Sulphur as a nutrient for agricultural crops in southern Australia

Scope
This review of the literature focuses on the function, importance and management of sulphur (S) for wheat production in dryland cropping systems of south-eastern Australia. The review draws on a selection of cornerstone journal articles that provide foundation information about the role of and importance of S for wheat production. Information is sourced from the international literature and, where available, literature that provides specific Southern Regional content. The selected research and extension literature focuses at the regional level but is underpinned by the basic universal principles of S nutrition provided by cornerstone journal articles and texts. Region-specific literature may be in the form of conference papers, fact sheets, technical reports or decision support systems (DSS).

These information sources are selected to assist advisers and growers to improve their understanding of S to provide the basis for improved decision making for managing S nutrition.

Outcome
This literature review is a guide that aims to enable advisers and growers to make better decisions about S management including whether additional S need to be applied, and if so, where, when, in what form and at what rate. The review summaries the function, importance and use of S by plants in dryland cropping systems and provides a bibliography of reliable information sources. This literature review will be combined with reviews of other agronomic topics to provide growers and advisers with a carefully targeted source of information that will assist them to make more informed decisions about agronomic management.

Function of S in broad-acre grain crops

Nature of S in plants
Sulphur is an essential nutrient required for the growth of wheat (Grundon 1987) and is a key element in the amino acids that form proteins essential for cellular structure and enzymes (Anderson 1975). Sulphur is also an essential part of proteins needed for wheat grain to produce flour suitable for bread-making (Zhao et al 1999). The essential role of S in the formation of grain protein leads to grain protein being low when S is deficient.

Vegetative symptoms of S deficiency are stunting, yellowing of the whole plant and severe yellowing of the younger leaves when S deficiency is persistent (Figure 1) (Grundon 1987, Wurst et al 2010). The mobility of S from older plant parts to younger tissue is limited when S is deficient (Grundon 1987). However, in wheat with
adequate S nutrition and water, 50% of S in the grain is derived from S accumulated before anthesis and S is cycling within the plant (Monaghan et al 1999).

**Figure 1.** Sulphur deficient wheat. Sourced from IPNI [http://anz.ipni.net/article/ANZ-3178](http://anz.ipni.net/article/ANZ-3178) presentation given 30 July 2013 at Bendigo, Victoria, by Dr Rob Norton, IPNI.

**Nature of S in soil**

Soil S is in several forms which are not all equality available to wheat (Williams 1975). Most soil S is in an organic form and not directly accessible to plants until undergoing mineralisation by micro-organisms (Freney and Swaby 1975). The rates of mineralisation and immobilisation are determined by the factors that effect growth of micro-organisms namely soil water, temperature, pH and availability of other nutrients. As such, available S varies throughout the year with more mineralisation or organic S during warm, moist conditions and less during dry, waterlogged or cold conditions. The forms of soil S available for uptake by plants are adsorbed and soluble sulphate which comprised about 10% or less of total soil S (Evans 1975). Sulphur can also be present in waterlogged soils as sulphides which are transformed to plant available sulphates when the soils dry out. Rarely, sulphur is naturally present as elemental sulphur and needs to be oxidised before it is available to plants. (Williams 1975).

**Access to S by plants**

Plant roots take up S from soil solution principally as water soluble sulphate (SO$_4^{2-}$) sourced from soil or fertiliser. The uptake of S from the soil and into the plant (Bouma 1975) depends on:

- the chemical availability of the nutrient
- movement of the nutrient via mass flow or diffusion (from the soil to the root)
- growth of roots through the soil (root interception)
- uptake of the nutrient at the root surface itself
- translocation from the root to other parts of the plant
Very small amounts of S are also taken up directly through wheat leaves in solution (Legris-Delaporte et al. 1987). Larger quantities of S are sourced from the atmosphere through stomata in the form of sulphur dioxide (SO$_2$) with this source being more important overseas where SO$_2$ is an air pollutant (Fowler and Unsworth 1975).

**S in context of south-eastern Australia**

Inherent sulphur-deficient soils occur in sections of the south-eastern Australian landscape. Soils deficient in S are historically dominated by pasture production; namely Gippsland in Victoria, the Tablelands in New South Wales, coastal regions with higher rainfall in South Australia, and northern coastal regions of Tasmania (Blair and Nicolson 1975). Subsequently S nutrition is more commonly researched and discussed in the context of pasture production than cereal production (Archer 1974).

The relatively rare diagnosis of S deficiency in cereals is also attributed in part to the dominant use of superphosphate fertiliser from the 1970s through to the 1990’s (Lipsett and Williams 1974, Shultz and French 1976). Dryland crops and pastures in south-eastern Australia also source S from the atmosphere and rain ranging from 0.4 kg S/ha at inland locations to 20.3 kg S/ha at coastal locations (Blair et al. 1997). Further, gypsum, a source of S, is applied to sodic soils which are extensive in Australia, to ameliorate sodicity as a subsoil constraint (The Profitable Soils Group 2009).

The combined outcome of these factors is that S concentration in wheat grain is above critical values in most cropped regions of south-eastern Australia (Norton 2012). Further, national nutrient audits in 1995/1996 and 2009/10 showed the S balance in cropped area of south-eastern Australia was neutral or positive throughout most of south-eastern Australia (Australia Natural Resources Atlas 2001, IPNI 2013).

**Local tools help S fertiliser decision making**

There are few summaries of information specifically about S nutrition for wheat grown in south eastern Australia. Information about S nutrition tends to be mixed with information about other nutrients or is specific to Western Australia or canola (Brennan and Walton 2006, Freebairn 2005, GRDC 2009b, Mason 2001). This reflects historic rarity of S deficiency in wheat grown in the region as well as grain price being unrelated to S content in the grain. Fact sheets from Western Australia highlight the need to consider the soil type as it relates to S adsorption capacity and potential for S leaching. Soils with clay, or iron and aluminium oxides retain S through adsorption and tend to be less prone to S leaching. Conversely, deep sandy soils, particularly subject to high rainfall conditions, are prone to S leaching (Brennan and Walton 2006, Bolland and Russell 2009). Under these conditions or when soil testing, plant testing or historical records show there is a risk of wheat becoming S deficient it is useful to know the amount of S removed by the crop.
The amount of S in wheat in south-eastern Australia is 1.5 kg S/t stubble and 1.7 kg S/t grain (Shultz and French 1976, Norton 2012). In New South Wales, the amount of S removed by dual purpose wheat (i.e. grazed and harvested for grain) is given as 0.4 kg S/t dry matter grazed and 1.5 kg S/t grain (Freebairn 2005). Calculations for the amount of S fertiliser needed in any crop is based on supplying the crop with enough S to cover immediate nutrient usage or removal. The amount of S removed from a wheat-grain crop is 3.4 kg/ha for a 2 t/ha crop and 6.8 kg/ha for a 4 t/ha crop when calculations are based on the amount of S in grain as measured in National Variety Trials conducted in southern Australia (Norton 2012). The amount of S required is given as 20 kg S/ha to meet the needs of dual purpose wheat in New South Wales and canola grown in poor soils in Western Australia (Freebairn 2005, Brennan and Walton 2006). However, S recommendations tend not to be based on preventing nutrient removal, rather S tends to be recommended when deficiencies are expected (GRDC 2011). S recommendations in Australia do not take into account the very low amounts of S sourced from the atmosphere unlike in the United Kingdom where intensive industrial sources of S can be significant. (HGCA 2007).

**Principles of better crop nutrition**

The principles for effective fertiliser use are to select the right source of nutrients, applied as the right rate, and in the right place and at the right time. These four rights (4Rs) of nutrient stewardship indicate that these four factors are all interlocking and if one is altered, the whole approach should be considered (Norton and Roberts 2012).

**Right source**

Solid sulphur in fertiliser comes in two forms; elemental S and sulphate-S. Elemental S in soil is not directly accessible by plants and needs to be converted to the sulphate form by microbial processes. Consequently, the size of the elemental S particle is an important factor in how quickly the nutrient becomes accessible to plants. A particle size of less than 80 mesh (approximately 0.18 mm diameter) is required for elemental S to be equally as effective as sulphate S in the year it is applied (Bixby and Beaton 1970). Elemental S is also used to coat other fertilisers such as urea and enable urea-N to be slowly released into the soil (Chen et al 2008). Elemental S in foliar sprays is taken up though wheat leaves at very low levels (2%) (Legris-Delaporte et al 1987) and is not an effective means of increasing S in wheat (Kettlewell et al 1998)

The sulphate form of S is readily available to plants and is present in many solid and fluid fertilisers used in Australia: superphosphate (11% S), gypsum (>12% S), sulphate fertilisers, thiosulphate fertiliser and fertilisers predominantly containing other elements. Several publications list S fertiliser types available in Australia and the ratios of S to other nutrients (Horizon Rural Management 2003, Brennan and Walton 2006, Edis and Norton 2012). It is worth noting that little S (<1%) is present in high-analysis fertilisers commonly used in wheat production included monoammonium phosphate (MAP), diammonium phosphate (DAP), urea and anhydrous N.
The type of sulphate-based fertiliser used with a wheat crop depends on the presence of soil constraints and other nutrient deficiencies (Randall et al. 1981, Edis and Norton 2012). The soil constraint, sodicity, that is common in much of the cropped soils in south-eastern Australia is alleviated by applying gypsum which is also a source of S to the immediate crop (The Profitable Soils Group 2009). The amount of sulphur in gypsum varies from below 12% up to 24% S depending on the source (Hazelton and Murphy 2007).

Sulphate-S is also applied with other nutrients, including P, N and K, as a fluid in Australia (Horizon Rural Management 2003). The benefits of applying fluid forms of S fertiliser as sulphate or thiosulphate ($S_2O_3^{2-}$) to the soil is briefly reviewed by Edis and Norton (2012) with an emphasis on the need to avoid direct contact between the crop and thiosulphates. Although there is no known benefit in applying S as a fluid fertiliser instead of a solid, applying P in a fluid form is more effective than solid P fertilisers for wheat grown in alkaline and calcareous soils (Hollaway et al. 2001, McBeath et al. 2007, GRDC 2009a). Therefore on these types of soils, if S and P are applied together in a fluid form it is to improve P use efficiency rather than S use efficiency.

Fluids containing sulphate-S can be applied to the soil during the season to correct S deficiencies (Edis and Norton 2012, Wells et al. 1986). However, the type of sulphate-S fertiliser applied (e.g. ammonium sulphate or potassium sulphate) and method of application is important since wheat foliage is damaged when S is applied even with low rates of N (9 kg/ha) (Legris-Delaporte et al. 1987).

Organic fertilisers such as chicken manure contain less than 1% S and principally in an organic form that is not readily available to plants (McNeill et al. 2005). Organic manures are not suitable as a source of any nutrient in no-tillage cropping systems as they need to be incorporated (GRDC 2009a).

**Right place**

Logistically, fertiliser placement in soil can be surface, shallow or at depth. Sulphur applied to the soil surface moves into the soil during the season with rainfall events and is available to plants in the same year (Randall et al. 1981, Chen et al. 1999). The mobility of S is particularly relevant on sandy soils such as those in Western Australia in area of high rainfall (Bolland and Russell 2009) and is less relevant in heavier soils (Podzols and Red Earths) in New South Wales even in higher rainfall environments (Chen et al. 1999). Wheat’s need for S during early development indicates that S should be placed near the seed at sowing with any S not taken up by the young wheat accessible later in the season by roots at depth (Barrow 1966, Riley et al. 2002).

How close S fertilisers can be to the seed without germination being reduced depends on the presence of other nutrients in the fertiliser. Nitrogen is the principle nutrient of concern. The presence of N as ammonium sulphate reduces germination of wheat when present near seed at rates above 70 kg N/ha under dry conditions (Carter 1967). This damaging rate of N as sulphate of ammonia is higher than the rate of N as urea (25 kg/ha) known to reduce wheat germination (Mason 1971). The issue of seed being damaged due to the proximity of high rates of N can be mitigated by banding fertiliser a few centimetres away from the seed (Mason 1971).
Placing fluid fertiliser directly on wheat leaves as a foliar S application is not recommended as there is potential for leaf damage and yield loss (Rob Norton, pers. Comm.)

**Right time**
The range of S fertiliser types available allows for timing of application to vary depending on the purpose. Organic manures must be applied for decades to provide even small amounts of S to crops (Eriksen 2002, McNeill *et al* 2005). Course elemental S needs to be applied well before fertiliser S is required so it can be processed by microbes into the sulphate form that is accessible to plants (Bixby and Beaton 1970). Application of S as a long-term strategy to build or maintain S in the soil can be undertaken well prior to sowing however S has limited residual value and consistent application over several decades does not mean S can be omitted from current fertiliser programs (Barrow 1966).

Sulphur application aimed at meeting the immediate needs of the crop early in the season can be undertaken during tillage operations. Technically, correction of visual S deficiency by foliar application can occur from growth stage 31 (GS31) when the plant has enough leaves to intercept a foliar spray through to post-flowering. However there is a high risk that leaves will be damaged by the fertiliser when S is applied with N, as in ammonium sulphate, and apply S as elemental S is ineffective (Kettlewell *et al* 1998). An alternative is to apply solid or fluid fertiliser containing S, such as ammonium sulphate or thiosulphate, directly to the soil and allowing the fertiliser to wash into the soil on the next rainfall event (Edis and Norton 2012).

**Right amount**
There are three general approaches to determining whether a nutrient needs to be applied and how much needs to be applied: soil testing, historical records plant testing.

*Soil testing*

Soil testing in a pre-emptive indicator for the amount of major nutrients (nitrogen (N), phosphorus (P) and potassium (K)) available to a planned crop. Soil samples are tested for S as part of a basic soil test. Soil testing of the top 10cm layer is promoted for the major cropping soils in Australia as being relevant for making decisions about immobile plant nutrients such as P (GRDC 2009a).

Testing only the 0-10cm soil layer in not an effective tool for diagnosing a need for S fertiliser despite being commonly used in Australian cropping regions (Blair *et al* 1997, Brennan and Bolland 2006). This is due the ability of S to leach from the soil surface to below sampling depth in a single year even in soils not considered prone to leaching (McLachlan and De Marco 1971).

The need for deeper soil sampling to get an accurate assessment of the total amount of S available to plants is demonstrated in the Mallee and Wimmera where surface soils were commonly measured as deficient in S in the 1980s (Brown *et al* 1992, Quigley and Ferguson 1982). However, in the same region S was also available deeper in the rooting zone (> 20 mg/kg) and contributed to meeting crop demands (Quigley and Ferguson 1982). Similar results are found for soils in Tasmania and
Victoria under pastures (Blair et al 1997). Data gathered from across Australia for S by KCl-40 method indicates that sampling to 30cm correlates with grain yield response and 90% maximum grain yield is attained with 5 mg S/kg (Figure 2). This critical value is at the lower end of the range given by Lewis (1999). However, the range in grain yield is broad and the database this information is sourced from (BFDC project) containing little data at greater depth.

![Figure 2: Sulphur response curve using data extracted from the Better Fertiliser Decisions for Crops database. Data is S as measured by KCl-40 method in 0-30 cm layer for all sites in Australia (http://www.bfdc.com.au/frontpage.vm)](http://www.bfdc.com.au/frontpage.vm)

There is insufficient S data in this database to produce a response curve for the whole of south-eastern Australia or any region or soil type within south-eastern Australia.

**Soil testing by S extraction**

Extractable S is commonly measured in cropped soils (0-10cm layer) by extraction in potassium chloride (Method 10D1) (Rayment and Lyons 2010). This method is known as the KCl-40 method. This method replaces calcium phosphate extraction methods 10B1 and 10B2 as it costs less to conduct and relate better to pasture responsiveness to S fertiliser in some soils in New South Wales (Blair et al 1997). All S extraction methods listed are designed to measure the S available to plants rather than the total S and are applied to a diverse range of Australian soil types as a diagnostic tool for detecting soils deficient in S for crop and pasture production (Rayment and Lyons 2010).

The critical range for extractable S in Australian soils is 5 – 10 mg/kg using either KCl-40 or calcium phosphate extraction methods (Lewis 1999). This is a general range applied to all crops and soils in Australia and is not refined for soil type, sampling time or crop type. The S sorption capacity of the soil effects soils ability to retain S (Williams 1975). however, unlike soil testing for P, no test is currently used to adjust extractable S results for this factor. The diffusive gradients in thin-films (DGT)
method developed to test soil for available P (Mason et al 2010) is currently under development for use as a method for measuring available S (Mason et al 2012).

**Soil sampling technique**

Testing the 0-10cm soil layer only provides information as to whether the crop is going to be S deficient early in the season. Sulphur at depth leads to crops being unresponsive to S fertiliser even when S is deficient in the topsoil (Blair et al 1997). Sampling soil for extractable S to rooting depth is therefore a more informative soil testing method and is promoted by GRDC as the most accurate means of testing for S status in soil (GRDC 2011).

Timing of S testing is important since soil S changes with temperature and moisture as S is mineralised and immobilised by microbes (Freney and Swaby 1975). Under pasture, S status is also related to plant growth with the lowest extractable S during periods of high growth and higher extractable S occurring when plants are dormant (Williams 1968). These factors of temperature, moisture and plant growth interact in an environment with even annual rainfall distribution to take soil S status from deficient (4 mg/kg) in winter to adequate (12 mg/kg) in summer (Williams 1968).

**Historical records**

Prior grain yields, stubble management, crop type, fertiliser application and S-deficiency symptoms provide an indication as to whether a planned crop needs S fertiliser. A history of symptoms of S deficiency and reduced grain yield in past crops provides direct evidence of a need for S fertiliser in future crops. However, a history of S-deficiency symptoms in young wheat, followed by recovery as the plant grows indicates that S is deficient in the topsoil and adequate deep in the rooting zone (Brennan and Bolland 2006).

Indirect evidence of a need for S fertiliser can be sourced from simple nutrient budgeting similar to that used in the national nutrient audit (Australia Natural Resources Atlas 2001, Anderson et al 2006). Sulphur is removed from the soil in grain and stubble that is burnt, grazed or baled (Shultz and French 1976). Removal of S is particularly high in canola; a crop with a high demand for S compared to other crops (Brennan and Bolland 2006, GRDC 2011). Sulphur is replaced by applying fertilisers that contain S such as elemental S, superphosphate or gypsum whilst using low-S fertilisers such as MAP and DAP leads to a depletion of S in cropping systems (Randall et al 1981). Nutrient budgeting at a regional scale in Western Australia shows that applying S at 1 – 10 kg S/ha is sufficient to maintain or improve the overall S status of cropped soils (Anderson et al 2006).

**Crop testing**

Wheat is responsive to in-season application of S with applications leading to an increase in S concentration in wheat leaves (Freney et al 1978). Thus crop testing is a useful diagnostic tool when results from tissue analysis are compared with the critical values established for wheat. Sulphur concentrations decline as wheat plants grow older therefore it is essential that the growth stage of the plant at sampling is considered during interpretation of results. Sulphur content below the range 0.14% - 0.32% in the youngest emerged blade (YEB) at GS23-30 indicates the plant is S deficient at the time of sampling Reuter et al (1997a).
Diagnosis of S deficiency by tissue testing is aided by considering N:S ratios and soil test results at the same time. The N:S ratio in wheat with adequate S is <17:1 whether measured in the YEB, the whole shoot (Reuter et al 1997b) or grain (Randall et al 1981).

**Other factors affecting availability of S to crops**

*Residual value*

Sulphur cycling is subject to seasonal fluctuations depending on plant growth, soil temperature and soil moisture. This makes the residual value of S after a crop difficult to measure and predict (McLachlan and Marco 1971). Even in soil that readily leaches S fertilisers, the total amount of S taken up by wheat has been measured to be more than the amount of S fertiliser applied due to S becoming available through mineralisation of organic matter (Riley et al 2002).

The residual value of S in fertilisers is low compared to relatively immobile nutrients such as zinc (Brennan and Bolland 2007). Gypsum-S has a residual benefit on dry matter production for up to three years when applied at 34 kg S/ha to pasture grown on a non-leaching clay loam soils in Western Australia (McLachlan and Marco 1971). Sulphate fertilisers are only detectable for a short time after application on sandy soils in Western Australia where up to 15% remains one year after application to a soil without leaching beyond 0.5m (Anderson et al 2006). Residual sulphate-S is higher on clay loam in south-west Victoria with 31% retained and 40% accounted for in soil and products removed from the site (McCaskill and Cayley 2000). Similarly, on a Podzol in New South Wales, 23% of applied elemental S was accounted for in soil and plant products (Chen et al 1999).

However, soluble S declines rapid in soil vulnerable to S leaching. The susceptibility of S to leaching in soil depends on clay content, adsorption capacity, rainfall and S fertiliser type (Anderson et al 2006). In sandy soil subject to heavy rainfall events, soluble soil S levels in fertilised pastures declines to that of unfertilised pasture when S is omitted for only one year (Barrow 1966). Conversely, soils with high iron or aluminium oxides or alkaline soils have the capacity to adsorp S and are less susceptible to S loss through leaching (Williams 1975). Finally, not all S fertiliser types are equally susceptible to loss through leaching with ammonium sulphate more readily leached under grassy pasture than elemental S (Riley et al 2002).

*Soil water*

The effect of soil water on access to S by plants is complex due to the interactions between effects related to soil physics (e.g. adsorption capacity) and soil biology (e.g. mineralisation). Under wet conditions, access to S increases due to root growth, diffusion of S through soil and mineralisation but decreases through leaching in soils with low S adsorption capacity that are subject to high rainfall events or when soil is waterlogged. Conversely, under dry conditions, there is a reduction in root growth, diffusion of S through soil and S mineralisation (Anderson et al 2006, Barrow 1966, Bouma 1975, Freney and Swaby 1975). However, under dry conditions S immobilisation in plant tissue is reduced due to a lack of plant growth (Barrow 1961).
In tandem with the effects of soil water on S mineralisation is soil temperature. Sulphur mineralisation is maximised in moist soils at temperatures between 10°C and 40°C (Anderson et al 2006, Freney and Swaby 1975)

**Soil physicochemical constraints**
Physicochemical constraints that restrict root growth reduce plant access to nutrients with limited mobility. Physicochemical constraints are identified in several studies in south-eastern Australia and are summarised by Adcock et al (2007) as boron toxicity, carbonate, aluninate, salinity, sodicity and alkalinity. Nuttall et al (2003) reports that root growth is restricted by some of these constraints in the subsoil of Calcarosols and Sodosols found in the Mallee. Conversely, physicochemical constraints are rarely found in Vertosols in the Wimmera (Dunbabin et al 2009). Unlike other nutrients particularly P (GRDC 2009a), there is no differentiation in extension literature between soil types for management of S nutrition in crops in south-eastern Australia despite lighter soils in higher rainfall environments being more likely to exhibit S deficiency in wheat that heavier soils in lower rainfall environments (Blair and Nicholson 1975).

**Effect of other nutrients on response to S**
Sulphur, nitrogen and phosphorus have a synergistic relationship with all nutrients interacting to affect the uptake and use efficiency of each nutrient by plants (Archer 1974). Inadequate supply of S restricts the uptake of N fertiliser when applied at high rates and inadequate N limits the effectiveness of higher rates of S fertiliser (Salvagiotti et al 2009). Hence N use efficiency is lower when S supply in low and maximum grain yields are obtained when both N and S are applied to wheat that is responsive to both nutrients (Muldoon 1986). Conversely, increasing the availability of N induce S deficiency in wheat with higher rates of S fertiliser required to balance higher rates of N fertiliser (Freney et al 1978). The same interactions occur for N and S concentrations in wheat grain (Randall et al 1981). Supply of S nutrition also effects the uptake of P and the redistribution of P from leaves to grain with S deficiency causing P movement to be limited (Archer 1974). Similarly to the interaction between N and S, the highest concentration of P in grain occurs when there is adequate supply of S.

**Genetics for S efficiency**
In New Zealand wheat, grain quality parameters associated with baking quality differ genotypically in their response to S and N fertiliser (Luo et al 2000). Similarly, Australian cultivars from the 1970s differ in their responsiveness to S nutrition in terms of S concentration in the grain, grain weight and grain numbers (Archer 1974). In addition, there is genetic diversity in grain S concentration in wild emmer wheat (Triticum turgidum ssp. Dicoccoides); a species that is compatible for crossing with bread wheat and durum wheat. Sulphur concentration in the wild wheat is higher than in Australian cultivars ranging from approximately 0.18% - 0.3% S (Chatzav et al 2010). Recent Australian cultivars are not identified in the literature for differing sulphur use efficiency or their ability to accumulate S in grain. Cultivars grown under farmer practices in south-eastern Australia in 2008/2009 show no cultivar differences in S concentration in the grain (Norton 2012).
Resources


Riley NG, Zhao FJ, McGrath SP (2002). Leaching losses of sulphur from different forms of sulphur fertilizers: a field lysimeter study. Soil Use and Management 18, 120-126.


