SULFUR DEFICIENCIES IN CROP PRODUCTION

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Response to sulfur (S) was recorded as early as 1768 by Rev. A. Meyer, who applied gypsum to experimental plots in Switzerland. Shortly after, Ben Franklin demonstrated response to S by writing "THIS LAND HAS BEEN PLASTERED" with gypsum on a hillside pasture in Pennsylvania. The incidence of S deficiency is increasing throughout the world and is fairly widespread in Australia, New Zealand, South America and tropical Africa and Asia. In the United States, S deficiency was known in the Pacific Northwest as early as 1900. Since then, S deficiency has been found in many states. The increasing incidence of S deficiency in the past 25 years is primarily due to increased use of high analysis S-free fertilizers, decreased use of S-containing insecticides and fungicides, decreased use of high S fuels, and increased crop yield, requiring more of all essential elements.

Response to S by alfalfa in Wisconsin was first demonstrated in 1968 in field plots in northwestern Wisconsin. Early work included field studies, greenhouse and laboratory studies and atmospheric deposition surveys. The need for a reliable diagnostic program for sulfur nutrition in crops was apparent as soon as S deficiency was recognized.

Sulfur is present in the soil in both organic and inorganic forms, although nearly 90% of the total sulfur in most non-calcareous surface soils exists in organic forms. The inorganic forms are solution $SO_4^{=}$, adsorbed $SO_4^{=}$, insoluble $SO_4^{=}$, and reduced inorganic sulfur compounds. Solution plus adsorbed $SO_4^{=}$ represents the readily available fraction of sulfur utilized by plants.

Sulfur is absorbed by plant roots almost exclusively as sulfate, $SO_4^{=}$. Small quantities of SO_2 can be absorbed through plant leaves and utilized within plants, but high concentrations can be toxic. Plants require approximately as much sulfur as phosphorus, one of the elements usually considered a major plant nutrient. Typical concentrations of sulfur in plants range between 0.1 and 0.5%. Sulfur is required for synthesis of the S-containing amino acids cystine, cysteine, and methionine, which are essential components of protein. Approximately 90% of the sulfur in plants is found in these amino acids. Sulfur activates certain enzyme systems and is a component of some vitamins (vitamin A). Increasing sulfur availability will normally increase the sulfur content in leaves, which increases S-containing amino acids. Sulfur is found in mustard oil glycosides, which impart characteristic odors and flavors to such plants as mustard, onions, and garlic. Sulfur fertilization has also been shown to increase the seed oil content of crops such as soybeans and flax.

Soil Testing for Sulfur

Testing soil for plant available sulfur is most prevalent in the more northerly and westerly states in the upper Midwest. This part of the region tends to have fewer industrial sources to produce gaseous emissions of sulfur. Even in the parts of the region where industry is more concentrated, S emissions have declined dramatically in the past few decades due to stricter environmental standards. A number of neighboring states report areas that show consistent plant response to sulfur mainly on sandy, low organic matter soils. Although the development of a

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reliable and repeatable soil test for sulfur has been quite problematic, due to client demand, a number of states in the upper Midwest offer soil tests for sulfur. North and South Dakota, Kansas, Minnesota and Wisconsin offer the North Central recommended monocalcium phosphate extraction/turbidimetric procedure for the determination of available sulfur in soils (NCR Publication 221). In general, the soil test is considered only one of the pieces of information needed to make a nutrient application recommendation. In nearly all cases, additional information is used to aid in making nutrient application recommendations.

There are several factors limiting the usefulness of a soil test program for sulfur. First, the laboratory method is somewhat problematic and difficult to get consistent repeatable results both within and between labs.

The second limiting factor is that the soil test only shows the amount of sulfate present in the depth sampled at the time the sample was taken and does not account for subsoil-S, atmospheric-S, S from manure or organic matter contributions that become available during the growing season.

Long-term soil test summaries for Wisconsin soils show little change in sulfate-S levels over time (Fig. 1). However, some differences based on soil type can be seen (Fig. 2). Organic soils have much higher levels of available sulfate-S than do mineral soils. Within mineral soils, sandy soils have slightly lower median levels of sulfate-S than do the medium and fine textured soils.

Figure 1

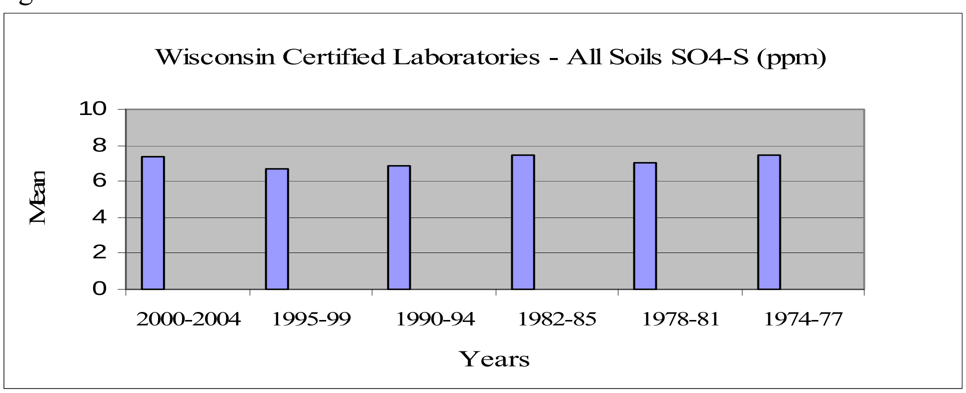
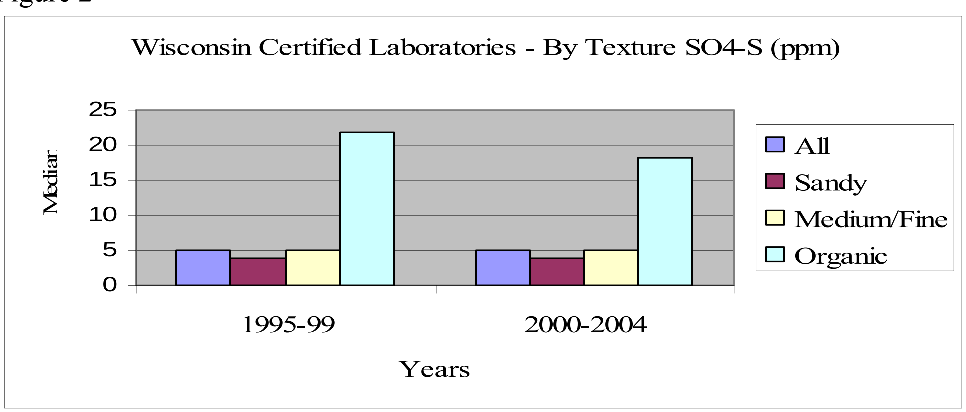


Figure 2



If the state is divided into the nine regions used for statistical reporting, it appears the more southerly portions of the state show a decline over time that is not as apparent in the north (Table 1). This is probably related to the fact that atmospheric sulfur levels were traditionally already much lower in the north when compared to the more populated and industrialized southern and eastern regions of the state.

Table 1. Average soil test sulfate-sulfur levels in Wisconsin, by region.

	---------- Soil Test Summary Period ----------			
	1974-77	1982-85	1990-94	2000-04
WI Region	SO_4-S *ppm*			
Northwest	4.1	5.9	6.0	5.0
North Central	6.7	7.5	6.1	7.3
Northeast	9.1	7.3	4.7	6.4
West Central	4.5	4.6	5.0	6.7
Central	8.6	7.2	5.5	6.4
East Central	9.8	9.3	9.2	7.6
Southwest	8.1	7.6	4.9	4.8
South Central	10.4	9.0	9.0	7.4
Southeast	11.0	8.9	8.7	10.8

The Wisconsin Approach

Since the 1970s, agronomists, soil scientists, consultants and farmers have recognized the potential for significant responses to applied sulfur fertilizer in northern and western Wisconsin. This is particularly true of course-textured, low organic matter soils that had not recently received manure applications. In more recent years, crop consultants and others have reported seeing sulfur responses on soils or in locations where they typically were not expected. Part of the reason sulfur responses may be occurring more frequently is that precipitation S levels have been decreasing. From 1969 to 1987, precipitation S decreased an average of 42% across Wisconsin (Andraski and Bundy, 1989). Furthermore, a Wisconsin Department of Natural Resources estimate showed Wisconsin sulfur emissions declined another 40% from the mid-1980s to the mid-1990s.

Wisconsin started testing soils for sulfate-S in the early 1970s, however, it is recognized that this approach only measures the amount of sulfate-S in the plow layer and does not account for several other sources of plant-available sulfur. The result is that the soil test value was useful in identifying situations where the amount of plant-available sulfur is adequate, but does not adequately determine if sulfur should be added if the test is low, since adequate S may be coming from other sources. When the Wisconsin soil test recommendations were revised in 1991, a new approach called the sulfur availability index (SAI) was introduced. This was an attempt to account for S from other sources such as precipitation, manure, soil organic matter, subsoil, as well as sulfate-S measured by soil test.

In more recent years, Keith Kelling conducted a survey of the sulfur status of alfalfa fields around the state. Results, as seen in Fig. 3, show the potential for significant alfalfa yield responses from sulfur additions in northern and western Wisconsin. Recent data suggests that the potential for a S response is now higher in southern and eastern Wisconsin than it was a few years ago. Research continued, and based on this new information, the SAI was again modified in 2005 to reflect changes that have occurred over the years in S contributions from precipitation and the subsoil. The modified SAI provides a better prediction of alfalfa S concentration in the deficient category (<0.25% S) than the original SAI.

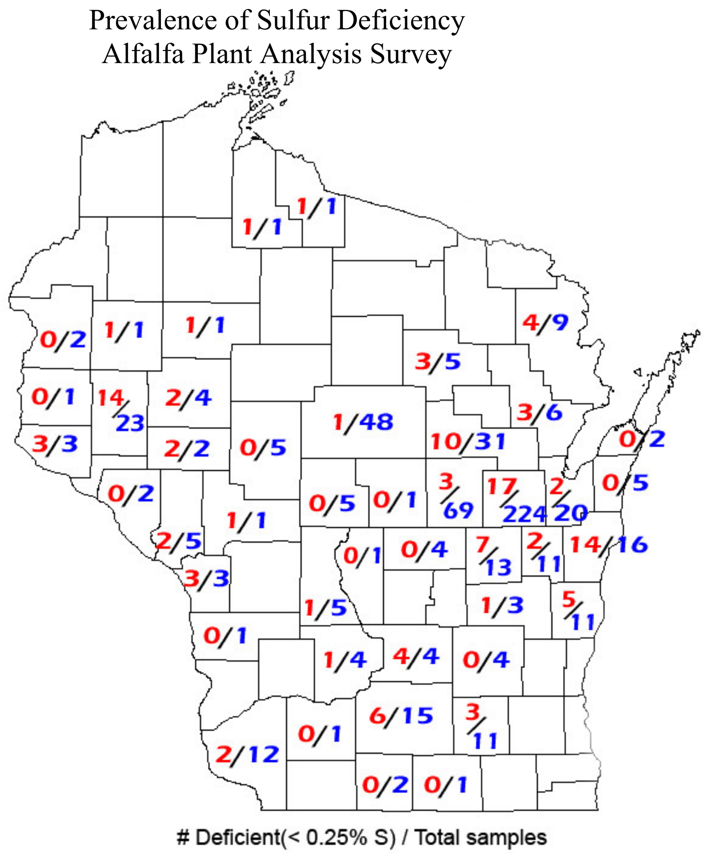


Figure 3. Alfalfa tissue samples testing < 0.25% S in 2000–2001.

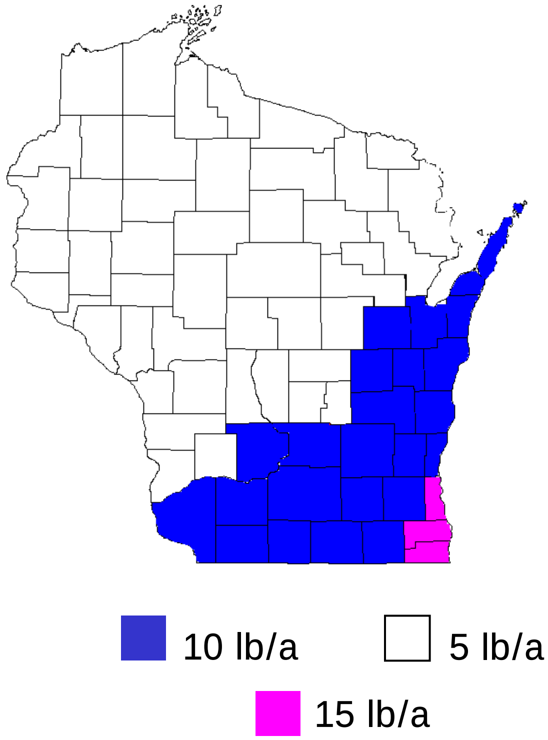
The Wisconsin Sulfur Availability Index (SAI)

Several factors in the SAI were modified in 2005 to reflect lower contributions from atmospheric and subsoil sulfur. The SAI value is made up of the sum of the following components; OM-S + manure-S + precip-S + subsoil-S + soil test- SO_4-S.

1. The soil test SO_4-S is calculated from ppm SO_4-S x 4

2. Precipitation sulfur contributions have been adjusted in many counties to reflect current levels of S in precipitation.

Precipitation-S by county



3. Subsoil S contributions based on soil group.

Soil group code	Subsoil sulfur code	Sulfur contribution
		--------- lb S/a ---------
A or B	L	5
	M	10
	H	10
C	M	5
	H	10
D	L	5
	M	5
	H	10
E	L	5
	M	5
O	H	20

4. Calculated contribution of sulfur from organic matter or manure.

OM-S (sulfur in organic matter) = % organic matter (from soil test) x 2.8 lb/a
Manure-S = tons (1000's gal) of manure applied x lb available S/ton (or 1000 gal)

When the calculated SAI is summarized using the WI statistical reporting districts it shows that the highest percentage of fields that are in the non-responsive range (SAI>40) are in the southeast, followed by the south central part of the state. This is followed by the north central,

central, and southwestern part of the state. The lowest SAI values are found in the northwest, followed by the northeast and then the east central district (Table 2).

Table 2. Wisconsin SAI values by region, 2000-2004.

Region	Total samples	Percent over 40 SAI	Avg of values where SAI <=40
Northwest	1683	28.1	33
North Central	2749	53.9	35
Northeast	3105	25.6	28
West Central	1086	18.4	31
Central	3657	46.8	34
East Central	9671	36.9	37
Southwest	1968	44.5	36
South Central	3436	75.0	37
Southeast	1108	81.3	36

Plant Analysis as a Tool

Plant analysis can be used as an additional tool to verify the need for sulfur additions. The Kelling alfalfa survey indicated an increased need for S on alfalfa in recent years. A summary of plant analysis data from the UW Soil and Plant Analysis Laboratory from the past 5 years show that a number of the most commonly tested crops frequently show average S levels in tissue that are near the critical levels (Table 3). In the case of soybeans, the average level is will below the critical level.

Table 3. Average tissue analysis sulfur levels for most frequently tested crops. UW Soil and Plant Analysis Laboratory, 2003-2007.

Crop	Type	Avg	Critical level
		-------------% S	-----------
Alfalfa	Top 6 inches	0.31	.25
Apple	Fully developed leaf at midpoint of new shoots	0.15	.14
Cranberry	Growth above berries	0.13	.08
Field corn	Ear leaf	0.20	.16
Field corn	Whole plant	0.21	.15
Soybean	Newest fully developed leaf	0.27	.38

Crops Responding to S Applications

Among the states in the upper Midwest that report a response to S applications, the crops most frequently mentioned as being responsive include alfalfa and canola, followed by wheat, corn and soybeans. All states indicate that response is most likely on low organic matter soils, as well as soils which have not had manure applied recently and are located farther from industrial sources of atmospheric S (Table 4).

Table 4. Crops most likely to respond to S additions (Email survey of NCR-13 representatives, Jan. 2007).

State	Crop response	Conditions favoring crop response
Iowa	alfalfa in NE Iowa	
Indiana	wheat, alfalfa	low OM, cool soils
Kansas	corn	check S level in irrigation water
Michigan	alfalfa, canola, wheat>corn>soybean	sandy, low OM soils
Minnesota	corn, barley, wheat, forages, corn	recs. Based on OM, not soil test
North Dakota	canola	always recommend, regardless of the soil test level
Ontario	canola	responses rare
South Dakota	corn>wheat>soybeans	no-till, and low OM fields
Wisconsin	alfalfa, corn, small grain, vegetable and fruit crops	low OM, far from urbanized areas

All sulfate forms of fertilizer are equally effective when surface-applied or incorporated. Elemental sulfur, however, is insoluble and must be transformed by soil bacteria before plants can use it. The rate of this transformation depends on particle size, degree of mixing with the soil, and soil temperature. To be effective, elemental sulfur should be mixed into the soil well in advance of the time the crop needs it. Without mechanical incorporation, elemental sulfur is incorporated to some extent by falling into cracks when the soil dries or by the activity of earthworms and burrowing insects. Certain crops, such as alfalfa and corn silage, can remove large amounts of sulfur in one season. Shallow-rooted crops grown on low-sulfur soils will generally benefit from annual applications of smaller amounts of sulfur. For annuals, it is usually most economical to incorporate elemental sulfur. When applied at the recommended rates, sulfate-sulfur will generally last for 2 or more years while elemental sulfur should last for the term of the alfalfa stand (3 to 5 years). Sandy soils may require annual applications of sulfate-sulfur because the sulfate leaches through these soils relatively rapidly. Table 5 shows the typical S content of several commonly available fertilizer materials.

Table 5. Sulfur content of selected fertilizer materials.

Material	Sulfur content (%)
Ammonium sulfate	24
Ammonium thiosulfate solution	26
Calcium sulfate (gypsum)	15 to 18
Magnesium sulfate	23
Potassium-magnesium sulfate	28
Potassium sulfate	18
Superphosphate (normal)	12
Sulfur-coated materials	variable

Summary

Proper sulfur fertility management in Wisconsin requires more background information than many other crop nutrients. Soil testing alone is often not the entire solution to determining if a sulfur application is needed and in most cases more information is needed. In the case where sulfate-S levels are high, growers can be reasonably assured that no additional sulfur is needed in most cases. However, if sulfate-S levels are normal or low, more information is needed to make a sound nutrient application decision. Factors such as the crop to be grown, atmospheric and subsoil S contributions, contributions from irrigation water, soil organic matter level, soil texture, and recent manure applications must all be considered.

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