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G2360

Sulfur Management in Agricultural Systems of Nebraska

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Fig. 1. (a) Mid-season (May 12, 2021) sulfur deficiency symptoms in rainfed no-till winter wheat following soybeans on an eroded hillside of Crete silty clay loam soil in Saline County southwest of Crete, NE (photo credit: Nathan Mueller), (b) Late-season (August 28, 2020) sulfur deficiency symptoms in rainfed soybeans growing on a Yutan, eroded-Aksarben silty clay loam soil in Saunders County east of Ceresco, NE. (photo credit: Aaron Nygren), (c) Mid-season (July 16, 2014) sulfur deficiency symptoms in rainfed corn growing in a low organic matter and sandy soil (Thurman loam fine sand & Leisy fine sandy loam) in Dodge County north of Scribner, NE. (photo credit: Nathan Mueller).

In recent years, soil sulfur (S) availability has declined worldwide. Factors contributing to S deficiencies include lowered S concentration in the atmosphere, the reduction of soil organic matter content, which contains most of the total S in the soil, and increased S removal in harvests with greater soil S extraction. Visual symptoms of S deficiency are a light green to yellowish color on upper leaves (Figure 1a and b). Specifically in corn, a marked yellowing between the veins is observed (Figure 1c). While current assessments of agricultural systems in Nebraska generally indicate low to no need for S, instances of S deficiency are becoming more common, particularly as crop S requirements increase and soil S levels deplete over time. Therefore, it is crucial to assess S needs using a systems approach and then look for the most effective S management strategy to address this emerging issue and overcome S deficiencies without over-applying S.

Optimized fertilizer-S use needs consideration of the **4Rs**: **R**ight rate, **R**ight source, **R**ight place, and **R**ight time. However, the first step for S management is determining when S fertilization is required. Here we present **1)** an overview of the S cycle in agroecosystems and its implications on S management in Nebraska, **2)** a four-step guide to diagnosing S deficiency in corn, soybean, and wheat, and **3)** a synthesis of the 4Rs of S fertilization.

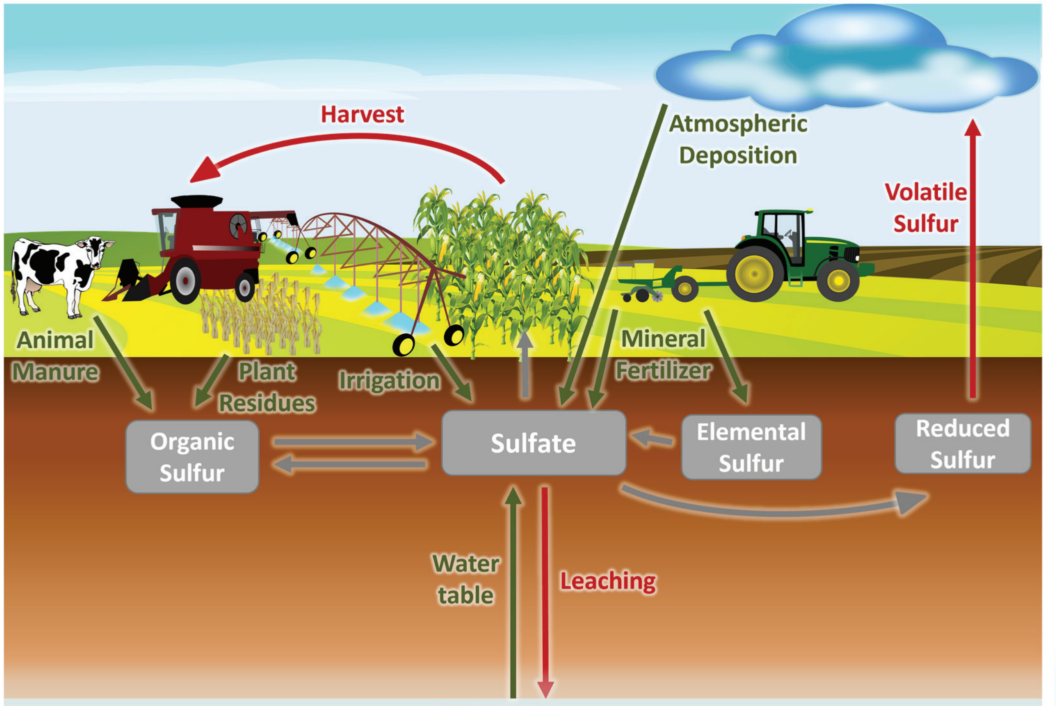

Fig. 2. The sulfur cycle. Green arrows show sulfur entries, gray arrows transformations, and red arrows losses. Adapted from IPNI.

Sulfur Cycle and its Implications on Sulfur Management

Sulfur Entries:

Each cropping system has specific sulfur entries (green arrows in Figure 2), affecting sulfur availability for the crops and, thus, sulfur fertilization requirements.

IRRIGATION SULFUR CONTRIBUTION

A significant difference is observed between irrigated and dryland systems in Nebraska. Irrigation water has variable and usually a substantial amount of sulfate. Sulfate concentration in irrigation water varies among and within aquifers and testing irrigation water for S concentrations is advised. Overall, wells survey research in Nebraska observed an increasing trend in sulfate-S concentration from the northwest to southeast, with exceptions for the Central Platte and Tri-Basin Natural Resource Districts (Figure 3). Also, wells of < 100 ft depth in the Great Plains Aquifer had higher S concentration (59 ppm S) than those of > 100 ft depth (24 ppm S).

Depending on the amount of irrigation applied, S contributions from irrigation water can be enough to fulfill the crop S requirement. For example, about 73% of irrigation wells in Nebraska supply through 10 inches of irrigation more S than what is removed in crop harvest. Therefore, it is necessary to test irrigation water for sulfate-S concentration and calculate the amount of S applied with irrigation (from sulfate-S concentration and the inches applied) and the crop demand (from S requirement and the yield goal) before considering S fertilization. To fully consider this S entry, sulfate-S concentration in irrigated water should be determined by submitting a water sample to the local plant and soil lab, and the total amount of S coming from irrigation water should be calculated as follows:

$$S\ (\text{lb/ac/in}) = \text{Sulfate-S}\ (\text{ppm}) * 0.23$$

For example, if irrigation water has 10 ppm of sulfate-S, 2.3 pounds of S per acre will be applied for each inch of irrigation water.

Considering the inches of irrigation applied, the sulfate-S concentration in water, and the rainfall differences between eastern and western Nebraska, a few inches (1–5 in) are usually applied in the east of Nebraska with a high S concentration in irrigation water. In contrast, several inches (12–20 in) are frequently used in the west central area with a low S concentration. Hence, being aware of S entry from irrigation water is key for S management in irrigated cropping systems. Furthermore, the time of irrigation should also be considered because if irrigation does not occur until the reproductive stages, early season S deficiency could occur if S availability in the soil is not enough to fulfill the crop demand.

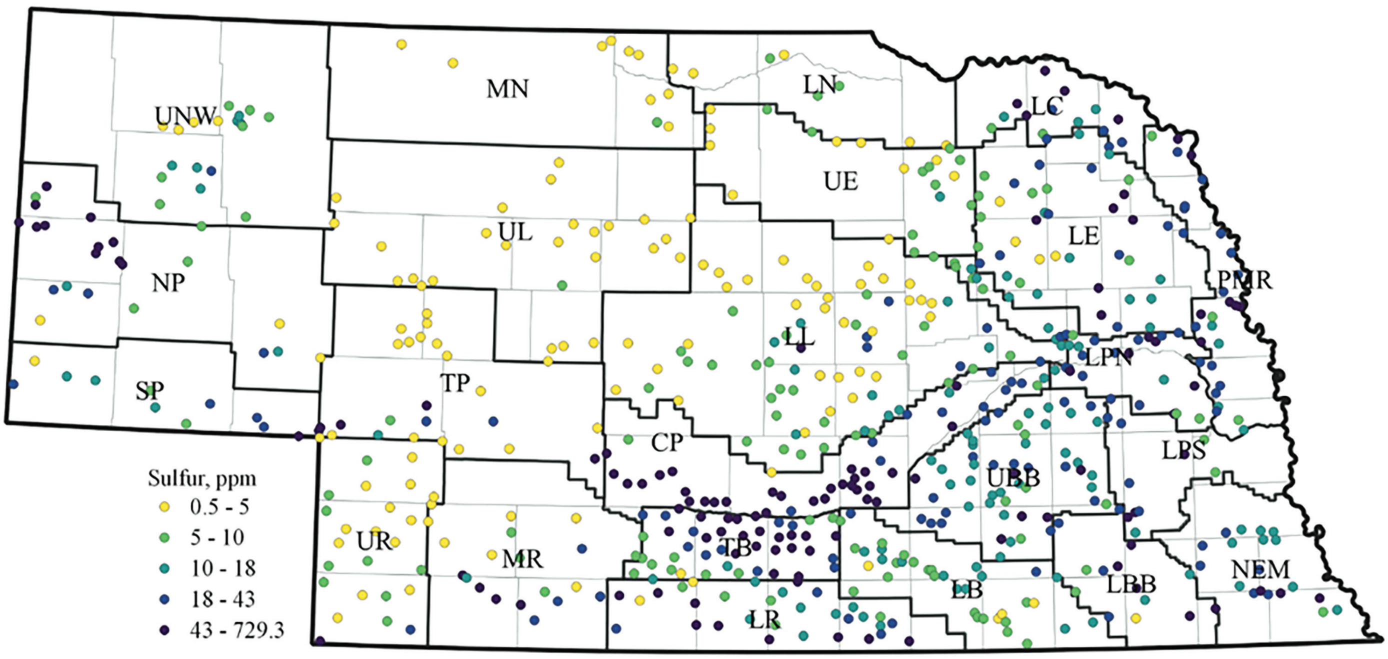

Fig. 3. Sulfur concentration in irrigation water in Nebraska (depth of wells varies from <100 ft to > 323 ft depending on the zone). Adapted from Wortmann (2021).

SULFUR CONTRIBUTION FROM SHALLOW WATER TABLE

Shallow water tables (saturated soil layer located in the upper 6 ft of the soil profile) may be a S source to rainfed crops once roots reach that depth. Water table depth varies with inputs (e.g., precipitation), outputs (e.g., evapotranspiration), and sub-surface lateral water flow. The water table depth for different areas of Nebraska can be checked at: https://maps.waterdata.usgs.gov/

Sulfur deficiencies are sometimes observed during early crop stages, but once the roots reach the water table, S deficiency symptoms disappear, if S in the water table is in high concentrations. Sulfate-S concentration in the shallow water table is variable, and its determination could help to get a more precise impact of the S from the water table provided to the crops. For example, sulfate-S concentration in shallow groundwater of northeastern Nebraska ranged from 3 to 66 ppm (Atkinson, 2012). Moreover, 4 ppm and 56 ppm sulfate concentrations have been observed for the southeast Nebraska and Central Platte, respectively.

MANURE SULFUR CONTRIBUTION

Sulfur concentration should be determined by laboratory analysis because it is variable among and within a manure type. On average, S concentration on a dry basis could vary from 0.25% for cattle to 0.60% for poultry manure, representing 5.5 lb S/ton and 13 lb S/ton, respectively (Eriksen, 2009; Shaver, 2014). Therefore, an average entry of 55 lb S/ac can be achieved by applying 10 tons/ac of cattle manure, which is usually achieved with the common application rates of >20 tons/ac every 3–5 years. Only about 50% of applied organic S may be available in the first year with more manure S mineralized to be available for following crops.

COVER CROPS SULFUR CONTRIBUTION

Cover crops uptake S from the soil, reducing possible S losses during the off-crop season period. The cover crop residue (after termination) can release the accumulated S, acting as a S source for the following cash crop in the sequence. The S entry from cover crops is valid for legumes with low C:S ratios that promote S mineralization but not for grasses that usually immobilize S. Considering a 0.32% S concentration and an aboveground biomass accumulation of 1,000 lb/ac for the east and 400 lb/ac for the west of Nebraska (Koehler-Cole et al., 2016), winter legumes could accumulate approximately 3 to 1.2 lb/ac, respectively, which will be almost entirely available for the following summer cash crop. Brassicas cover crops (*e.g.*, rapeseed and radish) have the highest S concentration in biomass (avg. 0.6%). However, the brassicas cover crops in Nebraska commonly have low biomass yield (avg. 250 lb/ac), making a very low S contribution to the system.

ATMOSPHERIC SULFUR DEPOSITION

This S source has been reduced from 3.6 to less than 1.5 lb S/ac/yr (1980–2022) in eastern and from 1.3 to 0.6 lb S/ac/yr (1985–2022) in western Nebraska. Therefore, S entry through atmospheric depositions is almost irrelevant (https://nadp.slh.wisc.edu/maps-data/ntn-interactive-map/).

NON-SULFUR FERTILIZERS

Non-S fertilizers contain low S impurities with little S supply to cropping systems. Details of S fertilizers are provided in Table 3.

Pools of Sulfur in the Soil and Their Transformations

Each cropping system differs in the intensity of S transformation (gray arrows in Figure 2) depending on the system-specific S entries and environmental conditions, affecting S availability for the crops and, thus, S fertilization requirements.

SULFATE (SO_4^{-2})

Inorganic S in aerobic agricultural soils is mainly in the sulfate form, an anion. As soils have net negative charge (*i.e.*, develop cation exchange capacity), the soil colloids do not retain sulfate; thus, sulfate is mobile in the soil. Therefore, soil sulfate concentration fluctuates throughout the year because of entries, turnovers, and losses.

ELEMENTAL SULFUR (S)

Plants cannot uptake S directly, and elemental S needs to be oxidized to sulfate by soil bacteria before being available for the plant. Oxidation depends on i) soil temperature and moisture (environmental conditions governing biological activity) ii) soil organic matter content (affects carbon and nutrients availability for microorganisms' growth), and iii) fertilizer granule size (defines the surface area exposed to bacteria). Therefore, elemental S oxidation is a slow-release sulfate source.

ORGANIC SULFUR

More than 95% of the total soil S is in organic forms (*i.e.*, in the soil organic matter, SOM) and needs to be transformed (i.e., mineralized) to sulfate (*i.e.*, inorganic) to be available for plants. Therefore, SOM content, which represents the size of the organic S pool, and factors controlling S mineralization (*e.g.*, soil temperature, moisture, aeration, and tillage method) will determine the availability of S for crops from SOM. Sulfur deficiencies are sometimes observed in the early stages of winter crops, but S deficiency symptoms could disappear when warmer spring temperatures promote S mineralization.

Sulfur Losses

Each cropping system differs in the amount of S losses (red arrows in Figure 2) depending on the crop rotation, yield level, and soil and weather conditions, affecting S availability for the crops and, thus, S fertilization requirements.

LEACHING

Sulfate can move downward through the soil with water, representing the main loss of S from the system. Leaching losses are greater in coarse-textured than fine-textured soils because of the combined effects of a lower rate of water movement and a higher sulfate retention capacity in the latter. Sulfate leaching will impact the efficiency of different S sources and the time and place of S fertilization.

HARVESTING

The worldwide crop yield increases made S removal through harvest a relevant soil S loss process. By considering average yields and S concentration in grain, it is observed a low S removal in wheat, followed by corn for grain, soybean, and the highest removal rate found in corn for silage (Table 1). High-yielding soybean and corn for silage in crop sequence deserve special attention because of the high S removal.

VOLATILIZATION

Volatilization of S occurs in waterlogged soils, a rare condition in NE, so this process has little relevance.

Table 1. Mean yield, S concentration in grain, seed, or total biomass (silage), and total S removal by harvest for soybean, wheat, and corn for grain and silage in irrigated and dryland conditions.

	Soybean		Wheat		Corn (grain)		Corn (silage)	
Crop	Irrigation	Dryland	Irrigation	Dryland	Irrigation	Dryland	Irrigation	Dryland
Yield (bu/ac or ton/ac) [1]	70	50	80	40	220	160	25	13
S concentration (lb/bu or lb/ton) [2]	0.18	0.18	0.07	0.07	0.05	0.05	2.2	2.2
S removal (lb/ac)	12.6	9.0	5.6	2.8	11.0	8.0	55.0	28.6

[1] Yield is expressed in bushel/acre for soybean, wheat, and corn grains and in ton/acre for corn silage.

[2] S concentration is expressed in lb/bushel for soybean, wheat, and corn grains and in lb/ton for corn silage.

Diagnosis of S Deficiency

Four steps should be followed to decide when S fertilization is required based on the probability of S deficiency (Figure 4):

1. **Characterize the site**: S deficiency commonly occurs when several (three or more) of the following conditions simultaneously occur:

    i. **sandy soils** (sulfate is easily leached),
    ii. **low organic matter** (*i.e.*, small organic S pool to be mineralized),
    iii. **no-till systems** (reduce S mineralization due to lower soil temperature),
    iv. **high amount of grass-based residues** (immobilize soil S in the short-term because of the high carbon:S ratio associated with high carbon:nitrogen ratios),
    v. **lack of fallow** (does not allow the accumulation of sulfate-S in soil coming from mineralization),
    vi. **no presence of shallow water table** (could represent a relevant S source to the crops if it contains high sulfate concentration),
    vii. **no manure application** (could provide significant amounts of S when applied at high rates),
    viii. **low irrigation or low sulfate in the water** (sulfate concentration in the water and the inches applied should be considered in determining the amount of S applied),
    ix. **high-yielding environments** (increase the S removal),
    x. **non-irrigated winter crops such as wheat** (early spring growth often exhibits symptoms of S deficiency, although the crop may recover as soil temperature increases to allow more microbial activity and root growth so that temporary deficiency does not constrain yield).

    Before moving to the following step, a comprehensive assessment of the aforementioned conditions should be made. For example, i) sandy soils may have low S availability, but irrigation-S may satisfy crop demand; ii) soils with low (<1%) SOM are relatively prone to S deficiency, but S from manure application may meet crop demand; iii) no-till dryland may reduce soil available S, but with a shallow water table containing high sulfate concentration, this might reduce or eliminate S fertilizer requirement.

2. If three or more conditions of step 1 are prevalent, S deficiency is likely to occur. Hence, a pre-plant **soil analysis** can help decide the need for S fertilization (for a guide on soil sampling see Ferguson et al., 2007). If sulfate-S (0–8 inches depth) is < 8 ppm and organic matter (0–8 inches depth) is < 1%, S deficiency is highly probable, and S fertilization is recommended (see section 3: The 4Rs). Sulfate-S determination at 0–24 inches depth is recommended in some areas (threshold = 7 ppm) as subsoil could contain substantial amounts of sulfur that should be considered (Hergert, 2014).

3. The diagnosis of S limitation on steps 1 and 2 should be monitored. If soil sampling at sowing is not possible, plant S status could be diagnosed with **plant analysis**. Although visual symptoms could help diagnose S deficiencies, plant analysis is recommended to avoid nutrient confusion or hidden hunger. Therefore, S concentration should be determined from a representative or random field sample of 30 uppermost fully expanded trifoliolates (petioles removed) at R1-R2 (beginning to full bloom) in soybean, 20 to 30 whole plants above ground biomass at V5-V6 (six collars) in corn, and 40 to 50 whole plants above ground biomass at Feekes 4 to 6 (late tillering to jointing) in wheat. If the S concentration is below the proposed threshold for each crop (Figure 4, step 3), S fertilization will be required, with a sulfate-S fertilizer, which is rapidly available to plants.

4. Lastly, it is possible to check S deficiency by analyzing at post-harvest **S concentration in grain** samples. Thus, S concentration below the proposed thresholds for each crop indicates that, under similar cropping conditions, the analyzed field will likely present S deficiency in the following crops in the sequence, and S fertilization requirement should be considered.

Example of How to Use the Four-Step Approach to Diagnose Sulfur Deficiency

If producing corn in a field with sandy soil and 1% organic matter, under a no-till system, deep water table, no manure application, and irrigation with low sulfate in water, there is a high probability of S deficiency (Figure 4, Step 1). Therefore, see section 3; the 4 Rs. Additionally, a pre-plant soil analysis can be done to better understand S deficiency (Figure 4, Step 2). If the soil test in the upper 8 inches shows low sulfate-S content (<8 ppm) and the sulfate-S analysis in irrigation water also indicates a low concentration (<6 ppm), suggesting a high probability of S deficiency and the need to apply S fertilizers. Therefore, see section 3; the 4 Rs. If a soil test was not done or a complementary in-season assessment of S status is needed, plant tissue analysis can be done (Figure 4, Step 3). For example, in corn, samples should be taken at the $V_{5\text{-}6}$ stage, S concentration is determined in the whole plant above ground biomass to check previous decisions on S fertilization, and then if the S concentration result (<0.18%) S application will likely have an economic response. Therefore, see section 3; The 4 Rs. Finally, if crop season is over and one wants to see if the following crop has a probability of incurring S deficiencies, grain samples can be analyzed (Figure 3, step 4). For example, if the soybean seed S concentration is lower than 0.33%, the following crop will likely experience S deficiency. Therefore, see section 3; the 4 Rs.

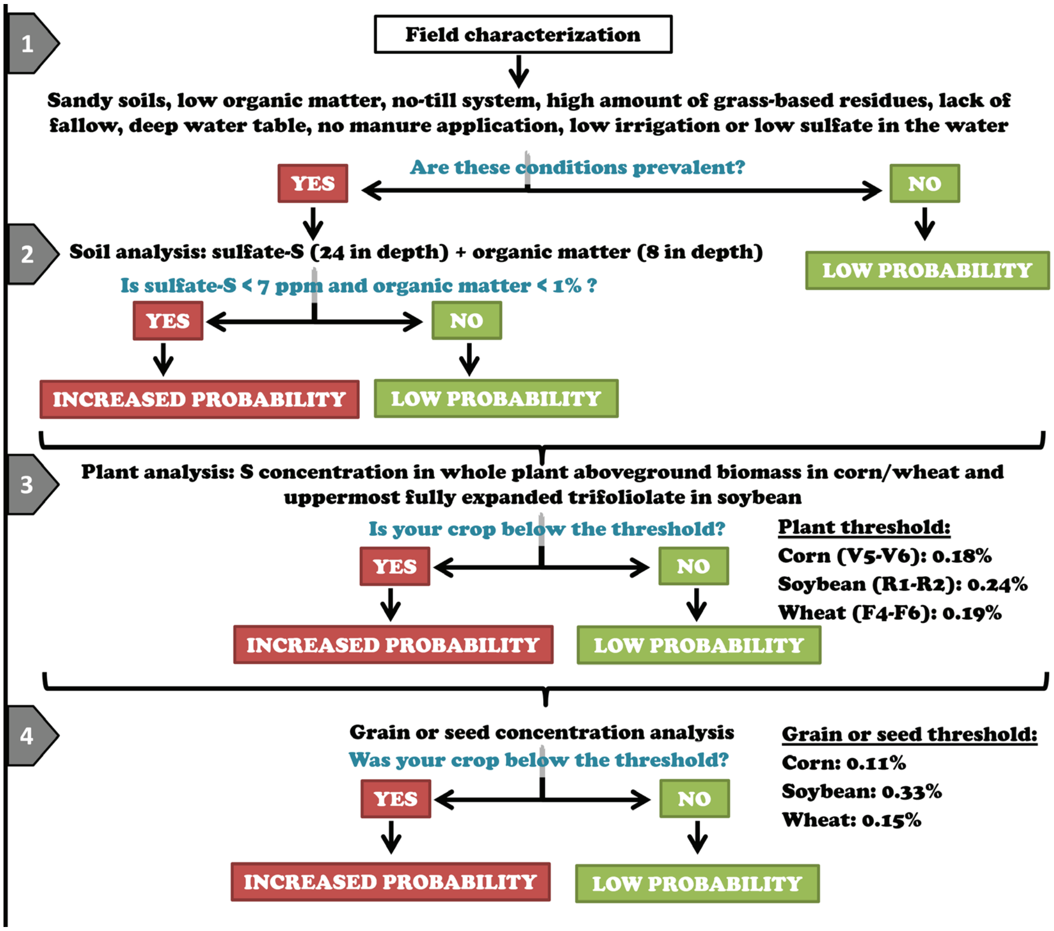

Fig. 4. Steps to diagnose sulfur (S) deficiency probability in corn, soybean, and wheat. Plant and grain sulfur concentration thresholds were obtained from international references (Blake-Kalff et al., 2000; Carciochi et al., 2019; Kaiser and Kim, 2013; Mueller, 2020; Reussi Calvo et al., 2011) and require a broad local validation.

The 4 Rs

Right Rate

The right rate should only be defined if S deficiency is diagnosed (see Figure 4). Defining S fertilizer rate could be difficult because of the complexity of the S cycle, the low accuracy of soil sulfate-S determination, and the relatively low amount of S fertilizer required compared to other nutrients such as nitrogen. Ideally, the S rate should consider crop yield goal, soil organic matter, sulfate-S in soil, and other eventual S credits, such as the amount of S applied by irrigation.

Overall, no crop yield response to S beyond 25 lb S/ac is expected. Most current scenarios across NE have low to no S deficiency. Therefore, S rates should not exceed 25 lb S/ac. Sulfur deficiencies found in the neighboring state of Iowa have been extended to some areas in eastern NE in which 16 lb S/ac are recommended for fine-textured soils and 24 lb S/ac for coarse-textured soils (ISU, 2015). For corn in Nebraska coarse soils, the rates are defined by soil organic matter, sulfate-S concentration in irrigation water, and sulfate-S soil test (Table 2):

Table 2. Sulfur recommendation rate for corn in Nebraska. Adapted from Shapiro et al. (2019)

Sulfate-S soil test 0–8 inches (ppm)	Amount to apply (lb S/ac)	
	Irrigation water with < 6 ppm sulfate-S	
	Soil organic matter < 1%	Soil organic matter >1%
< 6	20	5
6 to 8	10	0
> 8	0	0
	Irrigation water with > 6 ppm sulfate-S	
< 6	10	0
6 to 8	10	0
> 8	0	0

Right Source

Sulfate-S fertilizers contain S in a readily available form to plants, whereas elemental S must be oxidized. Consequently, elemental S can be applied at or before planting, allowing reductions in S, losses through leaching, and providing some residual effect for the successive crop in the rotation. However, elemental S is not suited as a preplant S source in dry areas or for corrective applications to S-deficient crops, because oxidation may take more than a crop growing season.

Fertilizers containing both sulfate and elemental S may have some advantages in reducing sulfate leaching and optimizing the synchrony between S availability and crop requirements. Details on S fertilizers are provided in Table 3.

Right Place

Sulfate is a mobile anion in the soil, so no differences in yield are usually expected between broadcast or banded applications for sulfate fertilizers. Elemental S oxidation could be accelerated if incorporated into the soil rather than surface broadcast.

Right Time

To optimize S use efficiency, the best time to apply S is at planting or during early vegetative periods because S affects some processes, such as tillering in wheat, that take place during early growth stages. However, the S uptake dynamic shows that from the total S uptake, 45% in corn, 68% in soybean, and 30% in wheat is accumulated after flowering (R_1 in corn and soybean and $F_{10.5}$ in wheat), indicating that S deficiencies could be partially overcome with S fertilization and with irrigation-S during late vegetative periods or even early reproductive stages in soybean. Elemental S oxidation to sulfate takes time and fluctuates depending on the conditions mentioned. Therefore, elemental S needs to be applied pre-planting.

Closing Remarks:

Sandy soils with <1% SOM usually presented S deficiency. S rates should not exceed 25 lb S/ac. A few recent S limitations cases in Nebraska were reverted with 16 lb S/ac. Studies exploring crop yield response to S fertilizer on medium and fine-textured soils have shown a low frequency and magnitude of yield response to fertilizer S in Nebraska. However, high crop removal of S indicates that S deficiency will become more frequent in future years. Therefore, a systems approach with four steps is described to identify S deficiencies. The first step is to characterize the cropping system, which could be accompanied in a second step by a soil analysis. In a third step, plant analysis could be used during the crop growing season to complement the soil test diagnoses or when previous steps were not possible to follow. Lastly, the fourth step is to conduct a *post-mortem* analysis of S concentration in grain or seed to decide the need for S fertilization for the following crops

Table 3. Characteristics of S fertilizers.

Fertilizer	S conc. (%)	S source	Other nutrients	Category
Gypsum (calcium sulfate)	18	Sulfate	Ca (23%)	Powdered, granular, prilled
Ammonium sulfate	24	Sulfate	N (21%)	Granular
Ammonium thiosulfate	26	Sulfate+Elemental[1]	N (12%)	Liquid
Potassium magnesium sulfate	22	Sulfate	K (18%) Mg (11%)	Granular
Elemental S	90–95	Elemental	-	Flakes, granules
Mixtures (N-P-S-others)	Variable	Sulfate+Elemental	Variable	Granular

[1] Ammonium thiosulfate fertilizer reacts with soil to initially form some colloidal elemental sulfur.

in the sequence. Additionally, on-farm trials comparing S-fertilized with no fertilized would provide *in-situ* information on S fertilization requirements. A protocol for on-farm assessment of yield response to S can be found here https://on-farm-research.unl.edu/pdfs/resources/protocols/Sulfur%20Protocol_OFRN_03.30.2021.pdf. If previous steps or on-farm trials indicate that S needs to be applied, the 4 Rs of S fertilization should be followed.

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Chuck Burr (UNL, Extension Educator), Dorivar Ruiz Diaz (KSU, Professor).

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