Sulfur Deficiency in Corn, Soybean, Alfalfa, and Wheat

Authors:

Jim Camberato
Department of Agronomy
Purdue University

Shaun Casteel
Department of Agronomy
Purdue University

Kurt Steinke
Department of Plant, Soil and Microbial Sciences
Michigan State University

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In recent years, sulfur (S) deficiency has been diagnosed in corn, soybean, alfalfa, and wheat in the Midwest, including Indiana and Michigan. There are a number of reasons why S deficiency appears to be more common, including reduced atmospheric S deposition, continued and increasing crop removal of S, higher amounts of crop residues, greater use of no tillage, and earlier planting into cool wet soils. It is wise to consider S deficiency as a cause of crop growth problems where yellowing of the foliage is the primary symptom.

Abbreviations

AMS – ammonium sulfate

ATS – ammonium thiosulfate

DAP – di-ammonium phosphate

MAP – mono-ammonium phosphate

TSP – triple superphosphate

SO_4-S – sulfate-sulfur

Atmospheric Deposition of Sulfur

Sulfur deficiency of crops may be more prevalent recently due to less S deposition from the atmosphere, a result of reductions in power plant S emissions (**Fig. 1**). As recently as 2000, soils in most of Indiana received more than 13 pounds of S per acre from the atmosphere and extensive areas in southern Indiana received 18 pounds per acre or more. In 2020, all of Indiana received less than 5 pounds of S per acre. Production acres in the lower peninsula of Michigan received about 10 pounds of S per acre from atmospheric deposition around the year 2000, down from the 25+ pounds per acre received during the mid-1980s. Most of Michigan received less than 5 pounds S per acre in 2020.

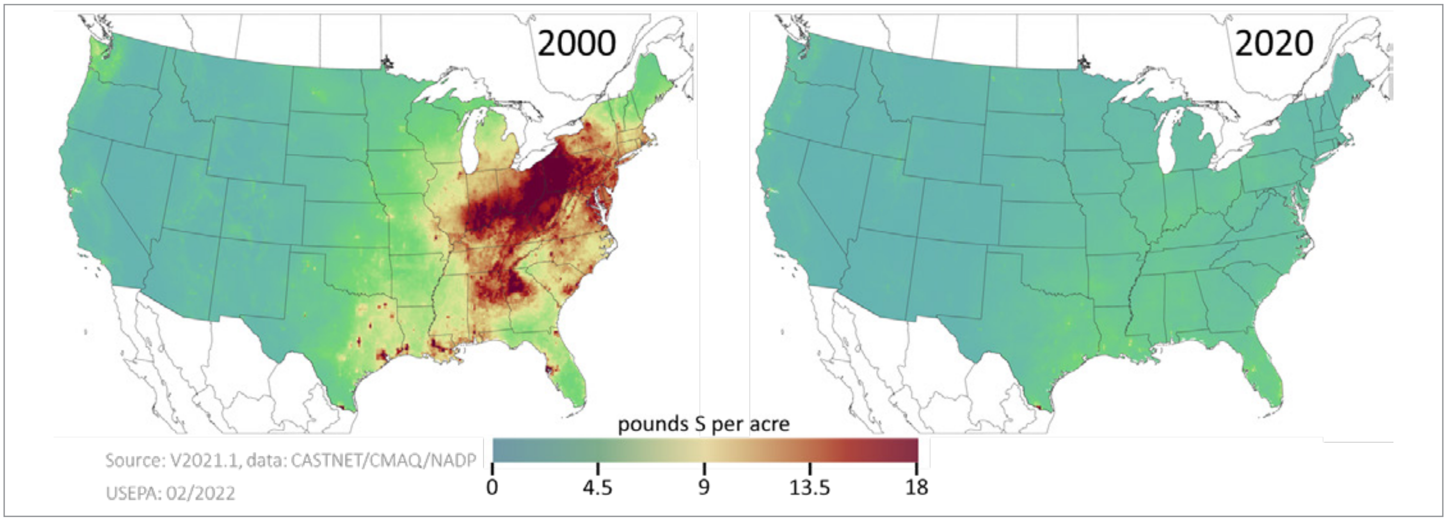

Fig 1. The amount of sulfur deposited on the land is much less in 2020 than in 2000. Red colors indicate high deposition and green low deposition.[1]

Crop Sulfur Removal

Crop harvest removes S from the field (**Table 1**). As recently as 10 years ago crop S removal was generally less than atmospheric S deposition, but now crop removal exceeds S deposition in all areas of Indiana and Michigan. Corn grain contains about 0.5 pound of S for every 10 bushels of grain, so about 10 pounds of S per acre is removed by corn grain that yields 200 bushels per acre. Soybean grain removes about 1.7 pounds of S per 10 bushels of grain – about 10 pounds of S per acre at 60 bushels per acre. Wheat grain removes about 0.7 pounds of S for every 10 bushels of grain, so about 7 pounds of S per acre is removed at 100 bushels per acre. Wheat straw may remove approximately 1 pound of S per 10 bushels of grain or about 10 pounds of S per acre at 100 bushels per acre. Crop uptake by corn and soybean is about twice that of crop removal. Wheat uptake will vary by varietal characteristics impacting plant height and thus straw production. Alfalfa hay removes about 5-7 pounds of S per ton of hay, so upward of 20-30 pounds of S per acre for a harvest of 4-5 tons of hay per acre.

As atmospheric deposition decreased in the last 20 years, crop yield and S removal increased. Corn and soybean grain yields have increased on average about 1.8 and 0.4 bushels per acre per year, respectively. With wheat growers paying greater attention to autumn planting dates, crop rotations/maturities, and variety selection, wheat grain yields have steadily increased. Michigan set a state record yield average of 89 bushels per acre in 2016. Wheat straw, which has become a secondary stream of income for many growers, more than doubles S removal from the field. Increasing grain yields across cropping systems results in greater S removal from the field and greater S need to meet crop demand.

Table 1. Approximate sulfur (S) content in above-ground plant material and removal from the field in the harvested portion of the crop.

Crop	Grain S Removal	Crop S Uptake
	lb/acre	
Corn, 200 bu/acre	10	20
Soybean, 60 bu/acre	10	20
Wheat, 100 bu/acre	7	17
Alfalfa, 5 ton/acre	—	30

Evidence of Reduced Sulfur Supplies in Indiana and Michigan Soils

Although traditional soil testing is not predictive of S deficiency (see discussion p. 3) it can be useful for tracking changes in soil S levels over time. Soil test summaries from A&L Great Lakes Laboratories indicate that the percentage of soil samples testing low and very low[2] in SO_4-S (less than 8 parts per million [ppm]) has increased over the past 15 years (**Fig. 2**). Eight ppm is equivalent to about 16 pounds per acre in the upper 8 inches of soil. In 2005-2007, less than 3% and 2% of Indiana and Michigan soil samples, respectively, tested less than 8 ppm SO_4-S.

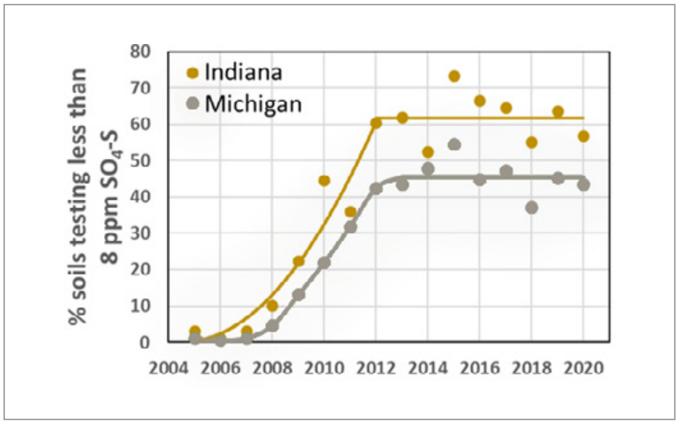

Fig 2. Percentage of Indiana and Michigan soils testing low and very low (less than 8 ppm SO_4-S) in summaries of samples analyzed by A&L Great Lakes Laboratories, Fort Wayne, IN.[2]

Since then, the percentage of samples less than 8 ppm increased steadily until 2012, averaging about 62% and 46% between 2012-2020 across Indiana and Michigan, respectively.

Soil Properties and Crop Management Affect Sulfur Availability

If fertilizer S is not applied to the soil, the main source of S in most soils arises from the mineralization of soil organic matter. Each percent of organic matter in the upper 6 to 8 inches of soil contains about 100 pounds of organic sulfur per acre. Organic S must be mineralized to sulfate-S (SO_4-S) to be taken up by crop plants, in much the same way that organic N is made available to crops. Therefore, the lower the organic matter content of the soil the less sulfate-S that is potentially available to the crop.

Because mineralization is a process carried out by microorganisms, soil temperature and moisture largely determine when and how much of the organic S is made available to the crop. Cold and excessively wet or dry conditions reduce microbial activity and reduce S availability from soil organic matter and crop residues. Thus, crops are more likely to be S deficient in the early spring (e.g., winter wheat and early planted corn and soybean) before soil temperatures warm substantially, particularly with minimum tillage, which results in colder soils. Estimates of mineralization range from 1-3%, which equates to 1-3 pounds of sulfate-S per acre released in the upper 6-8 inches of soil over a growing season per 1% organic matter.

Increases in no-till, early planting, and heavy residue from higher yields have also been implicated in increasing the occurrence of S deficiency.

Crop residues contain relatively low concentrations of S. During the decomposition of low S crop residues, inorganic S from the soil may be preferentially utilized by the microorganisms to build new cells, making it temporarily unavailable to the crop – a process called immobilization. Thus, S deficiency may occur more frequently with large amounts of low S crop residue early in the growing season.

Sulfate-S is relatively mobile in most soils (similar to nitrate) because it has a double negative charge and is repelled by the negative charge of the soil, unlike basic cations such as potassium, calcium, or magnesium. Although SO_4-S can bind to iron and aluminum in the soil, these elements are much more likely to bind phosphate at the exclusion of SO_4-S. As a result, SO_4-S is easily leached from surface soils, especially sandy soils (sand, loamy sand, sandy loam textures).

Within a field the occurrence of S deficiency may be highly variable since soil S availability varies considerably with soil organic matter, texture, depth to SO_4-S accumulations, etc., and the interaction of these factors with the weather. Sulfur deficiency is often seen in sandier, lower organic matter, higher elevation, and eroded areas of a field due to low supply of SO_4-S from organic matter. Unexpectedly, recent studies have found that S deficiency can also occur in very poorly drained soils with higher clay and organic matter content than are typically associated with S deficiency, possibly because high soil moisture suppresses the mineralization of organic S to SO_4-S.

Diagnosing Sulfur Deficiency

Soil testing for sulfate-sulfur

There are several reasons why soil testing is not particularly useful for predicting S deficiency.[3] First, soil sampling is usually performed in the fall or early spring of the year, and second, only the upper 6 to 8 inches of soil is typically sampled. Soil testing may overestimate S availability if SO_4-S measured in the fall is leached below the crop root zone prior to crop need for S in the spring. Conversely, SO_4-S remaining in the crop root zone – but below the sampling depth and available to the crop – will not be measured with a 6- to 8-inch sample depth. Third, commonly utilized soil testing methods do not measure organic-S, which after microbial mineralization can be a significant source of crop S supply. Sulfur deficiencies are notoriously transient because as the season progresses warmer temperatures result in S mineralization from organic matter, and crop residues in the topsoil and roots access S in the subsoil where SO_4-S may have accumulated with differences in soil properties.

Sulfur deficiency symptoms and plant analysis for diagnosing S deficiency

Sulfur deficient crops typically have an overall yellow appearance (**Figs. 3-7**) similar to N deficiency. However, S is not as mobile in the plant as N, so upper leaves do not show more severe deficiency symptoms than lower leaves. If an S deficiency is misdiagnosed as an N deficiency, the application of fertilizer N will worsen the S deficiency, so tissue sampling is recommended to positively identify which nutrient is deficient before fertilizing. In corn, S deficiency may also cause leaf striping (**inset Fig. 4**) which can be confused with magnesium, manganese, and zinc deficiency.[4]

Fig 3. Soybeans with 20 pounds sulfate-S per acre applied prior to emergence and without S.
Image: Shaun Casteel, Purdue University

Fig 4. Sulfur deficient corn in the foreground (pale green) and S sufficient corn in the background (dark green). Sulfur deficient corn plants may show striping as well as an overall yellow color.
Image: RL Nielsen, Purdue University

Fig 5. Light green alfalfa (background) was adequate in all nutrients except S, which was 0.14% - well below the critical level of 0.25%. Sulfur was 0.26% S in the darker green alfalfa.
Image: Alex Helms, Purdue University

Fig 6. Sulfur deficient wheat (pale green/yellow) surrounded by S sufficient wheat (dark green). Sulfur deficiencies may closely follow soil variabilities and texture changes through a field.
Image: Kurt Steinke, Michigan State University

Tissue sampling and analysis

The best way to identify an S deficiency is by tissue sampling from areas suspected of deficiency for comparison with healthy areas of the field. Guidelines for the number and type of plant parts to sample at different crop growth stages are listed in **Table 2.** Tissue samples contaminated with soil can be rinsed quickly in cold distilled water, but do not overdo it because some nutrients, especially potassium, may be leached out of the tissue. Wet samples should be air-dried before shipping to the laboratory in paper bags.

In the plant, S is a component of two amino acids and occurs in protein in a ratio of 1-part S to about 15-parts N. Therefore, the N:S ratio of plant tissue as well as the S concentration are used to identify S deficiency. The lower the S concentration and the higher the N:S ratio, the more likely S is deficient in the plant. Values

Fig 7. Sulfur deficiency in winter wheat may also affect plant tillering and row closure. Wheat pictured without S (left) and with 25 pounds of S per acre (right). Both photos received the same amount and timing of nitrogen. Image: Kurt Steinke, Michigan State University.

associated with deficiency, thus responsiveness to S fertilization, are shown in Table 2 for each crop at different growth stages.

A soil analysis from areas suspected of deficiency as well as from healthy areas is always helpful for distinguishing among possible nutrient deficiencies. In the case of S deficiency, the results of a soil analysis are often more useful for ruling out the possibility of other nutrient deficiencies than identifying S deficiency.

Correcting Sulfur Deficiency with Fertilizers

Sulfur fertilizer should be applied as close to crop need as possible to reduce the chance sulfate-S will be lost from the root zone by leaching. Often including S in a fertilizer program to avoid S deficiency is more efficient and less costly than correcting an S deficiency once it occurs.

Table 2. Plant tissue sampling guidelines for identifying sulfur deficiency.

Crop	Stage	Plant part	Number or area per sample	Values associated with S deficiency	
				%S	N:S
Corn	≤12 inches	Whole plant beginning ½ inch above soil	20-30	<0.18	>16:1
	>12 inches to tasseling	Youngest collared leaf or earleaf at tasseling	15-25		
Soybean	≤12 inches	Whole plant beginning ½ inch above soil	20-30	<0.25	>18:1
	>12 inches to early bloom	Most recently matured soybean trifoliate without petiole (usually 3-4 below the uppermost unrolled trifoliate leaf)			
Wheat	≤Feekes 5 (green up)	Whole plant beginning ½ inch above soil	1 square foot	<0.20	>16:1-18:1
	>Feekes 5 (jointing)	Upper half of stem and leaf tissue or flag leaf individually after Feekes 9	30-40		
Alfalfa[5-7]	≤8 inches	Upper half of stem and leaf tissue	30-40	<0.25	—
	>8 inches	Upper 6 inches of plant			

Sulfur Fertilization of Corn

Research conducted in Indiana from 2017-2021 found that sidedressing 15 pounds of SO_4-S per acre or less maximized corn yield across a range of responsive soils.[8,9] Research in Iowa resulted in recommendations of 15 pounds of SO_4-S per acre on fine-textured soils and 25 pounds of SO_4-S per acre on coarse-textured soils.[7] Although some carryover of S at higher than recommended rates of application may occur in silt loam soils, it likely will be necessary to make applications of S every year on sandy soils, particularly if irrigated and high yielding.

Sulfur Fertilization of Soybean

Broadcast application of 10 pounds of SO_4-S per acre prior to soybean emergence (PRE) maximized soybean yield in a highly S-responsive site from 2016-2017 when rainfall was not excessive. However, a higher rate of S, 15 to 25 pounds of SO_4-S per acre, is recommended for soybeans in S deficient fields to account for potential leaching due to early season rains.

The ideal application timing to maximize the benefit of S to soybean is close to planting or shortly thereafter (i.e., PRE to V1 or V2), because S is a co-factor for nodulation and thus N supply (**Fig. 8**). Foliar applications of S have corrected in-season deficiency at V4, R3, and R5 with an optimal rate near 3 pounds SO_4-S per acre at each of the timings. However, the foliar applications did not fully overcome the S deficiency in comparison to standard broadcast soil application prior to emergence. Higher rates of foliar S (e.g., 4 and 6 pounds SO_4-S per acre) have caused leaf burn and are not recommended.

Fig 8. Sulfur is a co-factor for nodulation and can have a season-long benefit. R6 (full seed) soybean on left had 20 pounds S per acre applied prior to emergence and were well nodulated. Soybean on the right had no S and were poorly nodulated. Image: Shaun Casteel, Purdue University

Sulfur Fertilization of Wheat

Research conducted on wheat in Michigan from 2017-2021 found that 25 pounds of SO_4-S per acre maximized wheat yield on responsive soils from this region.[10] Greater rates of SO_4-S did not increase yield. Winter wheat experiences rapid spring biomass growth during cool spring air and soil temperatures where minimal soil S mineralization has occurred. As winter wheat is an autumn-planted crop, few differences have been observed between at-plant autumn S application and S applied at spring greenup (Feekes 4-5). Differences in effectiveness between autumn versus spring S application will depend on the quantity of rainfall and winter precipitation received between autumn application timings and plant green-up in spring. The more rain in autumn, winter and early spring the greater the risk of SO_4-S leaching losses with autumn S applications.

Additionally, planting date has been shown to have a measurable impact on not only yield but also the ability of the wheat plant to uptake autumn-applied nutrients. Winter wheat must be planted early enough in the autumn to accumulate enough growing degree days to establish a root system for taking up autumn-applied nutrients, including S. Thus, a combination of previous crop, S application history, amount of winter precipitation, planting date, soil texture, autumn N applications, and other soil physical properties will influence wheat S response.

Sulfur Fertilization of Alfalfa

Sulfur rates of 15 to 30 pounds per acre are recommended for established stands of S deficient alfalfa based on research from Wisconsin and Iowa.[5-7] Applications should be made before substantial regrowth occurs in the spring or after a cutting. Researchers in Wisconsin suggest 25-50 pounds of SO_4-S per acre at seeding and annual topdress applications of 15-25 pounds of SO_4-S per acre on sandy soils where leaching of SO_4-S is more rapid than on loamy soils.[6]

Fertilizers for Correcting Sulfur Deficiency

There are several fertilizers available for correcting a S deficiency (**Table 3**). Adding ammonium thiosulfate (ATS) to urea-ammonium nitrate solutions or blending ammonium sulfate (AMS) with urea are convenient and cost-effective ways to provide S in a timely manner to non-legume crops. Potassium thiosulfate (KTS) is sometimes used in starter fertilizer to apply both potassium and S at planting. Sulfate-of-potash-magnesia (sul-po-mag or K-mag) or potassium sulfate

Table 3. Sulfur-containing fertilizers and their approximate composition.[11] The actual nutrient concentration of a fertilizer should be expressed on the guarantee.

Fertilizer	%N	%K_2O	%S	%Mg	%Ca
Ammonium sulfate (AMS)	21	0	**24**	0	0
Ammonium thiosulfate (ATS)	12	0	**26**	0	0
Elemental sulfur	0	0	**>90**	0	0
Gypsum (calcium sulfate)	0	0	**19**	0	23
Potassium magnesium sulfate	0	22	**23**	11	0
Potassium sulfate	0	50	**18**	0	0
Potassium thiosulfate (KTS)	0	25	**17**	0	0

can be blended with muriate of potash and broadcast to provide S and potassium. This is especially beneficial for alfalfa, which removes large amounts of potassium and requires multiple applications of potassium fertilizer. The inclusion of magnesium in sul-po-mag may be an extra benefit compared to potassium sulfate if soil magnesium levels are low.

Soybeans have responded most favorably to AMS and pelletized gypsum. ATS broadcast sprayed to the soil surface prior to soybean emergence has also provided good results when S was needed. Generally, these fertilizers are spread prior to planting, therefore the SO_4-S might be lost from the root zone before the time of crop need. A blend of AMS and elemental S (pre-mix product or two fertilizers blended) has performed well when abundant rainfall occurred during the early season of soybean and for timely planted winter wheat in the autumn. AMS is usually the fertilizer of choice for foliar applications.

Ammonium thiosulfate (ATS)

Ammonium thiosulfate is commonly added to urea-ammonium nitrate solutions to provide S to crop plants. Sulfur response trials have shown ATS to be an effective S fertilizer. However, thiosulfate and its first breakdown product, tetrathionate, are not utilized by plants. ATS can inhibit germination; hence, it is not recommended for in-furrow placement. ATS can also damage plant roots if applied at too-high rates.

Eventually tetrathionate is converted to sulfate, which is the form of S taken up by plants. Complete conversion of thiosulfate to sulfate may take 1-4+ weeks at temperatures typically encountered at planting and sidedressing time. Considerable variation in conversion rate exists among soils, but the soil factors affecting conversion have not been well identified. Even though sulfate availability is delayed with ATS, it should not be considered a "slow-release" fertilizer because sulfate, thiosulfate, and tetrathionate are all mobile in soil. Thus, leaching losses are expected to be a concern with applications of ATS well before planting.

In addition to providing S, ATS can also reduce ammonia volatilization by delaying urea hydrolysis. ATS also slows nitrification, the conversion of ammonium to nitrate, which can reduce loss of nitrate due to leaching and denitrification. However, the inhibitory properties of ATS are not considered as good as active ingredients specifically sold to target urea hydrolysis and nitrification, such as NBPT, NPPT, DCD, pronitridine, nitrapyrin, etc.[12]

Potassium thiosulfate (KTS)

Sulfur availability in KTS is affected by the same factors as discussed above for ATS. According to a manufacturer of KTS[13] it can be applied in furrow for corn and soybeans in addition to being sidedressed with UAN for corn. Consult the product label for mixing and application rate guidelines.

Ammonium sulfate

Ammonium sulfate is a 100% soluble fertilizer that is available in both granular and liquid formulations (variable analysis dependent on product, approximately 7-0-0-8). Liquid formulations are usually used as a water conditioner for herbicides; apply small amounts of S at recommended rates for that purpose. Low rates of AMS can also be applied in-furrow for corn. Granular AMS is the form most often used to apply nutritional rates of S to crops in a broadcast application.

Potassium sulfate and potassium magnesium sulfate

Potassium sulfate and potassium magnesium sulfate are 100% soluble sources of SO_4-S that also have significant potassium concentrations, 50 and 22%, respectively. Potassium magnesium sulfate also provides soluble magnesium (11%).

Gypsum

Naturally occurring mined gypsum (calcium sulfate) and several byproduct sources of gypsum can be applied to provide S. Gypsum, if pelletized, can be blended with other fertilizers, or if ground, applied with a lime spreader. Ground gypsum is difficult to spread at rates less than 500 to 1,000 pounds per acre, which results in S applications of 85 to 170 pounds of S per acre (assuming 17% S) – far more than is needed. If carryover of S occurs, the S will be utilized in later years. However, in situations where leaching is likely, the benefit in future years may be minimal.

Gypsum is classified as sparingly soluble so it does not dissolve immediately when applied to soil, especially at high rates typical of ground gypsum applications. Thus, it might be retained in the soil profile a little longer than other SO_4-containing fertilizers.

Additionally, ground gypsum applications are reported to increase flocculation of soil clays and modify the properties of water when on the soil surface, enhancing water infiltration and drainage.

Elemental sulfur

Elemental S must be oxidized by soil microbes to SO_4-S before becoming plant available. Elemental S particle size must be small and the S dispersed in the soil for oxidation to be significant in the year of application. Additionally, resident microbial populations, soil pH, and other soil properties affect the rate of oxidation. Warm temperatures and good moisture and aeration are necessary for S-oxidizing microbes to function. Sulfur oxidation is minimal at soil temperatures less than 50° F. Even at 75° F the oxidation rate of S is about 15% of that at 85° F, so peak rates of S oxidation do not occur until late spring. Since the availability of elemental S may be minimal in early spring, a fertilizer containing some SO_4-S, in addition to elemental S, is preferred over a fertilizer with elemental S alone.

Co-granulated fertilizers with elemental S and sulfate-S

Co-granulated fertilizers containing ammonium phosphate, ammonium sulfate, and elemental S, were developed to supply sulfate-S early in the season from the ammonium sulfate and later in the season from the oxidation of elemental S. The elemental S particles that are embedded in the standard-size fertilizer particle are very small, which enhances their oxidation to sulfate and allows for their uniform application on the soil at an appropriate rate.

Incidental applications of sulfur in common phosphorus fertilizers

Phosphorus fertilizers contain contain SO_4-S (**Table 4**). Applying the granular fertilizers to supply 70 pounds of P_2O_5 per acre (crop removal for 200 bushel per acre corn) supplies 1 to 5 pounds of SO_4-S. The fate of this sulfate applied in fall or winter would be uncertain, as discussed above. Using 10-34-0 as starter at a rate of 5 gallons per acre would apply less than 0.5 pounds of SO_4-S per acre, so would not contribute substantially to crop S need.

Table 4. Sulfur concentration of phosphorus fertilizers collected from 2019 thru 2021 by the Office of the Indiana State Chemist and the amount of sulfate-S applied with 70 pounds of P_2O_5 per acre in granular fertilizers or 5 gallons of ammonium polyphosphate.

			Sulfate-S concentration		Sulfate-S applied at 70 lb P_2O_5 per acre across %S range
Fertilizer	%N-P_2O_5-K_2O	# samples analyzed	Range	Average	lb S per acre
Mono-ammonium phosphate	11-52-0	256	0.9-2.7%	1.8%	1.2-3.6
Di-ammonium phosphate	18-46-0	247	0.9-3.3%	1.8%	1.4-5.0
Triple superphosphate	0-46-0	14	1.4-1.9%	1.6%	2.1-2.9
Ammonium polyphosphate	10-34-0	15	0.5-0.9%	0.6%	0.3-0.5†

†Based on 5 gallons 10-34-0 per acre, which applies 20 pounds P_2O_5 per acre.

Effects of sulfur containing fertilizers on soil pH

Soil pH is lowered by elemental S, ATS, and AMS. The oxidation of elemental S or chemically reduced S (thio-S, for example) creates acidity, which lowers soil pH. However, no acidity arises from the sulfate in any of the fertilizer materials including AMS. With AMS the conversion of ammonium to nitrate is the component that generates the acidity. When used to provide less than 30 pounds S per acre, the amount of acidity generated by each of these acid-producing fertilizers is equivalent to less than 150 pounds of limestone per acre. None of the S containing fertilizers in Table 1 increase soil pH. Gypsum, sulfate-of-potash-magnesia, and potassium sulfate do not affect soil pH.

Summary

Sulfur deficiency is occurring more frequently in Indiana and Michigan field crops due to decreased sulfur deposition from the atmosphere, increased crop removal due to higher yields, and adoption of cropping practices that reduce the release of sulfur from soil organic matter. Observation of deficiency symptoms, tissue sampling and analysis for sulfur concentration, and nitrogen to sulfur ratio are the best methods for identifying S deficiency. Soil sampling is useful to rule out other nutrient deficiencies that may cause symptoms similar to sulfur deficiency. Several fertilizers containing sulfate-sulfur can be utilized to correct sulfur deficiency. The choice of fertilizer material depends on the preferred method of application (liquid versus granular), the need for other nutrients contained in some sulfur fertilizers, and fertilizer cost. Applying sulfate-sulfur sources as near as possible to planting of annuals or the resumption of growth in perennials is recommended, because sulfate-sulfur can be lost from soils by leaching.

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