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Forage and Grain Yield Response to Applied Sulfur in Winter Wheat as Influenced by Source and Rate

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ABSTRACT

Recently, environmental quality issues related to sulfur (S) have made it necessary to reduce its release into the atmosphere in wet or dry forms, which in turn might influence the S requirement of crops. It is anticipated that by 2020, S deposition will decrease by up to 30% in eastern portions of Oklahoma and by 15% throughout the remainder of the state. This change calls for frequent monitoring and evaluation of S nutrition in wheat and other crops. Experiments were conducted at Hennessey and Perkins research stations for a period of seven years starting in the fall of 1996, with the objective of assessing the effect of different levels of elemental and sulfate-S fertilizers on the grain and forage yields of winter wheat in Oklahoma. The experimental design was a randomized complete block with three replications. Four S rates, 0, 56, 112, and 224 kg S ha^{-1}, were applied to the plots from 1996 to 2002 as $CaSO_4$. Another two rates, 56 and 112 kg S ha^{-1}, were included in the trials beginning in 1998 using 92% elemental S. Gypsum, as a source of S for winter wheat, resulted in a greater yield than did elemental S in cases where S fertilizer sources were deemed significant. In six of 14 trials from 1996 to 2002, applied S as CaSO4 significantly increased wheat-grain yields. Observing significant grain and forage yield increases due to applied S was important, but the response was sporadic and unpredictable from one year to the next.

Keywords: sulfur, winter wheat, grain and forage yields, elemental sulfur, $CaSO_4$, gypsum

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INTRODUCTION

Sulfur(s) is a building block of protein and a key ingredient in the formation of chlorophyll (Duke and Reisenaue, 1986). Without adequate S, crops cannot reach their full potential in terms of yield or protein content (Zhao et al., 1999c). Although the essential role of S for plant growth and development has long been recognized, deficiency of S in agricultural crops, especially wheat, was reported as rare (Withers et al., 1995). This is due largely to the belief that the S requirement of crops is satisfied from S deposited from wet deposition of S compounds and release from organic matter. On average, 10–12 kg ha^{-1} of sulfate-S is obtained from rainfall, which is slightly less than the wheat crop requirement of 15–20 kg ha^{-1} (Zhao et al., 1999b).

Wheat plants have a smaller requirement for S than legumes and oilseed crops (Duke and Reisenaue, 1986). A 2700 kg ha^{-1} wheat crop contained 12 kg ha^{-1} of S in the seed and straw, which was a very small quantity compared with that of nitrogen (N) (2%–3% or 54 to 81 kg ha^{-1}). Soil was found to contain adequate available S for most crops (Johnson et al., 2000). These researchers further indicated that the S addition from rainfall would satisfy the S requirement of wheat to harvest 4032 kg ha^{-1} wheat grain. Indeed, for all crops in Oklahoma, the current S recommendation is based on a 20:1 N:S ratio of the wheat grain yield for the last crop. This is because the N:S ratio is a reliable index for detecting deficiency and evaluating S-use efficiency of crops (Rasmussen, 1996), although the ratio reported was variable.

Recently, environmental quality issues related to SO_2 and other greenhouse gases have required to reduction in the release of such chemicals into the environment. As of the 1970s in the developed world, the inputs of S from atmospheric deposition were reduced by a significant level (Zhao et al., 1999a; Whelpdate, 1992; National Atmospheric Deposition Program/National Trends Network, 2000; USEPA, 1998). This reduction resulted in an obvious S deficiency in arable crops, as organic sources cannot supply the total required amount of S (McGrath and Zhao, 1995). In the United States, data show that sulfate concentrations in precipitation have decreased over the past two decades (National Atmospheric Deposition Program/National Trends Network, 2000; USEPA, 1998). During the last 10-year period, atmospheric concentrations of SO_2 and sulfate both showed average reductions of 38% and 22%, respectively, in the rural eastern United States as a result of phase I of the Acid Rain Program (USEPA, 1998). On the other hand, according to the 2000 Acid Rain Report (National Atmospheric Deposition Program/National Trends Network, 2000) at benchmark deposition monitoring sites in Oklahoma, sulfate deposition did not show a clear trend. However, it was indicated that S deposition would decrease by 30% in eastern portions of the state and 15% throughout the remainder of the state in 2020 (USEPA, 2003).

Globally, a recent switch has been made from the use of S-containing fertilizers to S-free fertilizers, which are, ironically, being used with newer, high-yielding cultivars that have increased S demand (McGrath et al., 1996). Cropping has been intensified (Knights et al., 2000) with the adoption of minimum-tillage techniques for crop establishment that may reduce the mineralization of soil organic matter and thus, organic S (Randall and Wrigley, 1986). Also, climatic and soil conditions are changing, driven by naturally occurring events influencing the dynamics of S in the soil and its availability for crop demand (Rasmussen, 1996). Considering these challenges, research initiatives have been undertaken to confirm S deficiency and response in arable crops (Spencer and Freney, 1980). In Britain, the concentration of S in wheat-grain samples decreased substantially from the early 1980s to the early 1990s (Zhao et al., 1995). Wheat is a crop that typically requires a relatively high amount of supplemental S due to incompatibility of conditions with its period of most rapid growth during early spring, when the rate of S release from soil organic matter is quite slow (Johnson, 1999). Significant yield increases of winter wheat in response to S additions have been reported elsewhere (McGrath and Zhao, 1995; Randall and Wrigley, 1986). Micronized elemental S and sulfate fertilizers resulted in a 36% increase of wheat grain yield (Riley et al., 2000). Sulfur application increased the grain S content at high rather than low N treatment (Randall and Wrigley, 1986; Blake-Kalff et al., 2000; Zhao et al., 1996). With added S, yields were increased by 15.7% in the plots where a high rate of N was applied (Zhao et al., 1996). The objective of this experiment was to assess the effect of different levels of elemental and sulfate-S fertilizers on the grain and forage yields of winter wheat over an extended period of time (1996–2002) in northern central Oklahoma.

MATERIALS AND METHODS

Fourteen trials were conducted from 1996 to 2002 at Hennessey (Shellabarger sandy loam-fine-loamy, mixed, thermic Udic Argiustolls) and Perkins (Teller sandy loam-fine-loamy, mixed, thermic Udic Argiustolls), Oklahoma to evaluate the response of winter wheat forage and grain yields to S rates and fertilizer sources. The Hennessey location is a typical environment for wheat production in northern central Oklahoma. The Perkins location is on a deep, sandy, low-organic-matter soil that is more prone to leaching of mobile nutrients including sulfate in soil solution. Initial soil-test data are reported in Table 1. Initial soil samples were analyzed for total extractable SO_4 concentration using an inductively coupled argon plasma spectrophotometer (ICP) with calcium phosphate to extract the SO_4 (Miller et al., 1997).

A randomized complete block experimental design with three replications was used at both sites. During the crop years 1996–2002, the experiment used four different rates (0, 56, 112, and 224 kg S ha^{-1}) of gypsum ($CaSO_4$); during the crop years 1998–2002, an additional two rates of (56 and 112 kg S ha^{-1}) of 92% elemental S were used. Plot sizes were 4.86 m $\times$ 6.08 m.

Table 1
Initial soil (0–15 cm) chemical characteristics and classification at Hennessey and Perkins during the experimental period

Location	pH	BI	NO_3-N mg kg^{-1}	P mg kg^{-1}	K mg kg^{-1}	SO_4-S mg kg^{-1}
Perkins	6	7.1	3	12.5	163	14
Classification: Teller sandy loam-fine-loamy, mixed, thermic Udic Argiustolls						
Hennessey	5.3	6.6	1.5	88.5	401	19.5
Classification: Shellabarger sandy loam-fine-loamy, mixed, thermic Udic Argiustolls						

The winter wheat variety Tonkawa was used during the 1996–1999 cropping seasons. This variety was replaced by Custer from 2000 to 2002. Wheat was planted between October and November for all trials. All other crop-management practices were conducted as per the recommendation of the respective sites. Wheat was harvested in June with a Massey Ferguson 8XP experimental combine, removing an area of 2.0 m $\times$ 4.6 m from the center of each plot. A Harvest Master yield-monitoring computer installed on the combine recorded yield data. Forage yields were determined from destructive samples collected from 1 m^2 for each trial at Feekes growth stages 7 and 10. The samples were dried in a forced-air oven at 66°C for three days, weighed, and total forage yields were determined for each trial by adding the dried weight of the two consecutive samples.

Forage and grain-yield data were subjected to statistical analysis using SAS (SAS, 2001). The S rates and sources were further analyzed using single-degree-of-freedom non-orthogonal contrasts.

RESULTS

Grain yield was significantly influenced by applied S as $CaSO_4$ in six of 14 site-years (Tables 2 and 3). Further investigation of the grain-yield data using orthogonal polynomial contrasts revealed that five out of 14 site-years showed a quadratic grain-yield response to applied S (Tables 2 and 3).

At Perkins in 2000 (Figure 1), 2002 (Figure 2), and Hennessey in 2001 (Figure 3), grain yield was increased for S rates between 56 and 112 kg ha^{-1} and decreased afterwards. In another two trials at Hennessey in 1997 (Figure 4) and 1998 (Figure 5), a significant linear trend was observed in response to applied S. Grain yield response to S fertilizers was not consistent across trials.

Forage yield was significantly affected by applied S as $CaSO_4$ in four of 12 site-years (Tables 4 and 5). In 2002 at both locations, a quadratic response

Table 2
Effect of S rates and sources on winter wheat grain yield (Mg ha^{-1}) at Hennessey, OK, 1996–2002

	Year						
Source	1996	1997	1998	1999	2000	2001	2002
Sulfur (S) rate	NS	***	**	NS	*	*	*
S-Linear	NS	***	***	NS	NS	NS	NS
S-Quadratic	NS	***	NS	NS	NS	**	NS
Elemental S vs $CaSO_4$ at 56 kg ha^{-1} S rate	NA	NA	NS	NS	*	NS	**
Elemental S vs $CaSO_4$ at 112 kg ha^{-1} S rate	NA	NA	NS	NS	NS	NS	NS
Mean	2.750	2.722	4.242	2.181	3.577	1.566	3.874

*, **, and *** indicate significance at 0.1, 0.05, and 0.01 significance levels, respectively. NS: non-significant. NA: not applicable.

was observed (Figures 6 and 7). In both cases, consistent trends were observed in which forage yield was increased and reached a maximum, but decreased afterwards.

Grain and forage yields were positively and significantly ($P < 0.05$) correlated in eight out of 12 site-years, with five of these results occuring at Perkins.

Table 3
Effect of S rates and sources on winter wheat grain yield (Mg ha^{-1}) at Perkins, OK, 1996–2002

	Year						
Source	1996	1997	1998	1999	2000	2001	2002
Sulfur (S) rate	NS	NS	NS	NS	NS	NS	**
S-Linear	NS	NS	NS	NS	NS	NS	NS
S-Quadratic	NS	NS	NS	NS	**	**	***
Elemental S vs $CaSO_4$ at 56 kg ha^{-1} S rate	NA	NA	NS	NS	NS	NS	NS
Elemental S vs $CaSO_4$ at 112 kg ha^{-1} S rate	NA	NA	NS	NS	NS	NS	***
Mean	1.567	1.396	1.933	1.234	2.246	1.922	2.411

*, **, and *** indicate significance at 0.1, 0.05, and 0.01 significance levels, respectively. NS: non-significant. NA: not applicable.

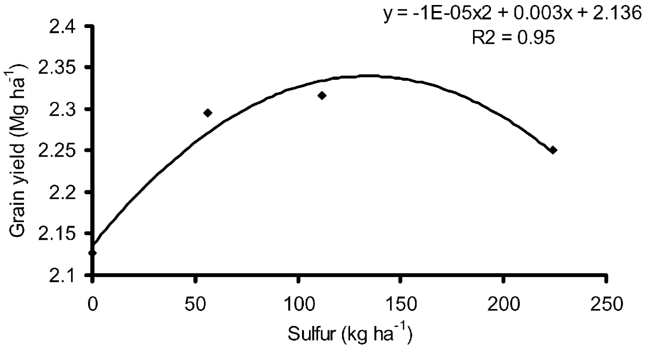

Figure 1. Grain-yield response to S fertilizer rates at Perkins in 2000.

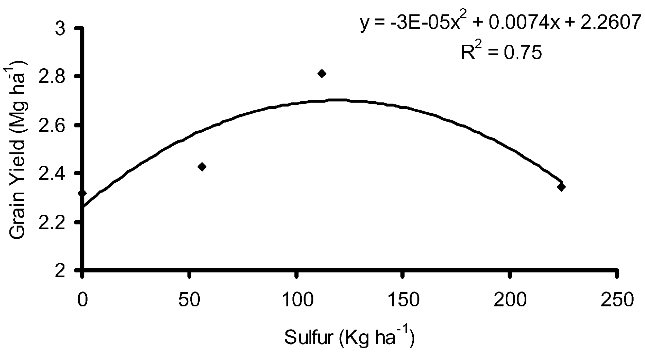

Figure 2. Grain-yield response to S fertilizer rates at Perkins in 2002.

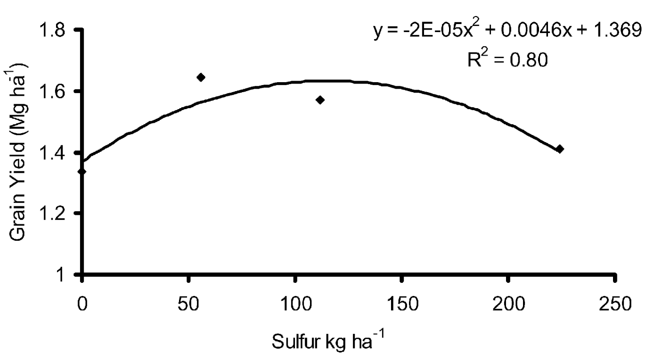

Figure 3. Grain-yield response to S fertilizer rates at Hennessey in 2001.

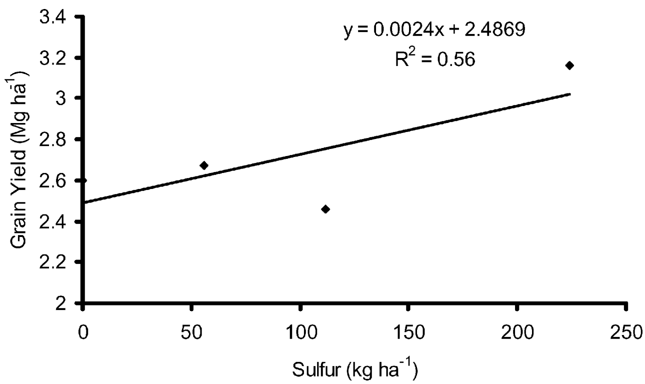

Figure 4. Grain-yield response to S fertilizer rates at Hennessey in 1997.

Another set of contrasts compared $CaSO_4$ and elemental S at each of the 56 and 112 kg ha^{-1} rates. Accordingly, for grain yield, three trials (Hennessey, 2000 at 56 kg ha^{-1} and Hennessey 2002 at both rates) were different (Figure 8). Similarly, for forage yield, five trials (at Perkins in 1998 at the 112 kg ha^{-1}rate, in 1999 and 2000 at the 56 kg ha^{-1} rate, in 2001 and 2002 at the 112 kg ha^{-1}, and at Hennessey in 2002 at the 56 kg ha^{-1} and 112 kg ha^{1} rates) were significant (Figure 9). Both grain and forage yields were consistently higher when the S source was $CaSO_4$ for both rates of S, except at Perkins in 1998 at the 112 kg ha^{-1} rate and in 1999 at the 56 kg ha^{-1} rate, where the opposite was observed.

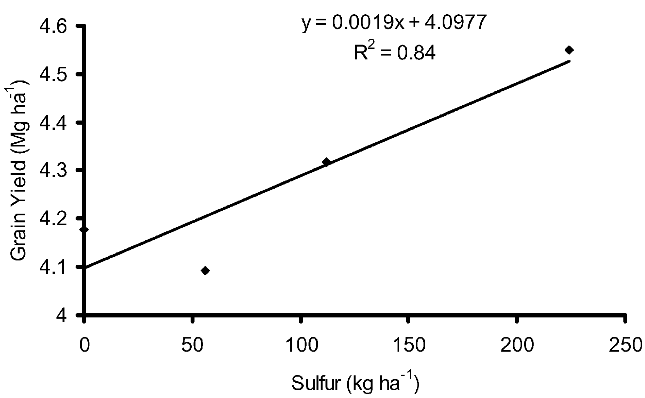

Figure 5. Grain-yield response to S fertilizer rates at Hennessey in 1998.

Table 4
Effect of S rates and sources on forage yield (kg ha^{-1}) at Hennessy, OK, 1997–2002

	Year					
Source	1997	1998	1999	2000	2001	2002
Sulfur (S) rate	NS	NS	NS	NS	NS	**
S-Linear	NS	NS	NS	NS	NS	NS
S-Quadratic	NS	NS	NS	NS	NS	*
Elemental S vs $CaSO_4$ at 56 kg ha^{-1} S rate	NA	NS	NS	NS	NS	**
Elemental S vs $CaSO_4$ at 112 kg ha^{-1} S rate	NA	NS	NS	NS	NS	**
Mean	8748	1712	1781	2209	942	5744

*, **, and *** indicate significance at 0.1, 0.05, and 0.01 significance levels, respectively. NS: non-significant. NA: not applicable.

DISCUSSION

In six out of 14 site-years, grain yield was significantly affected by S rates. In several past experiments it has been reported that wheat did not respond to S fertilization, at least for grain yield (Beaton and Wagner, 1985; Mitchell and Mullins, 1990; Sawyer and Ebelhar, 1995). Using three years of data, a non-significant S response was obtained on a silt-loam soil due to wet and dry deposition (Sawyer and Ebelhar, 1995). A study conducted in Alabama (Beaton

Table 5
Effect of S rates and sources on forage yield (kg ha^{-1}) at Perkins, OK, 1997–2002

	Year					
	1997	1998	1999	2000	2001	2002
Sulfur (S) rate	***	**	NS	**	NS	NS
S-Linear	NS	NS	NS	NS	NS	NS
S-Quadratic	**	NS	NS	NS	NS	*
Elemental S vs $CaSO_4$ at 56 kg ha^{-1} S rate	NA	NS	*	***	NS	NS
Elemental S vs $CaSO_4$ at 112 kg ha^{-1} S rate	NA	**	NS	NS	*	**
Mean	4183	1245	922	2291	1322	4633

*, **, and *** indicate significance at 0.1, 0.05, and 0.01 significance levels, respectively. NS: non-significant. NA: not applicable.

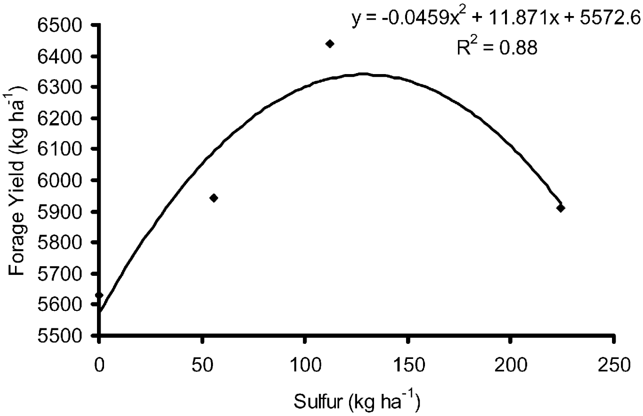

Figure 6. Forage yield response to S fertilizer rates at Hennessey in 2002.

and Wagner, 1985) also concluded that the lack of response to S fertilizer was due to the combined input of available S from sources other than fertilizer S, such as precipitation, dry deposition, atmospheric $S0_2$ absorption by plants, mineralization of organic matter, or subsoil sulfate supply. The researchers justified their statement with an example: The total amount of S taken up by a 5400 kg ha^{-1} wheat crop is approximately 22 kg ha^{-1}, which can be easily obtained from the above sources.

More S grain-yield response was observed over the years at Hennessey than at Perkins. This result could be due to inherently low levels of S in that soil. In fact, overall grain yields were higher for this site, which might explain the significant effects observed. High grain and or forage yields are associated with a high level of nutrient harvest. Soils that inherently supply less available

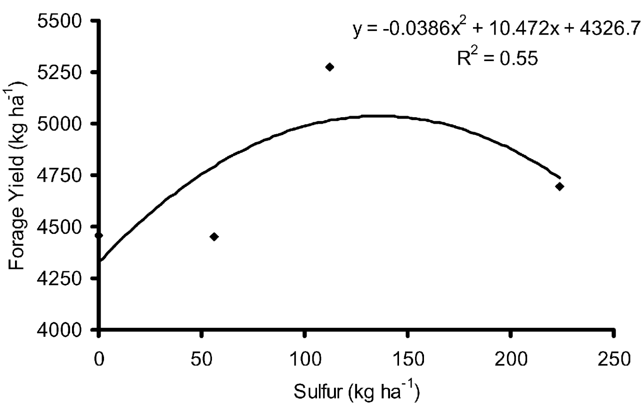

Figure 7. Forage yield response to S fertilizer rates at Perkins in 2002.

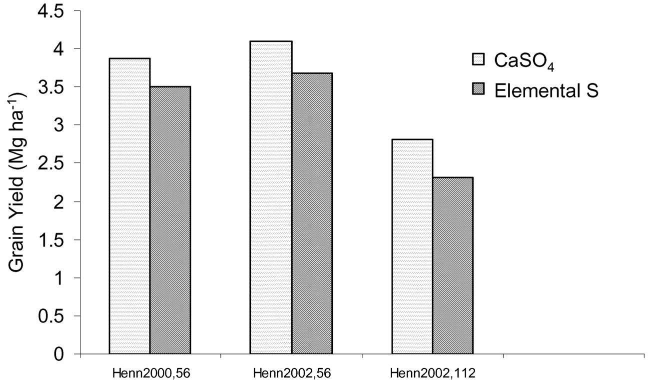

Figure 8. Response of grain yield to sulfur sources for three trials, (Location-year-sulfur rate combinations; e.g., Henn2000, 56, indicates location Hennessy, year 2002, sulfur rate 56 kg ha^{-1}, respectively) where sulfur sources were deemed significant.

S or can retain less available S within the rooting zone, such as low-organic-matter and coarse-textured soils, could be those where crop response to applied S fertilizer was found (Mahler and Maples, 1986).

The rainfall data during the crop season for the period of the experiment were used as a covariate to detect whether it influenced S response in wheat. The resulting conclusion is that the rates are not significant. A significant yield response to S fertilization in controlled laboratory conditions was observed, but

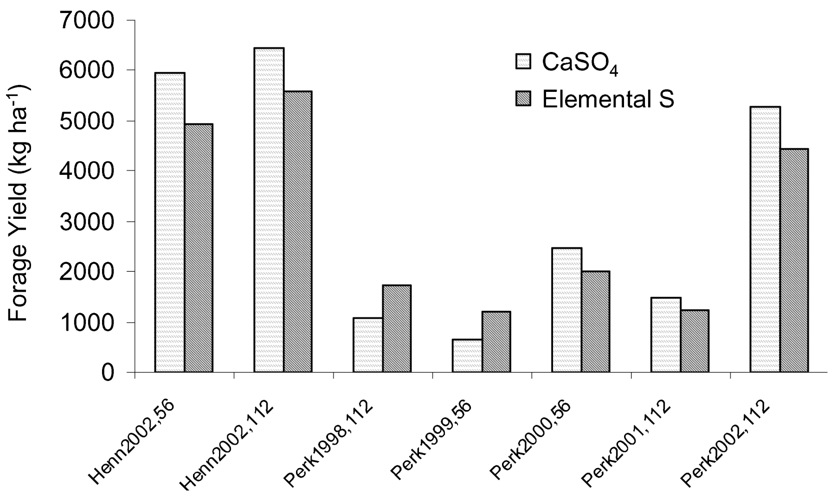

Figure 9. Response of forage yield to sulfur sources in seven trials (location-year-sulfur rate combinations; e.g., Henn2002, 56 indicates location Hennessy, year 2002, sulfur rate 56 kg ha^{-1}, respectively) where sources were deemed significant.

not under field conditions where rainfall was the sole source of S (Hoeft et al., 1985).

In this study, it was observed that the form of S applied played an equally important role in obtaining a significant response as the rate applied. The consistently higher yields obtained when $CaSO_4$ as opposed to elemental S was applied were attributed to the immediate availability of the sulfate in $CaSO_4$ when rainfall is modest. Elemental S needs to be oxidized before it becomes available to the crop (Mahler and Maples, 1987). At Perkins in 1998 and 1999, high forage-yield differences were observed between the two sources of S. This result can be explained by the fact that high rainfall was received during the growing season in these years, which presumably caused sulfate from $CaSO_4$ to leach out, causing lower forage yield, while the slow transformation of elemental S made S available for crop growth. In general, S sources other than elemental S are known to boost growth and yield of wheat (Mahler and Maples, 1987; Oates and Kamprath, 1985). The transformation process of elemental S to sulfate creates temporary acidity in the rhizosphere, which might reduce wheat yields.

CONCLUSIONS

Unlike past reports, the current study revealed a significant wheat-grain and forage-yield response to S rates in six and four trials, respectively. Quadratic trend analysis revealed that the biological optimum S rate was between 56 and 112 kg ha^{-1}. The form of S applied played an equally important role in obtaining a significant response as the rate applied. Consistently higher yields were obtained when $CaSO_4$ was applied than when elemental S was applied. In conjunction with the projected decrease in atmospheric S deposition, the results obtained from these experiments suggest that wheat response to S should be monitored to prevent possible forage and grain-yield loss.

REFERENCES

Beaton, J. D., and R. E. Wagner. 1985. Sulphur: A vital component of maximum economic yield systems. *Sulphur in Agriculture* 9(1): 1–7.

Blake-Kalff, M. M. A., M. J. Hawkesford, F. J. Zhao, and S. P. McGrath. 2000. Diagnosing sulfur deficiency in field-grown oilseed rape (*Brassica napus* L.) and wheat (*Triticum aestivum* L.). *Plant and Soil* 225(1/2): 95–107.

Duke, S. H., and H. M. Reisenaue. 1986. Roles and requirements of sulfur in plant nutrition. In *Sulfur in agriculture*, ed. M. A. Tabatabai, Agronomy Series No. 27, 124–168. Madison, WI: ASA, CSSA, SSSA.

Hoeft, R. G., J. E. Sawyer, R. M. Vanden-Heuvel, M. A. Schmitt, and G. S. Brinkman. 1985. Corn response to sulfur on Illinois soils. *Journal of Fertilizer Issues* 2(1): 95–104.

Johnson, G. V., W. R. Raun, H. Zhang, and J. A. Hattey. 2000. *Oklahoma soil fertility handbook,* 5th edition. Stillwater, OK: Oklahoma State University.

Johnson, J. W. 1999. Most asked agronomic questions. In *Ohio State University Extension*, eds. J. W. Johnson and C. Hudak, Extension Bulletin E-760-88. Columbus, OH: The Ohio State University.

Knights, J. S., F. J. Zhao, B. Spiro, and S. P. McGrath. 2000. Long-term effects of land use and fertilizer treatments on sulfur cycling. *Journal of Environmental Quality* 29(6): 1867–1874.

Mahler, R. J., and R. L. Maples. 1986. Response of wheat to sulfur fertilization. *Communications in Soil Science and Plant Analysis* 17(9): 975–988.

Mahler, R. J., and R. L. Maples. 1987. Effect of sulfur additions on soil and the nutrition of wheat. *Communications in Soil Science and Plant Analysis* 18(6): 653–673.

McGrath, S. P., and F. J. Zhao. 1995. A risk assessment of sulfur deficiency in cereals using soil and atmospheric deposition data. *Soil Use Management* 11(1): 110–114.

McGrath, S. P., F. J. Zhao, and P. J. A. Withers. 1996. Development of sulfur deficiency in crops and its treatment. In *Proceedings of the International Fertilizer Society*, No. 379, 1–47. York, U.K.: The International Fertilizer Society.

Miller, R. O., J. Kotuby-Amacher, and J. B. Rodriguez. 1997. Soil chloride. In *Western states laboratory proficiency testing program soil and plant analytical methods*, 90–91. Davis, CA: University of California.

Mitchell, C. C., and G. L. Mullins. 1990. Sulfur fertilization needed by wheat on coastal plain soils: Highlights of agricultural research. *Alabama Agricultural Experiment Station* 37(4): 8.

National Atmospheric Deposition Program (NRSP-3)/National Trends Network. 2000. *National atmospheric deposition program 2000 annual summary*, Champaign, IL: NADP/NTN Coordination Office, Illinois State Water Survey.

Oates, K. M., and E. J. Kamprath. 1985. Sulfur fertilization of winter wheat grown on deep sandy soils. *Soil Science Society of America Journal* 49(4): 925–927.

Randall, P. J., and C. W. Wrigley. 1986. Effects of sulfur supply on the yield, composition and quality of grain from cereals, oilseeds, and legumes. *Advances in Cereal Science and Technology* 8: 171–206.

Rasmussen, P. E. 1996. Effect of nitrogen, sulfur, and phosphorus sufficiency on nutrient content in soft white winter wheat. *Communications in Soil Science and Plant Analysis* 27(3/4): 585–596.

Riley, N. G., F. J. Zhao, and S. P. McGrath. 2000. Availability of different forms of sulfur fertilizers to wheat and oilseed rape. *Plant and Soil* 222(1/2): 139–147.

SAS. 2001. The SAS system for Windows, Version 8.02. Cary, NC: SAS Institute.

Sawyer, J. E., and S. A. Ebelhar. 1995. Sulfur nutrition of wheat varieties with till and no-till planting on highly weathered alfisol soils. *Communications in Soil Science and Plant Analysis* 26(7/8): 1257–1271.

Spencer, K., and J. R. Freney. 1980. Assessing the sulfur status of field grown wheat by plant analysis. *Agronomy Journal* 72(3): 469–476.

United States Environmental Protection Agency (USEPA). Clear Skies in Oklahoma. http://www.epa.gov/air/clearskies/state/ok.html (accessed February 2003).

United States Environmental Protection Agency (USEPA). 1998. Atmospheric deposition of sulfur and nitrogen compounds. In *National air quality and emissions trends report*, 105–115. Washington, DC: USEPA.

Whelpdate, D. M. 1992. An overview of the atmospheric sulfur cycle. In *Sulfur cycling on the continents*, eds. R. W. Howarth, J. W. B. Stewart, and M. V. Ivanov, 5–26. Chichester, U.K.: John Wiley.

Withers, P. J. A., A. R. J. Tytherleigh, and F. M. Òdonnell. 1995. Effect of sulfur fertilizers on the grain yield and sulfur content of cereals. *Journal of Agricultural Science* 225(3): 317–324.

Zhao, F. J., M. J. Hawkesford, and S. P. McGrath. 1999a. Sulfur assimilation and effects on yield and quality of wheat. *Journal of Cereal Science* 30(1): 1–17.

Zhao, F. J., M. J. Hawkesford, A. G. S. Warrilow, S. P. McGrath, and D. T. Clarkson. 1996. Responses of two wheat varieties to sulfur addition and diagnosis of S deficiency. *Plant and Soil* 181(2): 317–327.

Zhao, F. J., S. P. McGrath, A. R. Crosland, and S. E. Salmon. 1995. Changes in the sulfur status of British wheat-grain in the last decade, and its geographical distribution. *J. Sci. Food and Agri.* 68(4): 507–514.

Zhao, F. J., S. E. Salmon, P. J. A. Withers, E. J. Evans, J. M. Monaghan, P. R. Shewry, and S. P. McGrath. 1999b. Responses of bread making quality to sulfur in three wheat varieties. *J. Sci. Food and Agric.* 79(1): 1–10.

Zhao, F. J., S. E. Salmon, P. J. A. Withers, J. M. Monaghan, E. J. Evans, P. R. Shewry, and S. P. McGrath. 1999c. Variation in the bread making quality and mineralogical properties of wheat in relation to sulfur nutrition under field conditions. *Journal of Cereal Science* 30(1): 19–31.