

Development of a soil sulfur test and sulfur enhanced fertilisers from the soil up

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Abstract

A series of field and glasshouse studies, mostly utilizing ^{35}S , have been undertaken to study S pools and transfer rates in soil. These studies highlighted the role of ester sulfates in supplying S to the solution SO_4^{2-} pool, which supplies S to plants. This knowledge was used to assess the suitability of a range of soil extracts to predict the S supplying capacity of the soil. A test using 0.26 M KCl heated at 40°C for 3 hours was found to be most suitable and this has been adopted in most accredited soil test laboratories in Australia.

Similarly, a series of detailed studies on elemental S oxidation have been undertaken and the knowledge obtained from these have been used to develop a range of elemental S coated and S incorporated fertilisers. By working closely with commercial fertiliser manufacturers a range of S enhanced DAP, MAP and TSP fertilisers are now available, which commonly contain 8-12% S with 1/3 sulfate and 2/3 fine particle sized elemental S incorporated in the granule. These fertilisers have been tested extensively in a wide range of environments and crop and pasture systems.

Key words

sulphur, fertilizer, soil test, sulphur oxidation,

Introduction

Up until the 1950s little attention was paid to sulfur (S) as a plant nutrient mainly because it had been applied to soil in incidental inputs in rainfall and volcanic emissions and as a component of nitrogen, phosphorus and potassium fertilisers. Prior to that time experimentation concentrated on superphosphate responses, with the emphasis on phosphorus.

Reports in 1915 and 1926 from the Glen Innis Research Station in New South Wales mention responses to potassium sulfate and gypsum (Blair and Nicholson, 1975). The soils on which these experiments were conducted were subsequently shown to be non-responsive to potassium and calcium hence this may be the first recorded response to S in Australia. The first published experimental evidence was by Anderson and Spencer (1950) on soils from the Southern Tablelands of New South Wales.

Plant metabolism depends on S and a deficiency of this nutrient will cause basic metabolic impairment, which will not only reduce crop and pasture yield but also the quality of produce (Duke and Reisenauer, 1986). Deficiency symptoms of S in plants includes a yellowing of the younger leaves as a result of a low chlorophyll production and S non-mobility (Yoshida and Chaudhry, 1979) and a marked reduction in plant height and tiller number in cereals (Blair et al. 1979).

The awareness of S deficiency is increasing and areas of S deficiency are being recognised in previously S sufficient areas of the World.

There are many reasons of increasing S deficiency but the most important I have listed in Blair et al. (1978) as follows:

- i) the increasing use of high analysis, low S containing fertilisers;
 - ii) the increase in yields obtained as a result of other technological advances;
 - iii) the decreasing use of S containing pesticides and fungicides;
 - iv) environmental control of sulfur dioxide emissions in industrial areas and fuels; and,
- a greater number of experiments conducted where S is studied as a nutrient in its own right.

The S cycle

The S cycling literature has been extensively reviewed; for example Till (1975) and Blair (1986). The S cycle has similarities to both N and P cycles. The role of organic sources in supplying sulfate to plants is similar to both the N and P cycles and the adsorption reactions are similar to P reactions although the strength of sulfate adsorption is considerably less than for phosphate.

A diagram of the S cycle is shown in Figure 1. Uptake by plants is from the “available SO_4^{2-} ” pool, which also supplies SO_4^{2-} to, and receives SO_4^{2-} from, some of the other components in the soil-plant-animal cycle at a range of rates. In addition, there are various other environmental input and loss processes which can make significant differences to the S balance of the whole system.

The plant will continue taking up SO_4^{2-} from the available pool and, in its simplest case the fertiliser can be considered as another source of SO_4^{2-} that becomes available at some rate and the plants compete with the other processes for it. Under normal circumstances as soon as the fertiliser S enters the system it becomes indistinguishable from that already in the cycle.

Work on S cycling related to pasture improvement in temperate conditions has been conducted by Till and May (1970) using radiotracers. In these studies, ^{35}S applied in fertiliser could still be detected two years after the initial application, indicating a long residual effectiveness. This radiotracer work emphasized the role of organic matter as the major temporary storage pool for added fertiliser in the system and provided a basis for a simple model and simulation studies, which showed the importance of process rates within the cycle (May et al. 1973).

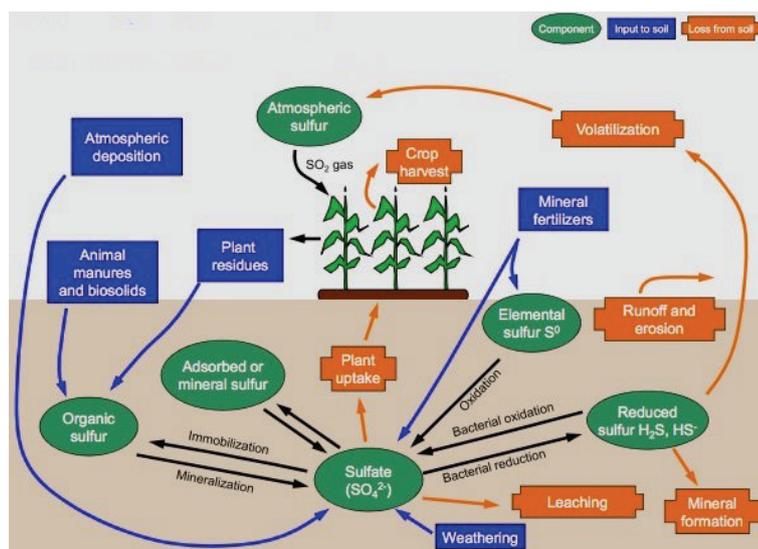


Figure 1. S pools and pathways in Agricultural systems

Source: https://upload.wikimedia.org/wikipedia/en/7/71/SulfurCycle_copy.jpg

Sulfur Soil testing

Soil testing to determine the S status of agricultural systems has met with variable success. The poor ability of the widely used mono-calcium phosphate extractant to identify S responsive soils is highlighted by the data from India in Figure 2.

A number of reasons for this have been outlined in reviews by Freney (1986). The nature of the S cycle in soil, which includes four main pools, contributes to this poor performance.

These pools contain:

- sulfate in the soil solution which is the source of S for plants and which can move in the soil water and/or be adsorbed.
- adsorbed sulfate, which is bonded weakly to positively charged colloid surfaces. In highly weathered soils not all of this S may be accessible to plant roots
- ester sulfates, which are a group of compounds containing a C-O-S linkage. The content of these •

compounds in the soil can be determined by digestion with hydriodic acid (HI). They are important because the C-O-S bond can be split on drying to release plant available SO_4^{2-} .

- carbon bonded S has a strong C-S bond which is difficult to break. This pool of S provides the long term supply to plants and is therefore less important to soil test results.

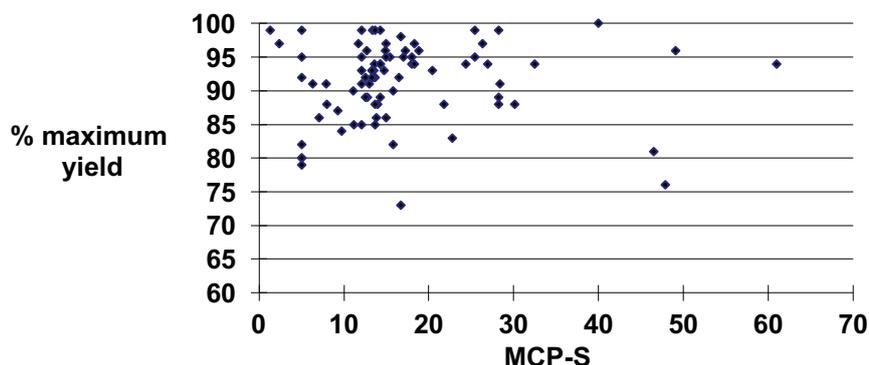


Figure 2. Relationship between mono-calcium phosphate (MCP) extractable S and % maximum yield in field trials in India conducted by The Sulfur Institute.

Plants take up their sulfate from the soil solution pool, which receives S from both the adsorbed and organic S pools. The organic S pool contains two major sub-pools, namely ester sulfates and carbon bonded S. Soil extractants used to determine the S status have most commonly involved a measurement of the sulfate in the soil solution plus adsorbed S. Amongst the extractants used, calcium dihydrogen orthophosphate containing 500 mg P/mL has been the most common.

Blair (1979) tabulated data from the world literature on critical levels of soil S. In doing this he partitioned the extractants into those which extract readily soluble sulfate, readily soluble plus portions of adsorbed sulfate, readily soluble, adsorbed and a proportion of organic sulfate. Within each of these groups, variable critical levels have been proposed. Generally, correlations between extractable S, using these types of extractants, and plant response have been poor. As for other nutrients local calibration of a soil test is critical if sensible predictions are to be made of S status.

Simulation modelling of agricultural systems (McCaskill and Blair 1988) indicates that fluxes of S from the organic pool play a major role in supplying S to agricultural plants, particularly in pasture systems where organic matter levels are high.

The importance of the ester sulfate pool is highlighted by the data of Blair et al. (1994) (Figure 3). In this experiment, where ^{35}S was used, the ryegrass plants acquired SO_4^{2-} from the MCP-S extractable pool and the HI-S (ester sulfate) pool and at 98 days in phase 1. When the plants and sulfate S were removed from the soil and new plants established in phase 2 the HI-S (ester sulfate) pool provided S to the plant and to the MCP-S pool.

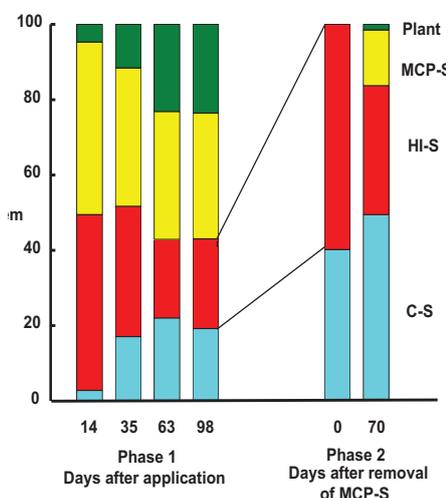


Figure 3. The pools of soil S accessed by ryegrass in a pot experiment showing the importance of HI-S (ester sulfates) in supplying sulfate to the plant available pool. Blair et al. (1994).

In the pot experiment of Blair et al. (1994) the loss of S from the MCP-S and gains to the plant, HI-S and C-S pools in the first 63 days (Table 1) shows how rapidly S fluxes occur in soils after the addition of $^{35}\text{SO}_4^{2-}$.

The incorporation rate of $^{35}\text{SO}_4$ into the HI-S and C-S pools was considerably higher than that found in New Zealand by Goh and Gregg (1982), who found that from 17 to 40% of added sulfate was present in organic forms within 34 to 75 days. The finding that only the HI-S pool had a negative transfer rate (loss of S from pool) in the 0-70 day period of phase 2 (Table 1) supports the finding of Freney et al. (1971). They found that most of the available S removed by plants over a 9-month period came from the ester sulfate fraction although there were changes in all soil fractions.

Table 1. Net transfer rate of ^{35}S in plant and soil pools in Phase 1 and Phase 2 of the experiment of Blair et al. (1994).

S Pool	Net transfer rate (%/day)	
	0-63 days	0-70 days
Plant	+0.36	+0.07
MCP-S	-1.05	+0.20
HI-S	+0.33	-0.38
C-S	+0.35	+0.02

An evaluation of a range of soil S tests has been undertaken by researchers at the University of New England, Australia. Blair et al (1991) compared H_2O , $0.01\text{M Ca}(\text{H}_2\text{PO}_4)_2$ (MCP), NaHCO_3 and KCl-40 in a series of field and glasshouse studies. In the KCl-40 procedure the soil is extracted with 0.25 M KCl at a temperature of 40°C for 3 hours and the inorganic and organic S in the extract measured. The various soil S pools being utilised by plants has been evaluated by Chaitep et al. (1994) in an experiment with flooded and non-flooded rice grown in a glasshouse. In this evaluation plants were grown in soil which had been incubated for 3 weeks with ^{35}S . This allowed equilibration of the radioactive tracer with the various soil pools. Flooded and non-flooded rice was then grown to maturity in the glasshouse and the ^{35}S and total S in the above-ground biomass determined. The ratio of ^{35}S / total S is termed the specific radioactivity and this ratio in the plant is compared with the specific radioactivity in the soil extract (termed the specific radioactivity ratio, SRR). When this ratio equals 1 it indicates that the plant is removing S from the same or similar soil S pools as the extractant. The data in Table 2 shows that the SRR value is closest to 1 for the KCl-40 extract among the extractants evaluated indicating that this extractant was removing S from similar pools as the plant.

Table 2. Specific Radioactivity Ratio (SRR) between plants and extracted S for a range of chemical extractants.

Extractant	System	
	Non-flooded	Flooded
H_2O	0.88	0.85
MCP	0.83	0.79
KCl-40	0.92	0.92
NaHCO_3	0.27	0.19

Research by Chinoim et al.(1997) has shown that the KCl-40 extract generally removes more S from the ester sulfate pool (shown as loss from HI-S in Figure 4) than MCP. In the data from a granite soil shown in Figure 4 the amount of S extracted from the sulfate and organic S pools was also greater than with MCP, but this is not always so. Because MCP removes more S from the adsorbed sulfate pool than KCl-40 the MCP value is always higher than KCl-40 in soils high in S and with a high S adsorption capacity.

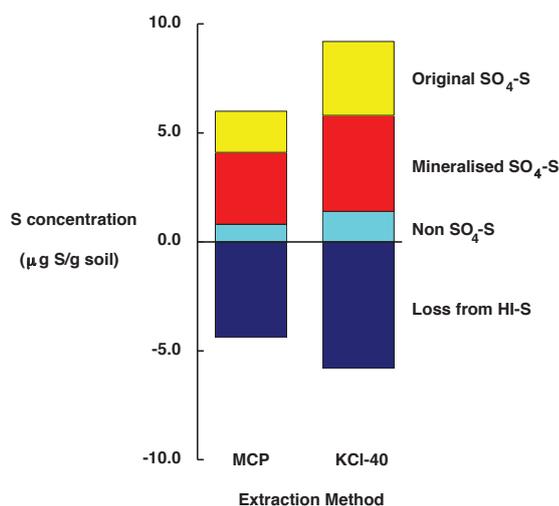


Figure 4. Sources of S removed by KCl-40 and MCP from a granite soil and S transformations that take place during extraction (Chinoim et al. 1997).

In the development of the KCl-40 method Blair et al. (1991) found a coefficient of determination (r^2) of 0.74 between extractable S and percent of maximum yield on a range of 18 pasture soils collected from Northern New South Wales, Australia (Table 3). In a supplementary study, where radioactive S had been added to rice soils, it was found that the KCl extract removes a portion of the HI reducible ester sulfates, which are believed to be rapidly turning over in soil systems. It is hypothesised that the greater accuracy of this test results from the extraction of soil sulfate, adsorbed S and a portion of the actively turning over organic S components in the soil.

Table 3. Coefficient of determination (r^2) between extractable S and percent of maximum yield for a range of extractants on a range of 18 pasture soils collected from Northern New South Wales, Australia.

Extractant	r^2
H ₂ O	0.47
MCP	0.48
KCl-40	0.74
NaHCO ₃	0.15
Total S	0.03

A schematic of the various pools accessed by plants, and removed by a range of extractants, is shown in Figure 5.

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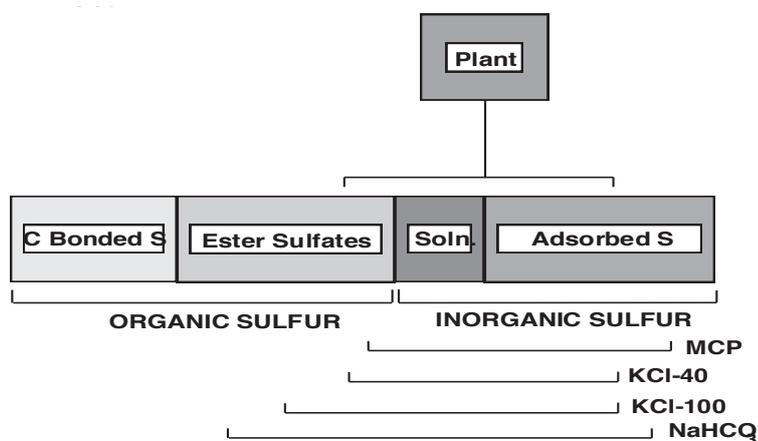


Figure 5. Schematic of the S pools accessed by plants and removed by a range of extractants.

The ability of S soil tests to indicate responsive and non-responsive sites was examined by evaluating the number of times the soil test, measured at the start of the experimental year, was above the critical level (6.5 µg/g for KCl-40, Blair et al. 1991), and 10 µg/g for MCP (Incitec) and the response to S in that year

was statistically non-significant (i.e. a correct prediction of a non-responsive site) or statistically significant (i.e. a correct prediction of a responsive site). In the first instance the soil test prediction was correct more often with the KCl-40 extract than with MCP. The KCl-40 extract was also more often correct in predicting responsive sites in 2 out of 3 years for which data was available.

Several sites were notable in the poor performance of the soil tests and these were those where extractable S was present below the sampling depth (e.g. Site Q1, Malanda, S23, Nangwarry Figure 6). Probert and Jones (1977) observed a similar situation in their North Queensland studies and used a weighted profile mean to overcome the problem.

The KCl-40 procedure has now been adopted by most accredited soil test laboratories in Australia.

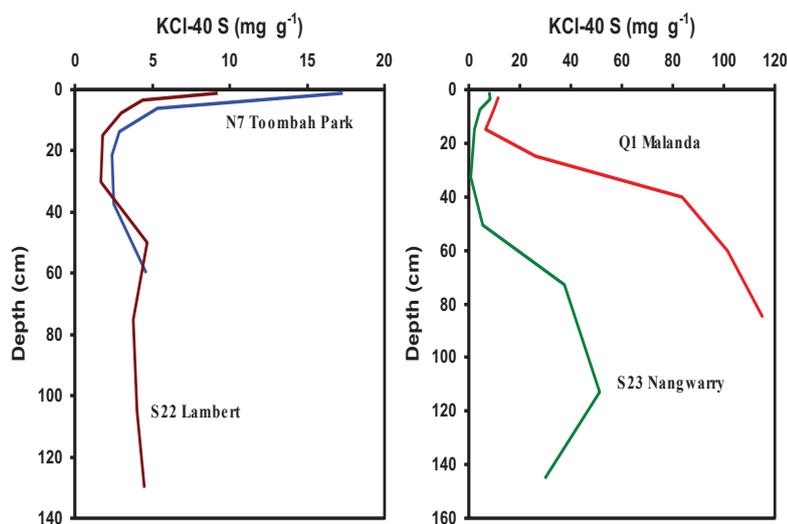


Figure 6. KCl-40 extractable S in profiles of four soils from Australia.

Development of new S containing fertilisers

Intensification of cropping systems using high-yielding varieties has accelerated S removal from the soil, which has resulted in more soils becoming S-deficient. Increased use of high-analysis S-free fertilisers such as MAP, DAP, TSP and urea has aggravated the S deficiency problem.

Many alternative sources of S fertiliser are available (Blair 2002). Fertiliser sulfate is immediately available to the crop (Friesen and Chien, 1986), but leaching losses may be significant from these fertilisers. Elemental S must undergo oxidation to plant available sulfate and both moisture and aeration are interrelated factors that affect the rate of oxidation of elemental S. Generally, elemental S is oxidised most rapidly at a moisture content of approximately field capacity (Moser and Olsen, 1953), which is the optimum soil moisture for plant growth (Burns, 1968), so the SO₄ is largely released in synchrony with plant demand.

Equations for incorporating the effects of soil temperature and moisture on S oxidation and plant S demand were developed from published data (McCaskill and Blair 1989) and these were incorporated into a simple model to predict sulfate supply from single superphosphate and elemental S. The model predicted that after 72 days 99% of the S in single superphosphate would have been released from the fertiliser granule. By contrast the release and oxidation of S from elemental S fortified single superphosphate (36% elemental S, 9% sulfate-S) was 54% after 1 year and only 23% from crushed agricultural grade elemental S.

Elemental S is an almost ideal fertiliser as it contains 100% nutrients, hence its inclusion into fertilisers such as DAP, MAP and TSP does not dilute the content of other nutrients in the fertiliser nearly as much as does the inclusion of sulfate.

Many studies have demonstrated that the rate of oxidation is proportional to the surface area of S exposed and hence inversely proportional to the particle size (Fox et al., 1964). Shedley et al. (1979) showed that S oxidation was complete from 50 µm particles 70 days after the commencement of his experiment and he also found that in the coarser particle size treatments the release of sulfate continued throughout the 1 year experimental period.

Sholeh et al. (1997) found marked differences in S oxidation between 50-150 and 150-250 μm particles in the presence of P but little difference when P was absent (Figure 7). This has important implications for incorporation of elemental S into fertilisers and indicates that P containing ones are the best candidates.

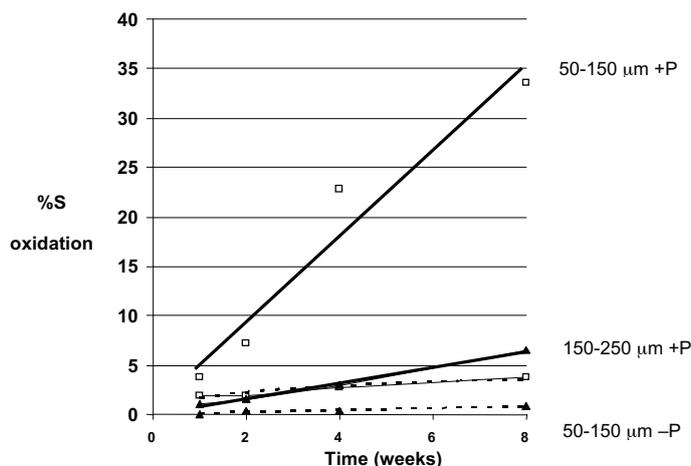


Figure 7. Effect of elemental S particle size and the presence of P on the % of elemental S oxidised over an 8 week period (Sholeh et al. 1997).

In studies undertaken at UNE (Kubelo, 2008) S oxidation rates were higher at 30°C than at 18°C over a range of particle sizes with the difference becoming less as particle size increased (Figure 8).

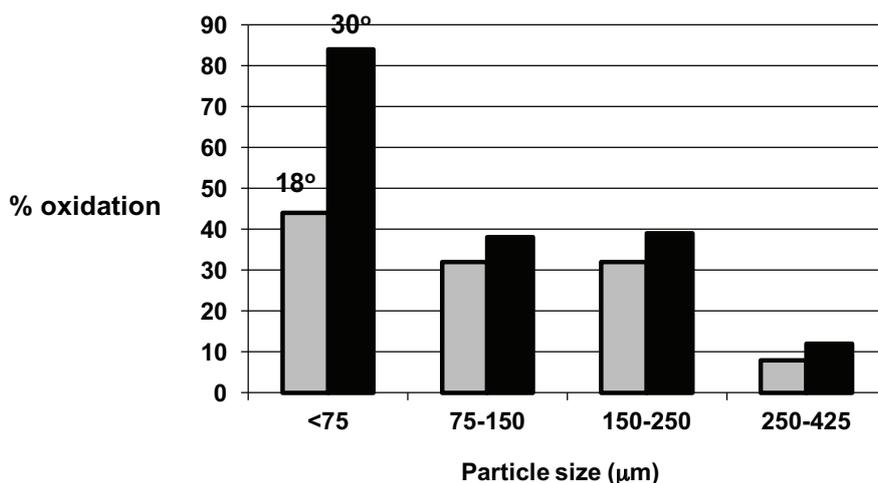


Figure 8. Effect of temperature and particle diameter on S oxidation at 6 weeks.

Elemental S containing P based fertilisers were introduced to the Eastern Australia market in 1957 in the form of S fortified SSP. This was made by spraying molten elemental S into the den during manufacture.

Freisen et al. (1987) compared the P and S release from partially acidulated rock phosphates and found that the presence of elemental S increased both P and S release from the fertiliser. Australian fertiliser manufacturers did not take up this technology as they had considerable investments in single superphosphate plants, which needed to be run at full capacity to be economical.

This basic research conducted by the University of New England (UNE) team has been used to develop a range of S coated fertilisers and in 1991 a patent was granted to UNE for a S coating process (Blair, 1991). Work continued for the next 15 years to refine the process and to develop a range of coated DAP, MAP, TSP and urea coated products (Blair et al. 1994, Dana et al. 1994, Yasmin et al. 2007). During this period Hi-Fert began marketing S coated products under the Goldphos name.

Shell invented a process in 2001 to include microfine elemental S into DAP and MAP and a patent for this was filed in 2003 (International Publication Number WO 2004/043878 A1). The design of the products to be produced was based on the UNE research and I was invited to become a Special Advisor on Agronomy and

Soils to the “Thiogro Project”. Much of the process developmental work on Shell Thiogro was undertaken at the International Fertilizer Development Centre (IFDC) in Muscle Shoals, Alabama, USA where a reactive granulation process was developed using pre-neutralizers (PN), pipe cross reactors (PCR) and combination of PN and PCR units with S concentrations ranging up to 20% by weight.

In the Shell Thiogro S enhanced MAP and DAP processes, molten S is added to the ammonium phosphate slurries, along with small concentrations of proprietary additives to emulsify the hydrophobic elemental S into a hydrophilic ammonium phosphate slurry/melt. This results in phosphatic slurry containing discrete elemental S particles with an average size ranging from 20 to 60 microns. The reactor slurry is subsequently granulated in conventional rotary drum granulator. Commercial fertilizers made using this process commonly contain 10-12% S. Because of the risk of a delay in oxidation following application, 1/3 of the S is added as sulfate and 2/3 as elemental S.

A distinguishing feature of the Shell Thiogro process is that the elemental S is uniformly distributed throughout the fertiliser granule, which reduces the risk of potentially explosive S dust being generated as the fertiliser particles abrade during handling and ensures that the elemental S and P are in close proximity to promote S oxidation.

S oxidation from fine elemental S (S⁰) and from S incorporated into Shell Thiogro MAP has been studied extensively at UNE and results from one such study are presented in Table 4. The trial was conducted in a temperature controlled glasshouse set to simulate subtropical conditions with day and night conditions fluctuating around 25 °C. The results showed that there was no significant difference in S recovery by the maize plants between fine elemental S (<48.1µm) mixed throughout the soil or from the 1/3 sulfate/ 2/3 elemental S contained within the Shell Thiogro MAP (12%S) when both were applied at the equivalent rate of 10 kg S/ha.

Table 4. Dry matter yield and S uptake by maize after 44 days.

Numbers within a column followed by the same letter are not significantly different (p<0.05).

Treatment	Dry Weight (g)	Total S uptake (mg/pot)	Recovered S (%)
Fine (<48.1µm) S ⁰	4.72a	7.03a	25.6a
Shell Thiogro MAP12	4.50a	6.11ab	20.5a

A total of 138 replicated randomised block plot experiments have been conducted to evaluate Shell Thiogro. Experiments have been conducted in China (101 experiments), Brazil (22 experiments), Argentina (10 experiments) and Australia (7 experiments). Two experiments in Australia did not produce results due to drought or hail damage meaning that results are available from 136 experiments in total.

Of the 136 experiments 84 were responsive (difference between minus S control and Shell Thiogro treatment significant at p=0.05 according to Duncan’s Multiple Range Test) to S with a weighted mean yield increase to Shell Thiogro of 14%, compared with the zero S control. The comparison treatment consisted of a mixture of MAP and gypsum used to simulate an addition of single superphosphate (SSP). Nitrogen and all other nutrients were balanced between treatments so that S was the only variable. Shell Thiogro produced yield responses equal to SSP at 50 sites, responses exceeding SSP at 28 sites and responses inferior to SSP at 6 sites.

An S enhanced triple superphosphate TSPS fertiliser has been developed by Yunnan Lufeng Qinpan Phosphor Chemical Co., Ltd., China, which is based on the UNE research and it contains 8.5% S present as 1/3 sulfate and 2/3 elemental S within the fertiliser granule and this is now on sale in the New England Tablelands of NSW.

Conclusion

The sound basic research, which has had good long term financial backing from Australian Research Corporations, AusAid, ACIAR and Commercial interests and an enthusiastic group of post-graduate students

and Research Fellows has led to the development of a robust S soil test and to a new generation of S containing fertilisers. Persistence pays!

References

- Anderson AJ and Spencer D (1950) Sulphur in Nitrogen metabolism of Legumes and non-legumes. Australian Journal of Soil Research, series B3, 431
- Blair GJ. (1986). Sulphur cycling in flooded rice. Proceedings of the International Sulphur Symposium. Bangladesh, April 1986.
- Blair GJ, Mamaril CP, Momuat E. (1978). The sulfur nutrition of wetland rice. IRRI Research Series No. 21.
- Blair GJ Momuat EO and Mamaril CP. (1979). Sulfur nutrition of Rice. II. Effect of source and rate of S on growth and yield under flooded conditions. Agronomy Journal 71, 477-480.
- Blair GJ. (1979). Sulfur in the tropics. Technical Bulletin IFDC-T12. Alabama, U.S.A. (Sulfur Institute International Fertiliser Development Center).
- Blair, G. (1991). 'Fertiliser coating process. PCT/AU91/00459.'
- Blair GJ, Chinoim N, Lefroy RDB, Anderson GC, Crocker GJ (1991). A soil sulfur test for pastures and crops. Australian Journal Agricultural Research 29,619-626.
- Blair GJ. (2002). Sulphur fertilisers: a global perspective. (2002) pp1-36 in Proceedings - International Fertiliser Society No.498, The International Fertiliser Society, Cambridge, UK, 16-17 December 2002.
- Blair GJ, Nicolson AJ (1975). The occurrence of sulphur deficiency in temperate Australia. In 'Sulphur in Australasian Agriculture.' (Ed. KD McLachlan) pp. 137-44, (Sydney University Press: Sydney, Australia.).
- Blair GJ, Dana M, Lefroy RDB. (1994). A glasshouse evaluation of sulfur fertiliser sources for crops and pastures. II. A comparison of sulfur coated triple superphosphates and gypsum. Australian Journal of Agricultural Research, 45, 1517-23.
- Burns G. (1968). Oxidation of sulfur in soils (reprinted). Technical Bulletin No. 13. pp 140. (The Sulphur Institute : Washington D.C).
- Chaitep W, Lefroy RDB and Blair GJ. (1994). Effect of placement and source of sulfur in flooded and non-flooded rice cropping systems. Australian Journal of Agricultural Research 45, 1547-56
- Chinoim, N. and Lefroy, R D B, Blair, G J (1997). The effect of crop duration and soil type on the ability of soil sulfur tests to predict plant response to sulfur. Australian Journal of Soil Research, 35, 1131-1141.
- Dana M, Lefroy RDB, Blair GJ. (1994). A glasshouse evaluation of sulfur fertiliser sources for crops and pastures. IV. Water solubility and physical losses of sulfur and phosphorus from S-coated triple superphosphates. Australian Journal of Agricultural Research, 45, 1539-1545.
- Duke, S.H. and Reisenauer, H.M. (1986). Roles and requirements of sulfur in plant nutrition. pp. 123-168 Sulfur in Agriculture. (Ed M. A. Tabatabai) (ASA, CSSA, SSSA: Madison, Wisconsin, USA.)
- Fox RL Atesalph HM Kampbell DH and Rhoades HF. (1964). Factors influencing the availability of sulfur fertilizers to alfalfa and corn. Soil Science Society of America Proceedings 28, 406-8.
- Freney JR. (1986). Forms and reactions of organic sulfur compounds in soils. pp. 207-232. In Tabatabai, M.A. (ed.) Sulfur in Agriculture. Agronomy Series No.27. ASA, CSSA, SSSA. Madison, Wisc.
- Freney JR, Melville GE and Williams CH (1971). Organic sulphur fractions labeled with ³⁵S-sulphate to soil. Soil Biology and Biochemistry 3, 133-141
- Friesen DK, Chien SH. (1986). Sulphur fertilizers and their application : General review and S source evaluation at IFDC. International Sulphur Symposium. Dhaka, Bangladesh, April 20-22, 1986.
- Friesen DK Sale PWG and Blair GJ. (1987). Long-term greenhouse evaluation of partially acidulated phosphate rock fertilisers: II. Effect of congranulation with elemental S on availability of P from two phosphate rocks. Fertiliser Research. 13, 45-54
- Goh HM and Gregg PEH (1982). Fiel studies on the fate of radioactivesulphurapplied to pastures. Fertilizer Research 3, 337-351
- Kabelo Mate (2008). Evaluation of Sulfur Sources for Tropical and Temperate Pastures.
- May PF Till ARand Cumming MJ (1973). Systems analysis of the effects of application methods on the entry of sulfur into pastures grazed by sheep. *Journal of Applied Ecology* 10, 607-626
- Moser US and Olson RV. (1953). Sulfur oxidation in four soils as influenced by moisture tension and bacteria. Soil Science 76, 251-257.

- McCaskill MR and Blair GJ (1988). Development of a simulation model of sulfur cycling in grazed pastures. *Biogeochemistry* 19, 77-84
- McCaskill MR, Blair GJ. (1989). A model for the release of sulfur from elemental S and superphosphate. *Fertiliser Research* 19, 77-84.
- Probert ME and Jones RK. (1977). The use of soil analysis for predicting the response to sulphur of pasture legumes in the Australian tropics. *Australian Journal Soil Research* 15, 137-46.
- Shedley CD Till AR and Blair GJ (1979). A radiotracer technique for studying the nutrient release from different fertiliser materials and its uptake by plants. *Communications in Soil Science and Plant Analysis*. 10, 737-745.
- Sholeh, Lefroy RDB, Blair GJ. (1997). Effect of nutrients and elemental sulfur particle size on elemental sulfur oxidation and the growth of *Thiobacillus thiooxidans*. *Australian Journal of Agricultural Research*, 48, 497-501.
- Till AR.(1975). Sulfur cycling in grazed pastures. pp. 68-75 In 'Sulphur in Australasian Agriculture.' (Ed. KD McLachlan) pp. 68-75, (Sydney University Press: Sydney, Australia.).
- Till AR and May PF. (1970). Nutrient cycling in grazed pastures. 2. Further observations with ³⁵S-gypsum. *Australian Journal of Agricultural Research* 21, 253-260.
- Yasmin N, Blair G, Till R. (2007). Effect of elemental sulfur, gypsum, and elemental sulfur coated fertilisers, on the availability of sulfur to rice. *Journal of Plant Nutrition*, 30: 79-91
- Yoshida S and Chaudhry MR. (1979). Sulfur nutrition of rice. *Soil Science and Plant Nutrition* 25, 121-134.