

Technical Bulletin: Sulfur in Soils

EXECUTIVE SUMMARY

- » Sulfur (S) is one of the 17 elements essential for plant growth and the fourth most important after nitrogen (N), phosphorus (P) and potassium (K) in terms of amounts required by crops.
- » Most of the S in productive agricultural soils is present in soil organic matter and is released by mineralization (like nitrate-N).
- » The predominant inorganic form of S in aerobic soils is sulfate in soil pore water and attached to minerals. Sulfate, like nitrate, is easily leached from soil, especially in sandy soils in high rainfall areas.
- » Plants take up S predominantly from soil as a sulfate ion via the soil pore water. Given S behavior in soil, crop S deficiencies are likely in light textured soils with low organic matter, in higher rainfall areas and with high yielding crops.
- » Soil testing to predict S deficiency is not highly accurate but plant tissue analysis is more precise. Deficiency of S is easily corrected by adding S fertilizers containing sulfate, elemental S, thiosulfate or organic manures containing S.
- » Sulfate fertilizers are immediately available to crops but are prone to leaching below the root zone. Elemental S fertilizers must first be oxidized by soil microorganisms to sulfate for crop uptake, but are not leached from soil.
- » Oxidation of elemental S is increased at higher soil temperatures, in moist soils and in soils with higher pH and higher amounts of organic matter.
- » Fertilizers with both sulfate and elemental S provide both a fast- and slow-release source of S for crop nutrition.

BACKGROUND

Sulfur (S) is one of the 17 elements essential for plant growth and the fourth most important after nitrogen (N), phosphorus (P) and potassium (K) in terms of amounts required by crops (Hopkins 1999). It plays a key role in plant nutrition through its activity in photosynthesis and in the synthesis of amino acids and proteins. Both N and S are key elements in proteins and hence there is strong nutritional interaction between these elements for crop growth and crop quality.

Deficiencies of S have become more common in agricultural systems due to the stricter controls on atmospheric emissions of S, use of S-free high analysis fertilizers and increases in S removal by high-yielding hybrid crops.

This factsheet describes how S behaves in soil, its uptake by plants and how we can increase crop production using S fertilizers.

FORM AND BEHAVIOR OF S IN SOILS

Sulfur is present in all soils and is derived both from parent rock materials (e.g. sulfides and sulfates, which are common minerals in the earth's crust) and from the atmosphere (e.g. through deposition of S on soil from marine aerosols, industrial gases or gases/particulates from volcanic eruptions) (Figure 1).

Despite the primary source of S in soil being mineral weathering, most of the S in productive

agricultural soils is present in soil organic matter (OM). Each percent OM in the topsoil (6 inches or 15 cm) contains about 100 pounds of S per acre (112 kg per hectare). This is because the predominant inorganic form of S in soil pore water, i.e. sulfate (SO_4^{2-}), is not strongly retained by soils against leaching, and hence moves through soil relatively easily, similar to N in the nitrate form. The S that is incorporated in organic matter is protected against leaching, again similar to N. In some soils that are waterlogged (e.g. rice paddies), S may also be held against leaching as reduced insoluble sulfides (mostly associated with iron).

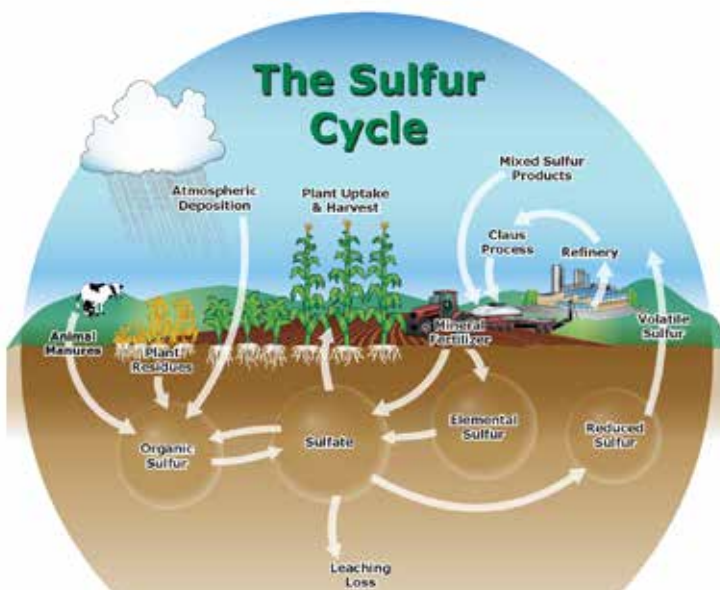


Figure 1. The S cycle in agricultural systems (IPNI).

PLANT UPTAKE OF S FROM SOIL

For healthy growth, plants require S at a concentration of between 0.1% to 0.5% of their dry weight (Marschner 2012). High yielding crops therefore take up significant amounts of S from soil and product harvesting removes significant amounts of S from the system (Table 1).

Table 1. Yield, S uptake and S removal from selected plants.

Crop	Yield (tonnes/ha) (and lb/acre)	Crop S uptake (kg/ha) (and lb/acre)	S removal in grain or fodder (kg/ha) (and lb/acre)
Corn	12.0 (10,706)	26 (23)	15 (13)
Soybean	4.0 (3,569)	22 (20)	12 (11)
Wheat	5.0 (4,461)	20 (18)	8 (7)
Alfalfa (hay)	6.0 (5,353)	14 (12)	14 (12)

Calculations based on data from Bender et al. (2013); Kaiser and Kim (2013); Nuttall (1985); Rasmussen et al. (1975).

Other losses of S can occur via leaching below the root zone, or by temporary immobilization of S in soil OM (Figure 2).

Leaching can be a significant loss mechanism in light textured soils in higher rainfall environments, or when significant rainfall is common after fertilizer addition and before planting (e.g. fall applications) (Devine and Holmes 1964).

Plants take up S predominantly from soil as a sulfate ion via the soil pore water. Hence in

unfertilized soils, the supply of S to plants is closely tied to the dynamics of mineralization and immobilization of soil OM. Soils high in OM will have a high potential to supply S to plants if temperature and soil moisture conditions are favorable (20-30°C, 68-86°F). On the other hand low OM soils will have a higher likelihood of S deficiency. Mineralization of S from soil OM is greater at higher soil temperatures and higher soil moisture. Enhancement of S supply from soil can be achieved by fertilization.

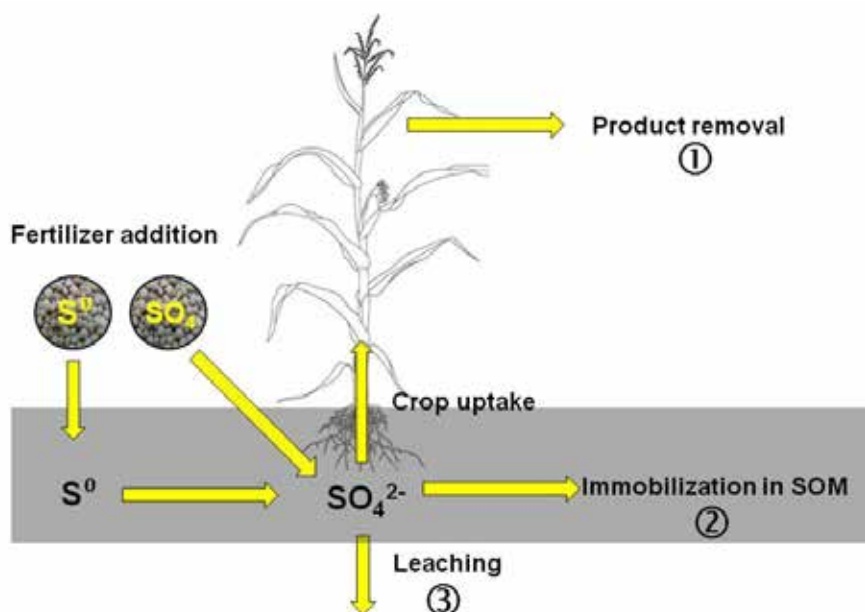


Figure 2. Fate of fertilizer S, added as either elemental S (S^0) or sulfate (SO_4^{2-}) in soil. The major pathways of loss for soil sulfate from soil are crop removal (1), immobilization in soil organic matter (SOM) (2) and leaching (3).

SULFUR FERTILIZERS

The most common S fertilizers are based on addition of sulfate to soil (e.g. gypsum, ammonium sulfate, potassium sulfate), as sulfate is the form in which plant roots take up S (Table 2).

Fertilizers based on elemental S or thiosulfates must first be oxidized to sulfate for plant uptake, and this process relies on microbial activity in soil. Like mineralization of soil organic S, oxidation of elemental S and thiosulfate requires microbial activity and hence is more rapid

in warm moist soils with high OM content. Oxidation reactions of elemental S are also faster in alkaline soils than in acidic soils (Germida and Janzen 1993). Elemental S fertilizers can therefore be regarded as slow-release sources of S for crops (less prone to leaching), while sulfate-based fertilizers are fast release fertilizers (more prone to leaching). Models have been produced which can predict the rate of oxidation of elemental S based on soil temperature, moisture, pH and OM content (McCaskill and Blair 1989).

Table 2. Common sulfur fertilizers.

Product	Chemical formula	Sulfur content (%)
Ammonium sulfate	$(\text{NH}_4)_2\text{SO}_4$	24
Ammonium thiosulfate	$(\text{NH}_4)_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$	26
Ammonium polysulfide	$(\text{NH}_4)_2\text{S}_x$	40-50
Potassium sulfate	K_2SO_4	18
Potassium magnesium sulfate	$\text{K}_2\text{SO}_4 \cdot 2\text{MgSO}_4$	22
Elemental sulfur	S^0	>85
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	12-18
Magnesium sulfate	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	14



SOIL AND TISSUE TESTING TO PREDICT RESPONSES TO FERTILIZER S

Like N, pre-plant soil testing to predict fertilizer responses is difficult for S given that sulfate is mobile in the profile (hence testing to depth is often required) and is produced during the crop growth cycle by mineralization of organic S (hence predictions of potential mineralization are needed). No one soil test procedure has proven effective across all environments but the most commonly used tests are monocalcium phosphate, calcium chloride and Mehlich-III.

Deficiencies of S in plants can be seen visually and confirmed by plant analysis – generally younger leaves are pale green to yellow in color (Figure 3). Deficiency of S can sometimes be confused with N deficiency so it is best to confirm using tissue analysis. Plants with tissue S less than 0.12% and a N:S ratio greater than 20:1 are most likely S deficient, although critical values should be checked for your crop/stage of growth.



Figure 3. Photo of S deficiency in corn (source: IPNI).

REFERENCES

- Bender RR, Haegele JW, Ruffo ML, Below FE (2013) Nutrient uptake, partitioning, and remobilization in modern, transgenic insect-protected maize hybrids. *Agronomy Journal* 105(1), 161-170.
- Devine JR, Holmes MRJ (1964) Field experiments comparing autumn and spring applications of ammonium sulphate, ammonium nitrate and calcium nitrate for winter wheat. *The Journal of Agricultural Science* 63(01), 69-74.
- Germida JJ, Janzen HH (1993) Factors affecting the oxidation of elemental sulfur in soils. *Fertilizer Research* 35(1-2), 101-114.
- Hopkins, WG (1999) *Introduction to Plant Physiology*, 2nd Edition. John Wiley and Sons, New York.
- Kaiser DE, Kim K-I (2013) Soybean response to Sulfur fertilizer applied as a broadcast or starter using replicated strip trials. *Agronomy Journal* 105(4), 1189-1198.
- Marschner P (Ed.) (2012) 'Marschner's Mineral Nutrition of Higher Plants (3rd Edition)'. Academic Press, Elsevier: London, UK
- McCaskill MR, Blair GJ (1989) A model for the release of sulfur from elemental-S and superphosphate. *Fertilizer Research* 19(2), 77-84.
- Nuttall WF (1985) Effect of N, P, and S fertilizers on Alfalfa grown on 3 soil types in northeastern Saskatchewan. 2. Nitrogen, P, and S uptake and concentration in herbage. *Agronomy Journal* 77(2), 224-228.
- Rasmussen PE, Ramig RE, Allmaras RR, Smith CM (1975) Nitrogen-sulfur relations in soft winter-wheat. 2. Initial and residual effects of sulfur application on nutrient concentration, uptake and N/S ratio. *Agronomy Journal* 67(2), 224-228.

Further information

The Fertiliser Technology Research Centre was established in 2007 via a partnership between The University of Adelaide and The Mosaic Company. The scope of the centre was further expanded in 2009 via a partnership between The Mosaic Company and Australian Grains Research and Development Corporation (GRDC). The centre has expertise in soil chemistry, fertiliser technology and plant nutrition, specifically in developing novel fertiliser formulations, advanced isotopic and spectroscopic investigations of fertiliser efficiency, and field scale agronomy trials.

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