Sulfur deficiency in corn. Source: IPNI Crop Nutrient Deficiency Image Collection.

4R NUTRIENT STEWARDSHIP

Sulfur 4R Management and the Changing Landscape of Fertility

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Decreased atmospheric inputs of sulfur (S) to cropland and increasing removal with harvested crops necessitates a closer look at sulfur fertility management using the 4Rs. Considering the soil organic matter, percent sand, crop status, and sulfur fertilizer solubility are critical to meeting crop nutrition needs for optimal production. Earn 0.5 CEUs in Nutrient Management by reading this article and taking the quiz at www.certifiedcropadviser.org/education/classroom/classes/889.

Decreased atmospheric inputs of sulfur (S) to cropland and increasing removal with harvested crops necessitates a closer look at sulfur fertility management using the 4Rs. Recently, Hinckley et al. (2020) called for attention to be focused on agriculture as a potential source of sulfur-driven environmental impairment and increased support for research of sulfur in agroecosystems. This effort identified agricultural inputs, such as pesticides and fertilizers, as major contributors to environmental sulfur balances. However, in the authors' presented case studies, data indicated that sulfur imports to these management systems were decreasing or flat over time (Hinckley et al., 2020). Changes in atmospheric sulfur deposition have led many states and regions to re-investigate the 4Rs of sulfur crop management.

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4R nutrient stewardship

This article is part of a series from The Fertilizer Institute highlighting some of the latest 4R research.

In a 2018 report from the USEPA (USEPA, 2020), sulfur deposition decreased by 58% from the time period of 2000–2002 to 2016–2018. This is corroborated on a smaller scale by an assessment of long-term data from tile drainage and rivers in two Illinois watersheds. David et al. (2016) saw negative sulfur balances of 11.5 to 20.5 lb sulfur per acre per year resulting from sulfur export from harvested crops being greater than sulfur input. The soil's organic sulfur pool saw the greatest depletion. In-field sulfur budgets did not predict the variation in river SO_4^{2-} concentration over time. The study found that surface runoff volumes and reductions in atmospheric deposition had a stronger relationship to riverine SO_4^{2-} trends.

While reductions in atmospheric sulfur deposition are well documented, changes in the sulfur status of soils are not always discussed; however, soil testing indicates soil sulfur values are decreasing. In a report based on data from U.S. soil-testing laboratories, samples testing under 3 ppm increased by ~7.5% while samples testing above 3 ppm decreased by an equivalent amount from 2001 to 2015 (IPNI, 2015). With these observed trends, a question to consider is how efficiently do cropping systems utilize sulfur? A recent analysis of sulfur use efficiency (SUE) estimated world SUE of applied sulfur in fertilizer to be 18% (Aula et al., 2019).

Sulfur in Soils and Plants

Sulfur concentration in soils varies depending on parent material, mineralogy, organic matter, and hydrology. In most agricultural soils, sulfur is present in both organic and inorganic forms with greater than 90% commonly found in the organic form. Organic matter and minerals are the primary soil sources of sulfur for growing crops. Availability is affected by mineral solubility and organic matter mineralization rates. For example, soil minerals and precipitates like gypsum ($CaSO_4 \cdot 2H_2O$) or epsomite ($MgSO_4 \cdot 7H_2O$) accumulate in regions with low rainfall and high evaporation. Many of the precipitates that contain sulfur return sulfur to the soil solution if conditions like low soil pH or saturation exist and the compounds dissolve. Sulfur in organic matter will be released when conditions favor mineralization. Other major non-applied sources of sulfur for crops are atmospheric deposition and irrigation water. Atmospheric deposition in the United States has decreased substantially in recent decades, and now is typically only ~1.5 lb of sulfur per acre per year. Sulfur concentration in irrigation water varies by water supply. A report of irrigation water samples in Nebraska showed a median sulfur supply of 53.5 lb applied in one acre-foot of water across the state (Wortmann, 2019).

Sulfur is primarily taken up in the sulfate (SO_4^{2-}) form from the soil. Prior to use in energy and protein production, SO_4^{2-} must be reduced and assimilated into organic compounds. Sulfur and nitrogen (N) are closely linked in many plant metabolic processes. For example, synthesis of enzymes and nitrogen fixation in legumes strongly requires adequate sulfur. The synergism between sulfur and nitrogen has been well documented (Salvagiotti et al., 2009; Fismes et al., 2000). The metabolic roles and mobility of sulfur in plants defines what deficiency symptoms will look like in specific crops. Sulfur is relatively immobile in plant tissue compared with nutrients like nitrogen, phosphorus, and potassium; and deficiency symptoms will appear on younger tissue first. Sulfur-containing proteins are necessary for photosynthesis; thus, chlorotic yellowing will appear in sulfur-deficient tissue. Sulfur tissue concentration in a healthy crop ranges from 0.1 to 0.5%. Other effects of sulfur deficiency are reduced grain protein content, inhibited shoot growth rates, and delayed maturation.

Source

The strong relationship of sulfur availability in the soil to soil organic matter is an important consideration when choosing a source of sulfur for fertilization. Sulfur fertilization sources vary by solubility, other nutrients associated, and sulfur content (Table 1). Additionally, some sulfur sources, such as ammonium sulfate and elemental sulfur, are acid forming, and a lime application may be required with continued use (Schwab, 2008). The most soluble forms of sulfur fertilizers are the bisulfates, thiosulfates, and polysulfides. Being water soluble, these sulfates are immediately available to plants and are a good choice when sulfur is applied to correct a deficiency (Table 1). Animal manures are also a source of sulfur for crops, and if they are being applied, they should be tested and accounted for when making sulfur applications.

TABLE 1. **Common sulfur fertilizer sources (The Fertilizer Institute, 2020).**

Fertilizer material	Chemical formula	Sulfur content, %
Ammonium sulfate	$(NH_4)_2SO_4$	24
Ammonium thiosulfate	$(NH_4)_2S_2O_3 \cdot 5H_2O$	26
Ammonium polysulfide	$(NH_4)_2S_2$	40–50
Potassium sulfate	K_2SO_4	18
Potassium-magnesium sulfate	$K_2SO_4 \cdot 2MgSO_4$	22
Elemental sulfur	S°	>85
Gypsum	$CaSO_4 \cdot 2H_2O$	12–18
Magnesium sulfate	$MgSO_4 \cdot 7H_2O$	14
Potassium thiosulfate	$K_2S_2O_3$	17

Rate

Soil analysis for sulfur has shown an inconsistent ability to predict a crop response to applied sulfur. Most soil-testing labs use either a monocalcium phosphate or potassium chloride extraction when measuring soil SO_4^{2-}. Soil sample depth and environmental conditions need to be considered when interpreting soil test results for SO_4^{2-} sulfur. Subsoil sulfur may be utilized for crops later in the season when both soil conditions and adequate root growth are ideal; however, as sulfur is very mobile in the soil, relying on a subsoil supply is often disadvantageous. Conditions that hinder or favor SO_4^{2-} leaching through the soil profile may either result in more or less sulfur available during the growing season.

Research to determine crop response curves to different sulfur application rates and soil test levels continues to evolve with the recent changes in sulfur atmospheric deposition. Trials in Indiana in 2017 and 2018 tested different combinations of sulfur source, rate, timing, and placement (Camberato & Nielsen, 2018). For the sulfur-responsive sites in the study, yield increases ranged from 4 to 22 bu/ac with rates of 10 to 15 lb of sulfur per acre at sidedress maximizing the yield response (Camberato & Nielsen, 2018). Response to sulfur applications varies, depending on soil characteristics and fertilizer source. Understanding these differences is critical to determining the sulfur application rate.

Timing and Placement

Sulfur released from soil organic matter can help meet crop need; however, depending on the soil, sulfur supply may be insufficient. Tissue testing in season is a reliable way to diagnose

Source: Dusan Kostic/Alamy Stock Photo.

crop sulfur status. If sulfur deficiency is diagnosed early in the season, it can be corrected with a prompt application of a sulfate-based fertilizer (The Fertilizer Institute, 2020). In Minnesota, research has shown that soybean plant tissue sulfur concentration at growth stages V5 and R2 displayed strong correlations with grain yield, and KCl-extracted soil SO_4^{2-} showed a negative correlation (Kaiser & Kim, 2013). The solubility of the sulfur fertilizer applied needs to be considered when making timing and placement decisions. For example, elemental sulfur will be slowly available compared with sulfate or sulfite fertilizers and should not be applied to correct in-season concerns.

Conclusions

Sulfur fertilization needs and practices are evolving due to reduced atmospheric sulfur deposition. Increasing crop yield, which further decreases soil sulfur concentrations, is also contributing to sulfur fertilizer applications to meet crop need. Considering the soil organic matter, percent sand, crop status, and sulfur fertilizer solubility are critical to meeting crop nutrition needs for optimal production.

References

Aula, L., Dhillon, J.S., Omara, P., Wehmeyer, G.B., Freeman, K.W., & Raun, W.R. (2019). World sulfur use efficiency for cereal crops. *Agronomy Journal*, *111*, 2485–2492. https://doi.org/10.2134/agronj2019.02.0095

Camberato, J., & Nielsen, B. (2018, 17 December). Sulfur fertilizer response of corn—background and research update. *Purdue University Pest & Crop Newsletter*.

David, M.B., Gentry, L.E., & Mitchell, C.A. (2016). Riverine response of sulfate to declining atmospheric sulfur deposition in agricultural watersheds. *Journal of Environmental Quality*, *45*, 1313–1319. https://doi.org/10.2134/jeq2015.12.0613

USEPA. (2020). *Progress reports. Clean air markets. Progress report*. Retrieved from www3.epa.gov/airmarkets/progress/reports/acid_deposition_figures.html#figure3

Fismes, J., Vong, P.C., Guckert, A., & Frossard. (2000). Influence of sulfur on apparent N-use efficiency, yield and quality of oilseed rape (*Brassica napus* L.) grown on a calcareous soil. *European Journal of Agronomy*, *12*, 2, 127–141.

Hinckley, E.L.S., Crawford, J.T., Fakhraei, H., & Driscoll, C.T. (2020). A shift in sulfur-cycle manipulation from atmospheric emissions to agricultural additions. *Nature Geoscience*, *13*, 597–604.

IPNI. (2015). *Soil test levels in North America*. Peachtree Corners, GA: International Plant Nutrition Institute.

Kaiser, D.E., & Kim, K.-I. (2013). Soybean response to sulfur fertilizer applied as a broadcast or starter using replicated strip trials. *Agronomy Journal*, *105*, 1189–1198. https://doi.org/10.2134/agronj2013.0023

Salvagiotti, F., Castellarín, J.M., Miralles, D.J., & Pedrol, H.M. (2009). Sulfur fertilization improves nitrogen use efficiency in wheat by increasing nitrogen uptake. *Field Crops Research*, *113*, 2, 170–177.

Schwab, G. (2008). Sulfur fertilization in Kentucky (AGR-198). Cooperative Extension Service, University of Kentucky.

The Fertilizer Institute. (2020). *Soil fertility manual*. Washington, DC: The Fertilizer Institute.

Wortmann, C. (2019, 18 December). *Crediting essential nutrients applied in irrigation water*. Retrieved from https://cropwatch.unl.edu/2019/crediting-essential-nutrients-applied-irrigation-water

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1. Sulfur is, in general, _______ in the soil and _______ in plant tissue.

- **a.** mobile, mobile
- **b.** mobile, immobile
- **c.** immobile, mobile
- **d.** immobile, immobile

2. Which of the following is NOT a major role of sulfur in growing crops?

- **a.** Enzyme development.
- **b.** Promoting optimum nodulation in legumes.
- **c.** Affecting osmotic turgor of cells.
- **d.** Chlorophyll formation.

3. Which of the following is one of the primary soil sources of sulfur?

- **a.** Organic matter.
- **b.** pH.
- **c.** Silicates.
- **d.** Cation exchange capacity.

4. What form of sulfur do plant take up?

- **a.** Elemental sulfur.
- **b.** Sulfate.
- **c.** Sulfite.
- **d.** Sulfur compounds.

5. Some sulfur fertilizers can

- **a.** harden the soil.
- **b.** soften the soil.
- **c.** acidify the soil.
- **d.** increase soil ph.