Evaluation of sulphur enhanced fertilizers in a soybean-wheat rotation grown in a Brazilian Cerrado Oxisol

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Abstract
The Brazilian savannas ("Cerrado") occupy 204 million ha with low-fertility acid Oxisols the dominant soils. Sulphur (S) deficiency is widespread in the region. Incorporation of sulphate sources (largely single superphosphate and ammonium sulphate) into fertilizer formulations leads to lower NPK concentrations and higher transport costs compared to high-analysis S-free NPK formulations. Elemental sulphur, with nearly 100% S, offers a cost-effective alternative to incorporate S into fertilizer formulations. A field experiment was carried out on a clayey Cerrado Oxisol to evaluate the agronomic efficiency of experimental "Sulphur Enhanced Fertilizers (SEF)" containing varying proportions of microfine elemental S and sulphate incorporated into granules of mono-ammonium phosphate and triple superphosphate. Powdered calcium sulphate (phosphogypsum) was used as the reference S source. Fertilizers were band applied and the fresh and residual effects evaluated in a soybean-wheat rotation for one year (two crops). Grain yields, aboveground S content, S concentration in diagnostic leaves and SPAD values were measured for both crops. There was no significant yield response to S or difference in above ground S content in the soybean crop. There was a significant response to freshly applied gypsum and SEF 774 in the wheat crop, with a higher S content in the gypsum treatment. The residual effectiveness of gypsum, and the two SEF treatments was equal in both yield and S content in the wheat crop.

Key Words
Elemental sulphur, sulphate, mineral nutrition, soil fertility, Latosols, Ferralsols.

Introduction
The savannas of central Brazil, so called Cerrados, occupy 204 million ha and correspond to approximately 24% of the national territory. It is considered one of the last and largest agricultural frontiers in the planet, and yet, the most biodiverse among the world's savannas. Soil science has played an important role in the incorporation of the low-fertility and acid Cerrado soils into the agricultural production systems. This fact can be considered as one of the greatest achievements of agricultural research in the 20th century and is related to targeted governmental programs since the mid 1970's, which have turned the once unproductive Cerrado soils into one of the most important agricultural regions of the country (Resck *et al.* 2008).

Rein and Sousa (2004) reported that since the mid 1950's, when research on the fertility of Cerrado soils began, significant responses to sulphur (S) fertilization have been observed in crops and pasture yields, and quality. The high annual rainfall, large distances from the oceans, the small industrial activity in the region and the frequent natural and human-made firing of the savanna vegetation most likely explains the widespread sulphur deficiency of these soils. The widespread utilization of low or non-sulphur containing TSP, DAP, MAP and urea has resulted in an increasing incidence of S deficiency in agriculture throughout the world (Blair 2009), which is also observed in Brazil.

In the Cerrado region the main sources of sulphur are calcium and ammonium sulphates, including single superphosphate, phosphogypsum ($CaSO_4.2H_2O$) and gypsite. Phosphogypsum (15% S), applied at rates between 1 to 6 t/ha depending on soil texture, is widely used as a soil amendment in the Cerrado region to alleviate the subsoil acidity, which improves chemical conditions for deep rooting. The high rates of sulphur applied as phosphogypsum have a very long nutrient residual effect, since sulphate is adsorbed in the subsurface layers of the rooting zone. However, phosphogypsum production is concentrated in few regions of the country, and the transport costs per unit of sulphur are high which is becoming an important constraint to the adoption of this technology.

Elemental sulphur, with nearly 100% S, is also used as fertilizer, supplying S to crops after oxidation to sulphate in the soil. The oxidation rate is determined by the particle size, as well as other soil factors (Boswell and Friesen 1993; Germida and Jansen 1993). The use of elemental sulphur is very limited in Brazil, despite its high agronomic efficiency observed in Cerrado oxisols when freshly applied as fine particles (Vilela *et al.* 1995; Rein and Sousa 2004). Incorporation of fine particles of elemental S into granules of NPK fertilizers offers an alternative to the use of this S source in agriculture (Boswell and Friesen 1993, Yasmin *et al.* 2007; Blair 2009). "Sulphur Enhanced Fertilizers" (SEF) have been experimentally developed by Shell, and consist of microfine particles of elemental sulphur with or without sulphate incorporated into phosphatic fertilizers. There is little information about the agronomic efficiency of SEF fertilizers in the Cerrado region. The aim of this work was to evaluate the fresh and residual effects of three SEF products as sources of sulphur in a soybean-wheat rotation in a Cerrado Oxisol.

Methods

Experimental site

A field experiment was carried out at Embrapa Cerrados ("Savannas Agricultural Research Center"), located near Brasilia in central Brazil, on a clayey red Latosol (fine, mixed, isohyperthermic Rhodic Haplustox). Soybean (cultivar BRS Valiosa RR) was grown in the period of December 2008 to April 2009 and wheat (cultivar BRS 254) from June to September 2009. The climate of the region is tropical, with mean annual temperatures and precipitation of 22°C and 1500 mm, respectively.

Prior to the establishment of the experiment the soil received dolomitic limestone to increase soil pH (water) to approximately 6.0, followed by 240 kg/ha P_2O_5 as thermalphosphate (0% S). Micronutrients and KCl were also applied to build up the fertility status. Pearl millet was planted as a cover crop in June 2008. Residues from the millet crop were quantified (above ground dry mass and sulphur concentration) and removed from the site at harvest in October 2008. The experiment started in December 2008, with treatments (S fertilizers) applied for the first crop (soybean). The experimental units (plots) had an area of 3.6 x 6 m. The experiment was cultivated under a no-till system at row spacing of 0.45 m for soybean and 0.20 m for wheat (second crop). The experiment had supplementary irrigation for soybean grown during the rainy season. The wheat crop growing during the dry season was irrigated with a sprinkler system during the whole crop cycle.

Experimental design and treatments

The experiment was performed in a randomized block design, with three replications. Eight treatments were established as shown in Table 1. SEF 881 and SEF 774 are sulphur enhanced mono-ammonium phosphate (MAP). SEF 881 (applied only in crop 1) had 9.9, 48.9 and 12.1 percent of N, P_2O_5 and S (0.6% sulphate), respectively. SEF 774 had 11.5, 43.6 and 12 percent of N, P_2O_5 and S (3.8% sulphate), respectively. TSP-S (applied only in crop 2) is a sulphur enhanced triple superphosphate with 43.1% P_2O_5 and 9.4% S (0.6% sulphate) and was tested only in crop 2. Due to differences in nutrient concentrations of the S fertilizers, rates of N and P_2O_5 were balanced for all treatments. Powder phosphogypsum (17.5% of sulphur as sulphate on a dry basis) was used as a sulphur reference source. The SEF fertilizers were applied at 20 kg S/ha, which is in the recommended range of 15-30 kg/ha for most crops in S-deficient Cerrado soils (Rein and Sousa 2004). Gypsum was applied at 20 and 40 kg S/ha.

Plant sampling and analysis

SPAD values were measured using a SPAD-502 chlorophyll meter on the diagnostic leaves (newly expanded leaf from the top to the shoot) of soybean and wheat during the flowering period. Grain yield (kg/ha), sulphur concentrations in the diagnostic leaves (g/kg), SPAD values and sulphur content in the above ground dry mass (grain plus straw, kg) were measured and statistically analysed using PROC GLM by SAS (SAS Institute 1996). Plant tissues were digested with $HClO_4$-H_2O_2 and sulphur analysed by ICP-AES. The treatments were compared by Tukey test ($P<0.05$). Apparent fertilizer recovery was computed as: {[(aboveground S content of fertilizer treatments – aboveground S content of control treatment) / fertilizer S applied] x100}.

Results

Few visual symptoms of sulphur deficiency were observed in soybean (crop1), expressed by somewhat shorter plants in no-S (1) and SEF 881 (4) treatments (data not shown). The youngest leaves were not chlorotic, and no differences in SPAD values were observed (Table 2). Batista and Monteiro (2007) studying the sulphur and nitrogen fertilization, and their concentrations in leaf tissue of Marandu grass (*Brachiaria* *brizanta*) reported that SPAD values were influenced by the S supply. In crop 2, the wheat plants for the no-S treatment (1) were shorter, with chlorosis in the whole plant. Sulphur nutrition status of wheat evaluated by SPAD values and S concentration of the diagnostic (flag) leaf (Table 2) showed that these variables were significantly correlated (Person correlation coefficient r=0.78).

In Crop 1 (soybeans), there was no significant difference in yield between the control and S sources (Table 1). Although differences were not significant, it appeared that SEF 881 was less effective than gypsum, as shown by the lower yield and aboveground S content. SEF 774 was not significantly different from gypsum. Evaluating the residual effect of these treatments in crop 2 (wheat), SEF 881 was as effective as gypsum. In crop 2 (wheat), a fresh application of gypsum at 20 kg S/ha or the residual effect of 40 kg S/ha resulted in grain yield responses of 38% and 30%, respectively, compared to the control treatment. Although grain yields in the SEF 774 treatments did not differ significantly from gypsum when applied at a fresh rate of 20 kg S/ha in crops 1 and 2, SEF 774 had a lower S concentration in the diagnostic leaf and a lower S content in the aboveground dry matter for the wheat crop, evidencing its lower initial effect compared to gypsum (Table 1). Blair (2009) reported that, of 84 experiments conducted to evaluate experimental SEF fertilizers in different countries, the yield responses to SEF were the same, exceeded or less than sulphate S at 50, 28 and 6 sites, respectively.

Table 7. Effect of sulphur enhanced fertilizers in the grain yield, sulphur concentration in the diagnostic leaves (S Leaves), SPAD values (SPAD) and sulphur content in the above ground dry matter (S content) in a soybean/wheat rotation grown in a Brazilian Cerrado Oxisol.

Crop 1 (Soybean)					Crop2 (Wheat)				
Treatment	Grain yield (kg/ha)	S leaves (g/kg)	SPAD	S content (kg)	Treatment	Grain yield (kg/ha)	S leaves (g/kg)	SPAD	S content (kg)
Control	3057 ab	1.48 ab	40.1 a	8.2 bc	Control	2197 c	1.37 d	35.7 d	2.5 b
MAP	3052 ab	1.53 ab	39.9 a	7.9 bc	SEF 774	2583 abc	1.92 bc	43.9 ab	3.9 b
MAP	2960 ab	1.60 ab	40.0 a	7.0 c	Gypsum	3035 a	2.79 a	44.9 a	5.5 a
SEF 881	2922 b	1.34 b	40.1 a	6.3 c	MAP	2724 abc	1.69 cd	38.6 bcd	3.5 b
SEF 774	3130 ab	1.40 b	41.0 a	8.9 bc	MAP	2488 abc	1.65 cd	37.4 cd	3.7 b
Gypsum 20S	3369 a	1.79 ab	42.7 a	10.8 ab	MAP	2633 abc	1.62 cd	38.4 cd	3.3 b
Gypsum 40S	3340 a	1.93 a	40.9 a	13.1 a	MAP	2861 ab	2.23 b	41.8 abc	4.0 b
MAP	3012 ab	1.49 ab	40.4 a	7.9 bc	TSPS	2270 cb	1.66 cd	37.3 cd	3.4 b
CV (%)	4.7	10.7	2.9	12.2		8.3	9.8	4.8	13.7

Both SEF 881 and TSP-S have predominately elemental sulphur incorporated into the granules, whereas in SEF 774 one-third of the incorporated S is sulphate. A slow oxidation rate of the elemental sulphur in SEF 881 applied for crop 1 would explain why this fertilizer became more effective in supplying sulphur for crop 2 (Table 2). It would also explain why TSP-S applied in crop 2 did not improve the grain yield of wheat. Results from previous experiments in the same site and soil showed that powdered elemental sulphur was as effective as gypsum in supplying sulphur to grain crops (Vilela *et al.* 1995; Rein and Sousa 2004). The reasons why finely ground elemental sulphur incorporated into the present fertilizers (SEF 881 and TSP-S) was less effective compared to calcium sulphate when freshly applied needs further investigation. Elemental S oxidation is governed by its particle size and a number of soil factors (Boswell and Friesen 1993; Germida and Jansen 1993) and the data presented here suggests that the soil environment in and around the granule zone after its dissolution should be studied further.

The apparent S-fertilizer recovery (Table 2), computed from S contents in the aboveground dry matter showed similar values for freshly applied gypsum, around 15%, for both soybean and wheat crops, which is higher than recoveries observed for the other sulphur sources. On the other hand, the residual apparent S-fertilizer recoveries in crop 2 were similar for gypsum, SEF 881 and SEF 774.

The residual effects and responses to reapplication of the tested S-fertilizers will be evaluated for one more soybean-wheat cycle in this ongoing experiment.

Table 2. Apparent S-fertilizer recovery in a soybean/wheat rotation grown in a Brazilian Cerrado Oxisol.

Crop 1	Crop 2	Apparent Fertilizer Recovery (%)	
Soybean	Wheat	Soybean	Wheat
Control	Control	-	-
MAP	SEF 774	-	6.7
MAP	Gypsum	-	14.9
SEF 881	MAP	-7.3	4.8
SEF 774	MAP	5.9	5.2
Gypsum 20S	MAP	15.3	3.6
Gypsum 40S	MAP	13.3	3.6
MAP	TSPS	-	4.2

Conclusion
The tested Sulphur Enhanced Fertilizers based predominately on elemental sulphur incorporated into granules of mono-ammonium phosphate and triple superphosphate produced lower yield or sulphur uptake responses compared to gypsum when freshly applied, but nearly equivalent residual effects for the second crop.

References

Batista K, Monteiro FA (2007) Nitrogen and sulphur in marandu grass: relationship between supply and concentration in leaf tissues. *Scientia Agricola* **64,** 44-51.

Blair GJ (2009) Sulphur Enhanced Fertilizer (SEF) – A new generation of fertilizers. In ‘Proceedings of the 16th International Plant Colloquium’. (UC Davis) http://escholarship.org/uc/item/16h5b2dm

Boswell CC, Friesen DK (1993) Elemental sulfur fertilizers and their use on crops and pastures. *Fertilizer Research* **35**, 127-149.

Germida JJ, Jansen HH (1993) Factors affecting the oxidation of elemental sulfur in soils. *Fertilizer Research* **35**, 101-114.

Rein TA, Sousa DMG (2004) Adubação com enxofre. In ‘Cerrado – Correção do Solo e Adubação’. (Eds. DMG Sousa, E Lobato), pp. 227-244. (Embrapa Informação Tecnológica, Brasília).

Resck DVS, Ferreira EAB, Santos Junior JDG, Sá MAC, Figueiredo CC (2008) Manejo do solo sob um enfoque sistêmico. In ‘Savanas – Desafios e Estratégias para o Equilíbrio entre Sociedade, Agronegócio e Recursos Naturais’ (Eds. FG Faleiro, AL Farias Neto), pp. 416-473. (Embrapa Cerrados, Planaltina).

SAS Institute (1996) SAS/STAT user's guide, version 6.11, 4th ed. Cary (Statistical Analysis System Institute: NC).

Vilela L, Ritchey KD, Silva JE (1995) Sulphur response of soybean and corn in Clayey Dark Red Latosol of the Brazilian Cerrados. *Revista Brasileira de Ciência do Solo* **19,** 281-285.