

Site-Specific Nutrient Management

For Nutrient Management Planning To Improve Crop Production, Environmental Quality, and Economic Return

Sulfur: Chapter 5 of 10

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Chapter 5: Sulfur Management

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Introduction

Sulfur (S) is often classified as a “secondary” plant essential element, mainly due to a smaller plant requirement but also because it is less frequently applied as a fertilizer and in smaller amounts compared to other nutrients like the “macronutrients” nitrogen (N), phosphorus (P), and potassium (K). However, if deficient, S can have a dramatic effect on plant growth and crop productivity – more than the classification “secondary” would imply.

Sulfur is a constituent of three amino acids which are essential to protein synthesis and represent approximately 90% of the S content in plants. Sulfur is also necessary in the formation of chlorophyll, vitamins, enzymes, and aromatic oils. As a constituent of amino acids, sufficient S is essential for high protein content in forages. Research has shown that S plays an important role in crop quality such as wheat grain for making bread and protein content of forages and grains. Breadmaking varieties of wheat have approximately 10% more S in grain than non-breadmaking varieties, although total plant S uptake is similar. Two important factors related to breadmaking are loaf volume and dough extensibility. Both of these factors are directly related to S concentration in grain, which in turn is dependent upon available S in the soil.

Sulfur deficiencies are on the rise in the U. S. and throughout the world. Three global trends are responsible for increasing S deficiencies:

- 1) The shift in modern fertilizers to more concentrated, higher-analysis products containing little to no S (historically S was a co-product of the manufacturing process);
- 2) The reduction of sulfur dioxide (SO₂) emissions from burning coal and oil, which decreases atmospheric S additions; and

- 3) The steady increase in crop S uptake and removal due to high-yielding varieties and more productive management.

Plants require significant S, with uptake varying considerably between crops. For example, alfalfa is a greater S demanding crop than corn. Also, the plant component harvested affects S removal. Harvesting all above ground material will result in more S removal. For example corn grain versus corn silage, stover removal or grazing, and multiple forage crop harvest. Table 1 lists the S removal per unit of yield, and can be used for estimating S removal. Crops take up S in the sulfate (SO_4^{2-}) form. They do not take up elemental S. Sulfate-S usually represents less than 10% of total S in the upper soil profile, with most S contained in the soil organic matter.

Sulfur deposition from the atmosphere can represent a significant S input, especially in locations downwind from sources, such as coal-burning facilities, metal smelters, geo-thermal areas, and urban areas. Atmospheric sulfate-S deposition ranges significantly, but usually is between 3 to 11 lb S/acre. In addition, plants can absorb sulfur dioxide directly from the air. Figure 1 shows a recent U.S map with sulfate wet deposition mainly due to industrial activity. Also, irrigation water can be a significant source of plant available S.

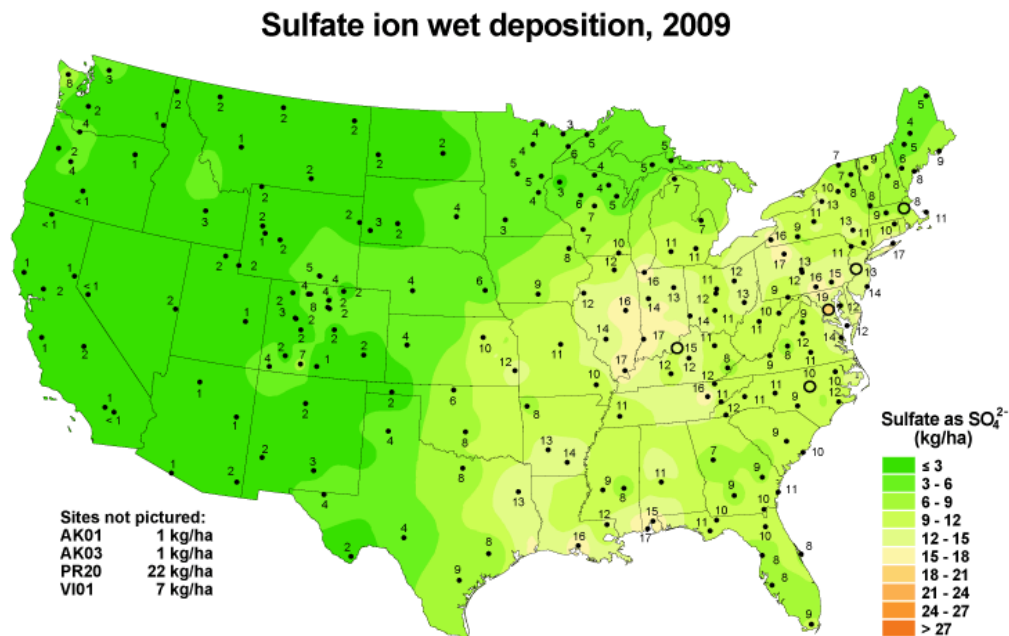


Figure 1. Sulfate wet deposition for the U.S. in 2009.

Source: National Atmospheric Deposition Program/National Trends Network. <http://nadp.sws.uiuc.edu>.

Table 1. Sulfur amounts required by common agricultural crops.

Crop	Unit of Yield	Pounds of S per unit of yield
Corn	bu	0.07
Corn silage	ton	0.58
Soybean	bu	0.10
Oat and Straw	ton	4.50
Wheat	bu	0.08
Barley	bu	0.08
Alfalfa	ton	5.00
Clover	ton	3.00

*Adapted from Modern Corn and Soybean Production. 2000.
MCPS Publications.*

Sulfur deficiency looks similar to N deficiency (yellowing and interveinal chlorosis), but because S is not very mobile in the plant, the younger leaves tend to show the deficiency first versus the older leaves as in N deficiency. With severe deficiency, the entire plant will have yellowing and reduced growth or spindly stems. Efficient N utilization requires adequate S because both are needed to form proteins in the plant. Sulfur is also needed for N fixation by legumes. Effective management of S requires an understanding of the processes that determine its availability to crops and the methods to manage soils with inadequate S levels.

Basic Sulfur Processes in the Soil-Plant System

Mineralization and Immobilization

Organic S compounds held in plant and microbial residues collect in the soil organic matter (OM) and represent the largest S pool in many soils. Over 90% of the total S in these soils exists in the organic form, except in soils where accumulations of gypsum (CaSO_4 , calcium sulfate) are significant.

Microorganisms decompose the OM and release plant available S through the process of mineralization, similar to that with N cycling. About 1 to 3% of organic S is mineralized each year, contributing 4-13 lb/acre of inorganic sulfate-S annually. The amount of S made available to plants annually via mineralization depends on the soil OM content and conditions suitable for mineralization. Therefore, practices to maintain or increase soil OM can help with plant available S supply.

Immobilization is the microbial process of converting inorganic sulfate-S to organic materials, and is essentially the reverse of mineralization. Microorganisms use available S from the soil and convert it into

proteins and other organic compounds. Although this process removes S from the available pool, the S is still in a reserve pool that could eventually become available to plants via mineralization.

Since mineralization and immobilization are primarily biological processes, factors affecting microbial growth will influence these S transformations. Important factors include soil temperature, soil moisture, pH, C:S ratio, aeration, and residue composition. The highest mineralization rates will occur under aerated, warm, and moist conditions with near neutral pH levels because these conditions are optimal for microbial activity. Conversely, cold-dry soils will have slow mineralization and low production of sulfate-S.

The N:S ratio is relatively stable in soil OM, remaining near 8:1; however the C:S ratio is more variable and strongly affects relative mineralization and immobilization. If residues and organic matter lack sufficient amounts of S, microbes will pull the needed available S from the soil and thus reduce plant available S.

Sorption and Precipitation

Inorganic S occurs in solid phases in the soil as sorbed S or S-containing minerals. Sorption of sulfate increases as anion exchange capacity (AEC) and clay content of soils increase. Highly weathered and acid soils dominated by positively charged Fe/Al oxide will have a high AEC and therefore sorb significant sulfate. Also, because sulfate interacts with soil clays, soils will retain sulfate, including sulfate accumulation in the subsoil where clay content is high in many soils.

Inorganic S-containing minerals represent an important S pool in some soils. Sulfur is also present in numerous primary and secondary minerals, which release either sulfate or sulfide (S^{2-}) as they weather. Gypsum, for example, is widely distributed in arid and semi-arid soils where precipitation is too low to leach the mineral out of the profile. In moderately humid regions, gypsum accumulates in the subsoil, forming a S-rich layer often in close proximity to calcium carbonate ($CaCO_3$) layers. Although the surface layers of soils may have low levels of plant available sulfate-S, sulfate in the lower soil profile maintains an adequate supply of S within the rooting depth. Early in the growing season, subsoil S may not be available to crops because it is out of reach of the growing roots. Later in the growing season, when plant roots have grown deeper, adequate S can then be accessible to crops.

Sulfur Losses

Sulfur loss from moderately to well-drained soils, other than by crop removal, is through leaching of sulfate. Sulfate is a negatively charged ion (SO_4^{-2} , an anion), and therefore not held on the cation exchange complex. Leaching is the physical removal of sulfate by water moving through the profile, like that with nitrate. Sulfate, however, is not subject to denitrification. The areas with the highest risk for sulfate leaching are associated with high precipitation and coarse texture soils. Excessive irrigation following fertilizer application can move sulfate through the soil profile and eventually out of reach of plant roots. In semi-arid climates, sulfate often collects in the subsoil, as described earlier, because there is insufficient water to move sulfate out of the profile.

Testing for Sulfur Sufficiency

Sampling soil, plant, and irrigation water are methods for determining S fertilization needs. Soil testing the topsoil for plant-available S has been and continues to be debated because testing for extractable sulfate-S or other S forms has a poor relationship with S sufficiency for crops, and is not reliable in soils of many regions for predicting yield response to applied S. Other suggested soil tests for S include measuring the organic S content and estimating mineralization during the growing season. For example, a study from Iowa has shown no value of extractable soil sulfate-S (0-6 inch depth) for predicting corn yield increase from S application (Figure 2), and several land-grant universities do not recommend sulfur application based on soil testing. A low testing soil may still supply a crop with adequate S because of ample S below the testing depth (i.e., subsoil sulfate or gypsum layer), significant organic S mineralized during the growing season, or high S levels in shallow groundwater. At issue is that soil tests by themselves cannot integrate all of the potential sources and variation in supply of plant-available S.

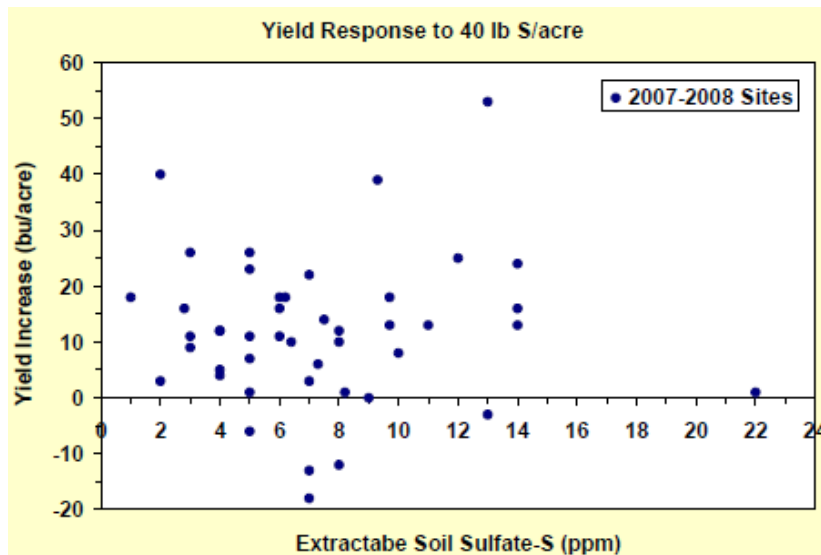


Figure 2. Corn grain yield response to S application as related to extractable soil sulfate-S concentration (0-6 inch soil depth) in the no-S control. Adapted from Sawyer, J.E., D.W. Barker, and G. Cummins. 2009. *Dealing with sulfur deficiencies in crop production: the Iowa experience*. p. 64-73. In *North-Central Extension-Industry Soil Fertility Conf. Proceedings*. Nov. 18-19. Vol. 25. Des Moines, IA.

Plant tissue testing can also be used to determine sufficiency of plant-available S. Samples are analyzed for total S concentration or the N:S ratio. These plant tests for S have greater reliability than soil testing in some crops. For example, the S concentration in the top six inches of alfalfa at early bud state (Figure 3). In research with corn in the same area of Iowa, plant S concentration of ear leaves at silking could not indicate a specific critical concentration.

In some crops and geographic areas, the plant N:S ratio has been successfully used as an indicator of S status. For example, the critical ratio for wheat is about 16:1, so, assuming adequate N supply, ratios greater than 16:1 would indicate a S deficiency in the plant (Figure 4). Unfortunately, deficiencies indicated by tissue tests in some crops taken during the growing season cannot easily be corrected until the following year. In other crops with multiple harvests per growing season, like alfalfa, deficiencies can be corrected after any harvest.

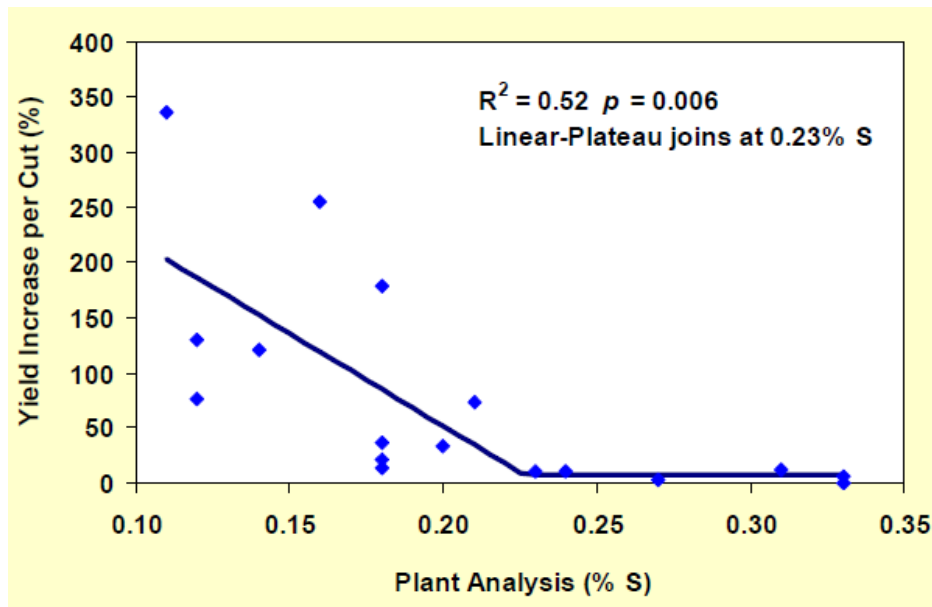


Figure 3. Yield increase per cut from S fertilization relative to the alfalfa plant tissue S concentration (6-inch plant top) with no S applied. Adapted from Sawyer, J.E., D.W. Barker, and G. Cummins. 2009. *Dealing with sulfur deficiencies in crop production: the Iowa experience*. p. 64-73. In *North-Central Extension-Industry Soil Fertility Conf. Proceedings*. Nov. 18-19. Vol. 25. Des Moines, IA.

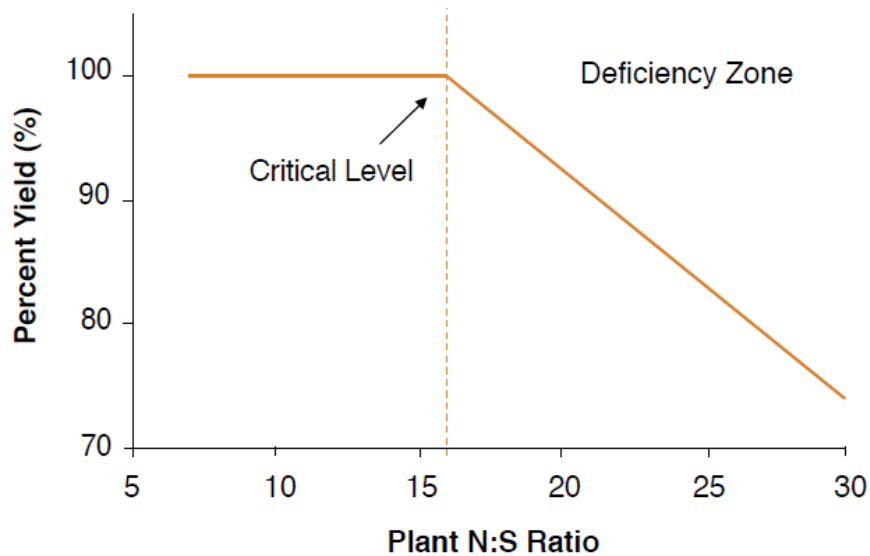


Figure 4. Relationship between relative yield of wheat and plant tissue N:S ratio. Adapted from K. Spencer and J.R. Freney (1980). *Agron. J.* 72:469-472.

Basis for Sulfur Fertilizer Recommendations

Yield responses to S occur most commonly in crops with higher S requirements such as alfalfa, canola, and corn; when most of the plant material is removed; in sandy or eroded soils; and soils low in organic matter or with low or very low sulfate-S content in the profile. Unlike N-P-K, S fertilization guidelines do not exist in many regions of the U. S. The existing S fertilization recommendations often are based on plant testing (for specific crops when reliable) or local yield response trials, and suggestions often include consideration of soil properties and other conditions commonly associated with response to S application. This is explained by the great complexity of S cycling and factors affecting plant available S levels; no single diagnostic method or recommendation system seems to be appropriate for all crops or regions. Therefore, diverse S management strategies have been implemented in different production areas, supporting the need to use locally developed information. Following are examples that represent some of the various approaches that universities and other research institutions are recommending to manage S fertilization.

The University of Wisconsin recommends the use of a S availability index (SAI) to determine relative plant available S. This index is comprised of: (soil test $\text{SO}_4\text{-S} \times 4$) + Subsoil-S + precipitation-S + (% OM $\times 2.8$ lb/acre) + available manure-S. For the SAI, values greater than 40 are considered adequate with no S application needed, and less than 30 considered low with application of 10-50 lb S/acre recommended (with rate depending of the placement method and crop). If the SAI is between 30 and 40, a tissue test is recommended to determine if additional S is needed. In other states, such as Alabama, S recommendations are more conservative in terms of preventing S deficiencies and suggest that all crops receive 10 lb S/acre per year except cotton which would receive 20 lb S/acre. In the Great Plains, a soil test critical value has been determined for canola. Soils with less than 5 ppm sulfate-S should be fertilized with 15 lb S/ac in an optimal N-P-K blend. In the same region, the critical soil test level for wheat and other small grains such as barley and oats is only 3 ppm $\text{SO}_4\text{-S}$ and fertilizer recommendations for deficient areas range between 10 and 15 lb S/acre.

Sulfur Fertilizer Application

Proper management of S applications is a key for optimizing yield and profitability. There are some guidelines regarding S source, timing, placement, and rate that producers should consider in order to maximize S use efficiency.

Sulfur Sources

There are several forms of S fertilizers available to producers, some with very different S solubility and crop-availability in the short term. The most common S fertilizers used in the U.S. are listed in Table 3. The major factors in choosing a S fertilizer are the analysis, availability to plants, acidifying effect of the material, fertilizer compatibility, and cost. Ammonium sulfate, ammonium thiosulfate, gypsum, potassium sulfate, and epsom salt (magnesium sulfate) are commonly used S sources because they quickly release sulfate for plant use. Therefore, these fertilizers can be applied before, at, or after planting. Elemental S, on the other hand, must be microbially oxidized to sulfate before plants can utilize it. The rate of oxidation depends on particle size, incorporation, temperature, moisture, and soil properties. Dispersible, granular elemental S can be broadcast to increase surface area and exposure of S, and thereby accelerate oxidation. This form of S must be applied well before the growing season if it is expected to supply the crop with S; otherwise some readily available S should be included. Another factor with application of elemental S is the acidifying affect it may have on the soil. Most soils are buffered and should not have pH affected by low rates typically applied to provide S for crop production, but sandy soils are more susceptible to acidification. Ammonium sulfate acidifies soil at about twice the rate as commonly used N fertilizers. Therefore, if it is applied as a N source, the soil pH decline may be large but the effect on soil pH will be minimal when it is applied based on crop S need.

Manures are a good source of S, and can eliminate the need for S fertilizer application. Also, many locally produced byproducts contain S, and can be an effective source of plant-available S. Examples include products from lysine manufacturing, soapstock processing, and wallboard. In some cases, application of a byproduct can supply adequate S for many years of crop production.

Table 3. Commonly used S fertilizers.

Fertilizer Source	Formula	Analysis (N-P-K-S)
Ammonium sulfate	$(\text{NH}_4)_2\text{SO}_4$	21-0-0-24
Ammonium thiosulfate (ATS)	$(\text{NH}_4)_2\text{S}_2\text{O}_3$	12-0-0-26
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	0-0-0.5-17
Epsom salt	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	0-0-0-14
Granular elemental S	S + bentonite	0-0-0-90
Potassium magnesium sulfate	$\text{K}_4\text{SO}_4 \cdot 2\text{MgSO}_4$	0-0-22-23
Potassium sulfate	K_4SO_4	0-0-50-18

Timing/Placement

The demand for S by a growing crop is not constant through the growing season, with the highest uptake associated with the periods of rapid growth. Timing S fertilizer applications so that they provide a plant-available supply when the crop needs it is the desired goal. Plants subject to deficiency during a high demand period may not recover to achieve full yield potential even with high S rates applied too late or when a form such as elemental S is not applied far enough ahead of crop need. Conversely, application of a sulfate form (or one that changes quickly to sulfate such as thiosulfate) well in advance of crop uptake can be subject to losses in soils with high leaching potential (coarse textured soils with excessive rainfall). In those soils, application close to or at planting would be desirable. Sidedress applications can be beneficial for correcting deficiencies, but should be a readily plant available form (such as sulfate or thiosulfate) and applied before large plant uptake. For crops with multiple harvests, like forages, there are multiple opportunities for application – at seeding or after any cutting. Applied S must be in the rooting zone for plant uptake, therefore banding or incorporation into the soil is desirable. Surface applications must be in a sulfate form so movement into the soil can take place with rainfall. Some S fertilizers may cause seedling injury and should not be placed in furrow, with thiosulfate an example.

Application Rate

Sulfur fertilizer application rates should be based on expected optimal economic return. Those rates vary among regions, crops, and years, so local research is important to determine economic response. For example, in a set of S rate trials with corn in Iowa, the maximum response rate for 21 fine-textured soil sites was 17 lb S/acre, with an economic optimum rate at 16 lb S/acre (Figure 5). However, for 7 coarse-textured soil sites, the maximum response rate was higher at 25 lb S/acre, with an economic optimum rate at 23 lb S/acre. The economic optimum S rate is near the maximum response because the fertilizer cost (rate times price) is low compared to the yield return (yield increase times corn price).

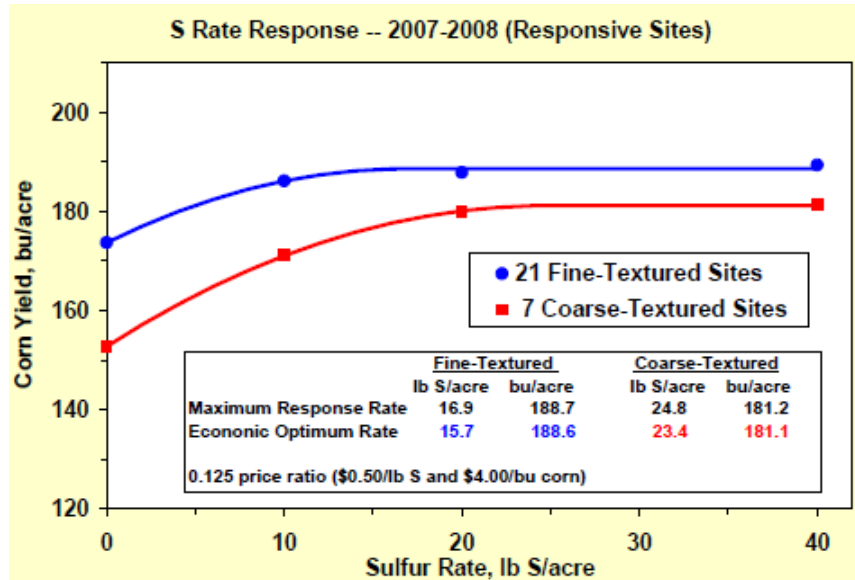


Figure 5. Corn grain yield response to S application rate at responsive sites. Adapted from Sawyer, J.E., D.W. Barker, and G. Cummins. 2009. Dealing with sulfur deficiencies in crop production: the Iowa experience. p. 64-73. In North-Central Extension-Industry Soil Fertility Conf. Proceedings. Nov. 18-19. Vol. 25. Des Moines, IA.

Another example of crop response to increasing rates of S application is presented in Figure 6 for research in Alabama with cotton. In this case, cotton yield reached maximum values with S applications of 20-35 lb S/acre.

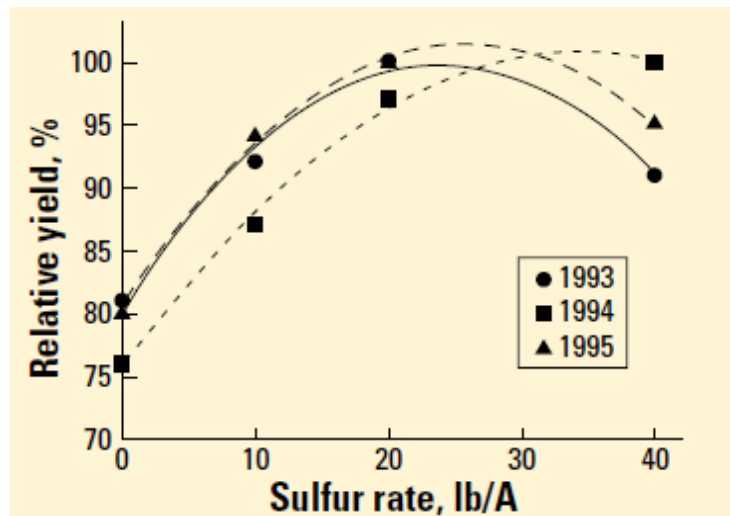


Figure 6. Cotton lint yields as affected by the rate of S on a Lucy loamy sand in Alabama. Adapted from Mullins, G.L. 1999. Cotton response to sulfur on a Coastal Plain soil. p. 64-73. In Better Crops. 83(4) 4-5.

Research to date has not fully documented the variability of S deficiency within fields or the potential for variable-rate S application. Work with alfalfa in Iowa clearly showed differential response in poor and good coloration/growth areas, indicating that it would not respond to S application across entire fields. Similar expression of S deficiency and yield response within fields has been observed in corn. However, until more is known about economically delineating S deficiencies or access to tools for determining deficiency, it is likely most prudent to simply fertilize entire fields when deficiency exists rather than attempt site-specific applications because of the relatively low cost of S fertilization. Site-specific management is possible, but increases production costs and reliable methods are needed to “map” S sufficiency across a field.

Summary

Effective S management requires not only a thorough understanding of S transformations in soil, but also an awareness of how several factors can affect the plant availability of S and potential deficiency. These include temperature, moisture, soil organic matter, erosion, tillage system, landscape position, soil texture, rooting depth, subsoil sulfate, past S inputs, atmospheric deposition, and cropping system. Although S deficiencies have been relatively infrequent in the past, the frequency of deficiencies is increasing and the need for S fertilization is increasing. Sustained high crop yields, with few if any S inputs, has resulted in greater chance of deficiency. Sulfur plays a major role in crop growth, yield, and quality, and improves the effectiveness of other nutrient inputs like N, P, and K. Therefore, S needs to be considered for developing successful nutrient management plans.