Sulfur for Plant Nutrition

By Rob Norton, Robert Mikkelsen and Tom Jensen

Sulfur (S) is essential for plant nutrition, but its concentration in plants is the lowest of all the macronutrients. Plants are able to assimilate sulfate and reduce it to essential amino acids, where S is involved in a range of metabolic functions, including protein synthesis. Greater attention needs to be paid to the role of S in balanced crop nutrition in many global regions.

Sulfur is an essential macronutrient for plants and animals, and is required for many important metabolic functions. Plants are able to convert sulfate (SO_4^{2-}) into organic compounds, but animals must consume S-containing amino acids (methionine and cysteine) for their dietary requirement.

The need for S in crops has taken a higher profile in recent years as many farming systems have fewer S inputs than previously. Higher crop yields, slower organic matter turnover, reduced use of S-containing crop inputs, and changing crop patterns have also contributed to the need for additional S fertilization.

While most S in soils is present in organic matter, soluble sulfate is present in most soils and is the primary source of S nutrition for plants. It is actively transported into the root, especially in the root hair region, and moves into plant cells through a variety of sulfate transporters. Within the plant, sulfate moves in the transpiration stream until it is stored in cell vacuoles or participates in a variety of biochemical reactions. Leaves are also able to assimilate sulfur dioxide (SO_2) from the atmosphere, but this amount is usually no more than 1 kg S/ha/yr. Plant leaves can also emit hydrogen sulfide (H_2S) gas, which is assumed to be a type of detoxifying mechanism after exposure to high SO_2.

Most of the sulfate taken up by roots is converted to cysteine in leaf chloroplasts. Cysteine is the primary starting point from which most other organic S compounds in plants are formed. This synthesis process begins with sulfate reduction to adenosine phosphosulfate and ultimately to various S-containing organic compounds (**Figure 1**). Sulfate reduction requires considerable plant energy. Other important S amino acids include the amino acids cystine (a linkage of two cysteine molecules), and methionine (**Figure 2**). Smaller amounts of S are incorporated into important molecules such as coenzyme A, biotin, thiamine, glutathione, and sulfolipids.

Once sulfate is converted to organic compounds, they are exported through the phloem to the sites of active protein synthesis (esp. root and shoot tips, fruits and grains) and then become largely immobile within the plant. The symptoms of S deficiency occur first in the younger tissues and are seen as leaves and veins turning pale green to yellow. These chlorosis symptoms look similar to those that occur with N deficiency, but because of its higher internal mobility a low N supply becomes first visible in the older leaves. When S deficiencies are first observed, some crops may not entirely recover the lost growth following S fertilization.

There are a large number of secondary S compounds that provide biochemical benefit to specific plant species. Some crops (e.g. *brassicas* such as canola and mustard) have a relatively high S requirement and produce glucosinolate compounds. Members of the *Allium* species (e.g. garlic and onions) produce alliin compounds that may contain >80% of the total plant S. The characteristic flavor and smell of onions and garlic related to these volatile S compounds are enhanced when plants are grown in high S soil. These and other S-containing compounds are linked with resistance to various pests and environmental stress.

Abbreviations and notes: N = nitrogen; Cu = copper; Fe = iron, Mn = manganese; Mo = molybdenum; Ni = nickel; Se = selenium; Zn = zinc.

Sulfur deficiency in wheat. The inset image compares a normal leaf (right) to a deficient leaf (left). (Sharma and Kumar, 2011).

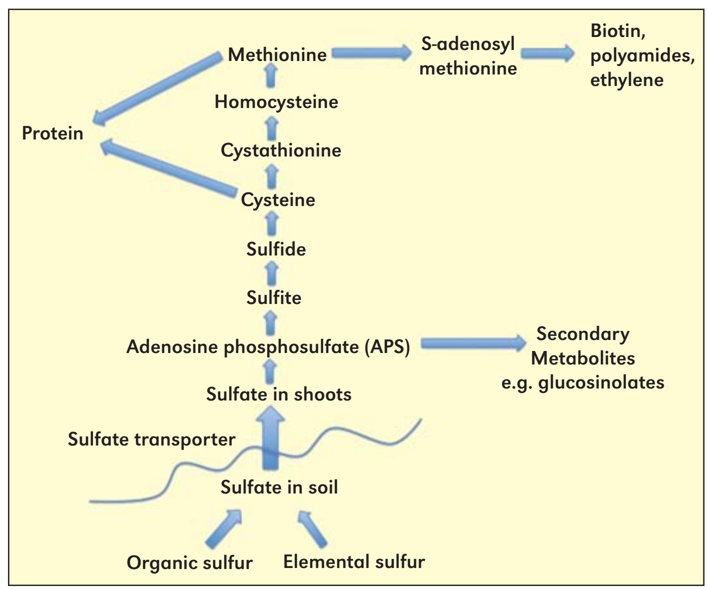

Figure 1. The general process of sulfate reduction and assimilation in plants. (Adapted from Hawkesford, 2012)

Crop Sulfur Requirement

Crops differ widely in their S requirement, with plant dry

Table 1. Sulfur removal in the harvest portion[1] of some typical crops. Grain values are at 10% moisture content.

Cereals	kg S/t	lb S/unit[2]	Oilseed	kg S/t	lb S/unit
Wheat	1.4	0.084 (bu)	Canola	5.0	0.25 (bu)
Barley	1.2	0.058 (bu)	Sunflower	1.7	0.17 (cwt)
Corn	1.1	0.062 (bu)	Cottonseed	2.9	0.29 (cwt)
Rice	0.9	0.041 (bu)	Flaxseed	2.0	0.11 (bu)
Pulses	**kg S/t**	**lb S/unit**	**Other Crops**	**kg S/t**	**lb S/unit**
Soybean	3.5	0.21 (bu)	Sugarcane (fresh wt.)	0.26	0.52 (ton)
Chickpea	1.8	0.11 (bu)	Alfalfa Hay (13% moist)	2.6	5.2 (ton)
Field Pea	2.1	0.12 (bu)	Grass silage (fresh wt.)	2.2	4.4 (ton)
Lentil	1.4	0.08 (bu)	Hops (dry)	3.6	7.2 (ton)

[1]The unharvested portion of the plant may contain as much or more S than the harvested crop.
[2]Unit of yield shown in parentheses.
Source: National Land and Water Resources Audit, 2001.

matter concentrations typically between 0.1 and 1% S. The S requirement is typically greatest for *brassicas* (such as cabbage, broccoli and rapeseed), followed by legumes, and then by cereal grasses.

The S demand will vary during the growing season. For example, S demand for canola is greatest during flowering and seed set. Uptake of S by maize is fairly constant through out the growing season, with grain accounting for >50% of the total S accumulation. Wheat may lose up to half of the total plant S between flowering and maturity. Each crop species needs to be examined for its specific nutrient requirement (**Figure 3**).

Removal of S during crop harvest is typically in the range of 10 to 30 kg S/ha depending on the crop and yield, but total plant uptake can be as high as 70 kg S/ha for some *brassica* species (**Table 1**).

Crop Quality

Crops grown in S-deficient soils can suffer reduced yields as well as poor product quality. An adequate S supply is a major factor in supporting plant protein quality, where it plays a major factor in the structure and function of enzymes and proteins in leafy tissues and seeds. For example, an adequate supply of cysteine plays a central role in giving cereal proteins their shape and functional properties. Because of this, bread baked with low-S wheat will not rise, and results in dense and poorly shaped loaves.

Sulfur Interactions

Because of the importance of both S and N in protein synthesis, these nutrients are intimately linked and are often considered to be co-limiting. It has been established that for every 15 parts of N in protein, there is approximately 1 part of S (i.e., 15:1 ratio of N:S). However this general guide will vary for different crops. For example, wheat grain has an N:S ratio of around 16:1, while the N:S ratio for canola seed is around 6:1.

Other crops such as wheat, sugar beet and peanut are generally considered to have a low S demand. There are many examples of how an adequate supply of both S and N are required to achieve desired yields (**Figure 4**). Sulfur deficiencies in legumes also decrease proper N utilization, since the number of root nodules and the effectiveness of atmospheric N fixation are reduced with low S.

An over-reliance on the N:S ratio for diagnostic purposes

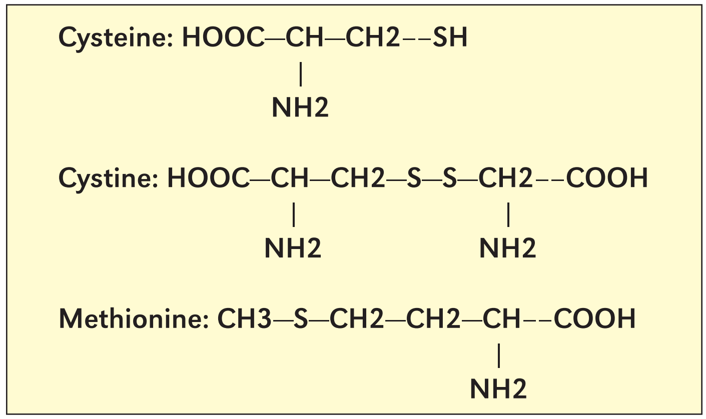

Figure 2. Three essential S-containing amino acids.

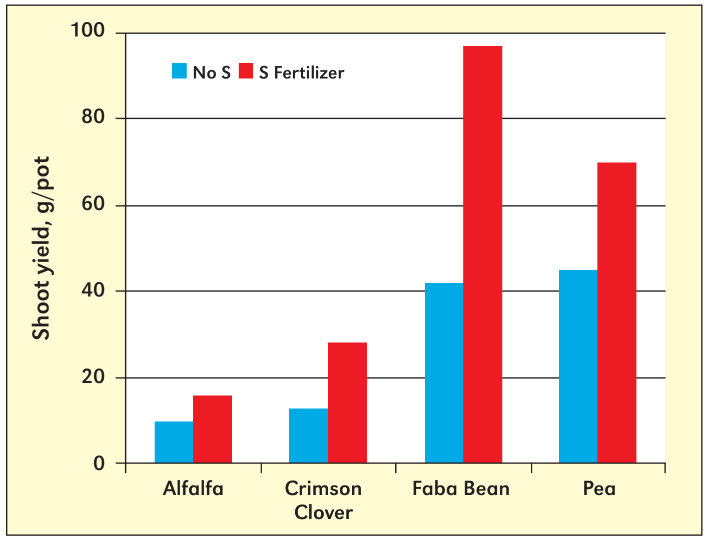

Figure 3. An adequate S supply improves the yield of alfalfa, crimson clover, faba bean, and pea. (Adapted from Lange, 1998).

can be misleading because this ratio can be maintained even when both N and S are both low. Also, an excess of either N or S can be falsely misinterpreted as a deficiency of the other.

An inadequate S supply will not only reduce yield and crop quality, but it will decrease N use efficiency and enhance the risk of N loss to the environment. Studies have demonstrated that supplying S to deficient pastures increased yields, N use efficiency, and lowered N losses from the soil. Due to the close linkage between S and N, Schnug and Haneklaus (2005) estimated that one unit of S deficit to meet plant demand can result in 15 units of N that are potentially lost to the environment. They calculated that S deficiencies in Germany may be contributing to an annual loss of 300 million kg of N (or 10% of the total N fertilizer consumption of the country).

Sulfur fertilization is known to induce Mo deficiency at high application rates. This is due to antagonism between sulfate and molybdate (MoO_4^{2-}) during root uptake as they compete for root membrane transporters. Coincidentally, Mo is an essential component of an enzyme that regulates the formation of organic S. Sulfur and Se (especially selenate, SeO_4^{2-}) are also antagonistic for essentially the same reason. Sulfur fertilization on soils with normally sufficient Se can reduce the pasture Se concentration, with consequences for grazing animals requiring adequate dietary Se. Sulfate additions have been shown to be an effective method of reducing the uptake by plants of

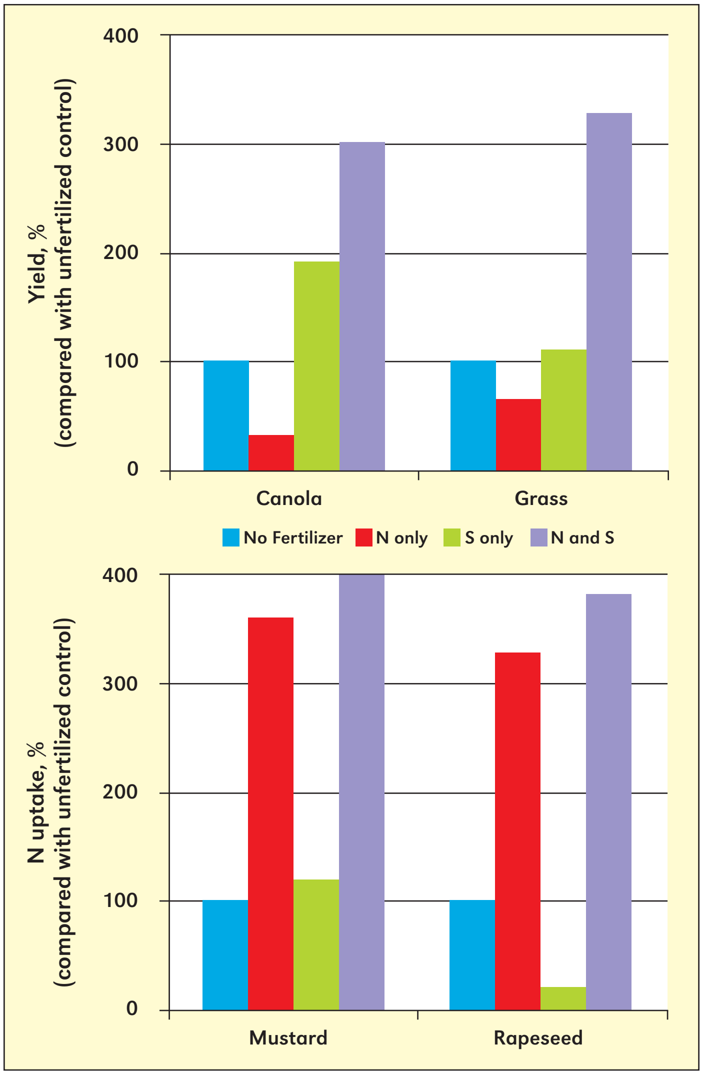

Figure 4. The influence of fertilization with N or S alone, or their combined benefit, on crop yield (top) and plant N uptake (bottom). (Aulakh and Malhi, 2004).

other elements in contaminated soil. However, fertilization with elemental S can stimulate the uptake of metal micronutrients (i.e., Cu, Mn, Zn, Fe, and Ni) due to rhizosphere acidification as S oxidation occurs.

Sulfur Management using the 4R Nutrient Stewardship Principles

The 4R Nutrient Stewardship principles (Right Source of nutrient applied at the Right Rate, Right Time, and Right Place) apply to all plant nutrients. Since S can be supplied from many different sources, including animal manures, the 4R principles help with efficient nutrient delivery. As an example of these 4R concepts, ammonium sulfate [Source] is commonly used in the seed-row [Place] of small-seeded crops at planting [Time], but fertilizer additions [Rate] must be low to reduce the risk of ammonia (NH_3) damage, especially with wide rows and when grown in dry and sandy soils. The following are considerations in applying the 4R Nutrient Stewardship principles to properly supply S for crop nutrition.

SOURCE: Sulfur fertilizers contain either soluble sulfate or a form of S that will be converted to sulfate. An estimate must be made of the time that will be required for conversion of insoluble S to plant-available sulfate. A variety of excellent dry and fluid fertilizers that contain various forms of S are available for blending or direct application. A combination of soluble sulfate and elemental S may be useful to provide both an immediate and a prolonged source of plant nutrition. The particle size of elemental S can be a key property for making this estimate, as smaller S particles tend to oxidize to sulfate more quickly than large particles.

TIME: Sulfate sources of fertilizer can be applied to match the time of crop demand since they are readily available. However elemental S must be applied far enough in advance of the crop need to allow microbial oxidation. In areas with cold winter temperatures, application may need to precede plant uptake by many months. The release of sulfate from soil organic matter and crop residues will proceed more quickly in warm soils and can supply significant amounts of S during the growing season. A constant supply of soluble sulfate is required by most plants.

PLACE: Placement of sulfate fertilizers in a band near the seed row of annual crops can be quite effective. However, avoid large amounts of sulfate in direct contact with seedlings to avoid osmotic damage to roots. Since sulfate is fairly mobile in soil, it will tend to move with water through the root zone. Elemental S is most effective when broadcast onto the soil and tilled into the ground. In flooded soils, elemental S is best left at the surface so it can be converted to sulfate in the thin aerobic zone at the soil-water interface.

RATE: Sulfur application rates should be adjusted for the crop demand, soil conditions (such as soil texture and organic matter content), and environmental factors (such as temperature and rainfall). Sulfur applications are commonly adjusted to account for multi-year crop rotations. For example in a canola-barley-wheat rotation in Western Canada, the high S demand by canola can be met with a single S application to supply nutrition over the three-year cycle.

An adequate supply of S is required for sustaining crop yields and quality. Inadequate S will reduce protein synthesis and will result in poor utilization of applied N and reduced N_2 fixation by legumes. Application of the 4R Nutrient Stewardship principles will identify the need for supplemental S to overcome potential limitations to plant nutrition. BC

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