Project Summary Report

Date:

Title: Evaluation of Sulfur-Containing Fertilizers for Sustained Delivery of Bio-available Sulfur in Three Texas Soils

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Executive Summary: A controlled laboratory study was performed to investigate the potential for sustained release of sulfur from SUL4R-PLUS®, a patented pelletized calcium dihydrate (gypsum) product, ammonium sulfate, and elemental sulfur as sulfur-containing fertilizer sources. Three soils of contrasting chemical and physical properties representing important agricultural niches in Texas received fertilizer from each source listed above at low and high rates of equivalent sulfur concentrations. The three soils (1 kg each) were packed into columns to a bulk density of 1.5 g cm^{-3} and leached at nine intervals over a 60-day period. Leaching water volumes applied were adjusted for each soil according to the relative pore space available. Leached water was collected from the bottom of each soil column and analyzed for plant available sulfate-sulfur (SO_4-S). Results indicate that ammonium sulfate released all applied fertilizer sulfur as plant-available, but also potentially leachable, sulfur within the first 5 days. Elemental sulfur applied to the soils released no appreciable amounts of plant-available sulfur over the entire duration of the study. SUL4R-PLUS®, however, released a moderate amount of sulfur over the initial 10 days of the study, and continued to release between 2 to 5 lbs per acre, depending on the rate applied, of plant available sulfur every 10 days thereafter. SUL4R-PLUS® demonstrated a statistically significant potential to provide sustained release of SO_4-S throughout the growth cycle of a crop plant, while protecting applied nutrient sulfur from losses due to early uncontrolled release and subsequent leaching below the root zone. Of the three sulfur-containing fertilizer sources evaluated in the study, the pattern of sulfur release from SUL4R-PLUS® best mimicked the sustained need of crop plants for sulfur nutrition over the course of a growing season.

Evaluation of Sulfur-Containing Fertilizers for Sustained Delivery of Bio-available Sulfur in Three Texas Soils

Introduction:

Sulfur (S) is a relatively abundant element, comprising approximately 0.1% of the earth's crust. In soils, S participates in a dynamic cycling between various inorganic and organic forms (Eriksen et al., 1998; Scherer, 2009; Bryson et al., 2014). Generally, 90% or more of the total S (Figure 1) present in soils occurs as organically-bound, and therefore plant-unavailable, S (Scherer 2009, Jamal et al., 2010). Inorganic S, a substantially smaller fraction of the total S in soils, may exist as hydrogen sulfide (H_2S), sulfides (S^{-2}) complexed with metallic minerals, elemental sulfur (S^0) under anaerobic conditions, or as sulfate (SO_4^{-2}) in soluble or insoluble salts (Havlin et al., 2005; Sherer 2009). Sulfate-S (SO_4-S) is the most abundant form of inorganic S, and the only form of sulfur that can be taken up by plants.

Major crop plants range in S-content from 0.1% to 0.5% on a dry weight basis (Havlin et al., 2005; Bryson et al., 2015). Sulfur deficiencies in crops have been increasingly reported for the past three decades and are well understood to be on the rise due largely to reduced emissions of sulfur dioxide from coal-burning power plants and other industrial sources, increased use of high-analysis low S-containing fertilizers, and decreased use of S-containing fungicides (Scherer, 2001). When sulfur is not supplied by soils at adequate levels, plant metabolic functions are impaired and crop yields and qualities are decreased (Havlin et al., 2005; Kovar & Grant, 2011) The recognition of this problem has resulted in an increase in the application of sulfur fertilizers with corresponding crop yield responses due to the added S (Wen, 2003; Kim et al., 2013; Kaiser 2013).

There are several commonly available sources of S-containing fertilizers, including ammonium sulfate ($(NH_4)_2SO_4$), potassium magnesium sulfate ($K_2SO_4 \bullet 2MgSO_4$), elemental sulfur (S), and gypsum ($CaSO_4 \bullet H_2O$) (Table 1). Elemental S is poorly soluble, and therefore cannot be relied upon as a fertilizer source to deliver the S-nutrition of a crop within a single growing season (Wen, 2003; Kovar & Grant, 2011). Fertilizers that contain sulfate are subject to rapid loss under high irrigation or rainfall due to the high solubility and mobility of SO_4-S in soils (Scherer, 2009, Jamal, 2010). Gypsum, being very hygroscopic, tends to absorb water easily. This can cause caking during storage and inside application equipment resulting in substantial handling difficulties. Ammonium thiosulfate and potassium sulfate are easily handled and applied in their liquid forms, but are converted in soils to approximately equal parts SO_4-S and elemental S

(Kovar and Grant, 2011). Therefore, some further breakdown of S is required, meaning that much of the applied S will remain unavailable to the crop until the following year. Furthermore, elemental sulfur, thiosulfate, and ammonium sulfate fertilizers contribute to the acidification of soils, a condition to be avoided in acidic or marginally acidic soils which comprise over half of the arable lands on the planet (Sumner & Noble, 2003).

In light of the recognized inefficiencies of S-fertilizer sources, it is surprising that there has been little work in the area of ensuring that S-nutrition derived from applied fertilizer is supplied to crops according to their pattern of need in the way that management practices and fertilizer delivery technology have been developed for nitrogen (N) nutrition (Dick et al., 2008; Bindraban, et al., 2015). For instance, where N-fertilization is concerned, potential losses and timing of availability to meet plant needs have been addressed through urease inhibitors, nitrification inhibitors, and through split applications as a best recommended practice (Cameron et al., 2013). Ideally, the delivery of S over time would follow the general uptake pattern of most crops, which can be represented by an S-shaped curve (Figure 2). 'Spoon-feeding' fertilizers to crops to supply nutrients in amounts that exactly match the changing need of the plant is impractical. However, any technology or management approach that could allow for a moderate early buildup of available SO_4-S, followed by a slow sustained release of same would better match the pattern of crop S uptake.

SUL4R-PLUS® pelletized calcium sulfate (16% S), formulated in a proprietary process by SUL4R-PLUS, LLC, represents a potential advance in the sustained delivery of S nutrition to plants. Technical information available from the manufacturer states that the product overcomes the hygroscopic limitations of conventional pulverized gypsum, is moderately water-soluble compared to other SO_4-S fertilizer sources, and is priced similarly to elemental sulfur sources (SUL4R-PLUS® Tech Sheet).

The purpose of this study was to evaluate the release patterns of SUL4R-PLUS® as compared to two other commonly available and widely applied S fertilizer sources. The three products (elemental sulfur, ammonium sulfate, and SUL4R-PLUS®) were applied to three soils of contrasting physical and chemical properties under agricultural production in Texas. The soil columns were leached at pre-determined intervals and the leachate collected to measure plant available-S as SO_4-S over a 60-day period.

Materials and Methods:

Soil Collection and Preparation

Soils were collected from three regions of Eastern Texas under agricultural production. A Burleson series soil under a corn/cotton/sorghum rotation was collected from Thrall, TX. A Weswood series soil under a corn/sorghum rotation was collected from near Snook, TX. Finally, a Rader series soil under perennial hybrid Bermuda pasture was collected from near Kauffman, TX. Soils were collected from the top 15 cm (6") at each location and dried at 65°C prior to grinding in a cone crusher to pass a 2 mm sieve.

Experimental Setup

One kg (~2.2 lbs) of each soil was placed into a 10 cm (4") diameter pvc schedule 40 pipe cut to 17.5 cm (7") in length. Prior to the addition of the soil, the bottom of the pipe segments were fitted with a floor drain cap secured with recessed galvanized screws and sealed with caulk. The drain caps were topped with a circle of cheesecloth over a circle of 1 mm mesh screen and a 2.5 cm (1") layer of #2 sand (Figure 3).

Each of the three soils received seven fertilizer treatments. The treatments included a control to which no fertilizer was added, a low rate and a high rate of SUL4R-PLUS®, a low rate and a high rate of ammonium sulfate, and a low rate and a high rate of elemental sulfur. The low rates were calculated to deliver 8 mg S kg^{-1} soil (16 lbs S / acre) of sulfur-S and the high rates were calculated to deliver 16 mg S kg^{-1} soil (32 lbs S / acre) regardless of the source of the fertilizer or relative S content. Soils and fertilizers were well mixed and placed into the pvc units. Each treatment was replicated four times.

Once assembled, the pvc units were placed into 4 plywood structures with 10 cm holes in 3 x 7 arrangement to facilitate addition and collection of water (Figures 4 & 5). Distilled water was added according to the water-holding capacity of each soil. The first collection event involved the introduction of one volume of water equivalent to the water content (WC) approximating saturation of the soil (Table 3). After equilibrating for 24 hours, 2 more volumes were introduced to the top of pvc columns and allowed to leach via gravity through 12.5 cm (5") funnels placed into 1 liter (1 quart) plastic collection containers at the bottom of each. Each sampling event after the first used two 'WC' volumes of water to displace sulfate from the soil matrix. The total volume of leachate collected for each unit was measured and a subsample taken in a 20 mL plastic vial for freezing until measurement for SO_4 concentration was performed.

Soil Analyses

Soil texture was measured by the bouyocous hydrometer method. Saturated soil water content was used to estimate pore volumes for each soil. Water content at saturation (WC_S) was measured by saturating the soil with distilled water and allowing to equilibrate for 24 hours. More distilled water was added carefully until a slight sheen was observed at the soil surface. After drying at 105°C for 24 hours, the difference in weight due to water evaporative loss was calculated. Soil pH was measured using a benchtop pH meter attached to a potassium chloride pH electrode inserted into a 1:2 slurry of soil to distilled water. Nitrate-N was measured by shaking 10 g of soil in 100 mL 1 M KCl solution for 1 hour, filtering the slurry, and measuring the filtrate by cadmium-reduction colorimetry. Total N and carbon (C) were measured by the combustion method. Phosphorus, potassium, magnesium, calcium, and sulfur were measured by extraction of the soil using Mehlich III solution, filtration, and measurement of the filtrate by ICP-AES. Sulfate-S concentrations in the collected leachate from the 60-day study were measured by ion-chromatography according to EPA method 300.1 (Hautman, 1997).

Statistical Analysis

Sulfate concentrations in the leachate are reported as mg SO_4-S kg^{-1} soil on a soil dry-weight basis. Statistical significance of differences between the means of each treatment at each sampling event were compared using Tukey's honestly significant difference adjustment to the GLM procedure in the SAS software. (version 9.3; SAS Institute, Cary, NC).

Results and Discussion

Soils

The soils used in the study differed substantially in terms of texture and chemical properties (Table 3). The Burleson soil contained 31% clay, while the Weswood and Rader soils contained 15% and 5% respectively. The water holding capacities of the soils increased, as expected, with increasing clay content. The use of volumes of water near to the saturation point of each soil was used in this study due to reports by others that the volume of water required for the displacement and transport of soluble sulfate from a soil matrix is associated with its relative pore volume (Evans & Anderson, 1990; Alva & Gascho, 1991). Soil pH values ranged from very nearly neutral to moderately alkaline. All three soils were found to potentially provide sulfur in only marginally sufficient amounts for crop production. Most crops would therefore receive a recommendation by the Texas A&M Soil, Water, and Forage Laboratory (College Station, TX) for a small to moderate addition of sulfur fertilizer to optimize yields.

Sulfur Release Patterns of Fertilizers

The initial sampling date (time = 0 days) was characterized by a substantial flush of SO_4-S from the ammonium sulfate treatments in all three soils (Figures 6, 14, 15, &16). This was significantly greater than the concentrations observed in leachate from the controls and/or other treatments. This flush was the result of rapid dissolution of SO_4^{2-} from the highly soluble salt from which this fertilizer is composed. Approximately 25 mg SO_4-S kg^{-1} soil were liberated from the high rate applied to all soils during this initial pour through, while 12-16 mg SO_4-S kg^{-1} soil were measured in the low rate leachates (Figure 6). In the Burleson soil, the high rate of SUL4R-PLUS® application resulted in a significantly greater release of SO_4-S than the control. All other treatments in each of the soils were observed to be statistically similar to the release of SO_4-S observed in the control. In the control treatments, the Rader, Weswood, and Burleson soils released 2, 2.5, and 5 mg SO_4-S kg^{-1} soil respectively.

At the day five sampling event, ammonium sulfate dissolution and release of SO_4-S decreased sharply to less than 5 mg SO_4-S kg^{-1} soil in all soils (Figure 7). The concentrations of SO_4-S in the leachates of the SUL4R-PLUS® and ammonium sulfate treatments were found to be statistically similar to each other at this time point, and statistically greater than the controls or elemental sulfur treatments. Release of SO_4-S from the control treatments on day 5 declined to approximately half that observed on day 0. From the 10-day sampling event through to the 60 day sampling event, SUL4R-PLUS® treatments at both rates released statistically greater amounts of plant available sulfur than any other treatment. The general pattern was characterized by release of 0.5 to 3 mg SO_4-S kg^{-1} soil (~1 to 6 lbs / acre) from the SUL4R-PLUS® treatments in all soils for every 10 days that passed (Figures 8-13). During this same 50 day period, release of SO_4-S from all other applied fertilizers was statistically inseparable from that of the control in almost every instance. Soils not receiving any S-fertilizer mineralized and released a very small amount of SO_4-S at each sampling event. This was usually less than 0.5 mg SO_4-S kg^{-1} soil (~ 1 lb / acre) for all three soils from the 10-day sampling event forward.

Cumulative release of SO_4-S from all treatments is shown in figures 17-19. All three soils were observed to follow the same pattern for each treatment.

1. Rapid release of large amounts of plant available sulfur was measured very early in treatments receiving ammonium sulfate fertilizer at both the 8 mg kg^{-1} (16 lbs/acre) and the 16 mg kg^{-1} (32 lbs/acre) rates. The total release by day 5 was equivalent to the total amount of sulfate-S applied as ammonium sulfate with no further residual provision of sulfate from this fertilizer source beyond day 10.

2. Elemental sulfur treatments at either rate were rarely observed to provide significantly more sulfate than the controls receiving no fertilizer-S. In the Rader and Weswood soils, the cumulative sulfate measured in the leachates was numerically less than that of the controls.

3. SUL4R-PLUS® treatments released a greater than sufficient amount of SO_4-S to supply the early growth stages of a typical crop without exhausting the applied fertilizer-S before the time of expected maximal growth stage. Sulfate-S was supplied from SUL4R-PLUS® treatments at both the high and low rates in amounts equivalent to 1 to 6 lbs per acre every 10 days thereafter, ensuring a more than adequate supply of SO_4-S to match the expected needs of a range of widely cultivated crops.

The patterns of release for plant available sulfur observed in this study carry important implications for strategizing the use of S-containing fertilizers in terms of economic, environmental, and crop physiological optimization (Scherer, 2001; Bindraban, 2015). As in pattern 1 above, a rapid early-season release of plant-available SO_4-S leaves that anionic form susceptible to losses due to leaching below the root zone prior to the maximal growth phase when the nutrient is most required (Scherer, 2009; Kovar & Grant, 2011). Failure to continue to supply S to crops after such losses will result in nutrient limitations to yields. Pattern 2 above, where no plant available sulfur is supplied during a 60 day period, creates a season-long deficit scenario. Pattern 3, however, best fits the expected needs of most major crops according to figure 2.

Conclusion

Laboratory studies provide controlled conditions under which to study the response of systems to hypothesis testing. In soil science, there is an understanding that observations made under laboratory conditions may change upon application to the field. The same is true of this study. However, the results of this experiment with respect to ammonium sulfate and elemental sulfur fertilizers are consistent with both laboratory and field studies performed by other researchers. Their direct comparison with a novel and new patented form of pelletized calcium sulfate under the conditions in this study should therefore provide a very good indication of their relative performances under field conditions as well.

Ammonium sulfate, when applied early season is vulnerable to rapid losses in soils of any texture when sufficient precipitation occurs. Elemental sulfur is not expected to deliver plant-available S-nutrition to crops within the growing season it is applied, even with sufficient water. A very promising result was observed from the pelletized calcium sulfate as found in the product SUL4R-PLUS®. This product does not suffer from hygroscopy-induced handling issues reported in pulverized gypsum and protects SO_4-S from rapid early losses while continuing to supply more than adequate amounts (depending upon rate applied) of sulfur nutrition in plant available form for the duration of the growing cycle of most major crops. Pelleted calcium sulfate in this form represents a measurable improvement in providing sulfur nutrition to crops. The results of this laboratory study should be followed up in field investigations of the performance of SUL4R-PLUS® in terms of sustained S-uptake and yield effects in major crops.

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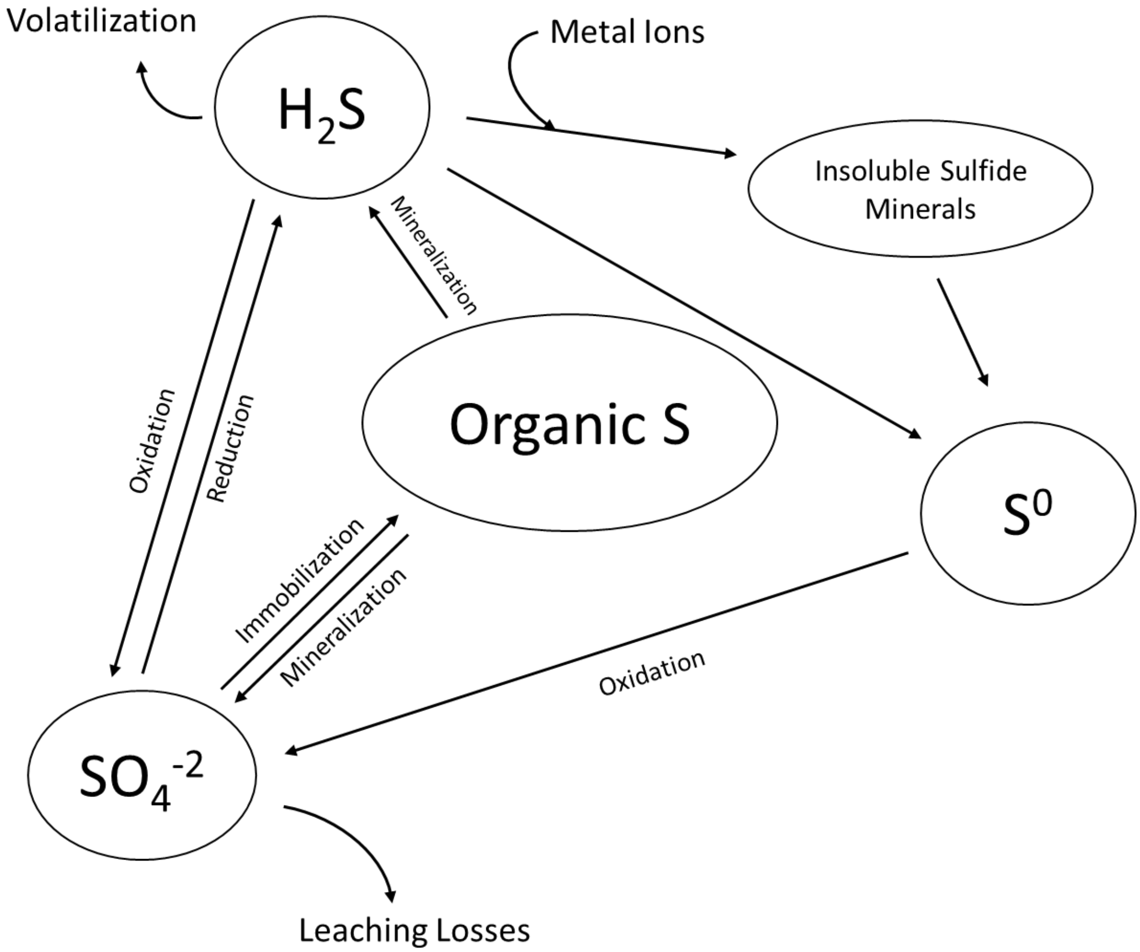

Figure 1. Sulfur cycle in soils.

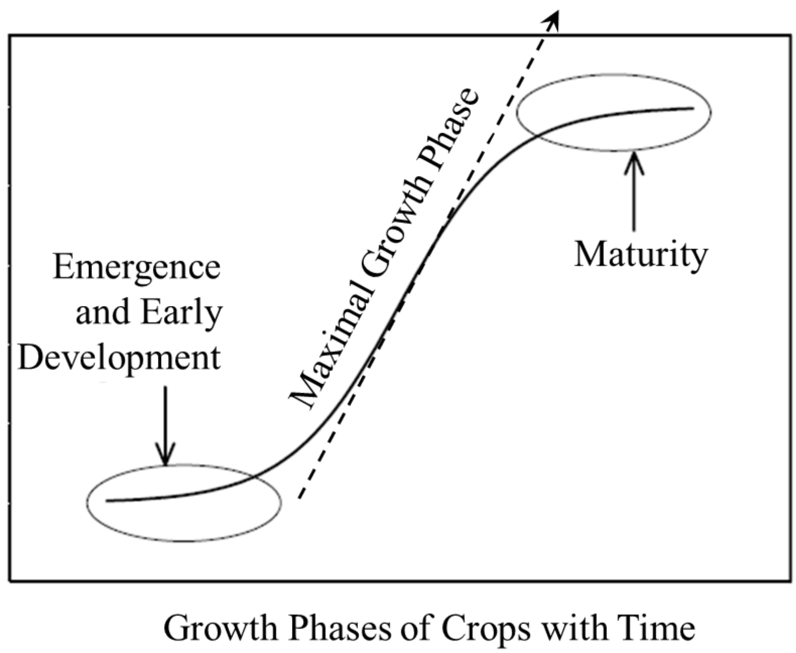

Figure 2. Generalized growth phases of crops illustrating need for sustained nutritional availability throughout growing season when potential for loss of early applied fertilizers is high. Loss of any fertilizer nutrient prior to the maximal growth and uptake phase represents a limiting condition for crop growth.

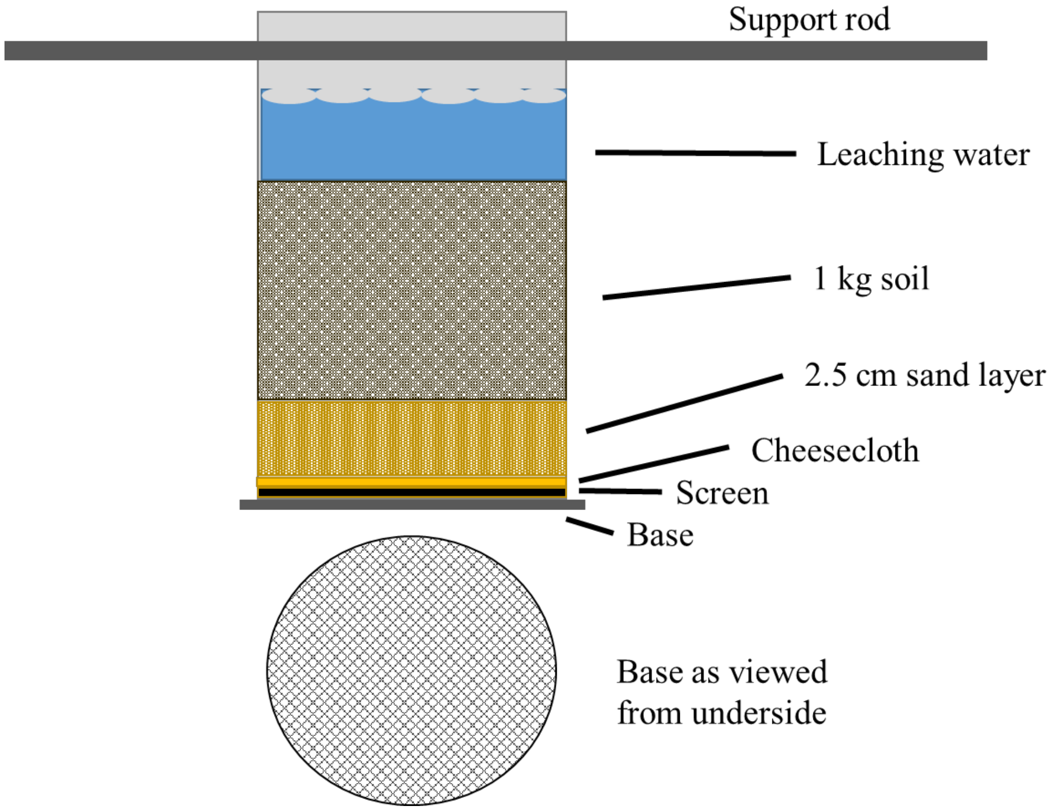

Figure 3. Schematic of experimental units.

Figure 4. Experimental unit replicate setup containing a total of 21 columns of 3 soils x 7 fertilizer treatments.

Figure 5. Replicates 3 & 4 on benchtop in laboratory with funnels placed on top of columns in between leaching events.

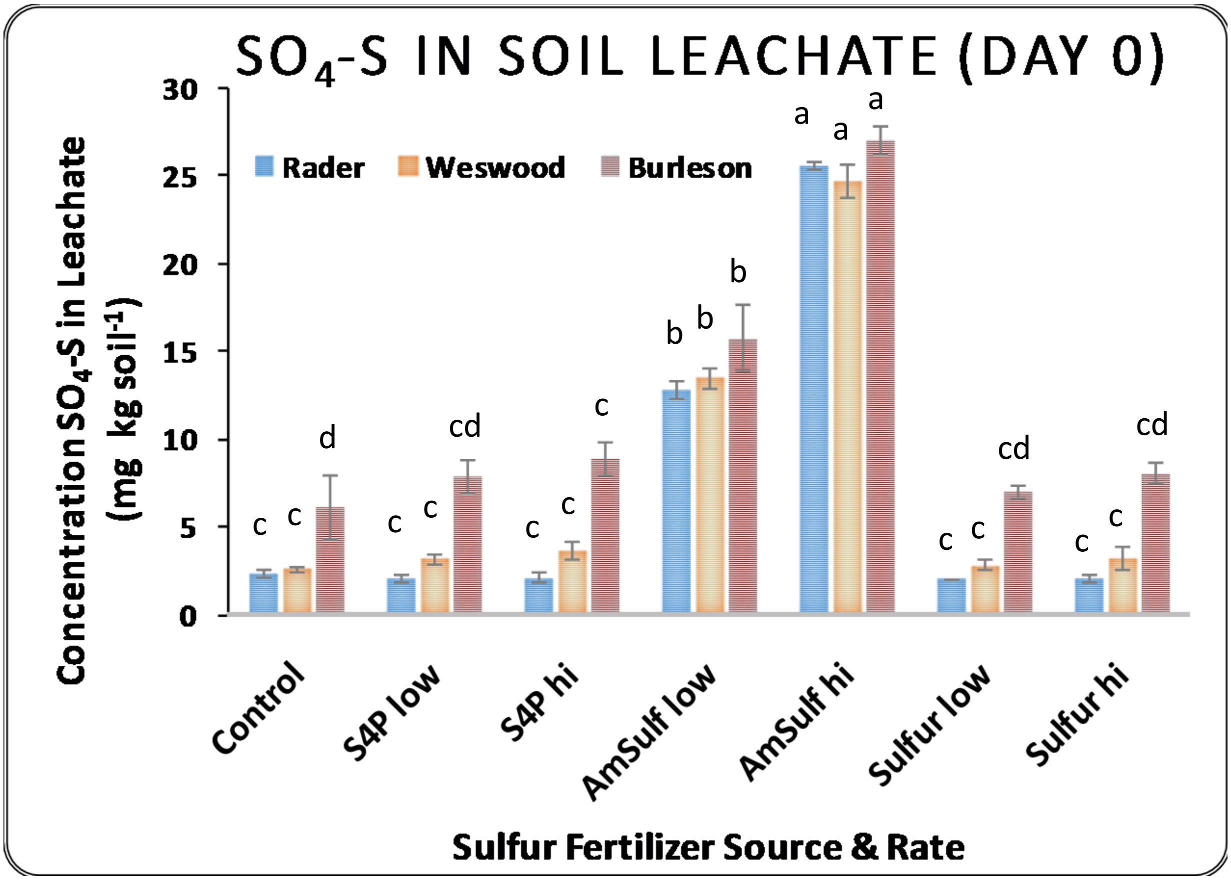

Figure 6. Concentration of SO_4-S in soil column leachate from initial pour through on day 0 of the study. Concentration corrected for volume collected and calculated as mg SO_4-S kg^{-1} soil. Treatments: Control = no fertilizer added. S4P low = SUL4R-PLUS® low rate. S4P hi = SUL4R-PLUS® high rate. AmSulf low = ammonium sulfate low rate. AmSulf hi = ammonium sulfate high rate. Sulfur low = elemental sulfur low rate. Sulfur hi = elemental sulfur high rate. Letters above columns indicate significant difference within (not between) soil types as evaluated using tukey's honestly significant difference procedure in SAS at the $\alpha = 0.05$ rate. Columns with the same letter do not differ significantly.

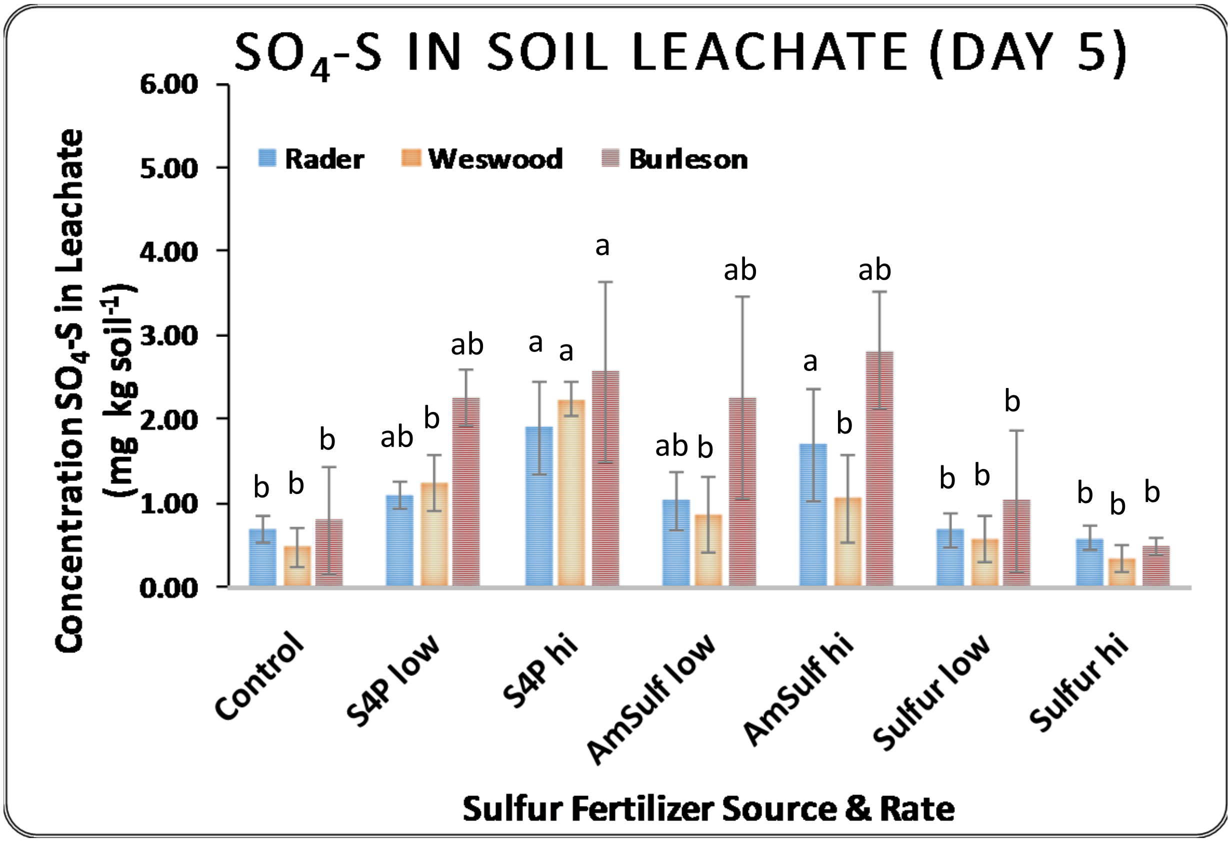

Figure 7. Concentration of SO_4-S in soil column leachate on day 5 of the study. Concentration corrected for volume collected and calculated as mg SO_4-S kg^{-1} soil. Control = no fertilizer added. S4P low = SUL4R-PLUS® low rate. S4P hi = SUL4R-PLUS® high rate. AmSulf low = ammonium sulfate low rate. AmSulf hi = ammonium sulfate high rate. Sulfur low = elemental sulfur low rate. Sulfur hi = elemental sulfur high rate. Letters above columns indicate significant difference within (not between) soil types as evaluated using tukey's honestly significant difference procedure in SAS at the $\alpha = 0.05$ rate. Columns with the same letter do not differ significantly.

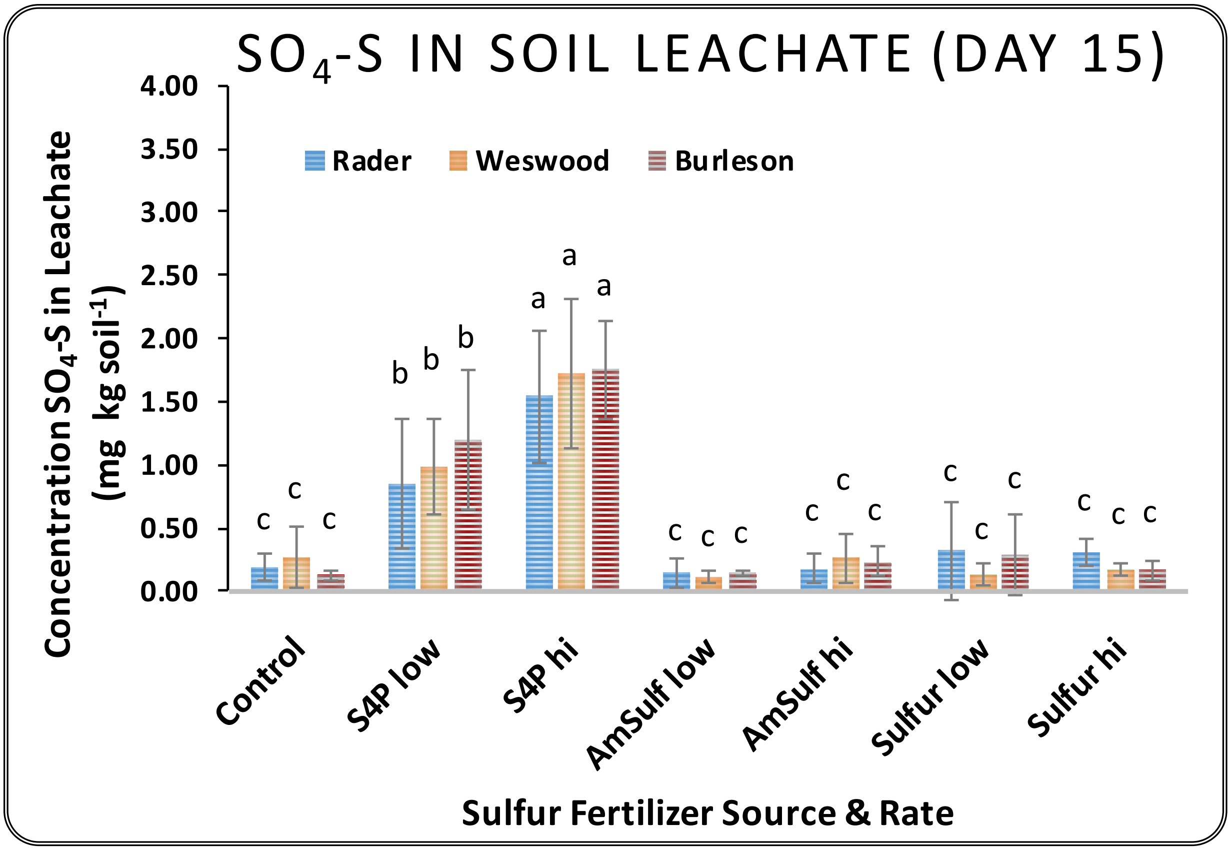

Figure 8. Concentration of SO_4-S in soil column leachate on day 15 of the study. Concentration corrected for volume collected and calculated as mg SO_4-S kg^{-1} soil. Control = no fertilizer added. S4P low = SUL4R-PLUS® low rate. S4P hi = SUL4R-PLUS® high rate. AmSulf low = ammonium sulfate low rate. AmSulf hi = ammonium sulfate high rate. Sulfur low = elemental sulfur low rate. Sulfur hi = elemental sulfur high rate. Letters above columns indicate significant difference within (not between) soil types as evaluated using tukey's honestly significant difference procedure in SAS at the $\alpha = 0.05$ rate. Columns with the same letter do not differ significantly.

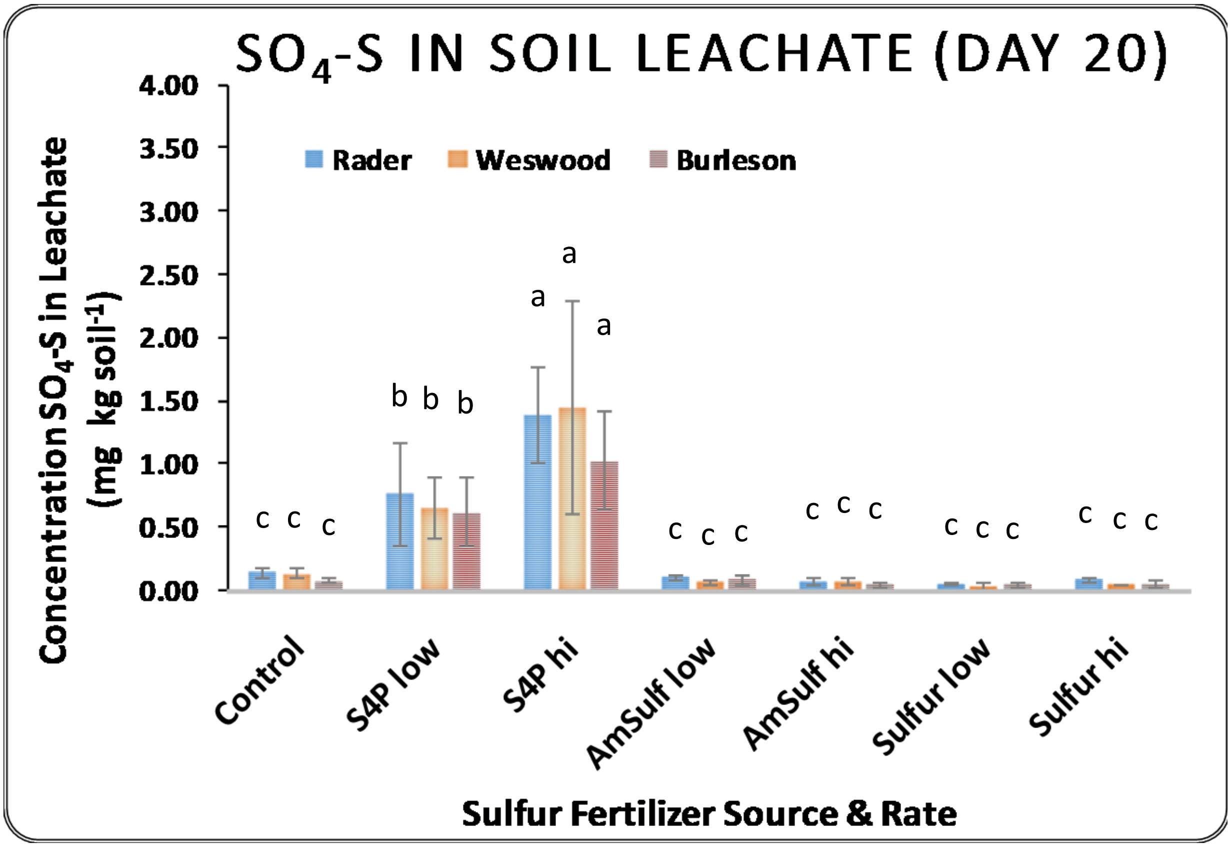

Figure 9. Concentration of SO_4-S in soil column leachate on day 20 of the study. Concentration corrected for volume collected and calculated as mg SO_4-S kg^{-1} soil. Control = no fertilizer added. S4P low = SUL4R-PLUS® low rate. S4P hi = SUL4R-PLUS® high rate. AmSulf low = ammonium sulfate low rate. AmSulf hi = ammonium sulfate high rate. Sulfur low = elemental sulfur low rate. Sulfur hi = elemental sulfur high rate. Letters above columns indicate significant difference within (not between) soil types as evaluated using tukey's honestly significant difference procedure in SAS at the $\alpha = 0.05$ rate. Columns with the same letter do not differ significantly.

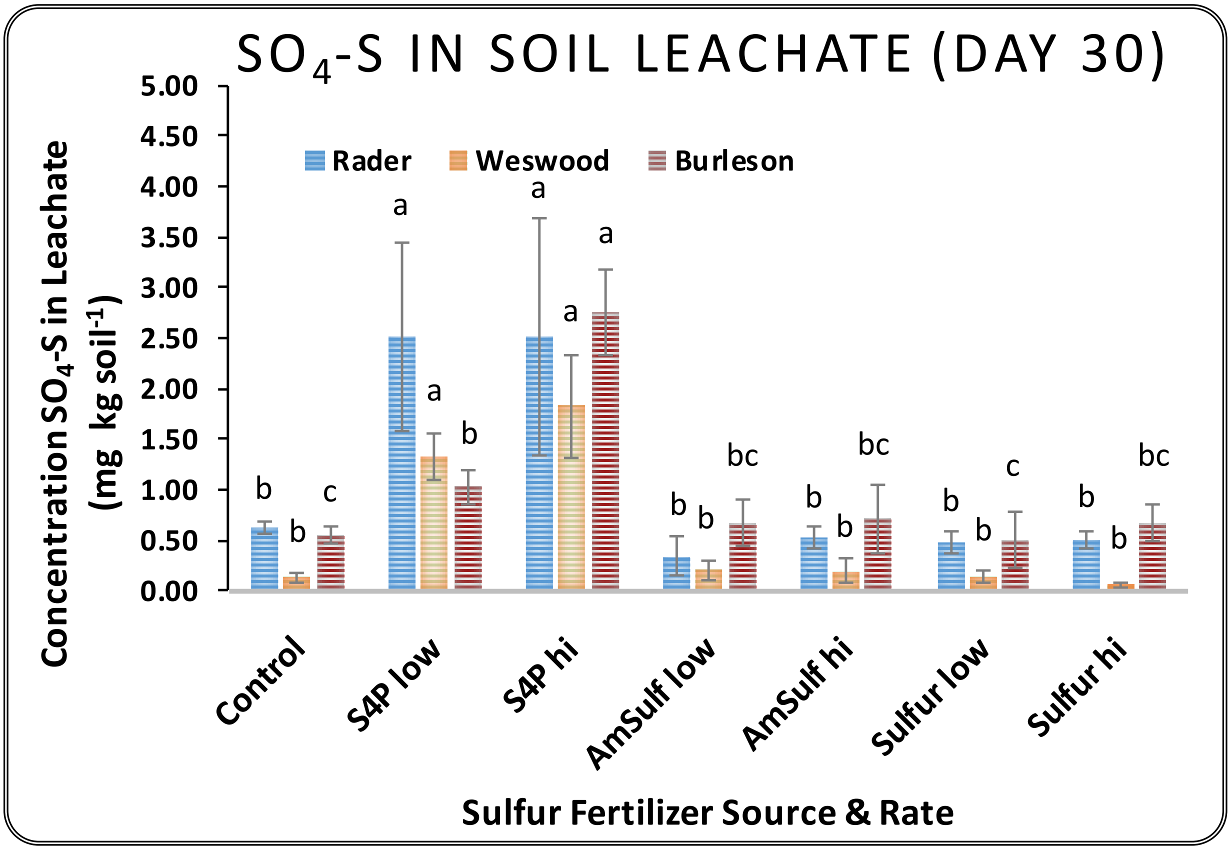

Figure 10. Concentration of SO_4-S in soil column leachate on day 30 of the study. Concentration corrected for volume collected and calculated as mg SO_4-S kg^{-1} soil. Control = no fertilizer added. S4P low = SUL4R-PLUS® low rate. S4P hi = SUL4R-PLUS® high rate. AmSulf low = ammonium sulfate low rate. AmSulf hi = ammonium sulfate high rate. Sulfur low = elemental sulfur low rate. Sulfur hi = elemental sulfur high rate. Letters above columns indicate significant difference within (not between) soil types as evaluated using tukey's honestly significant difference procedure in SAS at the $\alpha = 0.05$ rate. Columns with the same letter do not differ significantly.

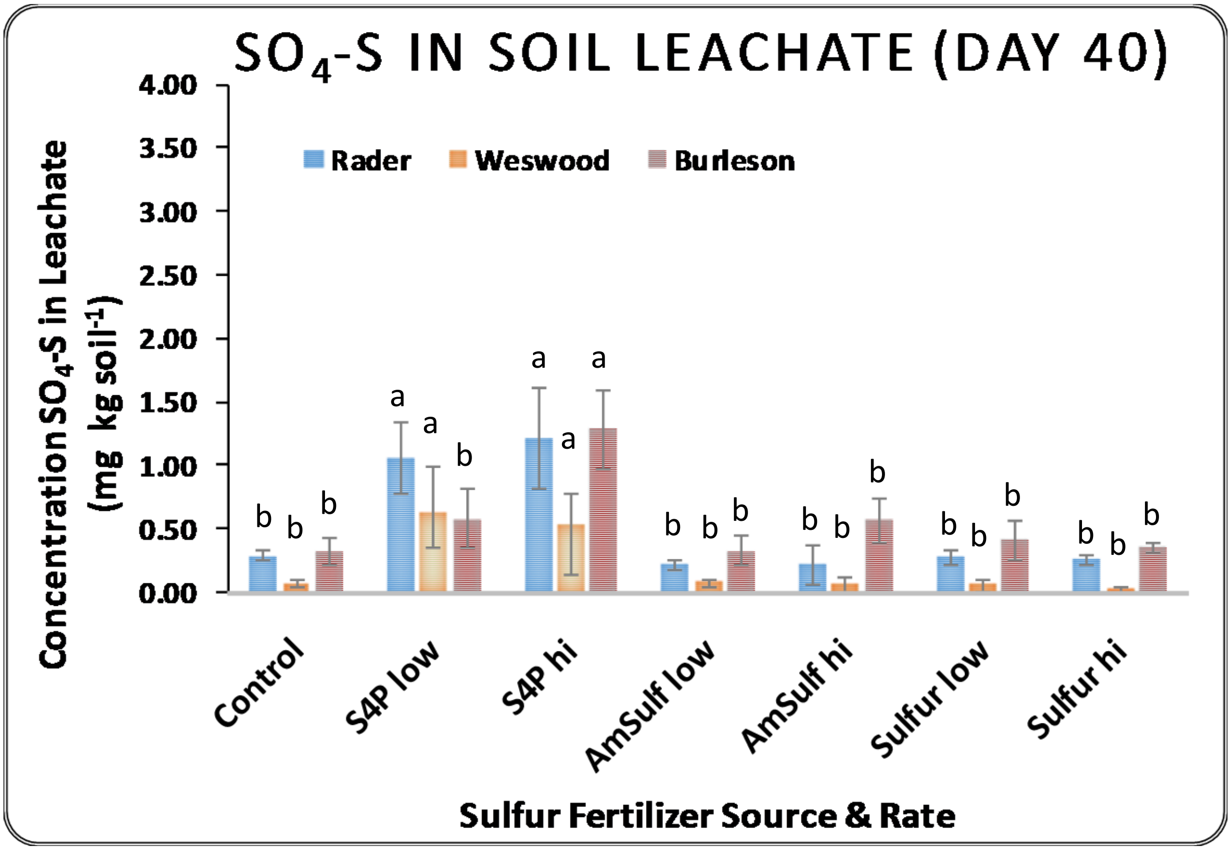

Figure 11. Concentration of SO_4-S in soil column leachate on day 40 of the study. Concentration corrected for volume collected and calculated as mg SO_4-S kg^{-1} soil. Control = no fertilizer added. S4P low = SUL4R-PLUS® low rate. S4P hi = SUL4R-PLUS® high rate. AmSulf low = ammonium sulfate low rate. AmSulf hi = ammonium sulfate high rate. Sulfur low = elemental sulfur low rate. Sulfur hi = elemental sulfur high rate. Letters above columns indicate significant difference within (not between) soil types as evaluated using tukey's honestly significant difference procedure in SAS at the $\alpha = 0.05$ rate. Columns with the same letter do not differ significantly.

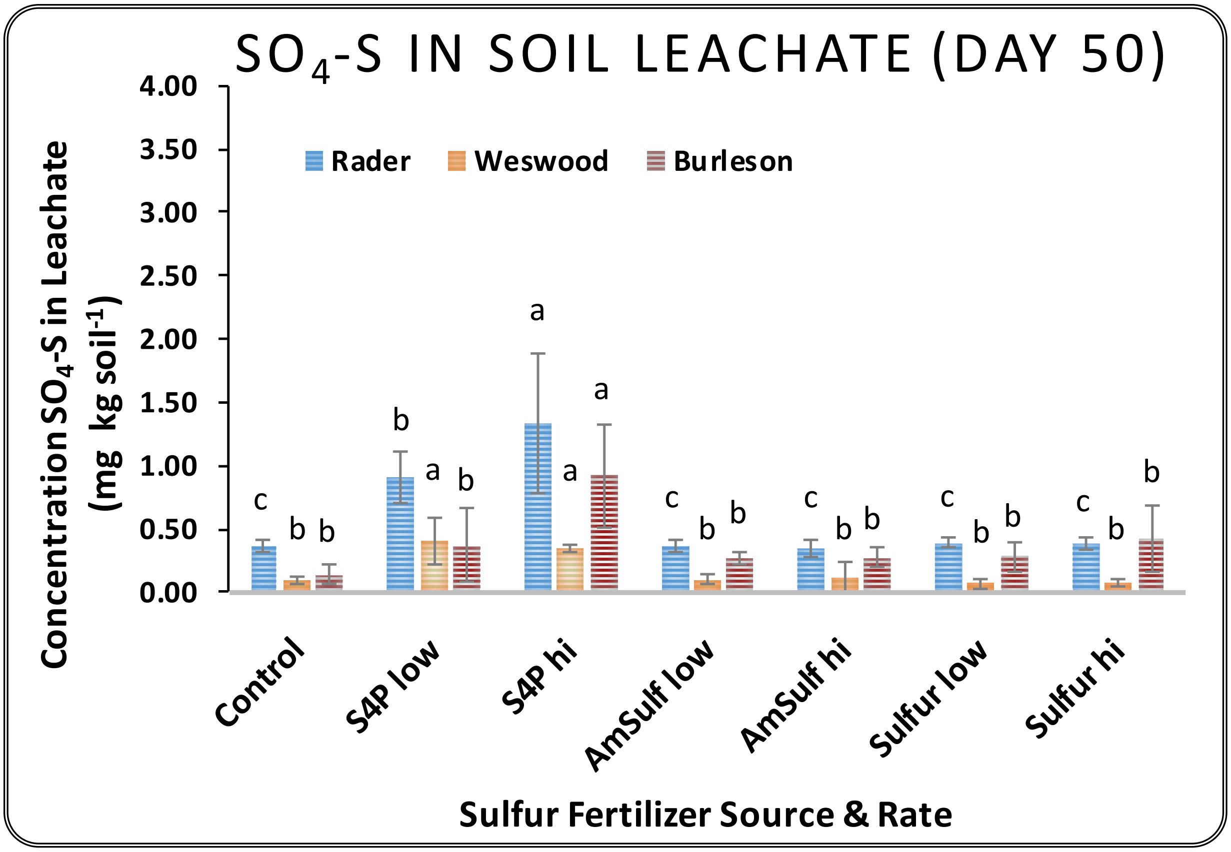

Figure 12. Concentration of SO_4-S in soil column leachate on day 50 of the study. Concentration corrected for volume collected and calculated as mg SO_4-S kg^{-1} soil. Control = no fertilizer added. S4P low = SUL4R-PLUS® low rate. S4P hi = SUL4R-PLUS® high rate. AmSulf low = ammonium sulfate low rate. AmSulf hi = ammonium sulfate high rate. Sulfur low = elemental sulfur low rate. Sulfur hi = elemental sulfur high rate. Letters above columns indicate significant difference within (not between) soil types as evaluated using tukey's honestly significant difference procedure in SAS at the $\alpha = 0.05$ rate. Columns with the same letter do not differ significantly.

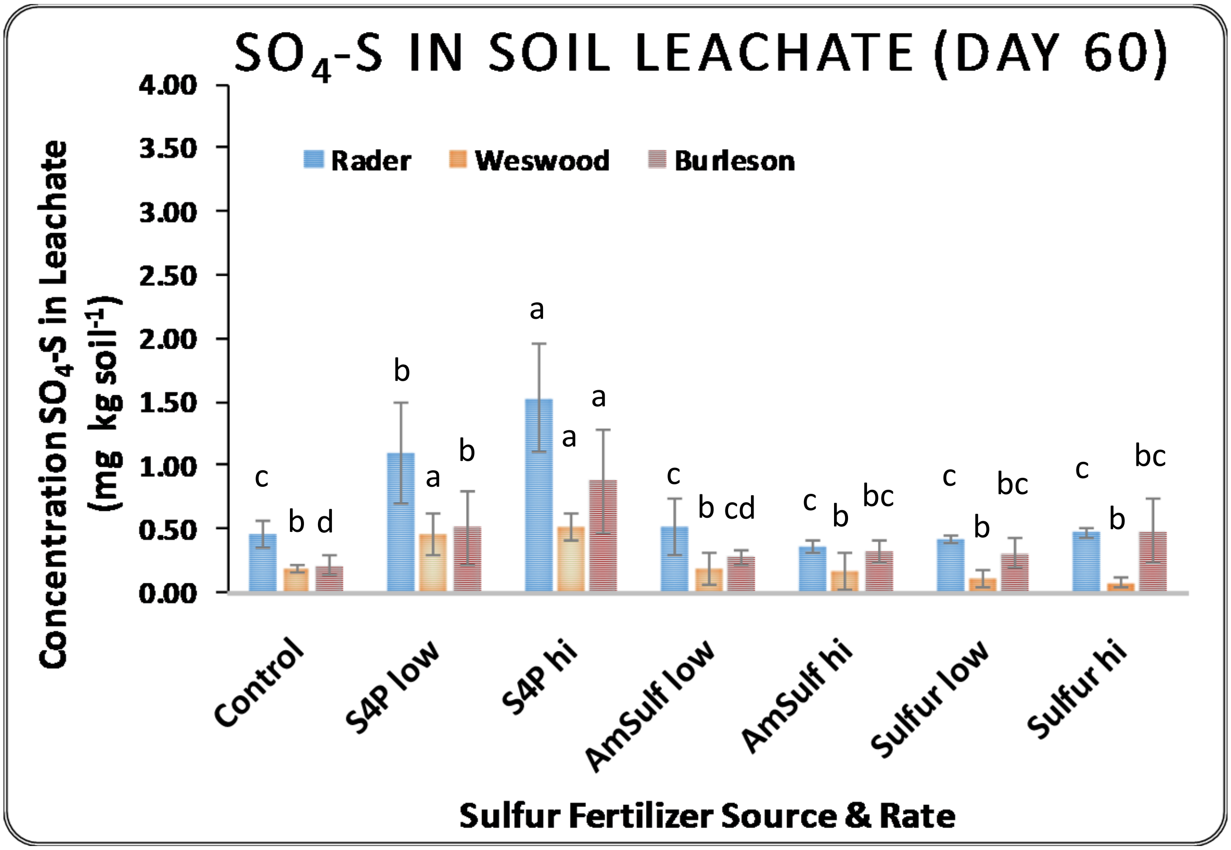

Figure 13. Concentration of SO_4-S in soil column leachate on day 60 of the study. Concentration corrected for volume collected and calculated as mg SO_4-S kg^{-1} soil. Control = no fertilizer added. S4P low = SUL4R-PLUS® low rate. S4P hi = SUL4R-PLUS® high rate. AmSulf low = ammonium sulfate low rate. AmSulf hi = ammonium sulfate high rate. Sulfur low = elemental sulfur low rate. Sulfur hi = elemental sulfur high rate. Letters above columns indicate significant difference within (not between) soil types as evaluated using tukey's honestly significant difference procedure in SAS at the $\alpha = 0.05$ rate. Columns with the same letter do not differ significantly.

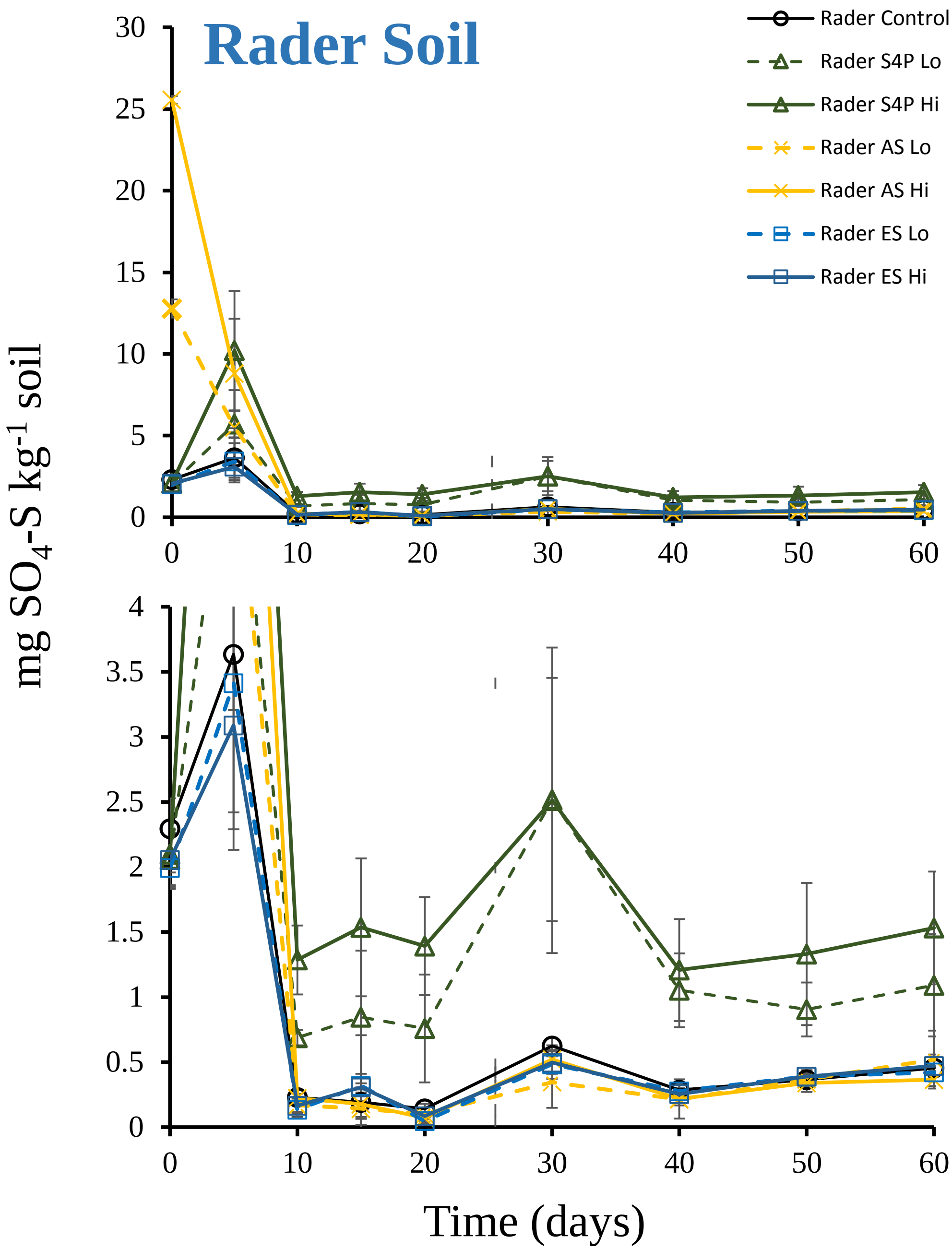

Figure 14. Time series for Rader soil leachate concentrations for each treatment (corrected for volume and expressed as mg SO_4-S kg^{-1} soil as above). Error bars = 1 standard deviation for replicate measurements. Same data presented in both graphs using different scales on the y-axis to provide better resolution of differences in plant-available SO_4-S following day 10. Control = no fertilizer added. S4P Lo = SUL4R-PLUS® low rate. S4P Hi = SUL4R-PLUS® high rate. AS Lo = ammonium sulfate low rate. AS Hi = ammonium sulfate high rate. ES Lo = elemental sulfur low rate. ES Hi = elemental sulfur high rate.

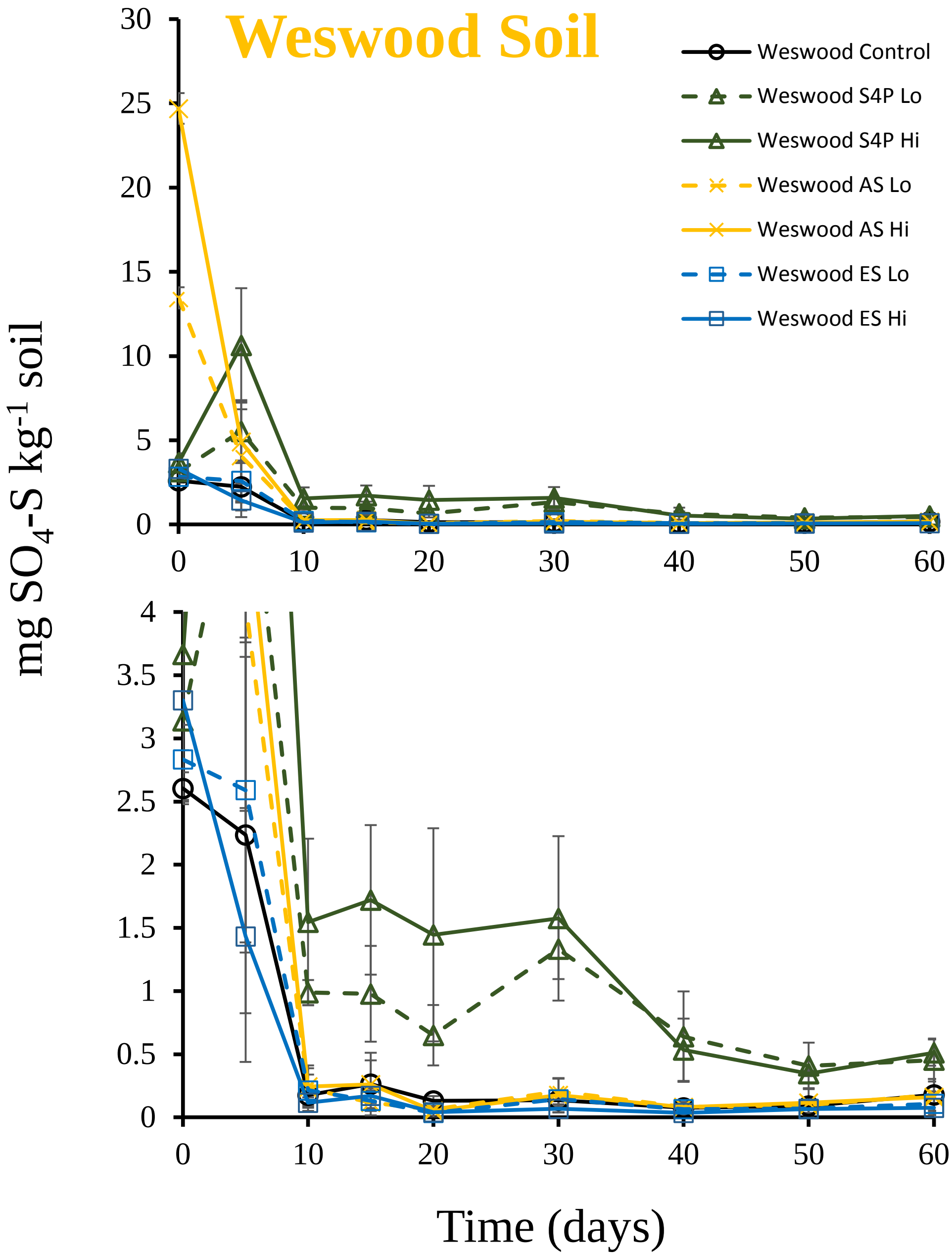

Figure 15. Time series for Weswood soil leachate concentrations for each treatment (corrected for volume and expressed as mg SO_4-S kg^{-1} soil as above). Error bars = 1 standard deviation for replicate measurements. Same data presented in both graphs using different scales on the y-axis to provide better resolution of differences in plant-available SO_4-S following day 10. Control = no fertilizer added. S4P Lo = SUL4R-PLUS® low rate. S4P Hi = SUL4R-PLUS® high rate. AS Lo = ammonium sulfate low rate. AS Hi = ammonium sulfate high rate. ES Lo = elemental sulfur low rate. ES Hi = elemental sulfur high rate.

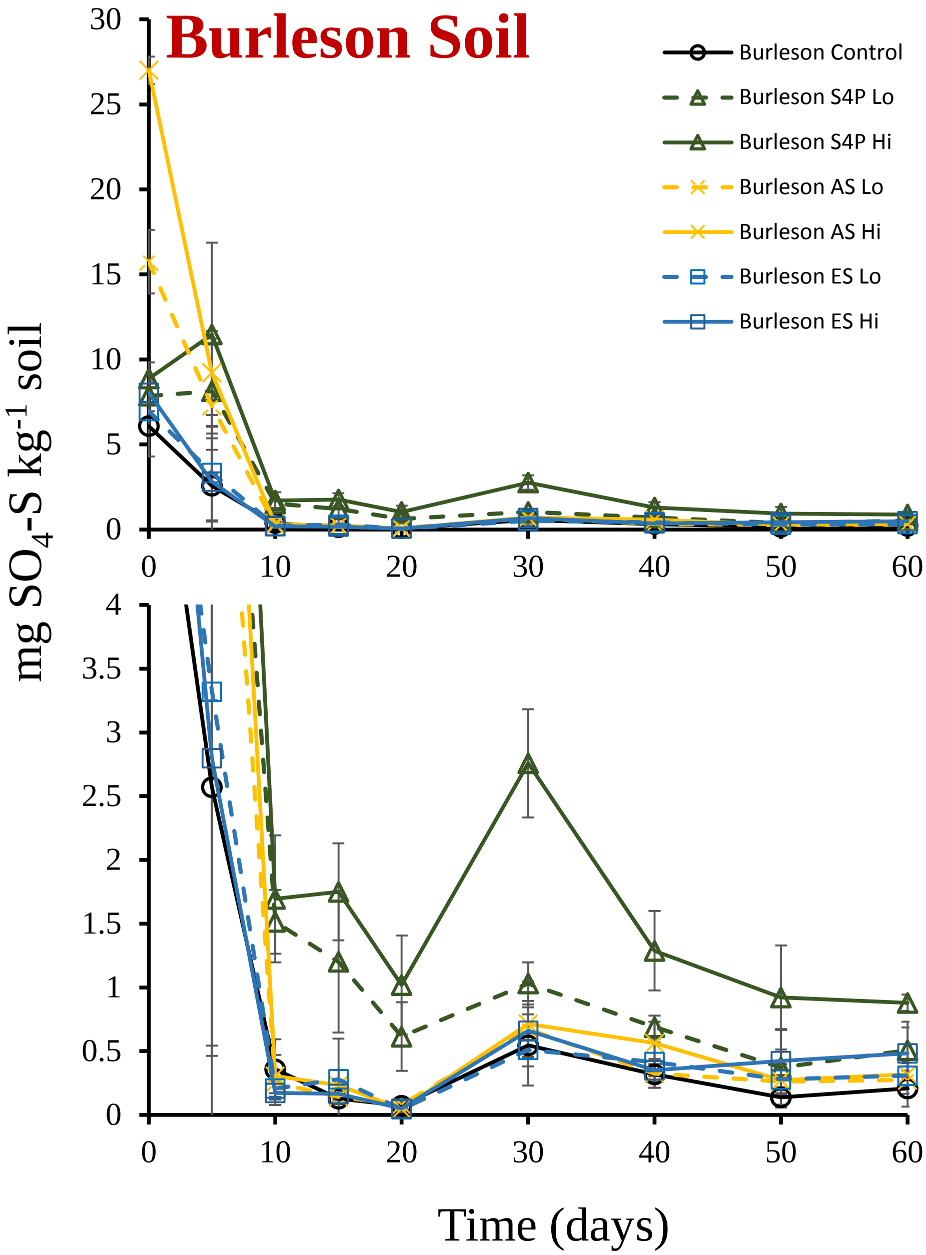

Figure 16. Time series for Burleson soil leachate concentrations for each treatment (corrected for volume and expressed as mg SO_4-S kg^{-1} soil as above). Error bars = 1 standard deviation for replicate measurements. Same data presented in both graphs using different scales on the y-axis to provide better resolution of differences in plant-available SO_4-S following day 10. Control = no fertilizer added. S4P Lo = SUL4R-PLUS® low rate. S4P Hi = SUL4R-PLUS® high rate. AS Lo = ammonium sulfate low rate. AS Hi = ammonium sulfate high rate. ES Lo = elemental sulfur low rate. ES Hi = elemental sulfur high rate.

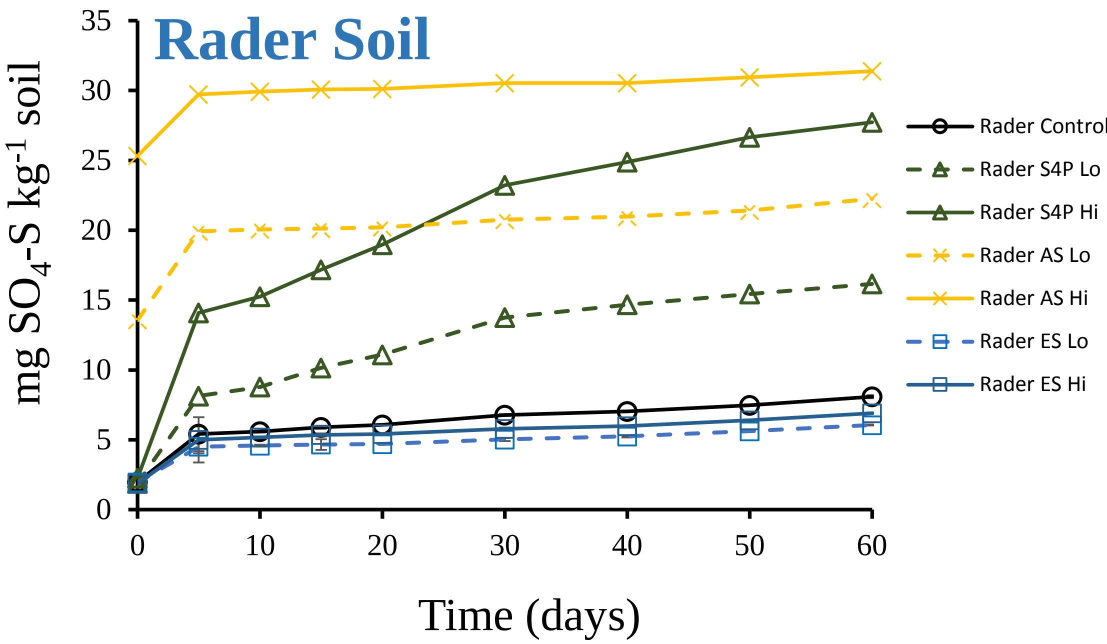

Figure 17. Cumulative pattern of SO_4-S release for each study treatment in the Rader series soil. Control = no fertilizer added. S4P Lo = SUL4R-PLUS® low rate. S4P Hi = SUL4R-PLUS® high rate. AS Lo = ammonium sulfate low rate. AS Hi = ammonium sulfate high rate. ES Lo = elemental sulfur low rate. ES Hi = elemental sulfur high rate.

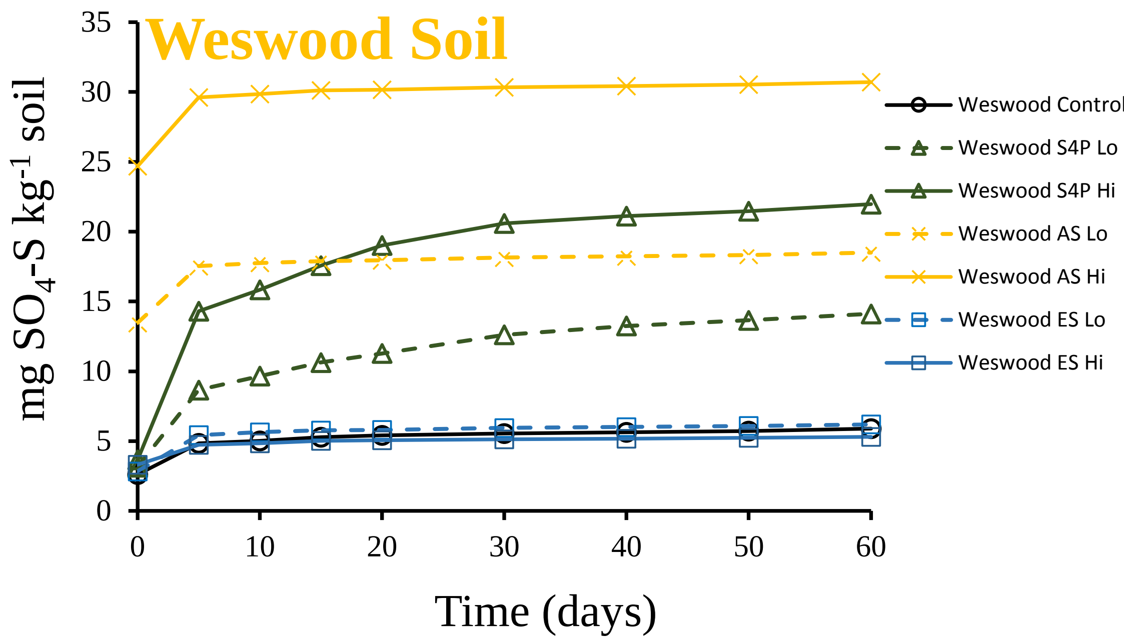

Figure 18. Cumulative pattern of SO_4-S release for each study treatment in the Weswood series soil. Control = no fertilizer added. S4P Lo = SUL4R-PLUS® low rate. S4P Hi = SUL4R-PLUS® high rate. AS Lo = ammonium sulfate low rate. AS Hi = ammonium sulfate high rate. ES Lo = elemental sulfur low rate. ES Hi = elemental sulfur high rate.

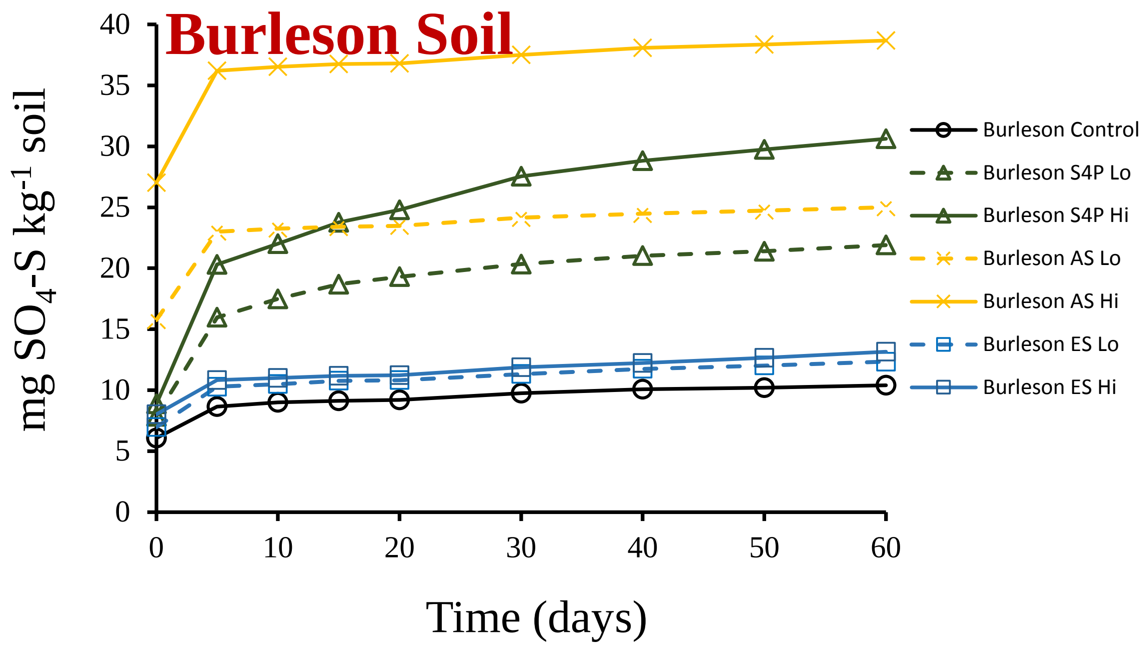

Figure 19. Cumulative pattern of SO_4-S release for each study treatment in the Burleson series soil. Control = no fertilizer added. S4P Lo = SUL4R-PLUS® low rate. S4P Hi = SUL4R-PLUS® high rate. AS Lo = ammonium sulfate low rate. AS Hi = ammonium sulfate high rate. ES Lo = elemental sulfur low rate. ES Hi = elemental sulfur high rate.

Table 1. Commonly Available Sulfur-Containing Fertilizers

Fertilizer	Chemical Formula	NPK	S
Elemental S	S	0-0-0	88-96
Calcium Sulfate (Gypsum)	$CaSO_4 \bullet H_2O$	0-0-0	18
Ammonium sulfate	$(NH_4)_2(SO_4)$	21-0-0	24
Ammonium thiosulfate	$(NH_4)_2(S_2O_3)$	12-0-0	26
Magnesium sulfate	$MgSO_4$	0-0-0	14
Potassium magnesium sulfate	$K_2SO_4 \bullet 2MgSO_4$	0-0-18	22
Aluminum sulfate	$Al_2(SO4)_3$	0-0-0	14
Ordinary superphosphate	$Ca(H_2PO_4)_2 \bullet 2CaSO_4$	0-9-0	12

Table 2. Treatments Applied to Three Soils in the Study

Treatments	Fertilizer Added	Sulfur-S supplied	Sulfur-S supplied
	(mg kg^{-1} soil)	(mg kg^{-1} soil)	(lbs $acre^{-1}$)
1 Control	0	0	0
2 SUL4R-PLUS® Low	50	8	16
3 SUL4R-PLUS® High	100	16	32
4 Ammonium Sulfate Low	39	8	16
5 Ammonium Sulfate High	78	16	32
6 Elemental Sulfur Low	10	8	16
7 Elemental Sulfur High	20	16	32

Table 3. Some Selected Physical and Chemical Properties of Soils Receiving Sulfur Fertilizers in the Study.

Soil	Textural Class	Sand %	Silt %	Clay %	WC_S* g kg^{-1}	pH	NO_3-N ppm
Rader	Sand	94	1	5	289	7.6	0
Weswood	Loam	36	49	15	316	7.8	6
Burleson	Clay Loam	28	41	31	444	7.1	17

	Total N ppm	Total C ppm	P ppm	K ppm	Ca ppm	Mg ppm	S ppm
Rader	1283	8739	59	96	4236	99	10
Weswood	1595	11407	63	221	5300	172	11
Burleson	1660	9574	120	472	4268	413	11

* WC_S - water content at saturation point (g H_2O kg^{-1} oven dry soil)