30	*
2013	Perryston	79	69	45
2014	Frostenden	80	79	77
2014	Woburn	63	62	61
2015	Gleadthorpe	*	30	*
2015	Perrystone	46	35	26
2016	Letton	*	30	*

Regression analysis showed fitting separate response curves to the gross output yield data at the two N rates was only statistically justified at two of the ten sites (Woburn 2014 and Perrystone, 2015). However, at Woburn the percent increase in the variance accounted for in the data by fitting separate curves compared to fitting a single curve was marginal and the economic optimum calculated from the separate curves for the two N rates were within 1 kg SO_3/ha, and therefore the economic optimum SO_3 rate reported for this site is based on a single curve. The 2015 Perrystone site was the only site where fitting separate curves to the gross output yield data at the two N rates was statically justified and impacted on the economic optimum S rate; the optimum S rate was 23 kg SO_3/ha for N rate 1 and 38 kg SO_3/ha for N rate 2. Although the optimum S was higher at the higher N rate, there was no significant effect of N rate on gross output yields (mean 5.6 t/ha at N rate 1 and 5.7 t/ha at N rate 2; P>0.05) and therefore it is not possible to conclude that the higher optimum was linked to higher yields. The economic optimum S rate based on a single curve was 35 kg SO_3/ha.

Regression analysis showed that fitting separate response curves to the different varieties (at four sites) was not statistically justified; there was no evidence of any difference in S requirements of DK Expower and MLCH175DK, or DK Expower and DK Extrovert varieties.

There was no relationship (P>0.05) between the optimum S rate and yield at the optimum rate, despite the range average yields between the sites (2.3 t/ha to 5.7 t/ha) (Figure 2) and therefore no evidence to suggest that higher yielding oilseed rape requires higher fertiliser S rates.

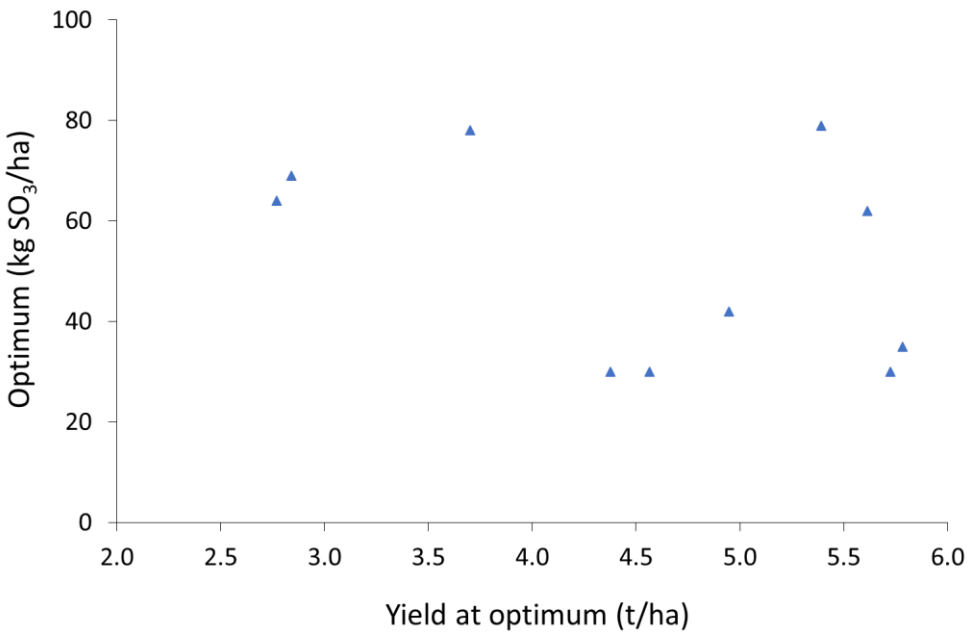


Figure 2. Comparison of optimum S rate and yield (gross output t/ha at 91% DM) at optimum S rate

3.3.3. Visual symptoms of sulphur deficiency (2015-2018 sites only)

At the Frostenden and Woburn sites in 2014, which showed the largest yield responses to S fertiliser, there were clear visual differences between the zero S control and S fertiliser treatments. At both sites, the zero S control treatments were clearly identifiable and showed symptoms of S deficiency including a 'stunted' thinner crop, diffuse yellowing on the leaves, paler flowers and a reduced number of pods (Figure 3 and Figure 4).

At the Gleadthorpe (2015), Perrystone (2015) and Letton (2015) sites, where yield responses to S were 0.6-1.0 t/ha, comparison of zero S control treatments to the S fertiliser treatments at all three sites showed slight visual symptoms of S deficiency including yellowing of the leaves, paler flowers and slightly delayed flowering. At the Perrystone and Letton sites, crop scoring identified trends for increasing leaf 'greenness' and flower 'yellowness' with increasing S rate (Figure 5) (scoring was not done at the Gleadthorpe site). Differences at these sites were apparent because the experimental design allowed direct comparison of treatments with and without S. It would have been difficult to identify the slightly yellower leaves/paler flowers and attribute this to S deficiency in the absence of a with S treatment comparison, i.e. in a typical commercial field situation. Based on visual observations from all sites, we conclude that it will be difficult to identify visual symptoms of moderate S deficiency which result in yield penalties of around 0.5 t/ha in commercial crops due to the absence of with and without S treatment comparisons.

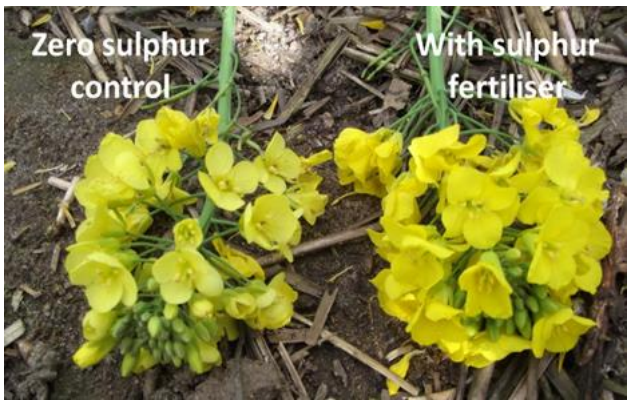


Photo taken 08/04/2014

Photo taken 24/04/2014

Photo taken 15/07/14 (harvest)

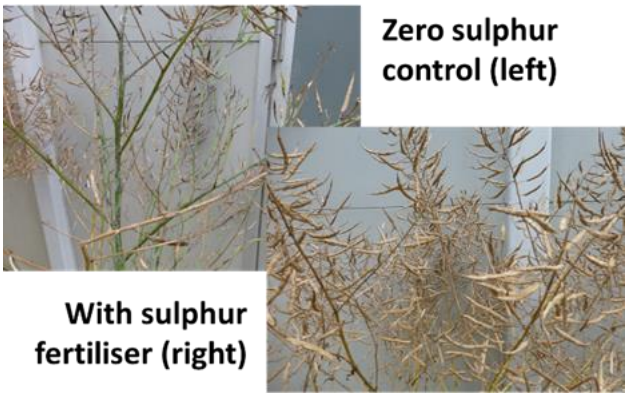
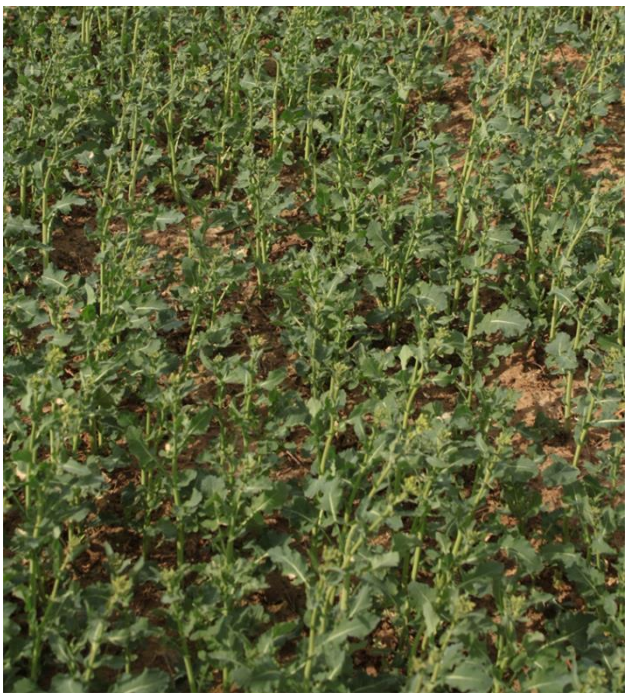


Photo taken 15/07/14 (harvest)

Figure 3. Visual symptoms of sulphur deficiency at Frostenden (2014)

Zero S control. Photo taken 21/03/2014

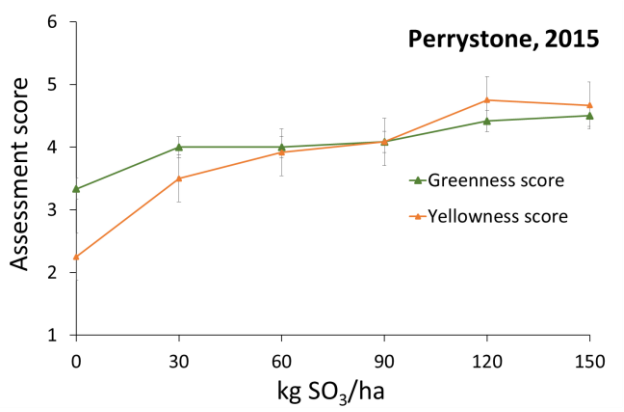


With S fertiliser. Photo taken 21/03/2014

Zero S control. Photo taken 08/04/2014

With S fertiliser. Photo taken 08/04/2014

Figure 4. Visual symptoms of sulphur deficiency at Woburn (2014)



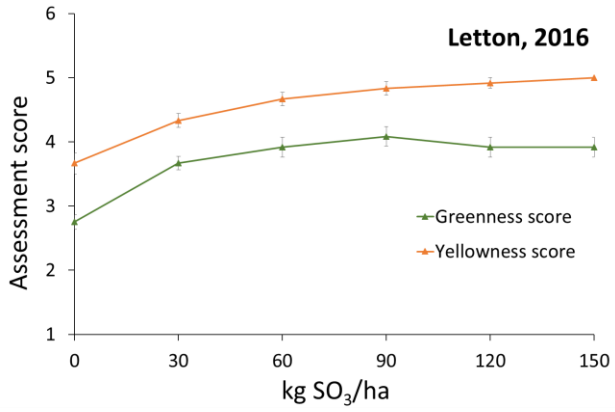


Figure 5. Crop scoring for leaf 'greenness' and flower 'yellowness' at Perrystone in 2015 (left) and Letton in 2016 (right). Larger scores indicate darker green or deeper yellow appearance.

3.3.4. Soil extractable S analysis

Soil extractable S analysis was not a reliable indicator of likely yield response to S fertiliser. Topsoil samples taken in the autumn for extractable S showed a mean of 13 mg S/kg across the five sites which showed a yield response to S (range 7-26 mg S/kg), compared to a mean of 8 mg S/kg from the five sites which didn't show a yield response to S (range 5-12 mg S/kg) (Table 6). The lowest extractable S content was measured from a site which didn't response to S fertiliser (5 mg S/kg at Rothamsted in 2017) and the highest extractable S concentration was measured from a site which did show a yield response to S fertiliser (26 mg S/kg at Perrystone in 2015). A critical value of <10 mg S/kg (Carver, 2005) is often cited as indicating a likely crop response to applied S; however, this threshold value is not supported by results from this project.

In addition, soil extractable S was also measured from the soil profile (0-90 cm) in January/February at the same time as SMN sampling, to determine whether soil profile extractable S concentrations were a better indicator of likely S deficiency than topsoil S analysis. Although on average soil profile extractable S concentrations were lower from the 'deficient' sites (mean 86 kg S/ha; range 43-174 kg S/ha) than the 'sufficient' sites (mean 104 kg S/ha; range 82-146 kg S/ha) (Table 6), there was considerable variability in the data and we do not consider soil profile S content to be a useful indicator of likely crop response to S fertiliser. Notably, the Woburn site in 2014, which showed a large 3-4 t/ha yield increase, had higher soil profile extractable S (102 kg S/ha) than both the 2017 Perrystone and Rothamsted sites (82 and 94 kg S/ha, respectively) which did not show a yield response to S fertiliser.

Table 6. Soil extractable S concentrations

Harvest year	Site	Yield increase (t/ha)[1]	Topsoil (0-15 cm) extractable S (mg S/kg)	Soil profile 0-90cm extractable S (kg S/ha)
2014	Frostenden	4.4	7	43
	Woburn	3.8	7	102
2015	Gleadthorpe	1.0	20	174
	Perrystone	0.6	26	67
2016	Letton	0.6	7	43
	Newark	*None*	9	146
	Boxworth	*None*	6	113
2017	Gleadthorpe	*None*	9	145
	Perrystone	*None*	12	82
	Rothamsted	*None*	5	94

1. Gross output yield at optimum SO_3 rate minus yield from zero S control treatment.

3.3.5. Leaf tissue tests to diagnose deficiency

Malate: sulphate

The malate:sulphate ratio in the youngest leaves of plants can be used as an indicator of crop S deficiency. A ratio greater than 1.5 is used to indicate that the plant is deficient at the time of sampling (Blake-Kalff *et al*. 2000); guidance on interpretation of malate: sulphate analysis is given in Table 7. The malate:sulphate ratio gives a snapshot of the S status of the crop at the time of sampling with four possible outcomes: (i) the crop is S sufficient at time of sampling and will remain so during the growth season (yield reduction unlikely); (ii) the crop is S sufficient at the time of sampling but will become deficient during periods of rapid growth (yield reduction likely); (iii) the crop is S deficient at the time of sampling because it is growing rapidly, but it will recover from this once growth slows down (yield reduction unlikely); (iv) the crop is S deficient at the time of sampling and will remain so during the growth season (yield reduction likely) .

Table 7. The interpretation of the magnitude of the malate: sulphate ratio and possible yield reduction (from Blake-Kalff et al., 2004)

Malate: sulphate ratio	Diagnosis	Possible yield reductions
Less than 1.5	Not deficient	0 %
1.5 - 2.0	Borderline	0 – 5 %
2.0– 30	Deficient	0 – 10 %
Above 30	Very deficient	10 – 40 %

Leaf tissue samples were taken from the zero S control treatments twice during the growing season from most sites (target sampling GS 3,6 and then again approximately two weeks later), however, only one sample was taken from the three 2011 sites and three samples were taken from two of the sites (Frostenden in 2014 and Gleadthorpe in 2015).

Malate: sulphate ratios varied from a minimum of 0.6 to a maximum of 33 (Table 8). Review of the data shows that for the nine sites which showed a yield response to S and for which malate: sulphate analysis is available (results of tissue analysis are not available from the Perrystone site in 2013):

- Deficiency was clearly diagnosed at each sampling at four sites: Fincham in 2011 (single test), Frostenden in 2014 (three tests), Perrystone in 2015 (two tests) and Letton in 2016 (two tests).
- Replicate tests at different times indicated both deficiency and sufficiency at three sites depending on the timing: Perrystone in 2012 (first sample sufficient; second sample deficient), Woburn in 2014 (first sample sufficient; second sample deficient) and Gleadthorpe in 2015 (first sample sufficient, second sample deficiency and third sample sufficient).
- Deficient crops were incorrectly diagnosed as sufficient at two sites: Towthorpe and Perrystone in 2011 (single sample at both sites).

For the eight sites which showed no yield response to S fertiliser:

- Sufficiency was clearly diagnosed at both samplings at one site: Newark in 2016.

- Replicate tests at different times indicated both sufficiency and deficiency at six sites: Towthorpe and Fincham in 2012 (first sample deficient, second sample sufficient), Terrington in 2013 (first sample deficient, second sample sufficient), and Gleadthorpe, Perrystone and Rothamsted in 2017 (at each site first sample sufficient and second sample borderline deficient).
- Deficiency was incorrectly diagnosed at one site: Boxworth in 2016 (both samples indicated the crop was deficient).

It is clear from measuring more than one malate:sulphate ratio per season that the timing of taking the sample is very important. Monitoring the trend of malate:sulphate ratios within a season, has potential to distinguish between permanent and transient S deficiency, which is not possible by taking only one sample.

The highest malate:sulphate ratios were measured from the Frostenden and Woburn sites in 2014, corresponding with the largest yield responses to S fertiliser, indicating that very deficient crops show much higher malate:sulphate ratios. At both sites the malate:sulphate ratio greatly increased between sampling times which is likely to reflect an increase in the degree of S deficiency as crop growth increases. Notably at Woburn, the first sample taken on 19th March at GS 3,6 showed a malate:sulphate ratio of 1.0 indicating the crop had sufficient S, but the later sample taken two weeks later on 1st April had a ratio of 26. Blake-Kalff *et al*. (2004) noted that a ‘not deficient’ malate:sulphate result does not guarantee that plants will not be deficient in S later in the season as they start to grow more rapidly. There was a tendency for tests carried out later in stem extension (after yellow bud) to provide a more reliable indication of S deficiency.

Table 8. Leaf tissue malate: sulphate analysis (zero S control treatment)

Year	Site	Yield response[1] t/ha ↑ (% penalty)	Growth stage GS	Malate: sulphate	Diagnosis based on all timings		Interpretation of results
					Diagnosis	Correct (Y/N)	
2011	Towthorpe	0.7 (-19%)	3,7	1.4	Sufficient	N	Single sample only, which was possibly taken before the period of rapid crop growth when the risk of deficiency increases
	Perrystone	0.9 (-18%)	*	1.3	Sufficient	N	Single sample only, which was possibly taken before the period of rapid crop growth when the risk of deficiency increases
	Fincham	0.4 (-15%)	3,3	9.2	Deficient	Y	Clear indication of deficiency
2012	Towthorpe	*None*	* *	1.7 1.3	Sufficient	Y	Clear indication of sufficiency
	Perrystone	0.1 (-3%)	3,7 4,3	0.9 2.1	Sufficient	Y	A borderline deficiency later in the season doesn't usually result in a yield reduction
	Fincham	*None*	3,7 4,1	4.8 1.9	Borderline	Y	Initial deficiency but crop recovered, maybe S became available through mineralisation
2013	Perrystone	0.5 (-16%)	*	*	*	*	*
	Terrington	*None*	3,7 4,5	2.0 1.4	Sufficient	Y	Clear indication of sufficiency
2014	Frostenden	4.4 (-82%)	3,5 3,7 4,5	2.6 7.1 32.6	Deficient	Y	Crop became progressively more deficient throughout the season
	Woburn	3.8 (-62%)	3,6 4,0	1.0 26.2	Deficient	Y	The crop wasn't deficient at the first timing, possibly because it wasn't growing rapidly. Very deficient at 2nd timing

Table 8 (continued). Leaf tissue malate: sulphate analysis (zero S control treatment)

Year	Site	Yld response[1] t/ha ↑ (% penalty)	Growth stage GS	Malate: sulphate	Diagnosis based on all timings		Interpretation of results
					Diagnosis	Correct (Y/N)	
2015	Gleadthorpe	1.0 (-17%)	3,5 3,7 4,5	1.3 6.1 1.1	Sufficient	Inconclusive	The yield reduction was not significant
	Perrystone	0.6 (-10%)	3,6 4,1	4.8 5.1	Deficient	Y	Clear indication of deficiency
2016	Letton	0.6 (-13%)	3,6 4,0	5.8 6.2	Deficient	Y	Clear indication of deficiency
	Newark	*None*	3,6 4,4	0.8 0.6	Sufficient	Y	Clear indication of sufficiency
	Boxworth	*None*	3,7 4,0	6.7 4.4	Deficient	N	This crop was clearly deficient, but the final yield was low and possibly impeded by another factor
2017	Gleathorpe	*None*	4,1 4,3	1.4 2.5	Sufficient	Y	A moderate deficiency later in the season doesn't usually result in a yield reduction
	Perrystone	*None*	3,7 4,2	1.4 2.2	Sufficient	Y	A moderate deficiency later in the season doesn't usually result in a yield reduction
	Rothamsted	*None*	3,6 3,7	1.1 2.0	Sufficient	Y	A borderline deficiency later in the season doesn't usually result in a yield reduction

1. Yield response given as yield increase (yield at optimum SO_3 rate minus yield from zero S control treatment) and as % yield penalty (yield increase divided by yield at optimum SO_3 rate).

Leaf tissue sulphur concentrations and N:S ratio (2014 – 2017 sites)

Leaf tissues samples from the 2014 to 2017 sites were also analysed for total N and S content and tissue N:S ratio was calculated. In general, leaf tissue S content was lower and N:S ratio greater at the sites which showed a yield response to S (Table 9).

Mean leaf S content from the zero S control treatment at the five 'deficient' sites was 0.5% (range 0.3-0.7%), compared to a mean of 0.8% (range 0.5-1.1%) for the four 'sufficient' sites[7]. Blake-Kalff *et al.* (2000) found that critical values for total S in oilseed rape leaves varied between 0.28 and 0.46% during the growing season. Based on the data from this project a threshold value of 0.5% best identifies responsive sites; four of five responsive sites had foliar S content <0.5% and three of four 'sufficient' sites had foliar S content >0.5%, with the Boxworth site in 2016 borderline between deficient and sufficient (contents of 0.5 and 0.6% S).

Table 9. Leaf N and S concentrations and N:S ratio (zero S control treatment)

Harvest year	Site	Yield increase (t/ha)[1]	GS	N (%)	S (%)	N:S
2014	FR	4.4	3,5 3,7 4,5	*3.2* 4.9 6.5	*0.4* 0.3 0.3	*8* 15 21
	WB	3.8	3,6 4,0	4.9 6.5	0.5 0.3	10 19
2015	GT	1.0	3,5 3,7 4,5	6.2 6.6 6.2	0.7 0.6 0.7	9 12 9
	PS	0.6	3,6 4,1	5.6 5.1	0.5 0.4	11 14
2016	LT	0.6	3,6 4,0	4.7 6.5	0.4 0.4	13 15
	NW	*None*	3,6 4,4	8.1 7.2	1.0 1.1	8 7
	BX	*None*	3,7 4,0	4.7 4.8	0.5 0.6	10 9
2017	GT	*None*	4,1 4,2	* 6.9	0.8 0.6	* 12
	PS	*None*		* *	* *	* *
	RT	*None*	3,6 3,7	3.2 6.1	0.9 0.8	4 8

1. Yield increase calculated as yield at optimum SO_3 rate minus yield from zero S control treatment.

Mean leaf tissue N:S ratio from the zero S control treatment at the five 'deficient' sites was 13 (range 8-21), compared to a mean of 8 (range 4-12) for samples from the four 'sufficient' sites[7]. Based on a critical N:S value of 9 (Blake-Kalff *et al*., 2000), 12 of the 13 tests from the five sites which showed

[7] Leaf tissue N and S analysis is not available from the Perrystone site in 2017.

a yield response to S correctly identified deficiency (one of three samples from Frostenden in 2014 indicated sufficiency), whilst four of the seven tests from the four sites which did not show a yield response to S correctly diagnosed sufficiency (samples from Boxworth in 2016 and Gleadthorpe in 2015 indicated deficiency).

3.3.6. Seed composition

Oil content

Sulphur fertiliser significantly (P<0.05) increased seed oil content at the Frostenden and Woburn sites in 2014 (Table 11 and Table 12). At both these sites the increase was achieved at the first S rate (30 kg SO_3/ha), and there was no further increase in oil content at higher S fertiliser application rates. At Frostenden, applying S fertiliser increased percentage seed oil content from by 4.2 from 40.8% (zero S control) to 45.0% (mean of all S treatments), and at Woburn applying S fertiliser increased percentage seed oil content by 3.4 from 42.0% (zero S control) to 45.4% (mean of all S treatments).

In contrast, application of S fertiliser decreased percentage oil content (P<0.05) by 1.2 at Towthorpe in 2011, 0.4 at Fincham in 2011, 0.5 at Perrystone in 2012 and 0.1 at Perrystone in 2015, possibly due to a dilution effect from the increased seed protein content (see below). However at each of these sites the application of S fertiliser also increased yields which more than compensated for the small reduction in oil content; the application of S fertiliser increased gross output yields (taking into account the premium paid for oil) by 0.4, 0.4, 0.1 and 0.5 t/ha at Towthorpe (2011), Fincham (2011), Perrystone (2012) and Perrystone (2015), respectively.

There was no effect (P>0.05) of S fertiliser on seed oil content at the other 12 sites. Across all sites, seed oil content from the zero S control treatments varied between 37.7% (DK Extrovert; Newark, 2016) and 48.3% (Catana; Terrington, 2013) with a mean of 43.9%. The mean oil content from the zero S control treatments at the 10 sites which showed a yield response to S was 44.4%, compared to 43.4% from the eight sites which did not show a yield response to S. This suggests that whilst application of S fertiliser significantly increased oil content at the two most response sites, other site/variety factors are more important in explaining variation in oil content between sites.

There was a significant effect of N fertiliser (P<0.05) on seed oil content at 11 of the 17 sites which included two N rates[8]. Percentage seed oil content was reduced by an average of 1.1 (range 0.3-2.8) at the higher N rate (extra 90 kg N/ha). However, at ten of these sites an increase in yields at the higher N rate usually more than compensated for the reduction in oil content and gross output yields (taking into account the premium paid for oil) were increased at the higher N rate. The exception was Perrystone site in 2012 where percentage seed oil content was 0.3 lower at the higher N rate and there was no effect of N on seed yields resulting in a reduction in gross output yields of 0.1 t/ha.

[8] There was only one N rate at the Gleadthorpe 2015 site.

There was no effect (*P*<0.05) of variety on seed oil content at Towthorpe in 2011 (DK Expower and MLCH175), However, at Perrystone in 2012, 2013 and 2015, percentage seed oil content was significantly (*P*<0.05) higher for DK Extrovert than DK Expower by a mean of 0.7 (range 0.6-0.8).

Protein content

Seed protein content increased with increasing S fertiliser rate *(P*<0.05) at five of 18 sites; at these sites percentage seed protein content was an average of 1.1 greater from the S fertiliser treatments than from the zero S control treatment (range 0.6-2.1). Seed protein content was also significantly higher (*P*<0.05) at the higher N fertiliser rate at all except one site (Perrystone in 2011). Percentage protein content was on average of 1.0 higher from the higher N rate (range 0.2-1.7).

There was a significant but inconsistent (*P*<0.05) effect of variety on seed protein content at Perrystone in 2012 and 2015, although the effect was not consistent between years. In 2012 the mean protein content of DK Extrovert was greater than from DK Expower, whilst in in 2015 the mean protein content of DK Expower was greater than DK Extrovert. There was no effect (*P*>0.05) of variety at Towthorpe in 2011 or Perrystone in 2012.

Glucosinolates

High concentrations of glucosinolates in oilseed rape are undesirable because of the toxicological effect of their breakdown products. Glucosinolates are an important sink for S taken up by the plant and crop S supply is reported to be the second most important factor affecting seed glucosinolate content after variety (Schnug, 1989). Sulphur fertiliser significantly (*P*<0.05) increased glucosinolate concentrations at eight sites, all of which showed a yield response to S fertiliser (Figure 6). Only two sites which responded to S fertiliser did not show an increase (*P*>0.05) in glucosinolates (Gleadthorpe in 2015 and Letton in 2016), and there was no effect of S fertiliser on glucosinolate concentrations at any of the eight sites which did not show a yield response to S (Figure 7).

At the 60 kg SO_3/ha application rate (i.e. within the current RB209 recommended range), mean glucosinolate concentrations from the 18 sites varied between 8.5 and 20.1 µg/g with an overall mean of 13.4 ug/g. The greatest increase in glucosinolate concentrations from 8 µg/g for the zero S control up to 17 µg/g for the highest S fertiliser rate (150 kg SO_3/ha) was measured at Frostenden in 2014. Averaged across all 18 sites, increasing the S application rate from 60 to 150 kg SO_3/ha increased glucosinolate concentrations by a mean of 1.1 µg/g (range 0-4.5 µg/g). Glucosinolate concentrations were below the current limit of 20 µg/g at all sites. At Newark in 2015, glucosinolate concentrations were at the limit (mean 19.9 ug/g).

There was a significant effect (*P*<0.05) of N rate on glucosinolates at four of the eleven sites where glucosinolate concentrations were measured at two N rates. However, the effect was not consistent between sites; glucosinolate levels were greater from the higher N rate at Towthorpe in 2012 (by 0.9 µg/g), but lower (by a mean of 0.8 µg/g) from the higher N rate at Towthorpe in 2011 and at Perrystone in 2013 and 2015. There was no effect of variety on seed glucosinolate levels at any of the four sites which compared two oilseed rape varieties.

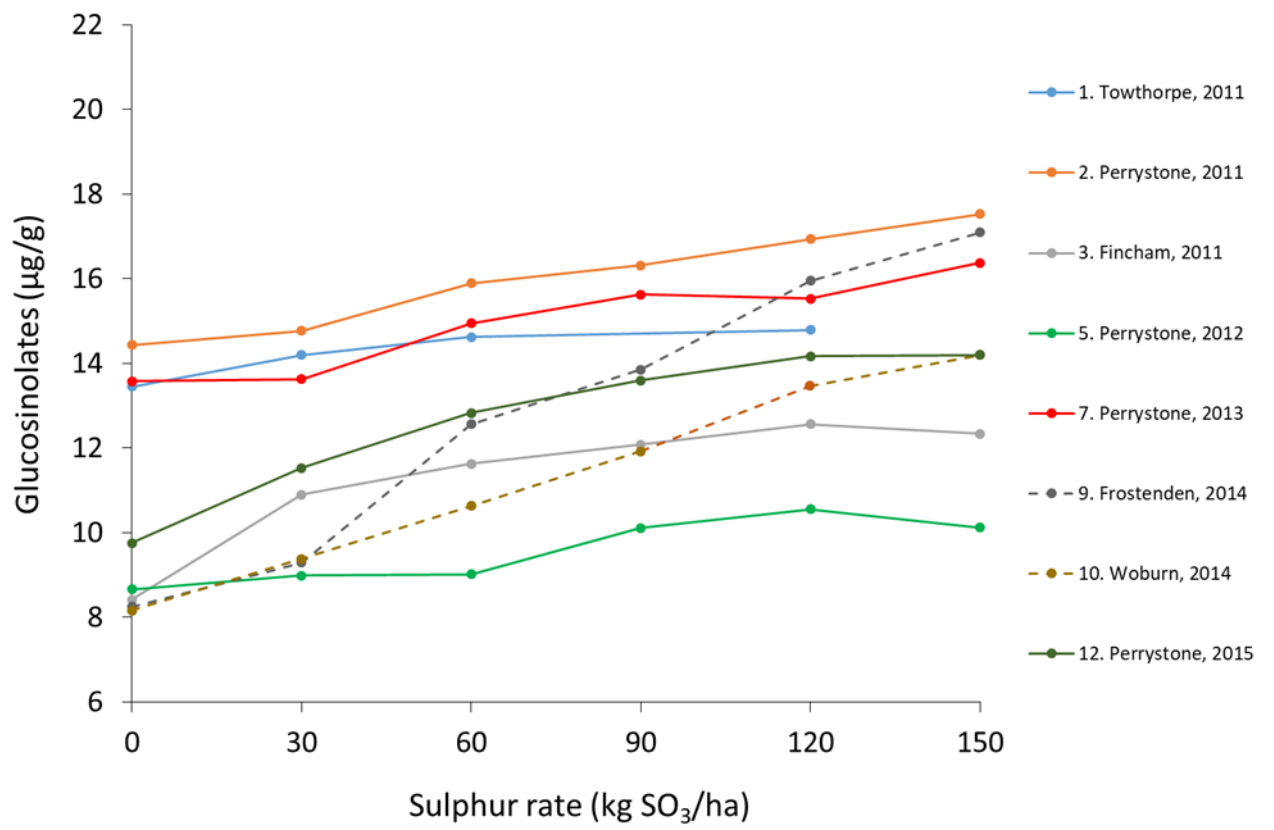


Figure 6. Glucosinolate concentrations increased with increasing S fertiliser rate at eight sites

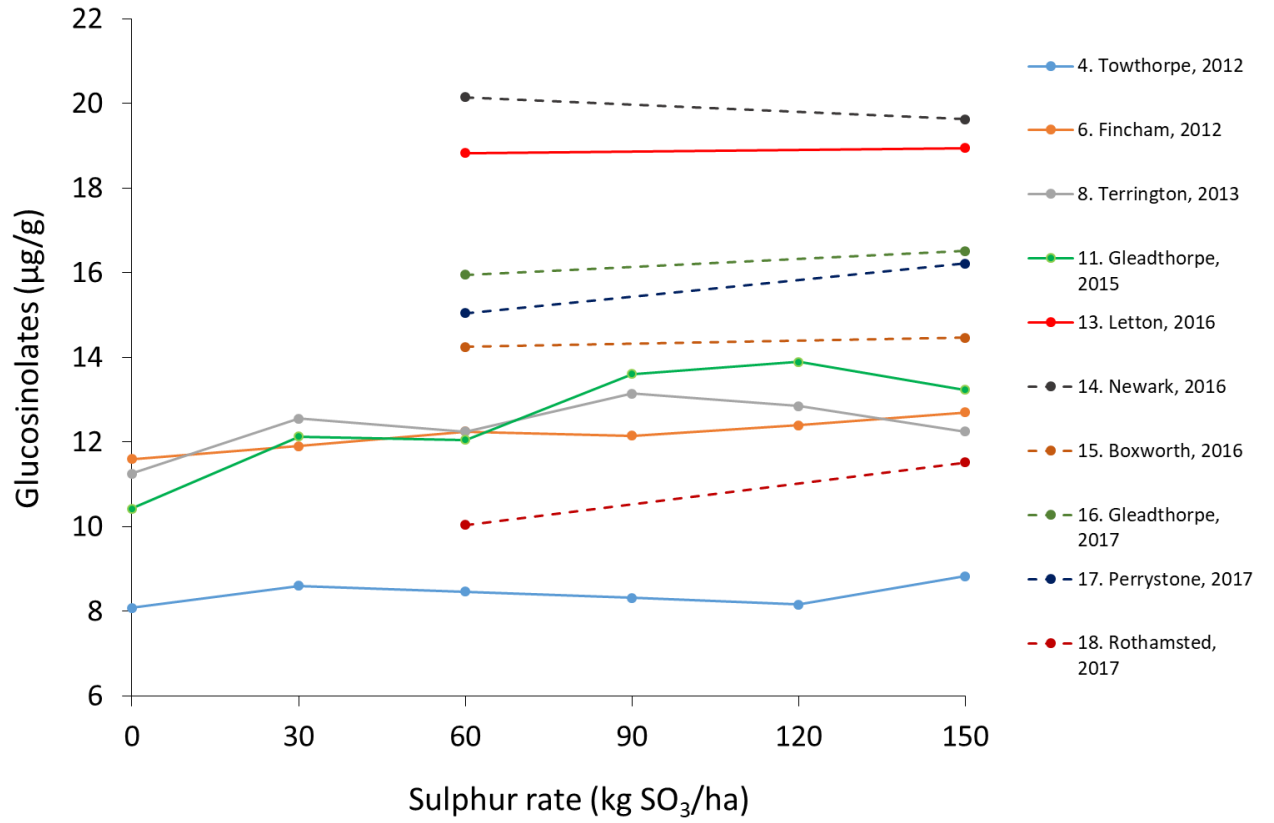


Figure 7. There was little effect of S fertiliser rate on glucosinolates at ten sites

Seed sulphur content (2014-2017 sites)

Seed S concentrations increased with S fertiliser application rate at all of the ten sites where this was measured (Table 11 to Table 20) The increase seed S content was statistically significant (P<0.05) at six of the ten sites, including four of the five sites where there was a yield response to S (with the exception of Gleadthorpe in 2015) and two sites where yield did not respond to S fertiliser (Gleadthorpe and Rothamsted in 2017). At the five sites which showed a yield response to S, the mean increase in seed S concentration between the zero S control and highest S rate (150 kg SO_3/ha) was 1216 mg/kg (range 535 to 1883 mg S/kg) compared to a mean of 325 mg S/kg (range 171 to 458 mg S/kg) at the five sites which did not show a yield response to S fertiliser.

Mean seed S concentration measured on the zero S control treatments at the five sites which showed a yield response to S was 3323 mg S/kg (range 2721-3914 mg S/kg), compared to 4094 mg S/kg (range 3703-4755 mg S/kg) from the five sites which did not show a yield response to S (Table 10).

Based on this data, we consider that seed S concentrations <3000 mg S/kg are likely to indicate the crop is deficient in S and values >4400 mg S/kg indicate the crop is not deficient in S. However, it is difficult to identify moderate cases of S deficiency based on seed S content. Seed S concentrations in the range of 3700-4000 mg S/kg were measured on the zero S control treatments at two sites which showed a yield response to S and at three sites where there was no yield response to S (Table 10).

There was a significant effect of N fertiliser (P<0.05) on seed S concentrations at six sites (three which showed a yield response to S fertiliser and three which didn't). At these six sites, mean seed S concentrations were 294 mg S/kg greater at the higher N rate (range 151 to 590 mg S/kg) (Table 11 to Table 20).

Table 10. Seed sulphur content and N:S ratio (zero S control treatment)

Harvest year	Site	Yield increase (t/ha)[1]	Seed S (mg/kg)	Seed N:S ratio
2014	Frostenden	4.0	2721	12.3
	Woburn	3-4	2856	11.8
2015	Gleadthorpe	0.9	3914	8.5
	Perrystone	0.5	3211	9.3
2016	Letton	0.5	3913	7.7
	Newark	*None*	4755	6.4
	Boxworth	*None*	3833	7.7
2017	Gleadthorpe	*None*	3703	8.0
	Perrystone	*None*	4431	7.2
	Rothamsted	*None*	3748	8.6

1. Yield increase calculated as yield at optimum SO_3 rate minus yield from zero S control treatment.

Seed N:S ratio (2014-2017 sites)

Sulphur fertiliser applications significantly reduced (P<0.05) seed N:S ratio at five of the ten sites (at which this parameter was measured), including four of the five sites which showed a yield response to S (with the exception of Gleadthorpe in 2015) and one site where there was no yield response to S fertiliser (Gleadthorpe in 2017) (Table 11 to Table 20).

The highest seed N:S ratios were measured from the zero S control treatments at the Frostenden (12.3; Table 11) and Woburn (11.8; Table 12) sites, which also showed the most pronounced symptoms of S deficiency. Seed N:S ratios from the zero S control treatments from the five sites which showed a yield response to S were a mean of 12.3 (range 7.7-9.9), compared to 7.6 (range 6.4-8.6) from the five sites which there was no yield response to S (Table 10).

There are no generally accepted critical values for N:S ratio in oilseed rape seed reported in the literature. Based on data from this project, we consider that a seed N:S ratio >9.0 is likely to indicate the crop is deficient in S and a ratio <7.5 to indicate the crop is not deficient in S. However, as noted for seed S concentrations, it is difficult to identify moderate cases of S deficiency based on seed N:S ratio. Seed N:S ratios in the range of 7.5 to 9.0 were measured from the zero S control treatments from two sites which showed a yield response to S and from three sites where there was no yield response to S (Table 10).

There was a significant effect of N fertiliser (P<0.05) on seed N:S ratio at two sites (Perrystone in 2015 and 2017), where N:S ratio was increased by a mean of 0.3 at the higher N rate.

3.3.7. Seed sulphur offtake (2014-2017 sites)

Seed S offtake is controlled by variation in both seed yields and S concentrations. S fertiliser significantly increased (P<0.05) seed S offtake at five of ten sites, including four of the five sites which showed a yield response to S (with the exception of Gleadthorpe in 2015) and one site which didn't show a yield response to S fertiliser (Gleadthorpe in 2017) (Table 11 to Table 20).

The largest increase in seed S offtake (of 46 kg SO_3/ha) was measured at Frostenden in 2014 where S fertiliser increased seed S offtake from 6 kg SO_3/ha on the zero S control treatment to a maximum of 52 kg SO_3/ha from the highest fertiliser S rate of 150 kg SO_3/ha (Table 11). Increases measured at the other sites were: 38 kg SO_3/ha at Woburn in 2014 (Table 12), 19 kg SO_3/ha from Perrystone in 2015 (Table 14c) and 14 kg SO_3/ha at Letton in 2016 (Table 15) and 5 kg/ha at Gleadthorpe in 2017 (Table 18).

There was a small increase in seed S offtake of between 3 and 6 kg SO_3/ha at the higher N rate (P<0.05) at six sites (Frostenden, 2014 Table 11; Perrystone, 2015 Table 14c; Letton, 2016 Table 15; Boxworth 2016 Table 17; Gleadthorpe 2017 Table 18; Rothamsted 2017 Table 20).

The mean seed S concentration from the 60 kg SO_3/ha fertiliser treatment (i.e. within the current RB209 recommended range) from all ten sites was 4157 mg S/ha (Table 11 to Table 20). Based on

this value, an oilseed rape crop yielding 3.5 t/ha would be estimated to remove 33 kg SO_3/ha in the seed and a crop yielding 5.0 t/ha will remove 47 kg SO_3/ha.

Table 11. Effect of fertiliser S and N treatments on oilseed rape yields and seed composition at Frostenden in 2014

S rate kg SO_3/ ha	Yield (t/ha 91% DM)			Oil content (%)			Gross output yield (t/ha 91% DM)			Protein (%)		
	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	Mean
0	0.9	1.0	**0.9**	39.0	42.7	**40.8**	0.9	1.0	**1.0**	20.5	19.5	**20.0**
30	4.4	4.3	**4.3**	46.1	44.2	**45.2**	4.8	4.5	**4.7**	18.5	19.1	**18.8**
60	4.9	5.0	**4.9**	46.0	45.0	**45.5**	5.3	5.4	**5.3**	18.9	19.9	**19.4**
90	4.7	5.4	**5.0**	45.5	44.5	**45.0**	5.1	5.7	**5.4**	19.4	20.3	**19.9**
120	4.9	5.0	**5.0**	45.4	43.7	**44.6**	5.3	5.3	**5.3**	19.6	21.1	**20.3**
150	4.7	5.2	**4.9**	45.2	44.1	**44.6**	5.0	5.5	**5.2**	19.8	20.8	**20.3**
Mean	***4.1***	***4.3***	***4.2***	***44.5***	***44.0***	***44.3***	***4.4***	***4.6***	***4.5***	***19.5***	***20.1***	***19.8***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	<0.001	0.164	0.340	<0.001	0.454	0.942	<0.001	0.178	0.370	<0.001	0.261	0.541
N	0.022	0.095	0.196	0.060	0.262	0.544	0.091	0.103	0.214	0.001	0.151	0.312
N x S	0.210	0.232	0.481	<0.001	0.642	1.332	0.206	0.252	0.523	0.002	0.369	0.765

S rate kg/ha SO_3	Glucosinolates (μg/g)			Sulphur content (mg S/kg)			Seed N:S ratio			Seed S offtake (kg SO_3/ha)		
	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**
0	7.3	9.3	**8.3**	2718	2724	**2721**	12.7	12.0	**12.3**	5.4	6.0	**5.7**
30	10.3	8.3	**9.3**	2635	2503	**2569**	11.7	12.9	**12.3**	26.5	24.5	**25.5**
60	13.4	11.7	**12.6**	3387	3639	**3513**	9.2	8.9	**9.0**	37.5	41.3	**39.4**
90	14.7	13.0	**13.9**	4338	4323	**4331**	7.3	7.8	**7.5**	46.2	52.7	**49.5**
120	16.3	15.6	**16.0**	3971	4832	**4402**	8.4	7.4	**7.9**	44.0	55.5	**49.8**
150	17.6	16.6	**17.1**	4417	4792	**4604**	7.4	7.3	**7.3**	46.9	56.2	**51.5**
Mean	***13.3***	***12.4***	***12.8***	***3578***	***3802.3***	***3690***	***9.4***	***9.4***	***9.4***	***34.4***	***39.4***	***36.9***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	<0.001	0.875	1.815	<0.001	237	492	<0.001	0.774	1.604	<0.001	1.801	3.735
N	0.100	0.505	1.048	0.115	137	284	0.863	0.447	0.926	<0.001	1.040	2.156
N x S	0.241	1.238	2.567	0.352	335	695	0.739	1.094	2.269	0.009	2.547	5.282

Table 12. Effect of fertiliser S and N treatments on oilseed rape yields and seed composition at Woburn in 2014

S rate kg SO_3/ ha	**Yield (t/ha 91% DM)**			**Oil content (%)**			**Gross output yield (t/ha 91% DM)**			**Protein (%)**		
	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**	N rate 1 220 kg/ha	N rate 2 310 kg/ha	Mean
0	2.4	1.2	**1.8**	41.7	42.3	**42.0**	2.4	1.3	**1.8**	20.6	21.2	**20.9**
30	4.6	5.1	**4.8**	45.6	45.9	**45.8**	4.9	5.6	**5.3**	19.6	19.5	**19.5**
60	5.1	5.1	**5.1**	46.0	45.3	**45.7**	5.6	5.5	**5.5**	19.5	20.2	**19.8**
90	5.1	5.1	**5.1**	45.8	45.3	**45.6**	5.6	5.5	**5.6**	19.8	20.4	**20.1**
120	5.1	5.3	**5.2**	45.6	44.9	**45.3**	5.5	5.7	**5.6**	20.1	20.8	**20.4**
150	4.7	5.0	**4.8**	45.5	44.4	**45.0**	5.1	5.3	**5.2**	20.1	21.3	**20.7**
Mean	***4.5***	***4.5***	***4.5***	***45.1***	***44.7***	***44.9***	***4.8***	***4.8***	***4.8***	***19.9***	***20.5***	***20.2***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	<0.001	0.252	0.522	<0.001	0.458	0.949	<0.001	0.268	0.557	<0.001	0.242	0.502
N	0.999	0.145	0.301	0.162	0.264	0.548	0.863	0.155	0.321	<0.001	0.140	0.290
N x S	0.038	0.356	0.738	0.481	0.647	1.343	0.049	0.380	0.787	0.226	0.343	0.711

S rate kg/ha SO_3	**Glucosinolates (μg/g)**			**Sulphur content (mg S/kg)**			**Seed N:S ratio**			**Seed S offtake (kg SO_3/ha)**		
	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**
0	6.1	10.2	**8.2**	2560	3153	**2856**	12.5	11.1	**11.8**	13.4	8.3	**10.9**
30	10.3	8.5	**9.4**	2969	2930	**2950**	10.9	10.9	**10.9**	30.9	34.3	**32.6**
60	10.0	11.2	**10.6**	3217	3455	**3336**	9.7	9.4	**9.6**	37.3	40.1	**38.7**
90	11.4	12.5	**11.9**	3717	3854	**3785**	8.5	8.5	**8.5**	43.4	44.9	**44.2**
120	14.0	12.9	**13.5**	4086	4192	**4139**	8.0	8.2	**8.1**	47.2	51.0	**49.1**
150	14.5	13.9	**14.2**	4272	4465	**4369**	7.7	7.4	**7.5**	45.6	50.6	**48.1**
Mean	***11.1***	***11.5***	***11.3***	***3470***	***3675***	***3572***	***9.5***	***9.2***	***9.4***	***36.3***	***38.2***	***37.2***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	<0.001	0.936	1.941	<0.001	150.7	312.5	<0.001	0.507	1.051	<0.001	2.361	4.897
N	0.392	0.540	1.121	0.028	87.0	180.4	0.316	0.292	0.607	0.174	1.363	2.827
N x S	0.056	1.324	2.745	0.444	213.1	441.9	0.663	0.716	1.486	0.358	3.339	6.926

Table 13. Effect of fertiliser S treatments on oilseed rape yields and seed composition at Gleadthorpe in 2015

S rate kg SO_3/ha	**Yield (t/ha 91% DM)**	**Oil content (%)**	**Gross output (t/ha 91% DM)**	**Protein (%)**	**Glucosinolates (µg/g)**	**Sulphur content (mg S/kg)**	**Seed N:S ratio**	**Seed S offtake (kg SO_3/ha)**
0	4.3	47.0	4.7	19.3	10.4	3914	8.5	39.5
30	5.3	47.0	5.8	19.3	12.1	4597	6.8	55.0
60	5.2	46.8	5.8	19.6	12.1	4593	7.0	54.5
90	5.1	46.4	5.6	19.6	13.6	4252	7.5	49.6
120	5.2	46.1	5.7	19.8	13.9	4544	7.0	53.6
150	5.2	47.4	5.7	19.1	13.2	4449	6.9	52.4
Mean	***5.0***	***46.8***	***5.6***	***19.4***	***12.6***	***4392***	***7.3***	***50.8***
***P*-value**	**0.133**	**0.249**	**0.172**	**0.199**	**0.235**	**0.353**	**0.266**	**0.125**
SED	0.354	0.507	0.410	0.293	1.424	336.8	0.716	5.46
LSD	0.790	1.130	0.913	0.653	3.172	750.3	1.595	12.17

Table 14a. Effect of fertiliser S and N treatments and variety on oilseed rape yields, oil content and gross output at Perrystone in 2015

S rate kg/ha SO_3	Yield (t/ha 91% DM)					Oil content (%)					Gross output (t/ha 91% DM)				
	DK Expower		DK Extrovert		Mean	DK Expower		DK Extrovert		Mean	DK Expower		DK Extrovert		Mean
	N1 160 kg/ha	N2 250 kg/ha	N1 160 kg/ha	N2 250 kg/ha		N1 160 kg/ha	N2 250 kg/ha	N1 160 kg/ha	N2 250 kg/ha		N1 160 kg/ha	N2 250 kg/ha	N1 160 kg/ha	N2 250 kg/ha	
0	4.8	4.6	4.9	4.8	**4.8**	47.0	47.9	47.9	46.4	**46.5**	5.3	4.9	5.5	5.2	**5.2**
30	5.1	5.5	5.1	5.3	**5.3**	46.9	47.5	47.5	46.3	**46.6**	5.7	5.9	5.7	5.8	**5.8**
60	5.1	5.4	5.2	5.4	**5.3**	47.0	45.6	47.3	46.0	**46.5**	5.6	5.8	5.7	5.9	**5.8**
90	5.0	5.4	5.2	5.5	**5.3**	47.1	44.9	47.5	46.2	**46.4**	5.5	5.8	5.8	6.0	**5.8**
120	5.1	5.3	5.2	5.4	**5.3**	47.2	44.8	47.3	45.6	**46.2**	5.7	5.7	5.7	5.9	**5.8**
150	5.0	5.3	4.9	5.2	**5.1**	46.7	44.6	47.8	45.4	**46.1**	5.5	5.6	5.5	5.6	**5.5**
Mean	***5.0***	***5.2***	***5.1***	***5.3***	***5.2***	***47.0***	***45.0***	***47.6***	***46.0***	***46.4***	***5.5***	***5.6***	***5.7***	***5.7***	***5.6***

Treatment	*P*-value	SED	LSD	*P*-value	SED	LSD	*P*-value	SED	LSD
S	<0.001	0.102	0.206	0.034	0.157	0.315	<0.001	0.116	0.233
N	0.001	0.059	0.119	<0.001	0.090	0.182	0.181	0.067	0.135
Variety	0.473	0.059	0.119	<0.001	0.090	0.182	0.123	0.067	0.135
S x N	0.114	0.145	0.291	0.008	0.222	0.446	0.118	0.164	0.330
S x Variety	0.710	0.145	0.291	0.035	0.222	0.446	0.675	0.164	0.330
N x Variety	0.837	0.084	0.168	0.051	0.128	0.257	0.997	0.095	0.191
SxN x Variety	0.992	0.205	0.412	0.298	0.313	0.631	0.990	0.232	0.467

Table 14b. Effect of fertiliser S and N treatments and variety on seed glucosinolates, sulphur and protein content at Perrystone in 2015

S rate kg/ha SO_3	Glucosinolates (µg/g)					Sulphur content (mg S/kg)					Protein (%)				
	DK Expower		DK Extrovert		Mean	DK Expower		DK Extrovert		Mean	DK Expower		DK Extrovert		Mean
	N1 160 kg/ha	N2 250 kg/ha	N1 160 kg/ha	N2 250 kg/ha		N1 160 kg/ha	N2 250 kg/ha	N1 160 kg/ha	N2 250 kg/ha		N1 160 kg/ha	N2 250 kg/ha	N1 160 kg/ha	N2 250 kg/ha	
0	10.9	8.5	10.1	9.5	**9.8**	3318	3115	3073	3336	**3211**	17.9	19.2	17.7	18.9	**18.5**
30	12.3	11.1	11.8	10.8	**11.5**	3432	3842	3867	3805	**3736**	18.2	19.0	18.0	19.0	**18.5**
60	13.7	12.3	13.0	12.4	**12.8**	3725	4099	4210	4297	**4083**	18.2	19.3	18.1	19.4	**18.8**
90	15.0	13.8	11.9	13.7	**13.6**	3878	4290	4168	4235	**4143**	18.0	20.0	18.0	19.4	**18.9**
120	14.7	13.7	14.5	13.8	**14.2**	3902	4700	4294	4932	**4457**	18.1	20.0	18.2	19.8	**19.0**
150	14.7	14.3	14.2	13.7	**14.2**	4211	4751	4220	4826	**4502**	18.3	20.2	17.7	20.1	**19.1**
Mean	***13.5***	***12.3***	***12.6***	***12.3***	***12.7***	***3744***	***4133***	***3972***	***4238***	***4022***	***18.1***	***19.6***	***18.0***	***19.5***	***18.8***

Treatment	*P*-value	SED	LSD	*P*-value	SED	LSD	*P*-value	SED	LSD
S	<0.001	0.475	0.956	<0.001	100.7	202.7	<0.001	0.143	0.289
N	0.008	0.274	0.552	<0.001	58.2	117.1	<0.001	0.083	0.167
Variety	0.093	0.274	0.552	0.006	58.2	117.1	0.043	0.083	0.167
S x N	0.531	0.672	1.352	0.011	142.4	286.7	<0.001	0.203	0.498
S x Variety	0.568	0.672	1.352	0.421	142.4	286.7	0.613	0.203	0.408
N x Variety	0.087	0.388	0.781	0.299	82.2	165.5	0.968	0.117	0.236
SxN x Variety	0.579	0.950	1.912	0.230	201.4	405.5	0.519	0.287	0.577

Table 14c. Effect of fertiliser S and N treatments and variety on seed N:S ratio and seed SO_3 offtake at Perrystone in 2015

S rate kg/ha SO_3	**Seed N:S ratio**					**Seed S offtake (kg SO_3/ha)**				
	DK Expower		**DK Extrovert**		**Mean**	**DK Expower**		**DK Extrovert**		**Mean**
	N rate 1 160 kg/ha	N rate 2 250 kg/ha	N rate 1 160 kg/ha	N rate 2 250 kg/ha		N rate 1 160 kg/ha	N rate 2 250 kg/ha	N rate 1 160 kg/ha	N rate 2 250 kg/ha	
0	8.5	10.2	9.3	9.2	**9.3**	36.3	32.4	34.6	36.3	**34.9**
30	8.5	8.2	7.3	8.1	**8.0**	40.3	48.1	44.9	46.2	**44.9**
60	7.8	7.8	6.8	7.4	**7.4**	43.0	50.5	49.6	52.9	**49.0**
90	7.3	7.8	6.8	7.6	**7.4**	44.0	52.8	49.4	53.4	**49.9**
120	7.3	7.1	6.3	6.4	**6.8**	45.8	57.0	50.7	61.0	**53.6**
150	6.8	7.1	6.7	6.8	**6.9**	47.9	56.6	47.1	56.6	**52.1**
Mean	***7.7***	***8.0***	***7.2***	***7.6***	***7.6***	***42.9***	***49.6***	***46.1***	***51.1***	***47.4***

Treatment	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	<0.001	0.2168	0.4364	<0.001	1.577	3.174
N	0.006	0.1252	0.2519	<0.001	0.911	1.833
Variety	<0.001	0.1252	0.2519	0.013	0.911	1.833
S x N	0.487	0.3066	0.6171	0.011	2.230	4.489
S x Variety	0.468	0.3066	0.6171	0.557	2.230	4.489
N x Variety	0.870	0.1770	0.3563	0.361	1.288	2.592
S x N x Variety	0.043	0.4336	0.8727	0.441	3.154	6.349

Table 15. Effect of fertiliser S and N treatments on oilseed rape yields and seed composition at Letton in 2016

S rate kg SO_3/ ha	**Yield (t/ha 91% DM)**			**Oil content (%)**			**Gross output yield (t/ha 91% DM)**			**Protein (%)**		
	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	Mean
0	4.0	3.7	**3.9**	43.0	41.5	**42.2**	4.2	3.8	**4.0**	16.6	18.2	**17.4**
30	4.2	4.4	**4.3**	43.2	42.4	**42.8**	4.4	4.5	**4.5**	16.8	17.8	**17.3**
60	4.2	4.3	**4.2**	43.7	42.7	**43.2**	4.4	4.5	**4.4**	16.7	18.2	**17.5**
90	4.3	4.7	**4.5**	43.1	42.8	**43.0**	4.5	4.9	**4.7**	16.8	18.2	**17.5**
120	4.3	4.4	**4.4**	43.3	42.9	**43.1**	4.5	4.6	**4.6**	16.6	18.1	**17.4**
150	4.4	4.5	**4.5**	43.6	42.4	**43.0**	4.7	4.7	**4.7**	17.1	18.7	**17.9**
Mean	***4.2***	***4.3***	***4.3***	***43.3***	***42.4***	***42.9***	***4.5***	***4.5***	***4.5***	***16.8***	***18.2***	***17.5***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	0.072	0.214	0.442	0.933	0.958	1.978	0.040	0.218	0.450	0.109	0.220	0.454
N	0.493	0.124	0.255	0.132	0.553	1.142	0.779	0.126	0.260	<0.001	0.127	0.262
N x S	0.693	0.303	0.626	0.990	1.355	2.797	0.616	0.308	0.636	0.764	0.311	0.642

S rate kg/ha SO_3	**Glucosinolates (μg/g)**			**Sulphur content (mg S/kg)**			**Seed N:S ratio**			**Seed S offtake (kg SO_3/ha)**		
	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**
0	N.D	N.D	**N.D**	3657	4170	**3913**	7.8	7.5	**7.7**	33.7	35.1	**34.4**
30	N.D	N.D	**N.D**	4224	4391	**4308**	6.8	6.9	**6.9**	40.5	43.8	**42.2**
60	N.D	18.8	**18.8**	4337	4739	**4538**	6.6	6.6	**6.6**	41.1	46.3	**43.7**
90	N.D	N.D	**N.D**	4401	4695	**4548**	6.5	6.6	**6.6**	42.9	50.1	**46.5**
120	N.D	N.D	**N.D**	4341	4864	**4602**	6.5	6.4	**6.4**	42.7	49.0	**45.8**
150	N.D	18.9	**18.9**	4626	4920	**4773**	6.4	6.4	**6.4**	46.5	50.5	**48.5**
Mean	***N.D***	***18.9***	***18.9***	***4264***	***4630***	***4447***	***6.8***	***6.7***	***6.8***	***41.2***	***45.8***	***43.5***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	0.919	1.073	3.414	<0.001	122.3	252.5	<0.001	0.176	0.363	<0.001	2.750	5.675
N	N.D	N.D	N.D	<0.001	70.6	145.8	0.662	0.102	0.210	0.008	1.588	3.277
N x S	N.D	N.D	N.D	0.664	173.0	357.1	0.821	0.249	0.513	0.912	3.889	8.026

Table 16. Effect of fertiliser S and N treatments on oilseed rape yields and seed composition at Newark in 2016

S rate kg SO_3/ ha	**Yield (t/ha 91% DM)**			**Oil content (%)**			**Gross output yield (t/ha 91% DM)**			**Protein (%)**		
	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	Mean
0	4.5	4.3	**4.4**	45.6	45.6	**45.6**	4.9	4.6	**4.7**	17.3	18.4	**17.8**
30	4.4	4.2	**4.3**	46.2	44.7	**45.5**	4.8	4.5	**4.6**	17.6	18.5	**18.0**
60	4.2	4.3	**4.3**	45.0	46.0	**45.5**	4.5	4.7	**4.6**	17.4	18.5	**17.9**
90	4.4	4.2	**4.3**	45.6	44.1	**44.8**	4.7	4.5	**4.6**	17.9	18.4	**18.1**
120	4.6	4.3	**4.5**	46.1	44.8	**45.5**	5.0	4.6	**4.8**	17.7	18.7	**18.2**
150	4.1	4.8	**4.4**	46.0	45.1	**45.5**	4.4	5.2	**4.8**	18.2	18.7	**18.4**
Mean	***4.4***	***4.4***	***4.4***	***45.7***	***45.0***	***45.4***	***4.7***	***4.7***	***4.7***	***17.7***	***18.5***	***18.1***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	0.983	0.335	0.731	0.918	0.746	1.625	0.981	0.384	0.836	0.444	0.292	0.637
N	1.000	0.194	0.422	0.126	0.431	0.938	0.836	0.222	0.483	<0.001	0.169	0.368
N x S	0.617	0.474	1.034	0.489	1.055	2.298	0.634	0.543	1.182	0.826	0.413	0.901

S rate kg/ha SO_3	**Glucosinolates (μg/g)**			**Sulphur content (mg S/kg)**			**Seed N:S ratio**			**Seed S offtake (kg SO_3/ha)**		
	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**
0	N.D	N.D	**N.D**	4716	4794	**4755**	6.3	6.5	**6.4**	48.2	46.4	**47.3**
30	N.D	N.D	**N.D**	4697	5010	**4854**	6.3	6.2	**6.3**	47.1	47.3	**47.2**
60	N.D	20.1	**20.1**	4885	4922	**4904**	6.2	6.2	**6.2**	46.4	48.6	**47.5**
90	N.D	N.D	**N.D**	4800	5006	**4903**	6.4	6.2	**6.3**	47.6	48.0	**47.8**
120	N.D	N.D	**N.D**	4741	5060	**4901**	6.6	6.2	**6.4**	49.4	49.6	**49.5**
150	N.D	19.6	**N.D**	4832	5040	**4936**	6.4	6.3	**6.3**	44.8	55.3	**50.1**
Mean	***N.D***	***19.9***	***19.9***	***4776***	***4972***	***4874***	***6.4***	***6.3***	***6.3***	***47.2***	***49.2***	***48.2***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	0.252	0.318	1.368	0.675	113.5	247.2	0.547	0.099	0.217	0.930	3.47	7.56
N	N.D	N.D	N.D	0.011	65.5	142.7	0.187	0.057	0.125	0.348	2.00	4.36
N x S	N.D	N.D	N.D	0.723	160.5	349.6	0.262	0.141	0.306	0.570	4.91	10.69

Table 17. Effect of fertiliser S and N treatments on oilseed rape yields and seed composition at Boxworth in 2016

S rate kg SO_3/ ha	**Yield (t/ha 91% DM)**			**Oil content (%)**			**Gross output yield (t/ha 91% DM)**			**Protein (%)**		
	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	Mean
0	2.3	2.5	**2.4**	38.9	36.4	**37.7**	2.2	2.4	**2.3**	18.1	19.7	**18.9**
30	2.3	2.7	**2.5**	38.2	36.0	**37.1**	2.2	2.5	**2.4**	17.8	19.1	**18.5**
60	2.3	2.3	**2.3**	40.1	37.1	**38.6**	2.3	2.2	**2.2**	18.0	19.6	**18.8**
90	2.2	2.3	**2.3**	38.3	37.0	**37.7**	2.2	2.2	**2.2**	18.1	19.6	**18.9**
120	2.1	2.5	**2.3**	39.0	36.2	**37.6**	2.1	2.4	**2.2**	18.5	19.3	**18.9**
150	2.2	2.5	**2.4**	39.6	37.1	**38.4**	2.2	2.4	**2.3**	17.9	19.4	**18.7**
Mean	***2.3***	***2.5***	***2.4***	***38.9***	***36.4***	***37.7***	***2.2***	***2.4***	***2.3***	***18.1***	***19.7***	***18.9***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	0.592	0.124	0.256	0.627	0.944	1.947	0.783	0.137	0.283	0.483	0.277	0.572
N	0.005	0.072	0.148	<0.001	0.545	1.124	0.114	0.079	0.163	<0.001	0.160	0.330
N x S	0.406	0.178	0.363	0.960	1.334	2.754	0.575	0.194	0.400	0.670	0.392	0.809

S rate kg/ha SO_3	**Glucosinolates (μg/g)**			**Sulphur content (mg S/kg)**			**Seed N:S ratio**			**Seed S offtake (kg SO_3/ha)**		
	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**
0	N.D	N.D	**N.D**	3918	3749	**3833**	7.3	8.1	**7.7**	20.4	21.4	**20.9**
30	N.D	N.D	**N.D**	3875	4206	**4041**	7.4	7.5	**7.5**	19.9	25.5	**22.7**
60	N.D	14.3	**14.3**	3994	4039	**4016**	7.2	7.4	**7.3**	20.8	21.3	**21.1**
90	N.D	N.D	**N.D**	4131	4009	**4070**	7.0	8.3	**7.6**	21.1	20.7	**20.9**
120	N.D	N.D	**N.D**	3955	4192	**4074**	7.5	7.6	**7.5**	19.0	24.0	**21.5**
150	N.D	14.5	**14.5**	3811	4771	**4291**	7.6	6.3	**7.0**	19.3	27.3	**23.3**
Mean	**N.D**	***14.4***	***14.4***	**3947**	**4161**	**4054**	**7.3**	**7.5**	**7.4**	***20.1***	***23.4***	***21.7***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	0.778	0.718	1.993	0.554	230.0	474.7	0.416	0.388	0.800	0.419	1.433	2.973
N	*	*	*	0.121	132.8	274.1	0.397	0.224	0.462	<0.001	0.828	1.716
N x S	*	*	*	0.191	325.8	671.3	0.065	0.548	1.131	0.042	2.027	4.204

Table 18. Effect of fertiliser S and N treatments on oilseed rape yields and seed composition at Gleadthorpe in 2017

S rate kg SO_3/ ha	**Yield (t/ha 91% DM)**			**Oil content (%)**			**Gross output yield (t/ha 91% DM)**			**Protein (%)**		
	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	Mean
0	4.4	4.7	**4.5**	43.7	40.5	**42.1**	4.6	4.7	**4.7**	16.1	19.2	**17.6**
30	4.3	4.6	**4.5**	43.4	40.4	**41.9**	4.6	4.6	**4.6**	16.4	19.1	**17.8**
60	4.4	4.8	**4.6**	43.2	40.8	**42.0**	4.6	4.9	**4.7**	16.6	19.4	**18.0**
90	4.5	4.7	**4.6**	43.4	41.6	**42.5**	4.7	4.8	**4.8**	16.3	18.4	**17.4**
120	4.5	5.0	**4.7**	43.1	40.6	**41.8**	4.7	5.0	**4.8**	16.7	18.8	**17.8**
150	4.5	4.7	**4.6**	43.5	39.8	**41.6**	4.7	4.7	**4.7**	16.4	19.5	**17.9**
Mean	***4.4***	***4.7***	***4.6***	***43.4***	***40.6***	***42.0***	***4.6***	***4.8***	***4.7***	***16.4***	***19.1***	***17.7***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	0.444	0.115	0.238	0.677	0.538	1.115	0.540	0.131	0.272	0.441	0.318	0.659
N	<0.001	0.066	0.138	<0.001	0.310	0.644	0.069	0.076	0.157	<0.001	0.183	0.380
N x S	0.765	0.163	0.337	0.564	0.76	1.577	0.728	0.186	0.385	0.414	0.449	0.931

S rate kg/ha SO_3	**Glucosinolates (μg/g)**			**Sulphur content (mg S/kg)**			**Seed N:S ratio**			**Seed S offtake (kg SO_3/ha)**		
	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**	N rate 1 120 kg/ha	N rate 2 210 kg/ha	**Mean**
0	N.D	N.D	**N.D**	3451	3955	**3703**	8.1	8.0	**8.0**	34.5	42.0	**38.2**
30	N.D	N.D	**N.D**	3553	4188	**3870**	8.0	7.7	**7.9**	35.0	43.8	**39.4**
60	N.D	16.0	**16.0**	3674	4385	**4030**	7.7	7.8	**7.7**	36.7	48.0	**42.3**
90	N.D	N.D	**N.D**	3671	4076	**3874**	7.6	7.8	**7.7**	37.5	43.7	**40.6**
120	N.D	N.D	**N.D**	3745	4252	**3999**	7.7	7.6	**7.7**	38.0	48.0	**43.0**
150	N.D	16.5	**16.5**	3680	4461	**4070**	7.7	7.6	**7.6**	37.4	47.7	**42.6**
Mean	***N.D***	***16.2***	***16.2***	***3629***	***4219***	***3924***	***7.8***	***7.8***	***7.8***	***36.5***	***45.5***	***41.0***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	0.204	0.3	1.29	0.049	117.5	243.6	0.011	0.113	0.233	0.037	1.6	3.317
N	*	*	*	<0.001	67.8	140.7	0.791	0.065	0.135	<0.001	0.924	1.915
N x S	*	*	*	0.604	166.1	344.5	0.542	0.159	0.330	0.617	2.262	4.692

Table 19. Effect of fertiliser S and N treatments on oilseed rape yields and seed composition at Perrystone in 2017

S rate kg SO_3/ ha	**Yield (t/ha 91% DM)**			**Oil content (%)**			**Gross output yield (t/ha 91% DM)**			**Protein (%)**		
	N rate 1 190 kg/ha	N rate 2 280 kg/ha	Mean	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	Mean
0	4.9	4.7	4.8	39.9	41.3	**40.6**	4.9	4.8	**4.8**	18.3	18.9	**18.6**
30	4.5	4.5	4.5	41.2	40.4	**40.8**	4.6	4.5	**4.6**	18.9	19.2	**19.1**
60	4.6	4.7	4.6	41.6	39.6	**40.6**	4.7	4.6	**4.7**	18.7	19.0	**18.9**
90	4.6	4.4	4.5	41.1	40.7	**40.9**	4.7	4.4	**4.6**	18.5	18.9	**18.7**
120	4.5	4.2	4.3	41.8	40.9	**41.4**	4.6	4.2	**4.4**	18.5	19.3	**18.9**
150	4.5	4.4	4.5	40.4	40.8	**40.6**	4.5	4.5	**4.5**	18.7	19.6	**19.1**
Mean	**4.6**	**4.5**	**4.5**	**41.0**	**40.6**	**40.8**	**4.7**	**4.5**	**4.6**	**18.6**	**19.2**	**18.9**
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	0.240	0.192	0.397	0.613	0.497	1.031	0.282	0.1834	0.3803	0.196	0.221	0.458
N	0.248	0.111	0.229	0.208	0.287	0.596	0.144	0.1059	0.2195	<0.001	0.128	0.265
N x S	0.949	0.271	0.562	0.044	0.703	1.459	0.942	0.2593	0.5378	0.535	0.312	0.648

S rate kg/ha SO_3	**Glucosinolates (μg/g)**			**Sulphur content (mg S/kg)**			**Seed N:S ratio**			**Seed S offtake (kg SO_3/ha)**		
	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**	N rate 1 190 kg/ha	N rate 2 280 kg/ha	**Mean**
0	N.D	N.D	**N.D**	4502	4361	**4431**	7.0	7.4	**7.2**	50.0	46.8	**48.4**
30	N.D	N.D	**N.D**	4717	4654	**4685**	6.9	7.0	**6.9**	48.6	47.2	**47.9**
60	N.D	15.0	**15.0**	4985	4687	**4836**	6.5	7.2	**6.8**	52.1	49.5	**50.8**
90	N.D	N.D	**N.D**	4740	4723	**4732**	6.7	7.0	**6.8**	49.8	47.0	**48.4**
120	N.D	N.D	**N.D**	4765	4921	**4843**	6.6	6.8	**6.7**	48.3	46.5	**47.4**
150	N.D	16.2	**16.2**	4692	5068	**4880**	6.8	6.8	**6.8**	48.0	51.0	**49.5**
Mean	***N.D***	***15.6***	***5.6***	***4734***	***4736***	***4735***	***6.7***	***7.0***	***6.9***	***49.5***	***48.0***	***48.7***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	0.988	0.93	11.82	0.109	163.5	339.1	0.133	0.190	0.393	0.687	2.21	4.583
N	*	*	*	0.982	94.4	195.8	0.014	0.110	0.227	0.266	1.276	2.646
N x S	*	*	*	0.417	231.2	479.6	0.623	0.268	0.556	0.744	3.125	6.481

Table 20. Effect of fertiliser S and N treatments on oilseed rape yields and seed composition at Rothamsted in 2017

S rate kg SO_3/ ha	**Yield (t/ha 91% DM)**			**Oil content (%)**			**Gross output yield (t/ha 91% DM)**			**Protein (%)**		
	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**
0	5.1	5.6	**5.3**	42.1	42.3	**42.2**	5.3	5.8	**5.5**	17.6	17.9	**17.7**
30	5.1	5.5	**5.3**	42.5	42.0	**42.3**	5.3	5.6	**5.5**	17.4	18.6	**18.0**
60	5.0	5.6	**5.3**	42.1	42.3	**42.2**	5.2	5.8	**5.5**	17.6	18.2	**17.9**
90	5.2	5.0	**5.1**	42.6	42.3	**42.4**	5.4	5.2	**5.3**	17.7	18.1	**17.9**
120	5.7	5.1	**5.4**	42.1	41.2	**41.6**	5.9	5.2	**5.5**	17.7	18.6	**18.1**
150	5.4	5.6	**5.5**	42.0	41.8	**41.9**	5.6	5.8	**5.7**	17.8	18.7	**18.3**
Mean	***5.3***	***5.4***	***5.3***	***42.2***	***42.0***	***42.1***	***5.4***	***5.6***	***5.5***	***17.6***	***18.3***	***18.0***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	0.666	0.218	0.452	0.738	0.547	1.135	0.843	0.249	0.516	0.169	0.214	0.443
N	0.254	0.126	0.261	0.426	0.316	0.655	0.365	0.144	0.298	<0.001	0.123	0.256
N x S	0.120	0.308	0.639	0.885	0.774	1.606	0.150	0.352	0.729	0.303	0.302	0.627

S rate kg/ha SO_3	**Glucosinolates (μg/g)**			**Sulphur content (mg S/kg)**			**Seed N:S ratio**			**Seed S offtake (kg SO_3/ha)**		
	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**	N rate 1 220 kg/ha	N rate 2 310 kg/ha	**Mean**
0	N.D	N.D	**N.D**	3648	3849	**3748**	8.7	8.5	**8.6**	42.1	48.9	**45.5**
30	N.D	N.D	**N.D**	3658	3796	**3727**	8.8	8.9	**8.9**	42.7	47.2	**45.0**
60	N.D	10.0	**10.0**	3661	3778	**3720**	8.6	8.7	**8.7**	41.9	48.1	**45.0**
90	N.D	N.D	**N.D**	3704	3850	**3777**	8.6	8.8	**8.7**	44.1	44.2	**44.1**
120	N.D	N.D	**N.D**	3853	3956	**3905**	8.4	8.4	**8.4**	49.9	46.2	**48.0**
150	N.D	11.5	**11.5**	3818	4020	**3919**	8.4	8.5	**8.5**	46.9	51.4	**49.1**
Mean	***N.D***	***10.8***	***10.8***	***3723***	***3875***	***3799***	***8.6***	***8.6***	***8.6***	***44.6***	***47.7***	***46.1***
Treat	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**	***P*-value**	**SED**	**LSD**
S	0.113	0.543	2.338	0.001	51.5	106.7	0.061	0.144	0.298	0.130	2.026	4.202
N	*	*	*	<0.001	29.7	61.6	0.575	0.083	0.172	0.015	1.170	2.426
N x S	*	*	*	0.888	72.8	150.9	0.703	0.203	0.422	0.119	2.866	5.943

3.4. Discussion

3.4.1. Yield response to sulphur fertiliser

Ten of the 18 sites showed a yield response to S fertiliser (section 3.2.1). Table 21 combines information on the sites which responded to S fertiliser along with details of soil texture, organic matter content and over-winter rainfall, which are the main factors cited as contributing to the risk of S deficiency.

Lighter textured sandy soils are at greater risk of S deficiency than heavier textured soils as they are less 'retentive' of sulphate, and in addition lighter textured soils tend to have lower organic matter levels which is likely to result in lower levels of organic S mineralisation. Of the 18 sites reported here:

- Nine sites were 'lighter' textured loamy sand/sandy loam soils, eight of which showed a yield response to S fertiliser.
- Four sites were 'medium' textured sandy clay loam soils, two of which showed a yield response and two of which didn't show a yield response to S fertiliser.
- Five sites were 'heavier' textured clay/clay loam/silt clay loam soils, none of which showed a yield response to S fertiliser.

Soil texture therefore appears to be a key factor controlling risk of S deficiency in oilseed rape. A recommendation to apply S fertiliser to all light and medium textured soils would have identified 13 of 18 sites as requiring S fertiliser, including all ten sites which showed a yield response to S.

Soil organic matter levels varied between 0.5 and 4.4%, but the majority were in the range of 1.3-3.4%. It is difficult to distinguish the effect of organic matter content on S deficiency from the effect of soil texture. The nine lighter textured sites had a mean organic matter content of 1.9%; the four medium textured sites had a mean organic matter content of 2.6%; and the five heavier textured sites had a mean organic matter content of 2.9%. The one lighter textured sandy loam site which didn't show a yield response to S fertiliser (Gleadthorpe in 2017) had a higher organic matter content (2.4%), than the other six sandy loam sites (mean 1.6%; range 0.5-2.2%). However, soil particle size analysis from 2014-2017 sites shows that the 2017 Gleadthorpe site also had a lower sand content (59%) than the three other sandy loam sites for which this particle size data is available (68-77% sand), and it is therefore difficult to speculate as to whether soil organic matter or texture were contributory factors to the lack of yield response at this site.

Cussans *et al*. (2007) adopted a risk matrix approach to estimating likely responsiveness of winter wheat and winter barley to S, which takes into account soil texture and over-winter rainfall, and is published in the AHDB Nutrient Management Guide. High amounts of excess winter rainfall can increase the risk of S deficiency by leaching crop available sulphate from the soil. Cussans *et al.,* (2007) divided over-winter rainfall (from November to February) into 'low' (<175 mm), 'medium' (175-375 mm) and 'high' (>375 mm) categories. Over-winter rainfall data has been sourced using the

'MetMake' function in the ADAS Irriguide software which use Met Office data from nearby weather stations to interpolate weather data for a specific location using an inverse distance-weighting algorithm. Based on the categories defined by Cussans *et al.* (2007), four sites are in the 'low' rainfall band, 13 sites are in the 'moderate' rainfall band and one site is in the 'high' over-winter rainfall band.

Table 21. Yield response to S fertiliser and site soil texture, organic matter content and over-winter rainfall

Harvest year	Site	Yield increase (t/ha)[2]	% SOM	Soil texture				Winter rainfall Nov-Feb (mm)
				Class	% sand	% silt	% clay	
2011	Towthorpe	0.7	*	SCL	*	*	*	303
	Perrystone	0.9	0.5	SL	*	*	*	166
	Fincham	0.4	2.2	SCL	*	*	*	161
2012	Towthorpe	*None*	3.3	SCL	*	*	*	173
	Perryston	0.1	1.3	SL	*	*	*	184
	Fincham	*None*	2.3	SCL	*	*	*	121
2013	Perryston	0.5	2.0	SL	*	*	*	375
	Terrington	*None*	2.1	ZCL	*	*	*	228
2014	Frostenden	4.4	2.2	LS	85	8	7	219
	Woburn	3.8	1.9	SL	68	19	13	327
2015	Gleadthorpe	1.0	2.2	SL	77	15	9	180
	Perrystone	0.6	1.9	SL	74	13	13	265
2016	Letton	0.6	2.3	LS	81	10	9	297
	Newark	*None*	3.4	C	16	44	40	221
	Boxworth	*None*	4.4	C	24	30	46	203
2017	Gleadthorpe	*None*	2.4	SL	59	30	11	177
	Perrystone	*None*	1.9	CL	25	52	23	251
	Rothamsted	*None*	2.6	CL	26	52	21	261

1. Yield increase calculated as yield at optimum SO_3 rate minus yield from zero S control treatment.

Table 22. Estimating likely responsiveness to sulphur (AHDB Nutrient Management Guide Section 4 Arable Crops)

Soil texture	Winter rainfall (Nov-Feb)		
	Low (<175 mm)	Medium (175-375 mm)	High (>375 mm)
Sandy	**High**		
Loamy and coarse silty	**Low**	**High**	
Clay, fine silty or peaty	**Low**		**High**

Based on the risk matrix outlined by Cussans *et al.* (2007) and using the soil texture classification into light/medium/heavy soils outlined at the beginning of this section, ten of the 18 sites are identified as 'high' risk of S deficiency, nine of which showed a yield response to S. The Gleadthorpe site in 2017 was identified as 'high' risk but didn't show a yield response to S. The Fincham site in 2011 was identified as 'low' risk but did show a yield response to S; although this site was on a 'medium' textured soil, the lower over-winter rainfall of 161 mm puts it in the 'low' risk category. The shift from 'low' to 'high' risk for medium textured soils as over-winter rainfall exceeds 175 mm and for heavy textured soils as over-winter rainfall exceeds 375 mm is very abrupt and places a lot of importance on over-winter rainfall; it may be more appropriate to re-categorize both the medium soil type low rainfall category and heavy textured high rainfall category as 'intermediate' risk. Using this approach, nine of the ten sites which responded to S fertiliser are identified as high risk and one as 'intermediate' risk, with only one site which didn't respond to S incorrectly allocated 'high' risk.

This risk matrix approach is currently used in RB209 to identify cereal crops at high risk of S deficiency. The risk matrix is not currently used for oilseed and RB209 recommends that S is applied to all oilseed rape crops grown on mineral soils (i.e. not organic or peaty). However, based on the results from this project, there is a clear effect of soil texture on oilseed rape S deficiency and the risk matrix approach could usefully be extended to oilseed rape crops.

3.4.2. Diagnosing sulphur deficiency

This project included a number of assessments which can be used to help diagnose S deficiency including:

- Topsoil analysis
- Visual symptoms
- Leaf tissue analysis – malate:sulphate
- Leaf tissue analysis – total S content and N:S ratio
- Seed analysis – total S content and N:S ratio

The results from this project indicate that topsoil analysis for extractable S is not a useful indicator of likely yield response to S fertiliser.

Visual symptoms can be used to diagnose the more severe examples of S deficiency. Clear visual symptoms of deficiency were observed at the Frostenden and Woburn sites in 2014 where large yield responses of up to 4.4 t/ha were measured. However, the visual symptoms associated with yield responses in the range 0.6-1.0 t/ha at the other three sites which showed a yield response were slight. We consider that it is not possible to identify moderate S deficiency (resulting in yield penalties of around 0.5 t/ha) in commercial crops. Therefore we do not recommend that farmers rely on the presence of visual symptoms to diagnose S deficiency.

Leaf tissue analysis can be used as a diagnostic tool to assess S deficiency. AHDB Information Sheet 28 'Sulphur for cereals and oilseed rape' recommends the malate:sulphate test as the most

reliable plant tissue test based on the work by Blake-Kalff *et al*. (2000). The results from this project suggest that the timing of taking the sample is very important. Following the trend of malate:sulphate ratios within a season will distinguish between permanent and transient S deficiency, which is not possible by taking a sample once during the season. Leaf S content and N:S ratio also provided an indication of S deficiency.

The recommended timing of taking the tissue samples is during stem extension (Blake-Kalff *et al*., 2004). In this study, there was a tendency for the later tests to give a more accurate prediction of S deficiency. Blake-Kalff *et al*. (2004) showed that a slight or moderate S deficiency can be corrected using S applications as late as the yellow bud growth stage, so a diagnosis during late stem extension is practically useful. However, many growers are making decisions about whether or not to apply S earlier when the first N split is applied at, or before, the start of stem extension. Additionally, for severe S deficiencies early S application would be preferable. In situations where an early decision is required on the use of S fertiliser then the risk matrix table would be the most appropriate guide.

Quantifying seed N:S ratio will provide a retrospective check on crop S status and a guide for the need for S in future oilseed rape crops. The results from this project, indicated that low seed S concentrations and high N:S ratios could be used to identify some S deficient sites, and high seed S and low N:S could be used to identify some sufficient sites. However, for both tests there was a 'middle' range of values within which there were both sufficient and deficient sites, consequently it is difficult to identify moderate cases of S deficiency based on seed S content and/or N:S ratio. Furthermore, there are no generally accepted critical values for seed S content or N:S ratio in oilseed rape seed reported in the literature and the analysis of samples from ten sites in this project (2014-2017 sites) is not sufficient to determine critical values for slight and moderate deficiencies. However, for more severe S deficiencies the data showed that seed S concentration of <3000 mg/kg and N:S ratio >9 are likely to be reliable critical thresholds.

For the 18 sites in this project, using soil texture with over-winter rainfall to identify the risk of S deficiency was more successful than soil S or tissue S diagnostic tests.

3.5. Recommendations

Based on the results of this project we recommend:

- Updating oilseed rape S recommendations to 50-80 kg SO_3/ha.
- Updating the guidance for S application to oilseed rape to include the risk matrix for estimating likely responsiveness to S.
- Consider revising wording in the AHDB Sulphur information sheet to highlight potential uncertainty in diagnosing S deficiency based on visual symptoms and tissue analysis:
    - Visual symptoms:

- Existing guidance*: 'Visual symptoms are usually the first sign of a deficiency, however, they can easily be confused and, by the time they appear, it can be too late to correct the deficiency.'*
- Update to: *'Visual symptoms can be used to diagnose moderate to severe cases of S deficiency, however they can easily be confused with other nutrient deficiencies or crop stress and, by the time they appear, it can be too late to correct the deficiency. It is likely to be difficult to identify the slight visual symptoms normally associated with minor S deficiency that may still result in significant yield loss.*

- Tissue analysis:
  - Existing guidance: '*If a deficiency is suspected, tissue analysis in the spring can be a useful diagnostic tool. There are a number of laboratory tests that can be used to detect S deficiency but HGCA trials have shown that the malate: sulphate test is the most reliable'.*
  - Update to: *'If a deficiency is suspected, tissue analysis in the spring can be a useful diagnostic tool used in combination with the sulphur deficiency risk matrix based on soil type and over-winter rainfall. There are a number of laboratory tests that can be used to detect S deficiency but AHDB trials have shown that the malate:sulphate test is the most reliable.'*
  - Include an additional point under the list of 'things to remember when collecting tissue samples': *It is recommended to take two tissue samples approximately two weeks apart to help distinguish between permanent and transient S deficiency.*

4. Sulphur supply from organic materials to oilseed rape

This aim of this work was to produce guidance for farmers on crop available S supply from organic material application to oilseed rape and robust 'typical' values for 'extractable' S in the main types of organic materials.

4.1. Organic material total and extractable S content

4.1.1. Methodology

Sampling approach

A sampling and laboratory analysis programme was carried out to provide new data on the S characteristics of different types of organic materials. A total of 110 samples were collected between 2014 and 2015. Livestock manure samples were taken by ADAS staff according to the sampling methodology in Appendix 6 RB209 8th Edition, from a range of geographic locations and farm types across England and Wales. Biosolids samples were provided by the five Water Companies co-funding the current project. Samples included digested, enhanced digested (thermally hydrolysed) and limed digested biosolids from a range of sewage treatment works. The number of organic material samples collected are listed in Table 23. The organic material analysis database includes samples of organic materials used in the field experiments (Section 4.2).

Table 23. Number of samples collected of each type of organic material

Organic material	Number of samples
Cattle FYM	15
Pig FYM	15
Cattle slurry	15
Pig slurry	15
Poultry manure:	
Broiler litter	10
Layer manure	10
Biosolids:	
Digested	19
Enhanced digested	6
Digested and limed	5
Total	**110**

Laboratory analysis

Samples of organic materials were analysed for:

- Dry matter.
- Total S, K, P and Mg (aqua regia acid digest and analysis by inductively-coupled plasma optical emission spectrometry - ICP-OES).

- Total carbon (Modified Walkley-Black method).
- Total N (Dumas combustion method).
- Readily available N (i.e. NH_4-N, NO_3-N and for poultry manures uric-acid N).
- Extractable S (0.016M KH_2PO_4 extraction and analysis ICP-OES i.e. total S in the extract consisting of SO_4-S plus dissolved organic S).
- Extractable SO_4-S (0.016M KH_2PO_4 extraction and analysis by ion chromatography (IC) i.e. SO_4-S).

The 0.016M KH_2PO_4 extraction is one of the most commonly used methods for assessing soil 'extractable' S and was used in AHDB Cereals & Oilseeds project 3606 for the analysis of organic materials. The method of analysis of the extract determines the form of S measured e.g.; IC analysis method measures SO_4, whilst the ICP-OES method measures total S in the extract, which will include SO_4 and dissolved organic S. In this report results for total S, extractable S and extractable SO_4 are all presented as kg SO_3/t or m^3 on a fresh weight basis in order to facilitate comparison between the analysis methods and for consistency with units used in the AHDB Nutrient Management Guide (RB209).

AHDB Cereals & Oilseeds project 3606 reported that manure extractable S content was a more robust indicator of crop available S than total S, although extractable S was only measured using ICP-OES. The extraction was performed on dried and ground (<2mm) samples, which is consistent with the method used in AHDB Cereals & Oilseeds project 3606. However, analysis of a dried sample for slurries is difficult because of the large sample volume required and time taken to dry the sample and whilst this method has been used in this project, analysis of dried slurry samples is unlikely to be offered commercially to farmers. Therefore, the pig and cattle slurry samples from this project were analysed for extractable S using both a dried and fresh sample in order to provide a method comparison. The field experiments (Section 4.2) assessed extractable S (as measured by both ICP-OES and IC) as a predictor of organic material fertiliser S replacement value.

The C: organic N (i.e. total N minus readily available N) and C:S ratio have been calculated for the organic materials to give an indication of their relative organically-bound S mineralisation potential.

Data analysis

An unbalanced ANOVA model was used to evaluate the effect of organic material type on total S, extractable S, proportion of total S in extractable form, proportion of extractable S in SO_4-S form and C:S ratio. Where ANOVA showed statistically significant differences between the types of organic materials (P<0.05), Bonferroni multiple range comparison tests were used to compare the individual organic material means.

4.1.2. Results

Full laboratory analysis results of all organic material samples is given in Appendix 1. These data were included in the 2016 RB209 review of organic material nutrient content (for dry matter, total N,

P_2O_5, K_2O, MgO, SO_3 and available N – NO_3-N, NH_4-N and uric acid-N). Table 25 lists mean S characteristics for each type of organic material. Total S, extractable S and extractable SO_4 are given both as kg/t or kg/m^3 SO_3 on a fresh weight basis, and as % S or mg/kg S on a dry matter basis[9]. The proportion of total S in the extractable form, and the proportion of extractable S in SO_4-S form has been calculated.

Total S content

The mean total S content ranged from 0.8 kg SO_3/m^3 for cattle slurry to 12.4 kg SO_3/t for enhanced digested biosolids, and was similar to 'typical' figures given in AHDB's Nutrient Management Guide (RB209) for cattle slurry, poultry manure, digested and limed biosolids, but slightly higher for cattle FYM, pig FYM and pig slurry. The 'standard' values for total S given in RB209 are based on the analysis of a large number of samples, including the sample analysis from this project.

The mean total S content on a dry matter basis ranged from *c.*0.5 % S for cattle slurry/FYM to 1.3% S for biosolids. Of the three biosolids 'types', the total S content was lower in digested limed than digested cake, which is consistent with the standard values for digested and digested limed biosolids in RB209. These data also indicate that the total S content of enhanced digested biosolids is greater than digested biosolids, however this is based on the analysis of a limited number of samples (6 samples) and RB209 does not currently distinguish between digested and enhanced digested biosolids.

Table 24. Typical S content of organic materials (AHDB Nutrient Management Guide, RB209)

Organic material type	**Dry matter** **%**	**Total S** **kg SO_3/t or m^3 FW**
Cattle FYM	25	2.4
Pig FYM	25	3.4
Cattle slurry	2 6 10	0.3 0.7 1.0
Pig slurry	2 4 6	0.4 0.7 1.0
Poultry manure	20 40 60 80	3.0 5.6 8.2 11.0
Digested biosolids	25	8.2
Limed biosolids	25	7.4

[9] Sulphur conversion factors: to convert S to SO_3 multiply by 2.5; to convert S to SO_4 multiple by 3.0. To convert SO_4 to S divide by 3; to convert SO_4 to S divide by 2.5.

Table 25. Sulphur content of organic materials

Organic material type	Total S		Extractable S		Extractable S (% total S)	Extractable SO_4		Extractable SO_4 (% Extractable S)	C:S
	kg/t or kg/m³ SO_3 FW	% S DM	kg/t or kg/m³ SO_3 FW	mg/kg S DM		kg/t or kg/m³ SO_3 FW	mg/kg S DM		
Cattle FYM	3.3 (ab)	0.52 (a)	1.01 (a)	1635 (ab)	30 (ab)	0.52 (a)	842 (a)	45 (ab)	76 (c)
Pig FYM	4.3 (b)	0.69 (a)	1.80 (abc)	2823 (abcd)	42 (b)	1.06 (ab)	1671 (ab)	59 (b)	66 (ac)
Cattle slurry	0.8 (a)	0.47 (a)	0.21 (a)	1270 (a)	28 (ab)	0.10 (a)	573 (a)	35 (a)	83 (c)
Pig slurry	1.2 (a)	1.24 (b)	0.18 (a)	2864 (abcd)	22 (a)	0.09 (a)	1789 (ab)	37 (ab)	25 (ab)
Broiler litter	9.2 (de)	0.64 (a)	6.24 (e)	4270 (bcde)	67 (cd)	3.49 (cd)	2396 (abc)	58 (ab)	63 (abc)
Layer manure	5.1 (bc)	0.51 (a)	4.88 (de)	4495 (bcde)	77 (d)	2.66 (bcd)	2671 (abc)	54 (ab)	60 (abc)
All poultry manure	*7.2*	*0.57*	*5.68*	*4363*	*71*	*3.08*	*2534*	*56*	*61*
Digested biosolids	8.0 (cd)	1.31 (b)	3.43 (bd)	5647 (ce)	45 (b)	2.13 (bc)	3473 (bc)	57 (b)	25 (ab)
Enhanced digested	12.4 (e)	1.68 (b)	5.42 (de)	7251 (e)	47 (bc)	4.36 (d)	5638 (c)	65 (ab)	22 (a)
Limed biosolids	7.3 (bcd)	1.04 (ab)	1.71 (ab)	2515 (abc)	27 (ab)	0.61 (ab)	886 (ab)	37 (ab)	33 (abc)
All biosolids	*8.7*	*1.34*	*3.54*	*5446*	*42*	*2.25*	*3400*	*55*	*26*
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Mean SED	0.13	0.168	0.64	899	6.78	0.54	918	8.77	13.68
Mean LSD	0.248	0.333	1.262	1785	13.47	1.07	1822	17.42	21.14

Note – values followed by different letters in brackets indicate significant differences between organic materials ($P<0.05$).

Extractable S content

Extractable S content ranged from *c*.0.2 kg SO_3/m^3 for the slurries to a mean of 5.7 kg SO_3/t for poultry manure. On a dry matter basis, extractable S content ranged from 1270 mg S/kg for cattle slurry to a mean of *c*.5400 mg S/kg for biosolids, and followed the order biosolids > poultry manure > pig slurry/FYM > cattle slurry/FYM (Table 25).

Averaged across all types of organic materials, 43% of total S was in the extractable form. There were clear differences between organic materials in the proportion of total S in the extractable form: *c*.20-40% of total S was 'extractable' for cattle/pig FYM/slurry, *c*.70% for poultry manure and *c*.45-50% for digested/enhanced digested biosolids, with limed biosolids lower at *c*.30%. Around half of extractable S was in SO_4-S form (range 35-65%), with the remainder being dissolved organic S.

Extractable S: impact of analysis of dried compared to fresh slurry samples

Cattle and pig slurry samples were analysed for extractable S using both a dried and fresh sample (Section 4.1.1). There was a good relationship between results obtained from dried and fresh samples for both extractable S and extractable SO_4 (P<0.001) (Figure 8). Sulphur recoveries were greater on the fresh samples with average extractable S and extractable SO_4 *c*.178% and 149%, of the dried sample. This highlights the importance of consistency in methodology within and between projects to ensure results are comparable. For consistency with the other organic material analysis and with the results from AHDB Cereals & Oilseeds project 3606, the results presented in this project (Appendix 1 and Section 4.2) are based on the analysis of extractable S and SO_4 on a dried sample basis.

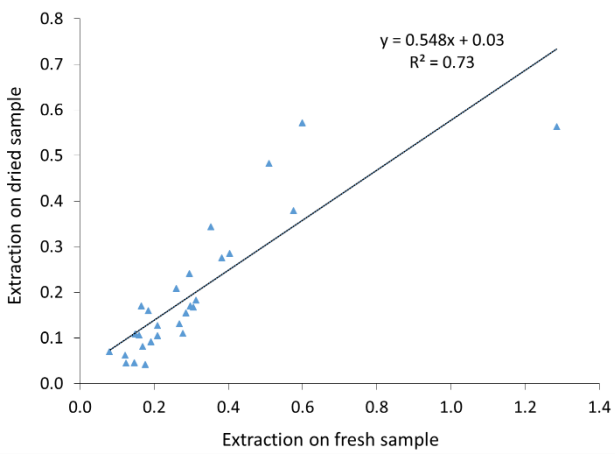


Figure 8a. Extractable S (expressed as kg SO_3/m^3 fresh weight) analysed on dried and fresh sample

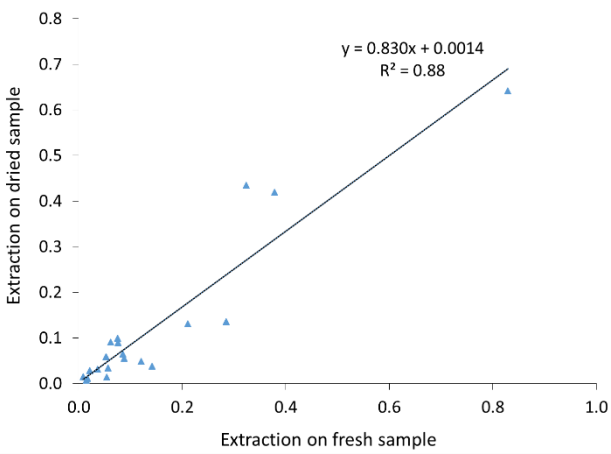


Figure 8b. Extractable SO_4 (expressed as kg SO_3/m^3 fresh weight) analysed on a dry and fresh sample

Carbon: sulphur ratio

The C:S ratio of the organic materials gives an indication of their relative organically-bound S mineralisation potential. Generally, a C:S ratio <200 will result in net mineralisation of S from organic materials, a ratio >400 will result in net immobilisation, and a ratio of 200-400 suggests no net mineralisation/ immobilisation (Eriksen, 2008). The mean C:S ratio of the different organic materials

varied from 22 to 83 (Table 25), indicating net mineralisation of S would occur from all organic materials. In general, the C:S ratio of biosolids (mean 26) was lower than livestock manures (mean *c*.60).

Relationship between dry matter and S content

There is generally a good relationship between the dry matter and total N, P_2O_5, K_2O, MgO and SO_3 for livestock slurries and poultry manures as these nutrients are held mainly in the solid phase of the material. The AHDB Nutrient Management Guide (RB209) includes 'typical' nutrient figures (including total SO_3) at different dry matter contents for cattle slurry, pig slurry and poultry manure. Table 26 gives details of the relationship between dry matter and total SO_3 for livestock slurries and poultry manure within the existing 2016 RB209 manure analysis database.

Table 26. Relationship between S and dry matter content of organic materials - RB209 9th Edition manure analysis database (Williams et al., 2016)

Organic material	Sample number	Regression equation	*P*-value	R^2 (%)
Cattle slurry	156	SO_3 = 0.15 + 0.1 DM	<0.001	65
Pig slurry	104	SO_3 = 0.27 + 0.16 DM	<0.001	61
Poultry manure	79	SO_3 = 0.39 + 0.13 DM	<0.001	58

The relationship between dry matter content and total and extractable S of the organic materials analysed within this project was evaluated using regression analyses (Table 27). There was a strong and statistically significant (P<0.001; R^2>60%) relationship between dry matter and total S for cattle slurry, pig slurry and poultry manure, which is consistent with analysis of the 2016 RB209 manure analysis database. There was a significant (P<0.05), but weaker (R^2=18%) relationship between dry matter and total S for biosolids. There was no relationship between dry matter and total or extractable S for cattle or pig FYM. Despite the good relationship between dry matter and total S for cattle and pig slurry, there was no relationship between dry matter and extractable S. There was only a significant (P<0.10) relationship between dry matter and extractable S content for poultry manure and biosolids, and for these organic materials the relationship with extractable S accounted for a lower proportion of variation in the data than for total S.

Table 27. Relationship between dry matter content and total and extractable S

Organic material	Number of samples	Total S (kg SO_3/t or m^3 FW)		Extractable S (kg SO_3/t or m^3 FW)		Extractable SO_4 (kg SO_3/t or m^3 FW)	
		P-value	R^2 (%)	*P*-value	R^2 (%)	*P*-value	R^2 (%)
Cattle FYM	15	0.277	9	0.979	<1	0.984	<1
Pig FYM	15	0.423	5	0.342	7	0.594	2
Cattle slurry	15	<0.001	76	0.110	18	0.607	2
Pig slurry	15	<0.001	78	0.923	<1	0.312	10
Poultry manure	20	<0.001	62	0.009	37	0.063	18
Biosolids	30	0.020	18	0.070	11	0.031	16

4.1.3. Discussion

This work has provided ‘typical’ figures for the extractable S content of different types of organic materials. The relatively low C:S ratio in all organic materials indicates that additional mineralisation of organic S in the organic material is likely. The analysis database has shown differences between the organic materials in both extractable S content and C:S ratio. The field experiments have assessed extractable S (as measured by both ICP-OES and IC) as a predictor of organic material fertiliser S replacement value and this is discussed further in Section 4.2

4.2. Quantifying the S supply from organic materials to oilseed rape

4.2.1. Methodology

Field sites

At five of the S response experiments in Work Package 1 (Section 3) organic material treatments were included to quantify the S supply from organic materials (Table 28 and Figure 1). These field sites were selected as they were 'high' risk of S deficiency (i.e. light textured loamy sand or sandy loam soils with no recent history of organic material application). There was a yield response to S at four of the five sites (Table 28 and Section 3.2.1). Results from each site are presented separately in Section 4.2.2.

Table 28. Field sites – sulphur supply from organic materials

Harvest year	Site number	Site name	County	Soil type	Yield increase (t/ha)[1]
2014	9	Frostenden	Suffolk	Loamy sand	4.4
2014	10	Woburn	Beds.	Sandy loam	3.8
2015	11	Gleadthorpe	Notts.	Sandy loam	1.0
2016	13	Letton	Norfolk	Loamy sand	0.6
2017	16	Gleadthorpe	Notts.	Sandy loam	*None*

1. Gross output yield at optimum SO_3 rate minus yield from zero S control treatment.

Experimental treatments and design

At Frostenden (2014), Woburn (2014) and Gleadthorpe (2015) there were ten organic material treatments (livestock manures and biosolids) including autumn applied FYM (cattle or pig), broiler litter and four biosolids products and spring applied slurry (cattle or pig), broiler litter and two biosolids products. At Letton (2016) and Gleadthorpe (2017) there were six livestock manure treatments, including autumn applied cattle FYM, pig FYM, cattle slurry and pig slurry, and spring applied cattle slurry and pig slurry. Table 29 lists the total number of organic material treatments across all five sites.

Table 29. Total number of organic material treatments (five sites 2014-2017)

Organic material treatment	Autumn applied	Spring applied	Total
Biosolids	12	6	18
Broiler litter	3	3	6
Cattle FYM	4	-	4
Pig FYM	3	-	-
Cattle slurry	2	3	5
Pig slurry	2	4	6

The autumn organic material treatments were applied to stubble in the autumn (prior to cultivation and drilling with oilseed rape) and the spring organic material treatments were top-dressed to the growing crop. Where an organic material was applied in both the autumn and spring (i.e. broiler litter and two biosolids treatments for the 2014 and 2015 sites, and cattle and pig slurry for the 2016 and 2017 sites) the same material was used for both the autumn and spring applications to allow direct comparison of the effect of application timing on yield response. Biosolids were supplied by Anglian and Severn Trent Water and were all digested cake, apart from the Teversham biosolids treatment at Frostenden in 2014 which was digested and limed. In the results section 4.2.2, all biosolids treatments have been named according to the sewage treatment works from which they were sourced (i.e. Stoke Bardolph, Minworth etc.)

All organic material treatments were applied by hand at a *target* application rate equivalent to 65 kg/ha total SO_3[10]. The application rate was selected to achieve a yield response mid-way between yield from the zero S control and maximum yields to facilitate calculation of fertiliser S replacement values. If the yields from an organic material treatment were the same or greater than the maximum yield at a site (i.e. at the top of the S response curve), then it would not possible to calculate a S fertiliser replacement value for the organic material treatment. Consequently the application rates for some of the organic material treatments were less than would be applied in practice, e.g. the biosolids application rates used were between 4.4 and 10.8 t/ha, compared to a typical field application rate of 18-20 t/ha.

The yields and S offtakes from the organic material treatments were compared with those from a zero S control treatment and inorganic fertiliser S response treatments (0, 30, 60, 90, 120 and 150 kg SO_3/ha; Section 3) to determine the fertiliser S replacement value and hence S availability of the applied organic materials. There were three replicates of each organic material and fertiliser S treatment arranged in a randomised block design.

In order to ensure, that S was the only limiting nutrient, manufactured fertiliser N was applied at RB209 recommended rates[11], taking into account supply of crop available N from the organic materials (estimated using MANNER-*NPK*) and the soil nitrogen supply index. Similarly, fertiliser phosphate and potash were applied at recommended rates based on soil analysis.

[10] The target application rate was calculated based on actual organic material analysis where this was available before the start of the experiment or, where organic material analysis was not available before the start of the experiment, on either biosolids analysis supplied by the Water Company for the water treatment works for biosolids, or 'typical' RB209 figures for livestock manures. There was some variability in the actual organic material SO_3 application rate due to differences between 'typical' and measured organic material analysis. Samples of all organic materials were taken at application and analysed for total SO_3 to calculate actual application rates.

[11] The N fertiliser rate applied to the organic material treatments was matched to 'N rate 1' for the fertiliser S response treatments at each site (section 3) and was sufficient to achieve a target oilseed rape yield of 3.5 t/ha.

Measurements

Samples of organic materials were taken at application and analysed for dry matter, total N, available N (NH_4-N, NO_3-N and for broiler litter uric acid-N), total S, total P, total K, total Mg, total C and extractable S and extractable SO_4 according to the analysis methods described in Section 4.1.1.

Oilseed rape seed yields (fresh weight) were determined at harvest using a small plot combine. Seed samples were taken and analysed for dry matter, total N, total S, oil content, protein content and glucosinolates[12]. Seed yield (91% DM), gross output yield and seed S offtake (kg SO_3/ha) were calculated. **All yield data is presented as gross output yields** (see section 3.2.3 for calculation method). Total S in plant tissue was determined by nitric/hydrochloric acid digest and analysis by ICP-OES; total N in plant tissue was determined by the Dumas combustion method; and oil, protein and glucosinolate contents were determined by NIR analysis.

Additional site measurements including soil analysis, leaf tissue testing (zero S control treatments only) and visual assessments of S deficiency are described in Section 3.1.3 and results presented in Section 3.2.

Data analysis

One-way ANOVA was used to evaluate the effect of organic material treatments on oilseed rape yields, gross output, SO_3 offtake, glucosinolates and oil content. Where ANOVA showed statistically significant differences between treatments (P<0.05), Duncan's multiple range comparison test was used to compare individual treatment means.

Where there was a response to the mineral fertiliser S treatments, a linear plus exponential response curve was fitted to the gross output yield data, or where this was not possible, from the seed S offtake data from the fertiliser S response treatments. The fertiliser S replacement values of the organic material treatments were calculated by comparing gross output yields from each organic material treatment with the fitted S response curve. At all sites apart from Gleadthorpe in 2015, there were S response treatments at two N rates; when calculating the organic material fertiliser replacement values, the S response curve fitted to N rate 1 was used as this N rate was equivalent to the target N rate (crop available N plus fertiliser N) for the organic material treatments.

Figure 9 gives an example of the calculation of fertiliser S replacement value from the autumn broiler litter treatment at Frostenden in 2015. A linear plus exponential model was fitted to the gross output yield data from the fertiliser S treatments (at N rate 1). The autumn broiler litter treatment had a mean gross output yield of 3.1 t/ha, which is equivalent to a fertiliser replacement value of 9.4 kg SO_3/ha. The 6.3 t/ha application of broiler litter applied 66 kg/ha total SO_3 and 29 kg/ha extractable SO_3; therefore, the 9.4 kg SO_3/ha fertiliser replacement value is equivalent to 14% of the total SO_3 applied and 32% of extractable SO_3.

[12] Oilseed rape seed from the organic material treatments was only analysed for glucosinolates in 2014 and 2015; in 2016 and 2017 glucosinolate analysis was only performed on two of the S fertiliser treatments and none of the organic material treatments.

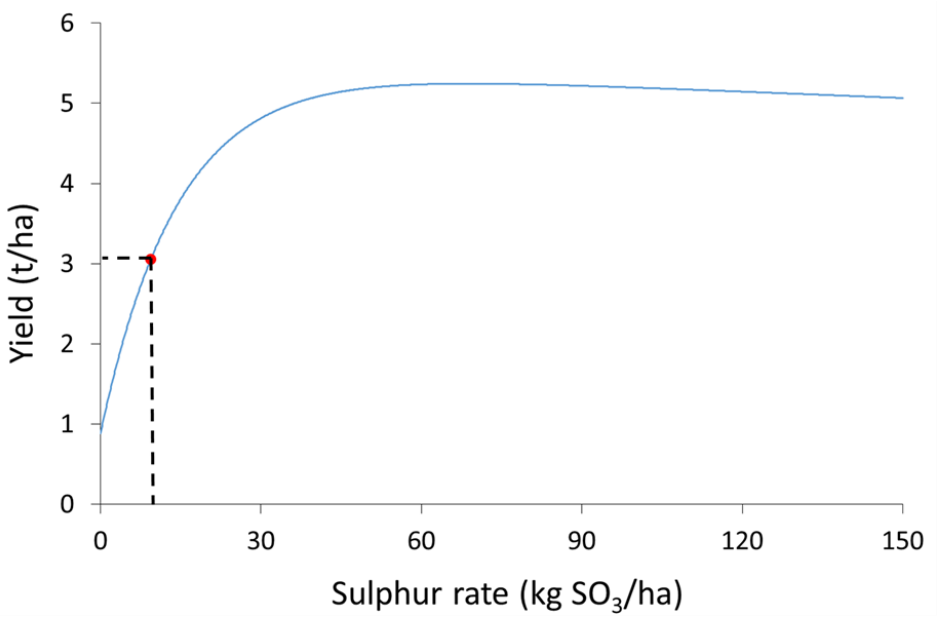


Figure 9. Calculation of organic material fertiliser S replacement value: Autumn broiler litter treatment at Frostenden in 2014

4.2.2. Results

Four of the five sites showed a yield response to S fertiliser (Table 28); and the response was statistically significant (P<0.05) at three of the four sites[13] (Section 3.2.1). There was no yield response to S fertiliser at Gleadthorpe in 2017. At the sites where there was a yield response, yields from the organic material treatments have been compared to yields from the S fertiliser treatments to assess the S fertiliser replacement value of the organic materials. This section presents results from each of the five sites in turn. Tables 31, 33, 35, 37 and 39 give organic material application rates, total and extractable SO_3 applied and (where calculated) fertiliser S replacement values for each site. Tables 32, 34, 36, 38 and 40 give mean treatment yields and seed composition from the organic material and zero S control treatments. The effect of the organic material treatments on oilseed rape seed composition (oil, protein, glucosinolates, seed S content and N:S ratio) were generally consistent with the effects of S fertiliser at each of the sites, which is discussed in detail in Section 3.2.6.

Frostenden, 2014

The organic material treatments at Frostenden applied a mean of 72 kg/ha of total SO_3 (range 36 to 107 kg SO_3/ha) and a mean of 22 kg/ha extractable SO_3 (range 9 to 47 kg SO_3/ha) (Table 30). There was a large yield response to S fertiliser; from 0.9 t/ha on the zero S control treatment to a maximum of 5.3 t/ha (Figure 10). All organic material treatments increased yields compared to the zero S control, and these increases were statistically significant for all treatments apart from the autumn applied cattle FYM (Table 31). Yield increases ranged from 0.4 t/ha for the autumn applied cattle FYM and between 2.2 and 4.3 t/ha from the other treatments. Yields from all organic material treatments were between the minimum and maximum yields from the S fertiliser treatments (Figure 10), enabling calculation of fertiliser replacement values for all organic materials.

A linear plus exponential response curve was fitted to the gross output yield data from the S fertiliser treatments at N rate 1 which accounted for 97.7% of variance in the data. The fertiliser S replacement values of the organic material treatments were calculated by comparing gross output yields from each organic material treatment with the fitted response curve (Table 30), and ranged from 9.4 to 47.5 kg SO_3/ha for autumn applied organic materials (excluding autumn applied cattle FYM), and from 13.1 to 33.3 kg SO_3/ha for spring applied organic materials. The S use efficiency (% of total S applied) of the organic materials was calculated by dividing the calculated fertiliser replacement value by the total SO_3 applied in the organic material (Table 30). Sulphur use efficiency was greatest at *c*.60% from the spring applied broiler litter and pig slurry. For broiler litter, S use efficiency was greater from the spring (57%) compared to autumn application (14%), possibly reflecting leaching of available S over-winter. However, S use efficiency from the biosolids were similar between the autumn (range 24 to 49%, mean 34%) and spring applied (range 24-38%, mean 31%) treatments.

[13] The 1.0 t/ha yield increase at Gleadthrope in 2015 was not statistically significant (P=0.172), reflecting the yield variability between treatment replicates.

Table 30. Organic material application rates and fertiliser replacement values – Frostenden, 2014

Treatment	Application rate (t/ha or m^3/ha)	Total S applied (kg SO_3/ha)	Extractable S applied (kg SO_3/ha)	Extractable SO_4 applied (kg SO_3/ha)	Fertiliser S replacement value			
					kg SO_3/ha	Efficiency % total S applied	Efficiency % extractable S applied	Efficiency % extractable SO_4 applied
Autumn applied (29/08/13)								
Cattle FYM	26	58	10	4	1.4	2	14	39
Broiler litter	6.3	66	29	22	9.4	14	32	43
Biosolids – Stoke Bardolph	8.6	87	28	19	26.2	30	92	141
Biosolids – Minworth	9.9	91	28	11	21.4	24	78	191
Biosolids – Teversham	6.8	107	17	4	36.0	34	217	923
Biosolids - Whitlingham	6.8	97	14	<0.16	47.5	49	334	*
Spring applied (06/03/14)								
Broiler litter	6.3	58	47	23	33.3	57	70	145
Pig slurry	45	36	9	1	23.3	64	273	2589
Biosolids - Minworth	9.9	54	21	9	13.1	24	62	139
Biosolids - Teversham	6.9	62	12	7	23.8	38	197	357

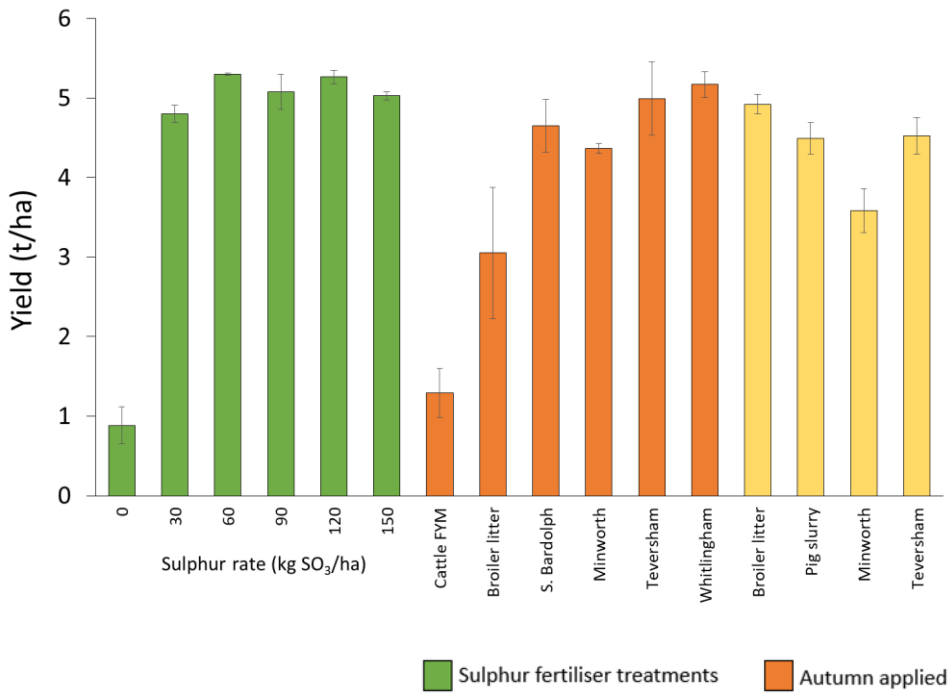


Figure 10. Oilseed rape yields (gross output t/ha at 91% DM) – Frostenden, 2014

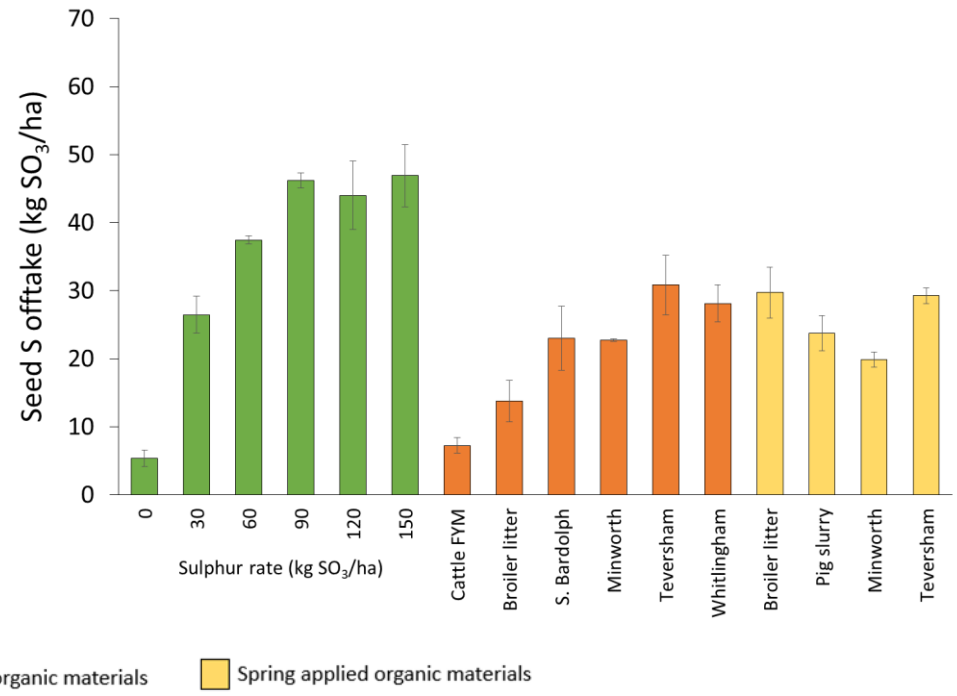


Figure 11. Oilseed rape seed S offtake - Frostenden, 2014

Table 31. Effect of organic material treatments on oilseed rape yields and seed composition at Frostenden in 2014

Treatment	Yield (t/ha 91% DM)	Oil content %	Gross output yield (t/ha 91% DM)	Protein %	Glucosinolates (μg/g)	Seed S (mg S/kg)	Seed N:S Ratio	Seed S offtake (kg SO_3/ha)
Zero S control (N rate 1)	0.9 (a)	39.0 (a)	0.9 (a)	20.5	7.3 (a)	2718	12.7 (abc)	5.4 (a)
Autumn applied (29/08/13)								
Cattle FYM	1.3 (a)	38.3 (a)	1.3 (a)	20.6	7.1 (a)	2476	13.7 (bc)	7.2 (ab)
Broiler litter	2.9 (b)	41.6 (b)	3.1 (b)	19.6	6.9 (a)	2096	15.4 (c)	13.8 (bc)
Biosolids – Stoke Bardolph	4.3 (d)	45.5 (c)	4.7 (cd)	18.5	9.0 (ab)	2316	13.8 (bc)	23.0 (de)
Biosolids – Minworth	4.1 (cd)	44.9 (c)	4.4 (cd)	18.7	8.7 (ab)	2456	12.4 (abc)	22.7 (de)
Biosolids – Teversham	4.6 (cd)	45.9 (c)	5.0 (d)	18.7	10.2 (b)	2932	10.7 (ab)	30.8 (e)
Biosolids - Whitlingham	4.7 (d)	46.6 (c)	5.2 (d)	18.4	9.4 (ab)	2617	11.6 (ab)	28.1 (e)
Spring applied (06/03/14)								
Broiler litter	4.5 (d)	45.8 (c)	4.9 (d)	20.6	11.2 (b)	2878	10.9 (ab)	29.7 (e)
Pig slurry	4.1 (cd)	46.1 (c)	4.5 (cd)	19.6	8.7 (ab)	2518	11.7 (ab)	23.7 (de)
Biosolids - Minworth	3.3 (bc)	45.1 (c)	3.6 (bc)	18.5	8.7 (ab)	2643	11.8 (ab)	19.8 (cd)
Biosolids - Teversham	4.2 (cd)	45.9 (c)	4.5 (cd)	18.7	11.1 (b)	3101	9.9 (a)	29.3 (e)
P-value	<0.001	<0.001	<0.001	<0.001	0.012	0.052	0.024	<0.001
SED	0.411	1.110	0.465	0.416	1.170	267.2	1.349	3.471
LSD	0.856	2.135	0.970	0.867	2.440	557.4	2.814	7.240

Note – values followed by different letters in brackets indicate significant differences between S rate treatments ($P<0.05$).

Woburn, 2014

The organic material treatments at Woburn applied a mean of 63 kg/ha of total SO_3 (range 35 to 84 kg SO_3/ha) and a mean of 24 kg/ha extractable SO_3 (range 7 to 48 kg SO_3/ha), with the exception of the autumn 'Milton Keynes' biosolids treatment which applied 167 kg/ha total SO_3 and 84 kg/ha extractable SO_3[14] (Table 32).

There was a large yield response to the application of S fertiliser from 2.4 t/ha on the zero S control treatment to a maximum of 5.6 t/ha (Figure 12). All organic material treatments increased yields compared to the zero S control, and the increase was statistically significant on the autumn applied Northampton and Milton Keynes biosolids treatments and all spring applied treatments (broiler litter, pig slurry and two biosolids) (Table 33). Yield increases ranged between 0.4 t/ha for the autumn applied 'Derby' biosolids treatment and 3.0 t/ha for the spring applied pig slurry treatment. As for the Frostenden site, yields from all organic material treatments at Woburn were between the minimum and maximum yields from the S fertiliser treatments (Figure 12), enabling calculation of fertiliser replacement values for all organic materials.

A linear plus exponential response curve was fitted to the gross output yield data from the S fertiliser treatments at N rate 1 which accounted for 75.6% of variance in the data. The fertiliser S replacement values of the organic material treatments were calculated by comparing gross output yields from each organic material treatment with the fitted response curve (Table 32), and ranged from 3.2 to 21.8 kg SO_3/ha for autumn applied organic materials, and from 20.8 to 45.8 kg SO_3/ha for spring applied organic materials. The S use efficiency (% of total S applied) of the organic materials was calculated by dividing the calculated fertiliser replacement value by the total SO_3 applied in the organic material (Table 32).

Sulphur use efficiency was greatest from the spring applied pig slurry; the fertiliser replacement value of 45.6 kg SO_3/ha was slightly more than the total SO_3 applied in the slurry (31 kg SO_3/ha) giving a calculated efficiency value of >100% of total S applied. As at Frostenden, S use efficiency from broiler litter was greater from the spring (47%) compared to autumn application (21%), which may reflect leaching of available S over-winter. Similarly, S availability from the autumn applied biosolids was lower than from spring applications; digested biosolids from Milton Keynes sewage treatment works had a S use efficiency of 12% from the autumn application and 27% from the spring application, whilst digested biosolids from the Derby sewage treatment works had a S use efficiency of 4% from the autumn application and 46% from the spring application.

[14] The application rate for Milton Keynes biosolids was based on a mean sewage treatment works total S content of 8.3 kg SO_3/t (fresh weight) provided by Anglian Water. The measured total S content of the autumn applied material was 21.4 kg SO_3/t.

Table 32. Organic material application rates and fertiliser replacement values – Woburn, 2014

Treatment	Application rate (t/ha or m^3/ha)	Total S applied (kg SO_3/ha)	Extractable S applied (kg SO_3/ha)	Extractable SO_4 applied (kg SO_3/ha)	Fertiliser S replacement value			
					kg SO_3/ha	Efficiency % total S applied	Efficiency % extractable S applied	Efficiency % extractable SO_4 applied
Autumn applied (Sep 2013)								
Cattle FYM	22	67	7	3	11.0	16	154	338
Broiler litter	6.3	62	33	23	13.2	21	40	58
Biosolids - Northampton	5.5	84	32	26	21.8	26	69	84
Biosoilds - Milton Keynes	7.8	167	84	68	19.4	12	23	29
Biosolids - Derby	10.3	74	30	25	3.2	4	11	13
Biosolids - Etwall	4.4	59	24	18	4.3	7	18	24
Spring applied (12/03/14)								
Broiler litter	6.3	59	48	23	27.4	47	58	119
Pig slurry	45	35	8	1	45.8	132	559	1411
Biosolids - Milton Keynes	7.8	77	22	9	20.8	27	95	224
Biosolids - Derby	10.3	54	14	6	24.5	46	170	384

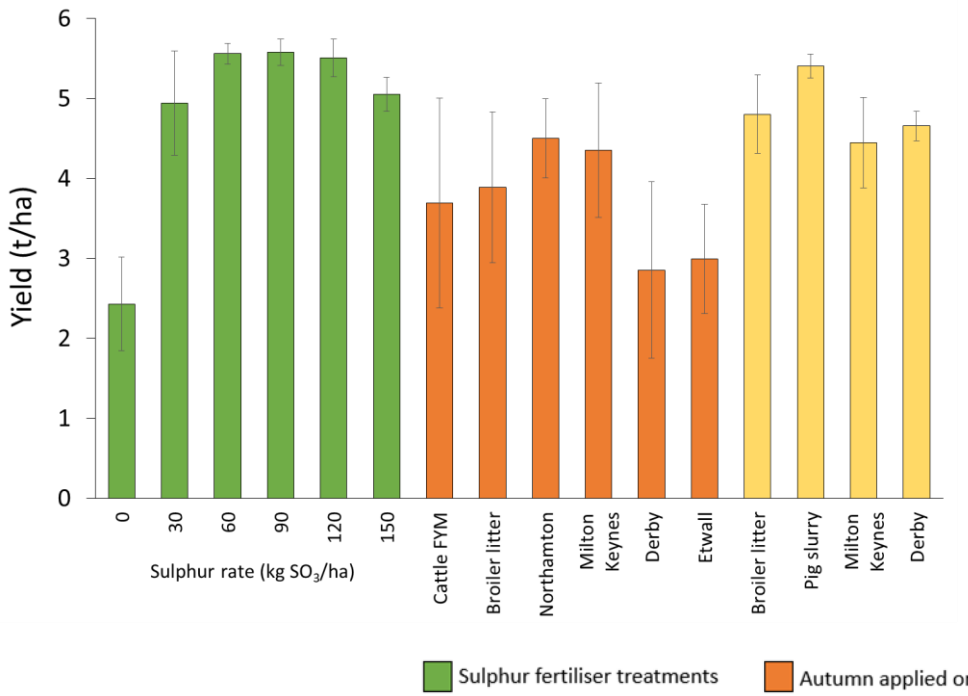


Figure 12. Oilseed rape yields (gross output t/ha at 91% DM) – Woburn, 2014

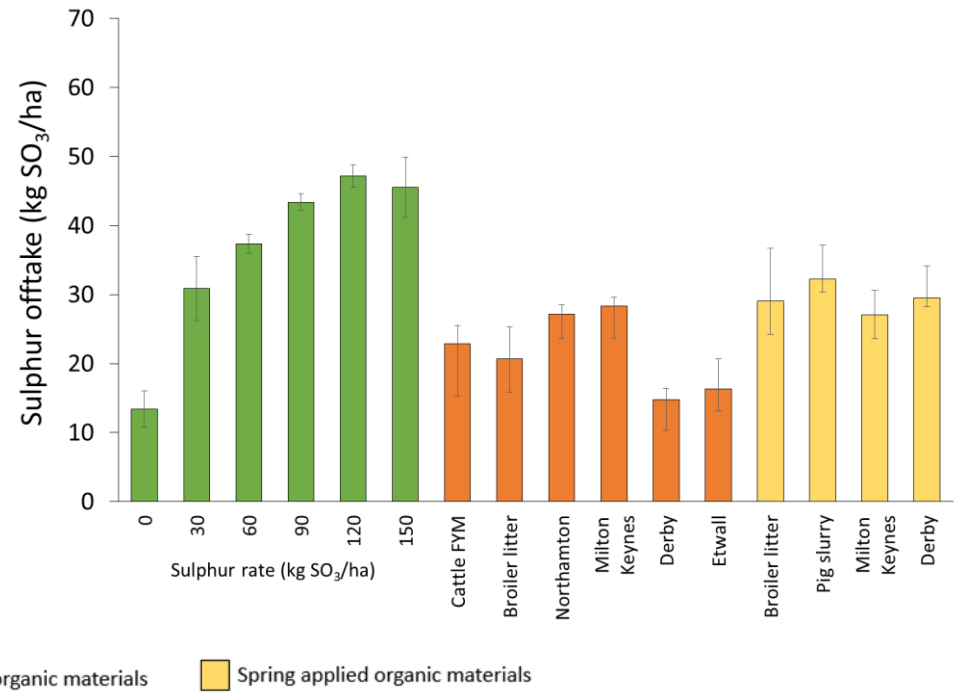


Figure 13. Oilseed rape seed S offtake - Woburn, 2014

Table 33. Effect of organic material treatments on oilseed rape yields and seed composition at Woburn in 2014

Treatment	Yield (t/ha 91% DM)	Oil content %	Gross output yield (t/ha 91% DM)	Protein %	Glucosinolates (μg/g)	Seed S (mg S/kg)	Seed N:S Ratio	Seed S offtake (kg SO_3/ha)
Zero S control (N rate 1)	2.4 (a)	41.7 (a)	2.4 (a)	20.6	6.1	2560	12.5 (ab)	13.4 (a)
Autumn applied (Sep 2013)								
Cattle FYM	3.4 (abcd)	43.3 (abc)	3.7 (abcd)	20.1	10.3	2968	10.7 (a)	22.9 (abc)
Broiler litter	3.7 (abcd)	43.1 (abc)	3.9 (abcd)	19.8	5.6	2465	13.1 (b)	20.7 (ab)
Biosolids - Northampton	4.2 (bcd)	45.3 (cd)	4.5 (bcd)	19.5	8.4	2853	11.1 (ab)	27.2 (bc)
Biosoilds - Milton Keynes	4.0 (bcd)	45.1 (bcd)	4.4 (bcd)	20.1	10.8	3145	10.4 (a)	28.3 (bc)
Biosolids - Derby	2.7 (ab)	42.4 (ab)	2.9 (ab)	20.2	7.8	2524	13.0 (b)	14.8 (a)
Biosolids - Etwall	2.8 (abc)	44.5 (abcd)	3.0 (abc)	19.5	8.7	2620	12.2 (ab)	16.3 (a)
Spring applied (12/03/14)								
Broiler litter	4.5 (cd)	45.1 (bcd)	4.8 (cd)	19.5	8.2	2826	11.5 (ab)	29.0 (bc)
Pig slurry	4.9 (d)	46.4 (d)	5.4 (d)	19.1	8.3	2871	10.8 (a)	32.3 (c)
Biosolids - Milton Keynes	4.2 (bcd)	44.5 (bcd)	4.4 (bcd)	19.8	7.9	2854	11.6 (ab)	27.0 (bc)
Biosolids - Derby	4.3 (bcd)	44.9 (bcd)	4.7 (bcd)	19.8	9.1	2992	10.8 (a)	29.5 (bc)
P-value	0.031	0.025	0.024	0.309	0.255	0.075	0.043	0.001
SED	0.712	1.184	0.780	0.503	1.830	211.7	0.859	4.156
LSD	1.486	2.470	1.626	1.050	3.818	441.6	1.793	8.670

Note – values followed by different letters in brackets indicate significant differences between S rate treatments ($P<0.05$).

Gleadthorpe, 2015

The organic material treatments at Gleadthorpe applied a mean of 78 kg/ha of total SO_3 (range 60 to 109 kg SO_3/ha) and a mean of 34 kg/ha extractable SO_3 (range 13 to 60 kg SO_3/ha) (Table 34). There was a 1.0 t/ha yield increase from the application of S fertiliser, however this increase was not statistically significant (P>0.05) reflecting the yield variability between treatment replicates. Mean yields from the zero S control were 4.7 t/ha, compared to 5.6-5.8 t/ha from the S fertiliser treatments (Figure 14). The organic material treatments increased yields by a mean of 0.7-1.4 t/ha compared to the zero S control, although this increase was not statistically significant (P>0.05). There was no clear effect of application timing (i.e. autumn and spring) on yield response, indicating that both autumn and spring application timings supplied S to the oilseed rape crop.

It was not possible to fit a response curve to either the gross output yield data or seed S offtake data from the fertiliser S response treatments because the majority of the increase in both yield and S offtake occurred at the first S application rate (Figure 14 and Figure 15). Fertiliser S replacement values have therefore not been calculated for this site.

Table 34. Organic material application rates and fertiliser replacement values – Gleadthorpe, 2015

Treatment	**Application rate (t/ha or m^3/ha)**	**Total S applied (kg SO_3/ha)**	**Extractable S applied (kg SO_3/ha)**	**Extractable SO_4 applied (kg SO_3/ha)**
Autumn Applied Manures (01/08/14)				
Pig FYM	19	74	45	33
Broiler litter	6.8	82	60	35
Biosolids – Cotton Valley	5.2	86	27	13
Biosolids – Teversham	5.8	60	13	7
Biosolids – Minworth	11	92	26	17
Biosolids - Hartshill	11	109	26	14
Spring Applied Manures (5-6/03/15)				
Broiler litter	6.8	69	51	40
Cattle slurry	55	62	32	8
Biosolids - Minworth	11	63	24	15
Biosolids – Cotton Valley	5.2	80	31	17

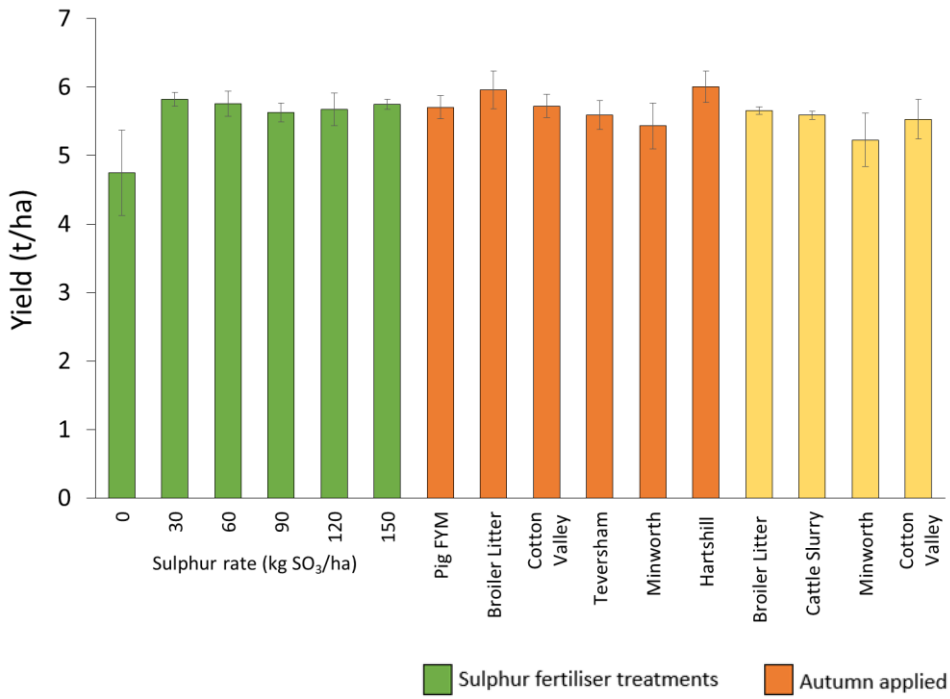


Figure 14. Oilseed rape yields (gross output t/ha at 91% DM) – Gleadthorpe, 2015

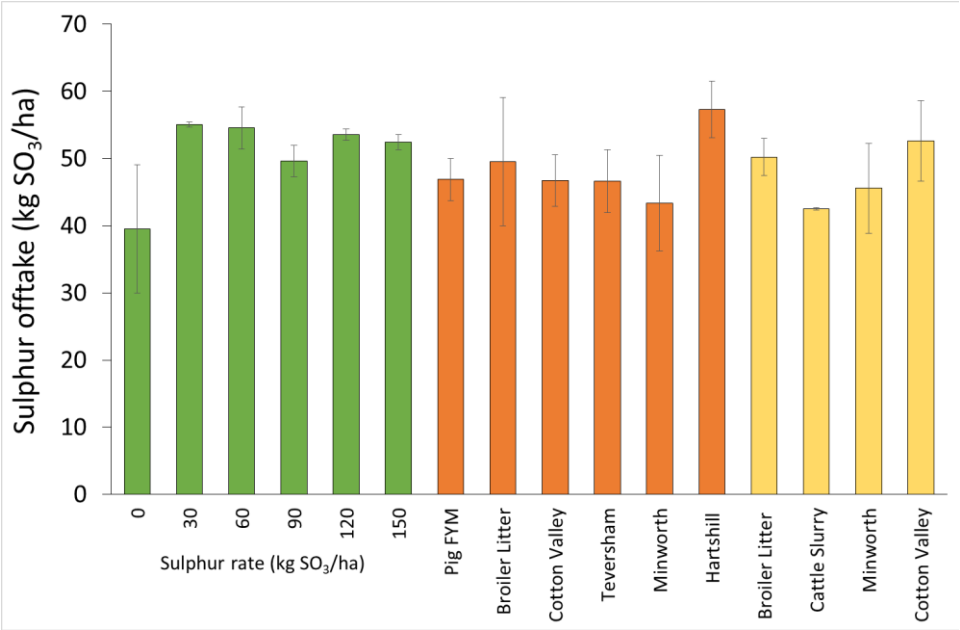


Figure 15. Oilseed rape seed S offtake - Gleadthorpe, 2015

Table 35. Effect of organic material treatments on oilseed rape yields and seed composition at Gleadthorpe in 2015

Treatment	**Yield (t/ha 91% DM)**	**Oil content %**	**Gross output yield (t/ha 91% DM)**	**Protein %**	**Glucosinolates (μg/g)**	**Seed S (mg S/kg)**	**Seed N:S Ratio**	**Seed S offtake (kg SO_3/ha)**
Zero S control	4.3	47.0 (a)	4.7	19.3 (bc)	10.4	3914	8.5	39.5
Autumn Applied Manures (01/08/14)								
Pig FYM	5.2	46.5 (a)	5.7	19.3 (bc)	12.5	3981	7.9	46.9
Broiler litter	5.4	46.6 (a)	6.0	19.2 (bc)	10.4	3963	8.4	49.5
Biosolids – Cotton Valley	5.2	47.0 (a)	5.7	19.1 (bc)	12.1	3985	7.8	46.7
Biosolids – Teversham	5.1	46.7 (a)	5.6	19.3 (bc)	12.3	4015	7.8	46.6
Biosolids – Minworth	4.9	46.7 (a)	5.4	19.0 (b)	10.9	3831	8.6	43.4
Biosolids - Hartshill	5.5	46.7 (a)	6.0	19.7 9 (cd)	12.0	4612	7.0	57.3
Spring Applied Manures (5-6/03/15)								
Broiler litter	5.2	46.5 (a)	5.7	19.6 (bcd)	11.9	4284	7.6	50.2
Cattle slurry	5.0	48.6 (b)	5.6	17.9 (a)	11.1	3775	7.3	42.5
Biosolids - Minworth	4.6	46.1 (a)	5.0	19.9 (d)	11.1	4358	7.6	45.6
Biosolids – Cotton Valley	5.0	46.8 (a)	5.5	20.0 (d)	11.2	4585	7.3	52.6
P-value	0.110	0.020	0.159	<0.001	0.818	0.731	0.902	0.635
SED	0.355	0.517	0.415	0.262	1.417	503.5	1.086	7.85
LSD	0.741	1.079	0.865	0.546	2.955	1050.3	2.266	16.37

Note – values followed by different letters in brackets indicate significant differences between S rate treatments ($P<0.05$).

Letton, 2016

The organic material treatments at Letton applied a mean of 82 kg/ha of total SO_3 (range 24 to 146 kg SO_3/ha) and a mean of 22 kg/ha extractable SO_3 (range 9 to 36 kg SO_3/ha) (Table 36). There was a *c.*0.5 t/ha yield increase from the application of S fertiliser; yields increased from 4.2 t/ha on the zero S control to a maximum of 4.7 t/ha (Figure 16).

All organic material treatments apart from the autumn applied cattle slurry increased yields by a mean of 0.2-0.5 t/ha compared to the zero S control (Table 37) although this increase was not statistically significant (P>0.05).

At this site, fertiliser S replacement values were calculated using oilseed rape seed S offtake data (Figure 17) which fitted a linear plus exponential model explaining 45% of variance in the data as; linear, exponential and linear plus exponential models all explained <17% of variance in the gross output yield data.

Fertiliser S replacement values were calculated by comparing seed S offtake from each organic material treatment with the response curve fitted to S offtake data (Table 36). Fertiliser replacement values range from 27.7 to 66.1 kg SO_3/ha for autumn applied organic materials, and from 31.8 to 46.1 kg SO_3/ha for spring applied organic materials. The S use efficiency (% of total S applied) of the organic materials was calculated by dividing the calculated fertiliser replacement value by the total S applied in the organic material (Table 36).

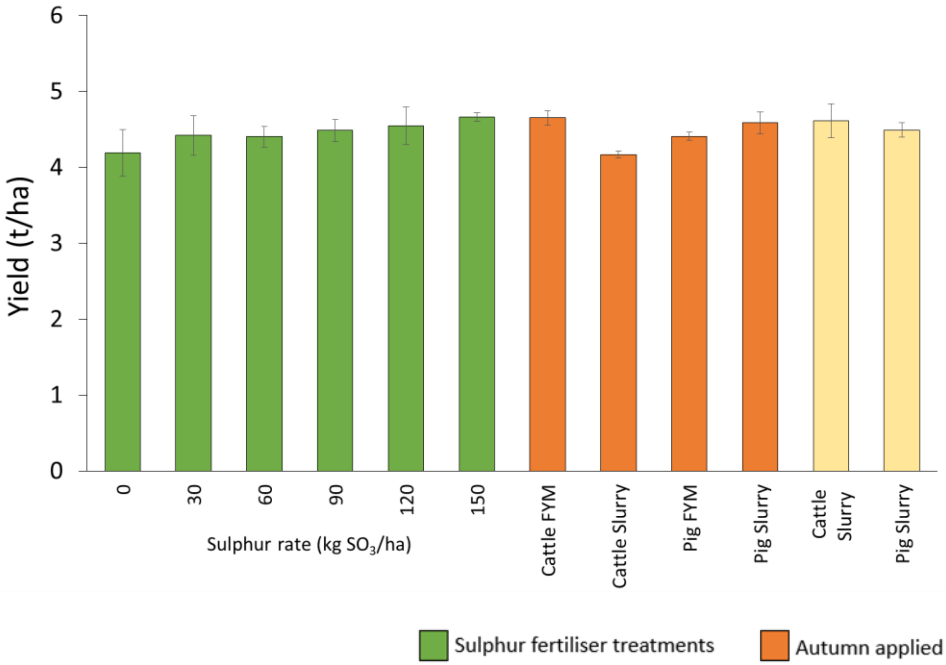
Sulphur use efficiency from the pig slurry treatments were >100% of total S applied for both autumn and spring applications. For the cattle slurry, S use efficiency was greater from the spring (75%) compared to autumn application (24%), which may reflect leaching of available S over-winter. Sulphur use efficiency from the autumn applied cattle and pig FYM treatments was 45 and 27% respectively.

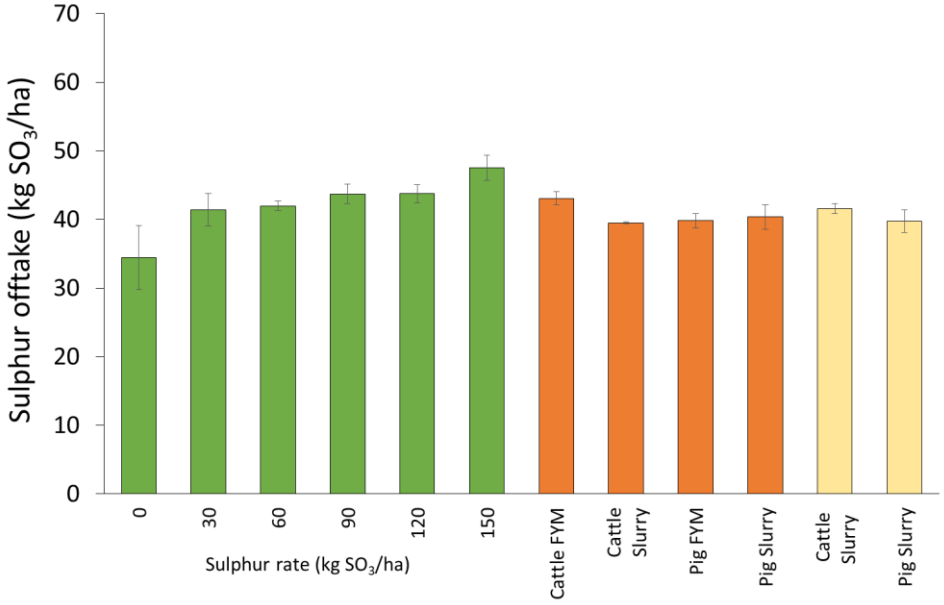
Table 36. Organic material application rates and fertiliser replacement values – Letton, 2016

Treatment	Application rate (t/ha or m^3/ha)	Total S applied (kg SO_3/ha)	Extractable S applied (kg SO_3/ha)	Extractable SO_4 applied (kg SO_3/ha)	Fertiliser S replacement value			
					kg SO_3/ha	Efficiency % total S applied	Efficiency % extractable S applied	Efficiency % extractable SO_4 applied
Autumn applied manures (13-14/08/15)								
Cattle FYM	27	146	28	14	66.1	45	239	483
Cattle slurry	94	117	27	12	27.7	24	103	234
Pig FYM	16	110	23	4	29.9	27	128	709
Pig slurry	66	24	9	*	35.0	144	381	*
Spring applied manures (24/02/16)								
Cattle slurry	48	62	36	16	46.1	75	129	287
Pig slurry	60	31	11	1	31.8	101	282	5141

Table 37. Effect of organic material treatments on oilseed rape yields and seed composition at Letton in 2016

Treatment	Yield (t/ha 91% DM)	Oil content %	Gross output yield (t/ha 91% DM)	Protein %	Seed S (mg S/kg)	Seed N:S Ratio	Seed S offtake (kg SO_3/ha)
Zero S control (N rate 1)	4.0	43.0	4.2	16.6	3657	7.8	33.7
Autumn applied manures (13-14/08/15)							
Cattle FYM	4.5	42.7	4.6	17.1	4145	7.2	42.1
Cattle slurry	4.0	42.8	4.2	17.4	4251	7.1	38.7
Pig FYM	4.1	44.3	4.4	17.0	4137	7.1	39.0
Pig slurry	4.3	44.5	4.6	17.2	4049	7.3	39.6
Spring applied manures (24/02/16)							
Cattle slurry	4.4	42.9	4.6	16.7	4058	7.1	40.7
Pig slurry	4.3	43.2	4.5	17.1	4014	7.3	39.2
P-value	0.343	0.821	0.272	0.563	0.086	0.223	0.101
SED	0.233	1.586	0.233	0.456	173.1	0.311	2.427
LSD	0.500	3.402	0.499	0.978	371.4	0.668	5.288





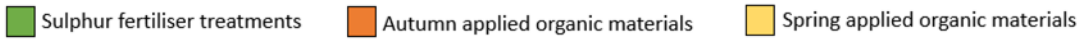


Figure 16. Oilseed rape yields (gross output t/ha at 91% DM) – Letton, 2016

Figure 17. Oilseed rape seed S offtake - Letton, 2016

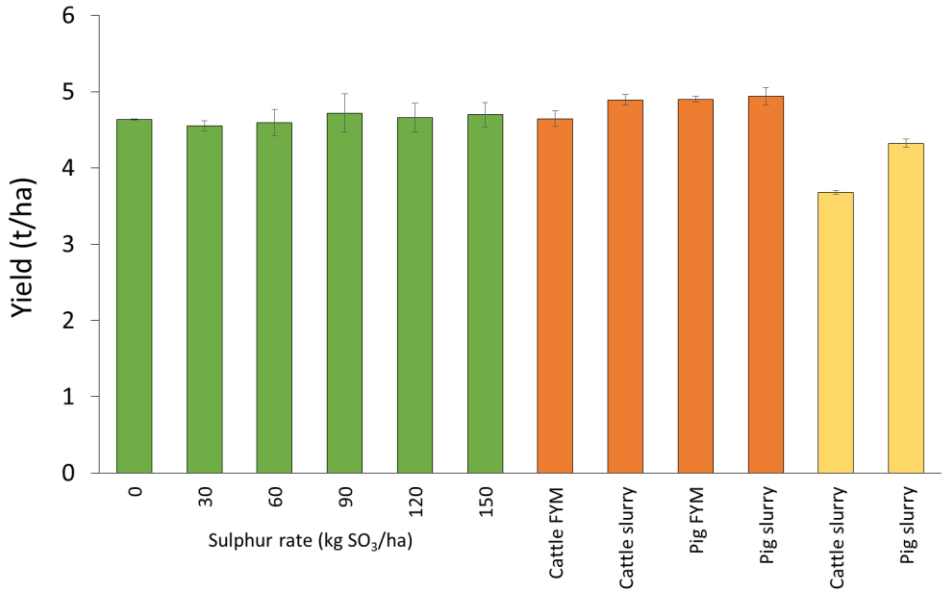
Gleadthorpe, 2017

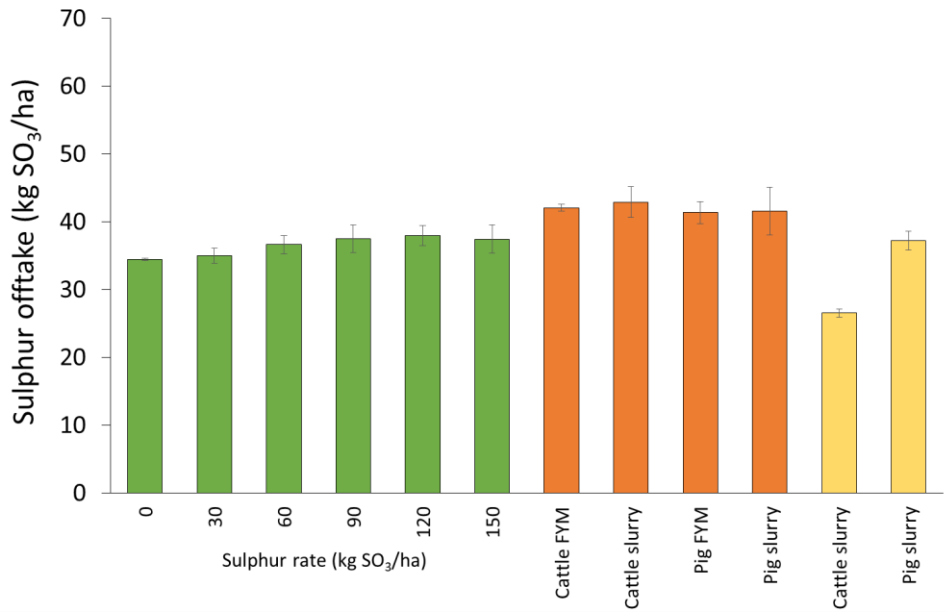
The organic material treatments at Gleadthorpe in 2017 applied a mean of 49 kg/ha of total SO_3 (range 20 to 66 kg SO_3/ha) and a mean of 13 kg/ha extractable SO_3 (range 5 to 27 kg SO_3/ha) (Table 38). There was no effect of S fertiliser on yields at this site (P>0.05, Table 18 and Figure 18). There was a significant (P<0.05) but small increase in seed S offtake from 34 kg SO_3/ha from the zero S control to a maximum of 38 kg SO_3/ha; however S offtake values from the organic material treatments were not within the narrow range of values measured from the fertiliser S response treatments (Figure 19) and it was not possible to calculate fertiliser S replacement values for this experiment.

There was a reduction in yields observed from the spring compared to autumn manure treatments (Table 39 and Figure 18) which may have been caused by crop damage from the spring treatment application, although no visible symptoms of damage were recorded after the application.

Table 38. Organic material application rates and fertiliser replacement values – Gleadthorpe, 2017

Treatment	**Application rate (t/ha or m^3/ha)**	**Total S applied (kg SO_3/ha)**	**Extractable S applied (kg SO_3/ha)**	**Extractable SO_4 applied (kg SO_3/ha)**
Autumn applied manures (31/08/16)				
Cattle FYM	10	49	13	5
Cattle slurry	72	65	12	5
Pig FYM	20	58	16	8
Pig slurry	60	37	5	2
Spring applied manures (09/03/17)				
Cattle slurry	72	66	27	14
Pig slurry	60	20	8	2





Sulphur fertiliser treatments | Autumn applied organic materials | Spring applied organic materials

Figure 18. Oilseed rape yields (gross output t/ha at 91% DM) – Gleadthorpe, 2017

Figure 19. Oilseed rape seed S offtake - Gleadthorpe, 2017

Table 39. Effect of organic material treatments on oilseed rape yields and seed composition at Gleadthorpe in 2017

Treatment	**Yield (t/ha 91% DM)**	**Oil content %**	**Gross output yield (t/ha 91% DM)**	**Protein %**	**Seed S (mg S/kg)**	**Seed N:S Ratio**	**Seed S offtake (kg SO_3/ha)**
Zero S control (N rate 1)	4.4 (c)	43.7 (bc)	4.6 (c)	16.1 (a)	3451 (a)	8.1	34.5 (b)
Autumn Applied Manures (31/08/16)							
Cattle FYM	4.6 (c)	41.3 (a)	4.6 (c)	18.6 (b)	4059 (b)	7.9	42.1 (cd)
Cattle slurry	4.8 (d)	41.3 (a)	4.9 (d)	18.5 (b)	3926 (b)	8.3	42.9 (d)
Pig FYM	4.8 (d)	41.5 (a)	4.9 (d)	18.5 (b)	3791 (ab)	8.3	41.4 (cd)
Pig slurry	4.8 (d)	41.7 (a)	4.9 (d)	18.5 (b)	3779 (ab)	8.5	41.6 (cd)
Spring Applied Manures (09/03/17)							
Cattle slurry	3.5 (a)	44.4 (c)	3.7 (a)	15.2 (a)	3381 (a)	7.8	26.6 (a)
Pig slurry	4.2 (b)	42.4 (ab)	4.3 (b)	17.7 (b)	3923 (b)	8.2	37.2 (bc)
P-value	<0.001	0.003	<0.001	<0.001	0.017	0.279	<0.001
SED	0.095	0.701	0.103	0.508	175.8	0.281	2.386
LSD	0.206	1.527	0.224	1.107	383.0	0.613	5.198

Note – values followed by different letters in brackets indicate significant differences between S rate treatments ($P<0.05$).

4.3. Discussion

Four of the five organic material sites showed a yield response to S fertiliser and each of these four sites also showed a yield increase from the organic material treatments demonstrating that organic materials supply crop available S that can contribute towards crop S requirement. Fertiliser S replacement values were calculated for the organic material treatments at three of these four sites. It was not possible to fit a response curve to either the gross output yield data or seed S offtake data from the fertiliser S response treatments at the 2015 Gleadthorpe site because the majority of the increase in both yield and S offtake occurred at the first S application rate.

AHDB Cereals and Oilseeds project 3606 (Sagoo *et a*l., 2013) quantified the S supply from organic materials to winter wheat crops and found a lower S use efficiency from autumn compared to spring applied organic materials, which was attributed to over-winter leaching of available sulphate (SO_4) from the autumn applications. The quantity of S lost via leaching will depend on the amount applied in the organic material, soil type and the volume of over-winter rainfall.

The results from this project also support a lower percentage S use efficiency from autumn compared to spring applications. Table 40 shows mean S use efficiency values for autumn and spring applied organic materials at the Frostenden, Woburn and Letton sites calculated as a percentage of total SO_3 applied. At both the Frostenden and Woburn sites in 2014, S use efficiency was greater from the spring (57 and 47%, respectively) compared to autumn (14 and 21%, respectively) applications. At Woburn, mean S use efficiency was lower from the autumn (12%) compared to spring (36%) applied biosolids, and at Letton S use efficiency was lower from the autumn (24%) compared to spring (75%) applied cattle slurry. However, there was no difference in mean S use efficiency from the autumn and spring applied biosolids at Frostenden or between the autumn and spring applied pig slurry at Letton. The mean % S use efficiency (across all three sites) for autumn application timings was 23% for biosolids, 18% for broiler litter and 23% for cattle/pig FYM (Table 40), which is greater than the 5-10% S use efficiency for livestock manures and 10-20% for biosolids measured in AHDB Cereals & Oilseeds project 3606 on winter wheat and included in AHDB Nutrient Management Guide (RB209). The increased S use efficiency from autumn applications to oilseed rape (compared to winter wheat) probably reflects greater crop S uptake by the oilseed rape crop in the period between application and the start of over-winter drainage, resulting in lower S leaching losses.

Table 40. Mean S use efficiency values for autumn and spring applied organic materials (fertiliser replacement value as % of total SO_3 applied)

Organic material	Sulphur use efficiency (% total S applied)	
	Autumn applied	Spring applied
Cattle/pig FYM	23 (n=4)	No data
Cattle/pig slurry	84 (n=2)	93 (n=2)
Broiler litter	18 (n=2)	52 (n=2)
Biosolids	23 (n=8)	34 (n=4)

n=number of organic material treatments across all sites

AHDB Cereals and Oilseeds Project 3606 showed that for spring applied organic materials (broiler litter and slurry; n=6), there was a good relationship between the recovery of S in the grain (treatment minus control) and the amount of extractable S applied in the organic materials. This suggested that, for spring applied organic materials 'extractable' S is a good indicator of the S that is available to the crop. At the three sites which responded to S in AHDB Cereals and Oilseeds Project 3606, it was only possible to estimate the fertiliser SO_3 replacement value of one of the two spring applied treatments because at each site the grain S offtake from one of the spring treatments exceeded the maximum from the fertiliser S response plots. Based on these limited data, for spring applications of organic materials, a linear relationship between fertiliser SO_3 replacement value and the quantity of extractable SO_3 applied in the organic materials was derived, and it was concluded that for spring applied organic materials, 'extractable' SO_3 was equivalent to inorganic (water soluble) SO_3 fertiliser. Therefore the availability of S from spring applications of organic materials was conservatively assumed to be equivalent to the proportion of total S in the 'extractable' form.

However, in this project there was no relationship (P>0.05) between recovery of S in oilseed rape seed or fertiliser SO_3 replacement value and total S applied, extractable S applied or extractable SO_4 applied – for the autumn or spring application timings either individually or together. The fertiliser SO_3 replacement vales for spring applied organic materials were generally greater than the amount of extractable S applied, indicating mineralisation of organic S following application, which is consistent with the low C:S ratios in organic materials reported in Section 4.1.2.

4.4. Recommendations

Based on the results of this project we recommend updating the guidance on S availability from organic materials as follows:

- **Autumn applied organic materials: increase the S use efficiency by 5% for oilseed rape and grass crops to 15% for livestock manures and 25% for biosolids.** The higher S use efficiency for oilseed rape and grass reflects greater autumn crop S uptake and reduced leaching losses compared to winter cereal crops and is consistent with current guidance in RB209 on N availability from organic materials. Although this project only measured S availability from organic

materials applied to oilseed rape, it is understood that grass is likely to take up more S in the autumn than winter wheat and therefore we recommend that the higher autumn S availability figures are applied to both oilseed rape and grass. The mean S use efficiency value for autumn applied cattle/pig slurry measured in this project (84%) is notably higher than the 15% recommended figure, however it is based on only two figures from the Letton site and is significantly influenced by the high S availability from the autumn applied pig slurry. Therefore we consider there is insufficient evidence to increase the S use efficiency figure for autumn applied slurries from 15%.

- **Spring applied broiler litter: no change to the current 60% S availability figure.** The mean S use efficiency value of 52% measured in this project is close to the existing recommendation.
- **Spring applied cattle/pig FYM: no change to the current 15% S use efficiency for cattle FYM and 25% S use efficiency for pig FYM.** This project provided no new data on spring applied cattle/pig FYM..
- **Spring applied biosolids: increase the S use efficiency to 35%.** This project has provided new data on S availability from spring applied biosolids and this revised figure is the mean S use efficiency value for spring applied biosolids measured in this project.
- **Spring applied cattle/pig slurry: increase the S use efficiency to 45%.** The mean S use efficiency value for spring applied cattle/pig slurry measured in this project (93%) is notably higher than the current 35% availability figure. We recommend a conservative increase to the percentage availability figure from 35 to 45% to reflect both the new and existing data on S availability from spring applied slurries.

Table 41 summarises the proposed new recommendations on S availability from organic materials.

Table 41. Sulphur availability form organic materials: existing recommendations and proposed new recommendations

Organic material	**Sulphur use efficiency (% total SO_3 applied)**	
	Current recommendations	**Revised recommendations**
Autumn applied		
Livestock manures	5-10%	5-10% [15%]
Biosolids	10-20%	10-20% [25%]
Spring applied		
Cattle FYM	15%	15%
Pig FYM	25%	25%
Broiler litter	60%	60%
Cattle/pig slurry	35%	45%
Biosolids	20%	35%

[ ] = use for grassland and winter oilseed rape cropping

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Appendix 1

Table A1. Cattle FYM analysis

Number	% DM	Total N	NH_4-N	NO_3-N	Total P_2O_5	Total K_2O	Total MgO	Total SO_3	Ext-S	Ext SO_4	Ext S % total S	Ext SO_4 % Ext S	Carbon % DM	C:N	C:S
		kg/t fresh weight							kg SO_3/t FW						
CM1	21	6.1	0.75	<0.01	4.2	7.0	2.3	2.8	0.29	0.07	10	24	36	14	67
CM2	34	9.0	0.11	<0.01	4.6	16.2	2.8	2.7	0.51	0.09	19	18	47	18	148
CM3	33	5.7	0.48	0.05	5.6	13.0	3.1	4.1	1.79	1.45	44	81	44	28	89
CM4	24	5.2	0.42	0.42	1.9	8.9	1.0	2.3	0.53	0.13	22	26	48	26	121
CM5	22	5.8	0.05	0.08	2.6	12.3	1.4	2.2	0.38	0.14	17	35	28	11	70
CM6	29	6.2	0.05	0.12	3.3	9.5	2.2	3.1	0.33	0.14	11	42	21	10	48
CM7	27	8.9	0.29	0.86	7.0	11.8	4.3	5.4	1.01	0.60	19	60	39	13	49
CM8	25	4.8	0.35	0.01	2.7	11.5	1.7	2.6	0.86	0.40	33	47	39	22	93
CM9	21	5.9	0.11	0.03	4.3	10.3	2.1	2.8	0.67	0.30	24	45	34	13	66
CM10	36	10.0	0.03	0.10	3.8	26.5	2.6	4.0	1.14	0.37	28	32	37	13	82
CM11	18	8.7	0.20	0.30	3.5	10.8	1.6	2.9	1.64	0.81	56	50	35	8	54
CM12	23	8.2	0.37	0.08	4.1	12.1	2.0	2.8	1.50	0.97	53	64	33	10	67
CM13	23	5.1	0.23	0.17	2.8	16.4	1.8	5.0	2.39	1.29	48	54	29	14	33
CM14	31	9.9	0.13	0.13	6.1	15.1	2.5	3.3	1.09	0.48	33	44	41	13	97
CM15	22	6.3	0.04	0.09	3.4	13.6	2.8	3.2	1.07	0.61	33	57	36	13	61
Mean	26	7.1	0.24	0.16	4.0	13.0	2.3	3.3	1.01	0.52	30	45	36	15	76
Min	18	4.8	0.03	0.01	1.9	7.0	1.0	2.2	0.29	0.07	10	18	21	8	33
Max	36	10.0	0.75	0.86	7.0	26.5	4.3	5.4	2.39	1.45	56	81	48	28	148

Table A2. Pig FYM analysis

Number	% DM	Total N	NH_4-N	NO_3-N	Total P_2O_5	Total K_2O	Total MgO	Total SO_3	Ext-S	Ext SO_4	Ext S % total S	Ext SO_4 % Ext S	Carbon % DM	C:N	C:S
		kg/t fresh weight							kg SO_3/t FW						
PM1	30	10.9	0.74	0.80	7.2	15.7	3.2	6.2	3.53	2.51	56	71	29	10	36
PM2	28	10.2	1.08	0.42	6.3	16.5	3.6	5.0	2.40	1.59	48	66	27	9	37
PM3	27	5.8	0.59	0.07	7.6	9.7	3.6	3.8	1.33	0.61	35	46	28	14	48
PM4	29	7.2	2.45	<0.01	6.0	8.5	2.8	3.3	2.09	1.21	63	58	8	5	18
PM5	25	7.9	2.49	<0.01	5.5	7.8	1.7	4.8	2.54	1.30	53	51	45	21	59
PM6	36	3.8	0.31	0.01	2.4	3.6	1.0	2.0	0.56	0.31	28	55	59	62	267
PM7	29	1.0	0.19	0.12	6.0	15.5	2.7	6.5	2.60	1.13	40	43	37	156	41
PM8	24	6.2	1.03	<0.01	8.8	9.7	4.1	4.9	2.11	1.25	43	59	36	17	44
PM9	18	7.7	1.75	<0.01	5.4	4.0	1.8	2.0	0.82	0.58	42	71	43	13	99
PM10	33	8.0	0.68	0.09	10.9	3.5	3.3	4.9	1.77	0.97	36	55	23	11	39
PM11	17	5.1	0.35	0.02	5.8	5.5	2.4	3.7	0.89	0.84	24	94	60	21	69
PM12	18	5.2	1.69	<0.01	5.2	4.3	1.6	2.2	1.07	0.62	48	58	44	22	87
PM13	21	5.3	3.92	<0.01	4.6	10.6	1.9	3.8	2.35	1.73	61	73	46	70	63
PM14	23	8.0	3.41	<0.01	6.6	12.2	3.2	7.1	1.49	0.26	21	17	33	17	27
PM15	29	9.1	0.05	1.40	7.5	8.4	4.1	4.5	1.51	0.92	34	61	37	14	60
Mean	26	6.8	1.38	0.20	6.4	9.0	2.7	4.3	1.80	1.06	42	59	37	31	66
Min	17	1.0	0.05	0.01	2.4	3.5	1.0	2.0	0.56	0.26	21	17	8	5	18
Max	36	10.9	3.92	1.40	10.9	16.5	4.1	7.1	3.53	2.51	63	94	60	156	267

Table A3. Cattle slurry analysis

Number	% DM	Total N	NH_4-N	NO_3-N	Total P_2O_5	Total K_2O	Total MgO	Total SO_3	Ext-S	Ext SO_4	Ext S % total S	Ext SO_4 % Ext S	Carbon % FW	C:N	C:S
		kg/m³ fresh weight							kg SO_3/m³ FW						
CS1	7.3	3.0	1.96	<0.01	2.0	2.8	1.1	1.1	0.11	0.02	9	16	2.8	27	62
CS2	4.4	1.7	1.49	<0.01	0.7	3.6	0.7	0.5	0.13	0.09	28	71	1.8	84	98
CS3	7.1	2.7	1.58	<0.01	0.9	3.4	0.7	0.9	0.48	0.43	53	90	2.7	24	72
CS4	1.9	1.2	0.97	<0.01	0.5	2.9	0.3	0.3	0.06	0.02	24	25	0.6	26	57
CS5	4.4	1.5	0.93	<0.01	0.7	3.1	0.4	0.5	0.13	0.06	24	42	1.5	27	71
CS6	10.3	3.1	0.84	<0.01	1.5	1.8	1.0	1.0	0.11	0.03	11	32	3.6	16	89
CS7	9.8	3.1	0.95	<0.01	1.5	2.8	1.3	1.1	0.21	0.06	19	28	3.3	15	76
CS8	7.7	4.5	3.08	<0.01	1.9	5.1	1.3	1.3	0.28	0.09	22	33	2.7	19	52
CS9	13.7	4.2	2.59	<0.01	2.9	5.5	2.2	1.4	0.34	0.10	24	29	5.4	34	94
CS10	12.0	2.8	0.43	<0.01	1.4	3.1	1.0	1.0	0.17	0.03	17	19	3.1	13	76
CS11	3.8	0.7	0.25	<0.01	0.4	1.3	0.2	0.2	0.07	0.01	39	10	1.4	32	199
CS12	7.6	3.2	2.37	<0.01	1.1	2.7	1.5	1.1	0.57	0.42	51	73	2.0	25	44
CS13	8.2	2.7	1.70	<0.01	1.3	2.8	0.8	1.3	0.29	0.13	23	46	3.2	32	63
CS14	7.0	2.7	1.75	<0.01	1.0	2.9	1.2	0.7	0.17	0.01	23	7	2.8	29	94
CS15	1.0	0.6	0.51	<0.01	0.2	0.9	0.3	0.1	0.05	0.00	50	11	0.4	40	100
Mean	7.1	2.5	1.43	<0.01	1.2	3.0	0.9	0.8	0.2	0.1	28	35	2.5	29	83
Min	1.0	0.6	0.25	<0.01	0.2	0.9	0.2	0.1	0.0	0.0	9	7	0.4	13	44
Max	13.7	4.5	3.08	<0.01	2.9	5.5	2.2	1.4	0.6	0.4	53	90	5.4	84	199

Table A4. Pig slurry analysis

Number	% DM	Total N	NH_4-N	NO_3-N	Total P_2O_5	Total K_2O	Total MgO	Total SO_3	Ext-S	Ext SO_4	Ext S % total S	Ext SO_4 % Ext S	Carbon % FW	C:N	C:S
		kg/m³ fresh weight							kg SO_3/m³ FW						
PS1	5.4	4.1	2.7	<0.01	4.1	3.5	1.6	1.6	0.24	0.07	15	27	0.4	3	7
PS2	4.0	2.6	2.5	<0.01	1.5	2.9	0.7	0.7	0.17	0.05	23	28	0.2	15	8
PS3	3.4	2.8	2.1	<0.01	1.6	2.0	0.7	1.1	0.08	0.04	7	47	0.5	8	12
PS4	2.4	2.5	2.5	<0.01	0.3	4.3	0.2	1.0	*	*	*	*	0.4	193	10
PS5	1.8	1.2	1.1	<0.01	0.7	1.9	0.4	0.4	0.11	0.03	29	27	<0.1		
PS6	4.8	3.7	2.9	<0.01	2.2	3.0	0.9	1.0	0.09	0.02	10	25	1.8	22	46
PS7	2.4	1.6	1.6	<0.01	1.0	1.4	0.5	0.5	0.05	0.01	10	31	0.9	177	47
PS8	10.4	5.6	1.5	<0.01	8.4	1.8	3.5	5.5	*	*	*	*	0.8	2	4
PS9	1.6	2.7	2.6	<0.01	0.6	2.9	0.3	1.3	0.56	0.64	43	114	0.5	78	10
PS10	1.9	2.9	2.8	<0.01	0.7	2.1	0.3	0.4	0.04	0.01	10	27	0.6	42	36
PS11	2.7	3.1	3.0	<0.01	0.8	2.4	0.4	0.7	0.11	0.03	16	30	0.9	107	31
PS12	5.2	3.5	2.8	<0.01	2.4	1.5	1.0	0.8	0.18	0.02	23	12	1.3	18	41
PS13	1.3	3.3	3.2	<0.01	0.3	2.3	0.1	0.4	0.15	*	42		<0.1		
PS14	2.2	1.8	1.6	<0.01	0.7	1.7	0.5	0.5	0.16	0.06	32	36	1.0	54	48
PS15	4.2	4.2	3.2	<0.01	2.5	3.5	1.3	1.6	0.38	0.14	23	36	1.7	16	26
Mean	3.6	3.0	2.4	<0.01	1.9	2.5	0.8	1.2	0.18	0.09	22	37	0.7	56	25
Min	1.3	1.2	1.1	<0.01	0.3	1.4	0.1	0.4	0.04	0.00	7	12	<0.1	2	4
Max	10.4	5.6	3.2	<0.01	8.4	4.3	3.5	5.5	0.56	0.64	43	114	1.8	193	48

Table A5. Poultry manure analysis (broiler litter and layer manure)

Number	% DM	Total N	NH_4-N	NO_3-N	Uric N	Total P_2O_5	Total K_2O	Total MgO	Total SO_3	Ext-S	Ext SO_4	Ext S % total S	Ext SO_4 % Ext S	Carbon % DM	C:N	C:S
		kg/t fresh weight								kg SO_3/t FW						
BL1	79	40.9	1.80	<0.01	7.05	17.6	23.4	5.6	9.2	8.20	3.43	89	42	10	2	21
BL2	52	32.3	4.85	<0.01	5.90	20.4	26.0	6.2	9.5	6.83	3.52	72	52	43	10	59
BL3	40	10.8	0.27	0.70	1.71	20.6	15.0	8.6	7.0	3.95	2.08	56	53	35	17	50
BL4	66	26.8	3.24	<0.01	7.41	16.1	20.4	6.0	10.2	7.30	3.77	72	52	47	19	75
BL5	49	24.6	4.24	<0.01	3.48	12.4	18.5	4.7	7.0	4.24	2.22	60	52	48	14	83
BL6	57	31.8	3.75	<0.01	7.21	14.8	22.3	5.6	10.5	7.58	4.04	73	53	41	11	56
BL7	51	26.1	3.60	<0.01	5.84	12.0	21.9	6.6	10.5	6.87	3.97	65	58	45	14	54
BL8	58	33.1	5.31	<0.01	5.13	16.1	18.9	4.9	5.9	3.86	3.28	65	85	41	11	102
BL9	69	32.3	6.47	<0.01	4.95	18.5	29.3	6.4	10.5	4.71	3.47	45	74	44	14	72
BL10	67	25.3	5.16	<0.01	5.77	17.7	25.6	6.5	11.9	8.82	5.11	74	58	41	19	57
LM1	32	10.5	6.42	<0.01	<0.01	13.4	15.3	3.8	5.4	2.65	1.29	49	49	19	15	28
LM2	50	18.7	4.75	<0.01	1.31	23.8	22.5	6.4	9.2	7.66	4.01	83	52	28	11	37
LM3	49	30.3	5.80	<0.01	8.28	15.2	16.3	4.5	6.6	4.50	1.83	68	41	34	10	63
LM4	27	9.1	7.10	<0.01	1.46	9.6	8.0	2.4	3.3	2.11	1.03	63	49	30	148	60
LM5	60	27.8	5.42	<0.01	2.65	15.7	17.3	3.7	6.5	5.23	2.74	81	52	26	8	60
LM6	44	11.2	6.12	<0.01	0.43	19.9	20.2	5.2	8.1	9.41	8.65	116	92	26	24	35
LM7	28	12.9	0.87	<0.01	3.77	9.2	7.2	2.3	3.0	*	2.33	*	*	25	8	58
LM8	27	14.7	1.50	<0.01	5.97	7.4	6.8	1.9	2.3	*	2.02	*	*	29	11	88
LM9	44	22.2	1.38	<0.01	8.97	10.5	12.0	3.1	3.2	*	1.53	*	*	30	11	102
LM10	33	11.1	7.60	<0.01	*	8.5	11.6	2.7	3.4	2.60	1.17	78	45	27	26	67
Mean	49	22.6	4.28	0.04	4.59	15.0	17.9	4.9	7.2	6.83	3.52	71	56	33	20	61
Min	27	9.1	0.27	<0.01	<0.01	7.4	6.8	1.9	2.3	3.95	2.08	45	41	10	2	21
Max	79	40.9	7.60	0.70	8.97	23.8	29.3	8.6	11.9	7.30	3.77	116	92	48	148	102

BL = Broiler litter; LM = layer manure

Table A6. Biosolids analysis

Number	Biosolids type	% DM	Total N	NH_4-N	NO_3-N	Total P_2O_5	Total K_2O	Total MgO	Total SO_3	Ext-S	Ext SO_4	Ext S % total S	Ext SO_4 % Ext S	Carbon % DM	C:N	C:S
			kg/t fresh weight							kg SO_3/t FW						
BS-D1	Digested	24	12.1	4.63	<0.01	15.5	0.9	2.9	10.1	3.29	2.12	33	64	33	11	19
BS-D2	Digested	23	10.3	2.88	<0.01	18.2	0.6	2.9	9.2	2.77	1.15	30	41	26	8	16
BS-D3	Digested	26	9.7	0.30	<0.01	15.3	0.4	2.0	13.4	5.49	3.98	41	72	29	8	14
BS-D4	Digested	28	9.8	1.50	<0.01	17.1	0.7	3.5	7.3	2.97	2.04	41	69	19	6	18
BS-D5	Digested	30	15.3	2.00	<0.01	29.5	0.3	1.6	15.2	5.76	4.71	38	82	29	6	14
BS-D6	Digested	25	12.4	3.50	<0.01	22.8	0.4	2.0	10.0	2.42	1.33	24	55	30	8	18
BS-D7	Digested	27	10.4	2.55	<0.01	15.4	1.3	1.5	6.2	2.66	1.19	43	45	25	9	27
BS-D8	Digested	22	9.9	1.98	<0.01	20.0	0.3	1.0	5.6	2.40	1.01	43	42	29	8	29
BS-D9	Digested	20	11.2	0.17	<0.01	11.6	0.5	2.6	7.0	4.15	3.29	59	79	32	6	23
BS-D10	Digested	24	11.5	2.33	<0.01	17.3	0.4	1.8	8.4	4.81	3.45	57	72	32	8	23
BS-D11	Digested	21	11.8	1.98	<0.01	9.8	0.3	1.6	7.2	2.05	0.57	28	28	35	8	25
BS-D12	Digested	21	9.0	2.43	<0.01	15.1	0.5	1.4	6.2	1.97	0.68	32	34	35	11	30
BS-D13	Digested	28	10.5	2.54	<0.01	14.7	0.4	2.0	5.6	1.93	1.19	35	62	32	11	39
BS-D14	Digested	26	9.0	1.61	0.55	35.9	0.5	1.6	4.2	2.75	1.92	66	70	21	8	33
BS-D15	Digested	27	12.0	0.57	0.60	16.6	0.4	2.5	6.8	5.07	3.54	75	70	33	8	32
BS-D16	Digested	23	10.7	3.40	<0.01	11.8	0.4	3.5	9.9	5.22	2.74	53	52	39	12	23
BS-D17	Digested	23	10.8	2.12	<0.01	14.6	0.3	1.8	6.5	5.27	4.05	81	77	32	8	28
BS-D18	Digested	21	12.1	1.98	<0.01	8.8	0.4	1.6	6.4	1.96	0.67	30	34	34	7	27
BS-D19	Digested	24	11.3	2.06	<0.01	11.6	0.3	2.0	5.8	2.22	0.93	38	42	31	8	32
Digested biosolids	**Mean**	24	11.0	2.13	0.07	16.9	0.5	2.1	8.0	3.43	2.13	45	57	30	8	25
	Min	20	9.0	0.17	0.01	8.8	0.3	1.0	4.2	1.93	0.57	24	28	19	6	14
	Max	30	15.3	4.63	0.60	35.9	1.3	3.5	15.2	5.76	4.71	81	82	39	12	39

Table A6 (continued). Biosolids analysis

Number	Biosolids type	% DM	Total N	NH_4-N	NO_3-N	Total P_2O_5	Total K_2O	Total MgO	Total SO_3	Ext-S	Ext SO_4	Ext S % total S	Ext SO_4 % Ext S	Carbon % DM	C:N	C:S
			kg/t fresh weight							kg SO_3/t FW						
BS-E1	Enhanced	28	14.2	3.04	<0.01	27.1	0.7	3.5	14.3	2.08	*	15	*	33	8	16
BS-E2	Digested	38	18.7	3.97	<0.01	37.7	0.7	3.4	21.8	11.01	9.24	51	84	31	8	14
BS-E2	Digested	29	13.6	2.67	<0.01	29.0	0.5	2.3	16.8	5.17	2.49	31	48	33	9	14
BS-E4	Digested	22	10.7	2.15	<0.01	16.1	0.3	1.2	6.9	3.86	2.27	56	59	36	9	28
BS-E5	Digested	30	15.4	3.91	<0.01	14.0	0.4	2.1	9.3	8.05	6.45	87	80	36	9	28
BS-E6	Digested	25	12.1	2.48	<0.01	15.1	0.4	1.2	5.6	2.39	1.33	43	56	29	8	33
Enhanced digested biosolids	**Mean**	29	14.1	3.04	<0.01	23.1	0.5	2.3	12.4	5.42	4.36	47	65	33	9	22
	Min	22	10.7	2.15	<0.01	14.0	0.3	1.2	5.6	2.08	1.33	15	48	29	8	14
	Max	38	18.7	3.97	<0.01	37.7	0.7	3.5	21.8	11.01	9.24	87	84	36	9	33
BS-L1	Limed	28	10.8	3.66	<0.01	25.4	0.2	1.1	15.6	2.28	0.58	15	25	29	12	13
BS-L2	Limed	31	11.7	0.91	<0.01	9.1	0.4	1.0	5.5	1.17	0.25	21	22	27	8	38
BS-L3	Limed	24	12.0	1.37	<0.01	13.7	0.3	1.5	6.5	2.50	0.86	39	34	29	6	26
BS-L4	Limed	25	12.5	2.30	<0.01	11.5	0.2	1.4	5.0	1.52	0.73	30	48	33	8	41
BS-L5	Limed	38	9.4	0.25	<0.03	10.7	0.4	1.5	4.0	1.09	0.62	27	57	20	8	48
Limed biosolids	**Mean**	29	11.3	1.70	0.01	14.1	0.3	1.3	7.3	1.71	0.61	27	37	28	8	33
	Min	24	9.4	0.25	<0.01	9.1	0.2	1.0	4.0	1.09	0.25	15	22	20	6	13
	Max	38	12.5	3.66	0.03	25.4	0.4	1.5	15.6	2.50	0.86	39	57	33	12	48
All biosolids	**Mean**	26	11.7	2.24	0.05	17.7	0.5	2.0	8.7	3.54	2.25	42	55	30	8	26
	Min	20	9.0	0.17	<0.01	8.8	0.2	1.0	4.0	1.09	0.25	15	22	19	6	13
	Max	38	18.7	4.63	0.60	37.7	1.3	3.5	21.8	11.01	9.24	87	84	39	12	48