

Sulfate Loss Mechanisms in Arkansas Agricultural Production

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Introduction

Crop nutrient losses from soil-applied fertilizers are a concern for agricultural producers worldwide. Soil-applied nutrient loss mechanisms, such as soil profile leaching, surface runoff and volatilization can reduce crop productivity and profitability.

Research concerning agricultural nutrient losses has primarily focused on nitrogen (N) and phosphorus (P) (Daniels et al., 2019). But other types of soil-applied macro- and micronutrients can also experience similar loss mechanisms and subsequently affect crop development and fertilizer efficiency. One macronutrient that can significantly impact agricultural and economic productivity via specific loss mechanisms is sulfur (S).

The Role of Sulfate in Agricultural Production

Sulfur primarily exists in soil in the form of the sulfate ion (SO_4^{2-}) (Bekele and Birhan, 2021). Developing plants readily assimilate SO_4^{2-} upon contact with root hairs and associated root exudates. Sulfate is highly mobile in the soil and can be transported by mass flow and/or diffusion (Brady and

Weil, 2008). Sulfate's mobility in the soil enhances the ion's uptake potential by various crop species. Once assimilated into the plant, sulfate becomes a key factor in numerous plant physiological and metabolic functions, such as enzyme activation, amino acid synthesis and enhancing plant cellular structure (Sun et al., 2024). Any severe SO_4^{2-} deficiencies during a growing season can decrease crop productivity (Edis and Norton, 2012).

Sulfate is also a component of various fertilizer products and their respective formulations. Sulfate-based fertilizers, such as ammonium sulfate $[(\text{NH}_4)_2\text{SO}_4]$ and potassium sulfate (K_2SO_4), are used by producers to supply a source of S to emergent crops (Till, 2010). However, soil-applied SO_4^{2-} -containing fertilizers can also be susceptible to losses from the soil environment similar to losses observed for soil-applied N and P (Hinkley et al., 2020). Even when strictly adhering to the 'four Rs' of nutrient management (i.e., right time, right place, right rate and right source) for S fertilization, the highly mobile nature of SO_4^{2-} in the soil can exacerbate SO_4^{2-} losses if not assimilated by crops.

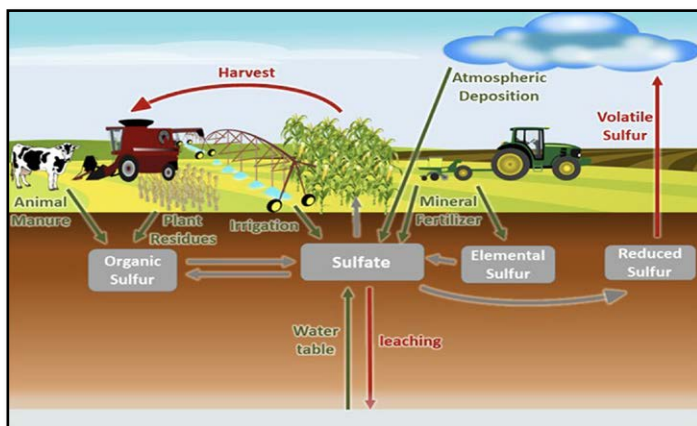
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Sulfate Losses from Soil Profile Leaching and Immobility

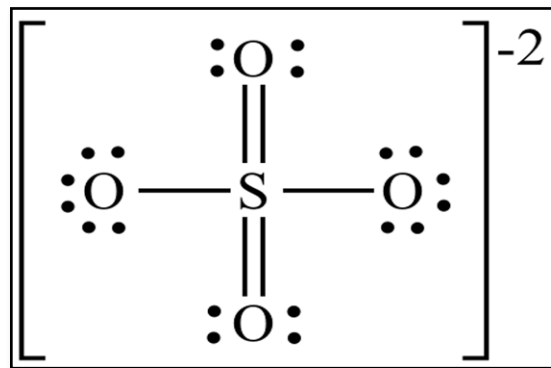
Sulfate and nitrate (NO_3^-) are similar in that they are both highly prone to losses via leaching (Degryse et al., 2018) as a result of enhanced mobility in the soil as a negatively charged anion. Leaching is the process whereby nutrients are transported downward with water through the soil profile and away from the plant's root zone (Figure 1). Nutrient leaching can deprive crops of essential amounts of SO_4^{2-} needed for proper plant growth and development. Leaching can also lead to elevated SO_4^{2-} concentrations in watershed resources (Hermes et al., 2021). Predominantly sandy-textured soils, soils with low soil organic matter (SOM) levels and large permeability are most susceptible to SO_4^{2-} leaching (Narayan et al., 2023). Soil series in Arkansas that are predominantly sandy and conducive to row crop agriculture include Savannah sandy loams, which are located throughout southern Arkansas (Francis, 2025).

Figure 1. Image displaying the leaching potential of sulfate. Green arrows denote sulfate inputs, red arrows indicate sulfate losses, and gray arrows define sulfate transformations. (Image from Carciochi et al., 2023).



Sulfate is an anion with a -2 valence that decreases its potential to interact with clay particles and soil colloid exchange sites (Stewart and Sharpley, 1987) (Figure 2). However, SO_4^{2-} that is not adsorbed due to typically lower amounts of iron (Fe) and aluminum (Al) oxides in certain soils can also be vulnerable to leaching as well. In addition, SO_4^{2-} that is leached has the potential to be immobilized and rendered insoluble within the soil profile due to binding chemically and forming precipitates with certain cations, such as calcium (Ca^{2+}), magnesium (Mg^{2+}) or sodium (Na^+), depending on the soil solution pH and chemistry, which can greatly decrease

Figure 2. Structural image of the sulfate ion with one sulfur (S) atom, four oxygen (O) atoms and an overall charge of -2. (Image from Hardinger, 2017).



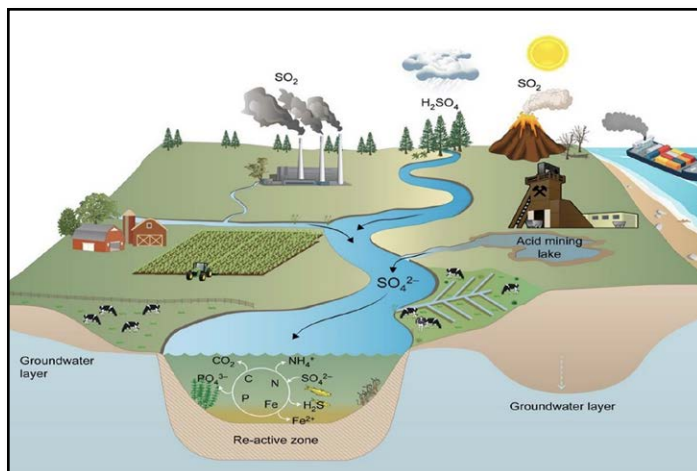
plant availability of SO_4^{2-} at times of peak plant demand (Zenda et al., 2021).

Sulfate Losses from Surface Runoff

Sulfate losses through surface runoff can be detrimental to SO_4^{2-} fertilizer-use efficiency and farm profitability. Similar to N and P, SO_4^{2-} can freely migrate with surface runoff and be deposited into nearby aquatic systems (David et al., 2016) (Figure 3). Although agricultural surface runoff research mainly involves N and P (Daniels et al., 2023), excess SO_4^{2-} can be problematic as well, as evidenced by the Environmental Protection Agency setting a SO_4^{2-} safety threshold of 250 milligrams per liter (mg L^{-1}) for well/drinking water (EPA, 2016). Even if SO_4^{2-} surface runoff levels do not surpass the 250 mg L^{-1} threshold, excess SO_4^{2-} in surface runoff can be an indicator of the amount of SO_4^{2-} lost to the amount of SO_4^{2-} applied via fertilizers or manures in cropping systems.

From 2022 to 2024, the Arkansas Discovery Farms Program (ADFP) examined the effects of contrasting Arkansas agricultural production systems and their respective approaches to nutrient management on SO_4^{2-} concentrations and mass losses during surface runoff events (Burke et al., 2025). A row crop operation involved in growing cotton (*Gossypium hirsutum* L.) applied 112 kilograms (kg) (i.e., 100 pounds (lbs.)) of ammonium sulfate fertilizer (24 percent S) per hectare (i.e., $26.8 \text{ kg S ha}^{-1}$) during the project and experienced elevated SO_4^{2-} levels (i.e., $227 \text{ mg SO}_4^{2-} \text{ L}^{-1}$) observed in surface runoff samples. Another row crop operation cultivating rice (*Oryza sativa* L.) and soybean (*Glycine max* L.) also exhibited large levels of SO_4^{2-} in surface runoff (i.e., $180 \text{ mg SO}_4^{2-} \text{ L}^{-1}$). Although the rice farm did not apply any form of SO_4^{2-} -based fertilizers or

Figure 3. Sulfate (SO_4^{2-}) in surface runoff from a variety of point and non-point sources. Sources include sulfur dioxide (SO_2) and sulfuric acid (H_2SO_4). Re-active zone constituents include carbon (C), nitrogen (N), phosphorus (P), iron (Fe), carbon dioxide (CO_2), the phosphate ion (PO_4^{3-}), the ammonium ion (NH_4^+), hydrogen sulfide (H_2S) and ferrous iron (Fe^{2+}). (Image from Zak et al., 2021).



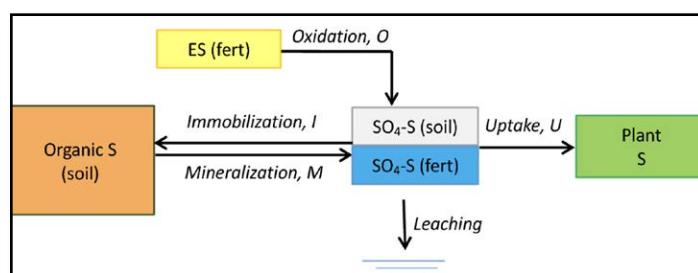
animal manures during the study, the crop rotation used suggests poorly drained soils at the location, which can be beneficial for growing flooded rice, but may be vulnerable to nutrient losses by surface runoff when other crops are produced. In addition, surface runoff from poultry houses on a forage/livestock operation in northwest Arkansas also experienced large SO_4^{2-} levels in collected surface runoff samples (i.e., $62 \text{ mg SO}_4^{2-} \text{ L}^{-1}$) comparable to several row crop systems associated with the ADFP.

Another consideration of the behavior of SO_4^{2-} in surface runoff involves irrigation. Row crop operations often rely on obtaining irrigation water by pumping aquifer water on their farms (Sharpley et al., 2015). Although this is a convenient method of supplying water to crops throughout a growing season, irrigation water drawn from deep-placed wells can be laden with various nutrients originating from the weathering of underlying bedrock. In particular, underlying bedrock sources, rich in metal sulfide (S^{2-}) materials, can produce copious amounts of SO_4^{2-} (Havlin et al., 2014), which can be present in irrigation water, masking the effects of SO_4^{2-} fertilization (Zielinski et al., 2006). In fact, irrigation/well water in eastern Arkansas has been reported to have substantial $\text{SO}_4\text{-S}$ concentrations, ranging from 2 to $> 100 \text{ mg SO}_4^{2-} \text{ L}^{-1}$, which can influence elevated SO_4^{2-} concentrations and loads (Roberts et al., 2021). Therefore, routine testing of irrigation well water should be made to determine annual SO_4^{2-} inputs via irrigation water and assist with S-fertilization decisions.

Sulfate Losses from Biological/Chemical Processes

Similar to N, soil organic matter (SOM) can also affect the availability of SO_4^{2-} for developing crops (Blum et al., 2013). Soil microorganisms associated with the formation of SOM can both mineralize and immobilize SO_4^{2-} (Figure 4) depending on the carbon (C):S ratio of decomposing organic materials such as corn (*Zea mays* L.) stover, rice hulls and wheat (*Triticum aestivum* L.) straw (Havlin et al., 2014). Sulfur mineralization occurs with plant residues possessing a C:S ratio of $< 200:1$, while S immobilization typically occurs with plant residues having a C:S ratio of $> 400:1$ (Brady and Weil, 2008). As a result, soils with low levels of SOM may reduce SO_4^{2-} availability for plant assimilation via decreases in soil microbial activity that can stimulate SO_4^{2-} mineralization.

Figure 4. Fates of elemental sulfur (ES), organic and plant sulfur (S) and sulfate-sulfur ($\text{SO}_4\text{-S}$) in the soil through the processes of oxidation (O), mineralization (M), immobilization (I) and uptake (U). (Image from Degryse et al., 2021).



Sulfate can also be lost from the soil through chemical and soil microbial transformations that are reliant on surrounding environmental conditions. Volatilization of SO_4^{2-} can occur in both aerobic and anaerobic conditions (Bekele and Birhan, 2021), with SO_4^{2-} volatilization potential correlating with an abundance of SOM content (Brady and Weil, 2008). Losses of SO_4^{2-} by volatilization are relatively negligible compared to N (Havlin et al., 2014). However, SO_4^{2-} lost via volatilization and other associated microbial processes should be considered as another avenue in which SO_4^{2-} can be lost from the soil and into the surrounding atmosphere.

Over the last few decades, as a result of the Clean Air Act (Baumgardner et al., 2002) and reduced atmospheric emissions, there has been a significant reduction in overall atmospheric S deposition across the US (Figure 5). While the central southern United States showed a 51 percent reduction in total S deposition, other

parts of the US experienced even more pronounced reductions (i.e., 87 percent, 83 percent, and 81 percent reductions in S deposition in the Mid-Atlantic, Northeast, and Midwest areas, respectively) (USEPA, 2024). While this reduction in total S deposition is beneficial from an air quality standpoint, this reduction also represents a reduced input of an essential plant nutrient, as the S deposition rates in early 2000s (Figure 5) were close to S removal in crop harvested grain (approximately 13.3 kg S ha⁻¹ for 13,809 kg ha⁻¹ corn and 4,035 kg ha⁻¹ soybean, which is equivalent to 11 lbs. S per acre (ac⁻¹) for 220 bushel (bu) ac⁻¹ corn and 60 bu ac⁻¹ soybean) (Culman et al., 2019). Hence, over the last decades, there has been an increased frequency of S deficiencies across the US, including in Arkansas, as well as the need to supply S via fertilization to agricultural crops.

The most effective means of diagnosing a soil's ability to supply nutrients for adequate plant development is soil testing. The University of Arkansas System Division of Agriculture (UADA) soil testing program considers S to be low in soil when the soil test indicates a sulfate concentration 10 mg SO₄²⁻ kg⁻¹ or lower, resulting in a situation where S fertilization may be needed to maintain adequate crop growth and yield potential. However, attention is necessary regarding field conditions at the time of soil sampling to accurately assess soil S availability (Drescher et al., 2024). Soil samples collected with large soil moisture or following rainfall events may not accurately capture soil SO₄²⁻ availability due to sulfur's large mobility in the soil, as SO₄²⁻ may have leached out of the top 0-10 or 0-15 centimeter (cm)

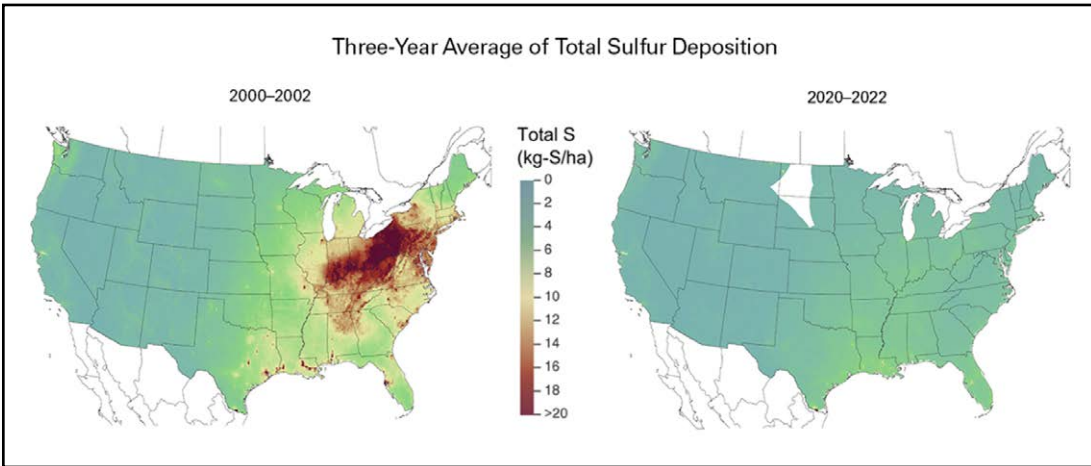
(0-4 and 0-6 inch (in.)) layer, which is typically sampled for soil testing in Arkansas. Low soil-test S values are most commonly observed in sandy soils with low SOM, where sulfate is more vulnerable to leaching and the amount of S mineralized from SOM is limited.

Plants can visually exhibit S deficiency by yellow vegetation at the growing point. Sulfur does not move within the plant once it is taken up and assimilated by the crop, unlike N, which can be translocated to newer parts of the plant from lower plant structures. For Arkansas crop production systems, S deficiencies are most commonly observed during early growth stages when crops have limited root growth to take up SO₄²⁻ from deeper soil layers, and crop irrigation has not yet been initiated, where groundwater irrigation can be an important source of S in Arkansas. Oftentimes, S deficiency symptoms may disappear later in the season, when plants have developed a more extensive root system and irrigation has been initiated. If a crop appears to be yellowing only at the growing point and young leaves, it is recommended to confirm S deficiency with a plant tissue test. If a S deficiency is diagnosed, S fertilization is recommended.

There are multiple sources of S fertilizers with ammonium sulfate, which contains 21 lbs. of N, zero lbs. of P (as P₂O₅), zero lbs. of potassium (as K₂O) and 24 lbs. of S per 100 lbs. of fertilizer (21N-0P-0K-24S) and gypsum, which contains 19 lbs. of S and 34 lbs. of Ca per 100 lbs. of product (0N-0P-0K-19S-34Ca), being more accessible to Arkansas growers and therefore more commonly used for corrective S applications.

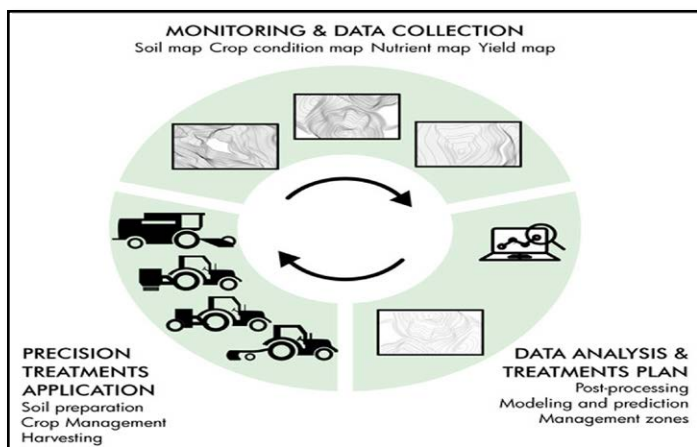
Additionally, other fertilizer sources, such as elemental S, which contains 100 lbs. of S (0N-0P-0K-100S) and potassium (K) magnesium sulfate [(K₂Mg₂(SO₄)₃], which contains 22 lbs. of K, 22 lbs. of S and 11 lbs. of Mg (0N-0P-22K-22S-11Mg), have been used. However, there are multiple considerations when

Figure 5. Change in atmospheric sulfur (S) deposition rates over two decades in the US. Red colors indicate high deposition, while green color indicates low deposition (USEPA, 2024). To convert kilograms of sulfur per hectare (kg-S/ha) to pounds of S per acre (lbs.-S/ac), divide kg-S/ha by 1.121.



Source: CASTNET/CMAQ/NADP USEPA, 2024

Figure 6. Major components of precision agriculture.
(Image from Botta et al., 2022).

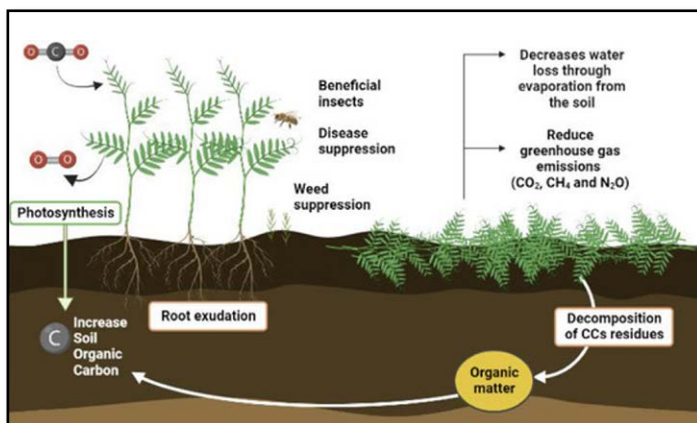


deciding on the best S source, including S concentration, fertilizer costs and fertilizer solubilization time, as elemental S has low solubility and needs time to become plant-available, while sulfate forms are more readily available for plant uptake.

Methods to Mitigate Agricultural Sulfate Losses

Agricultural SO_4^{2-} losses can be alleviated by a variety of methods and practices. One such practice involves the creation of additional stores of SOM. Increasing SOM can stimulate soil microbiological activity and promote SO_4^{2-} mineralization (Havlin et al., 2014) and thus make SO_4^{2-} readily accessible for plant uptake when released into the soil solution. Many types of organic materials can be added to the soil in order to enhance SOM production. When incorporated into the soil, materials such as crop residues and animal manures, along with soil amendments, such as biochar, can

Figure 7. Benefits of cover cropping in agriculture including reduction of the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions, along with the influence on atmospheric and soil organic carbon (C), oxygen (O), and decomposing cover crop (CC) residues. (Image from Quintarelli et al., 2022).



significantly increase SOM (Dick et al., 2008). However, increasing SOM in Arkansas soils can be difficult because of recurrent rainfall events, warm temperatures and agricultural practices that are not conducive to SOM formation, such as conventional tillage and crop-residue burning (Fryer et al., 2022).

Another method to reduce agricultural SO_4^{2-} losses is precision agriculture (Gerson and Hinckley, 2023) (Figure 6). Precision agriculture allows fertilizers to be applied at various rates and in specific areas of a field, along with applying fertilizers at rates optimal for peak plant demand, in a timely manner that can reduce the potential for nutrients to be lost via surface runoff and/or leaching (Hedley, 2015). Although the cost and implementation of precision agriculture may be a hurdle for some producers, it is nonetheless a worthwhile investment to insure SO_4^{2-} fertilizer efficacy and profitability.

Figure 8. Grassed waterway in between two corn fields.
(Image from USDA-NRCS, 2006).



Agricultural conservation practices can also have an effect on reducing SO_4^{2-} losses. Conservation practices, such as growing cover crops (Daniels et al., 2019) (Figure 7), implementing conservation tillage, and the use of vegetative filter/buffer strips (Sharpley et al., 2015) (Figure 8), can increase nutrient cycling within the production system and significantly reduce SO_4^{2-} loss from agricultural fields. In addition to N, P and K, conservation methods can also trap and retain SO_4^{2-} in a field while facilitating SO_4^{2-} plant uptake and assimilation (Arkansas Discovery Farms, unpublished data). Many conservation practices are relatively inexpensive to implement, and their maintenance is often minimal at best. Therefore, the use of conservation practices in areas that experience large SO_4^{2-} levels in surface runoff can be beneficial.

Conclusions

Sulfur is an essential plant nutrient that limits adequate crop development and yield potential when not present in adequate amounts. Sulfate is highly mobile in the soil and can be lost from the soil environment by several loss mechanisms, such as surface runoff, soil profile leaching and immobilization, which can all reduce the amount of SO_4^{2-} necessitated by developing crops, along with diminishing S fertilizer-use efficiency and economic viability. Awareness of the numerous pathways through which SO_4^{2-} can be lost from the soil and the associated methods that can be used to mitigate SO_4^{2-} losses should all be considered in order to ensure a successful cropping season.

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