ASPECTS OF AGRONOMICAL AND PHYSIOLOGICAL RESEARCH ON SULFUR DEFICIENCY IN AGRICULTURAL CROPS

Elke Bloem, Silvia Haneklaus, Susanne Schroetter and Ewald Schnug

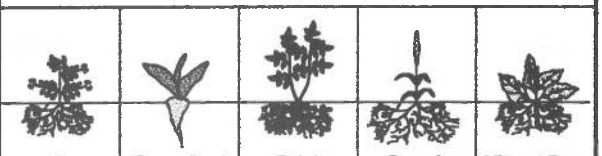
Institute for Pflant Nutrition and Soil Science, FAL
Bundesallee 50, 38116 Braunschweig, Germany

In northern Germany severe sulfur (S) deficiency symptoms were first observed in the beginning of the 80´s in oilseed rape and ten years later in cereals, because of continuously decreasing atmospheric S depositions and changes in fertilizer practice [29,30]. In 1999 severe S deficiency was observed in sugar beet under field conditions [35]. A comprehensive description of macroscopic S deficiency symptoms in different crops is given by Schnug and Haneklaus [29,34] and Schnug et al. [35] and is available on the world wide web (www.pb.fal.de).

The most common methods for the determination of the S nutritional status are soil (S_{min}) and plant analysis (total S, SO_4-S, glutathione). The plant available SO_4-S in the soil is commonly used to evaluate the S nutritional status but the spatial and temporal mobility of SO_4-S is a major handicap for the use of these values for a prognosis of the S supply [3,34]. Leaching [e.g. 20,36] and import of SO_4-S from subsoil or shallow groundwater sources [3,10] may change the amount of plant available SO_4-S within a very short time span. Plant analysis (total S) is a well adopted method for the determination of the S status of crops but practically not applicable due to possible contamination by foliar application of S containing products and the short time span between sampling and fertilization [16,34,37].

MOPS (MOdel for the Prognosis of S deficiency) is a model which integrates all relevant soil and crop parameters for the prognosis of S deficiency [3,4]. The key variables are: soil hydrology, soil texture and climatic conditions, especially the amount of precipitation during winter, the actual S need of the crop, the possibility of capillary rise of soil and ground water, respectively during the vegetation period, and irrigation with S containing ground water (Fig.1). The risk of S deficiency is generally higher on light textured soils with a deep ground water level and is especially promoted by high rates of leaching. MOPS works without elaborate soil or plant analysis and provides information on the S status early enough for fertilization. Future research will focus on the generation of nationwide site-specific risk maps for S deficiency and S fertilization based on MOPS. The suitability of S containing secondary raw materials as a S source were tested in long-term field experiments [22,23] and possible side effects such as the possibly detrimental effect of sulphite on plant growth or contamination with inorganic xenobiotics were studied. Different types of S fertilizer (oxidized S or elemental S fertilizer as soil or foliar application) were compared with view to their efficiency, best application technique and optimum timing.

An increasing problem in agriculture is the enhancement of S deficiency where Tebuconazol (0.063 ml/l) was applied for regulating growth as it apparently reduces not only the growth of the above-ground vegetative plant parts but also root depth and density (Fig. 2). Reduced root growth limits the ability of the plant to explore the soil spatially for available S and hampers its access to S resources in sub-soil water, respectively (see above). First results indicate that this effect is also consistent in the crop rotation.

Parameter	Risk of S deficiency: Low → High				
Crop	 Pea	Sugar Beet	Potato	Cereals	Oilseed Rape
Total S uptake [kg ha⁻¹] [*1]	~10	10 - 20	20 - 30	15 - 40	40 - 100
Symptomatological value [mg g⁻¹] [*2]	1 - 1.2	1.7 - 2.1	1.7 - 2.1	1.2	< 3.0 (0) < 3.5 (00)
Critical value for max. yield [mg g⁻¹] [*2]	~ 3.0	3.5 - 4.0	~ 4.0	4.0	6.5
Texture	Loam ←→ Loamy Sand ←→ Sand				
Climate	Low Winter Precipitation < 200 mm ←→ 300 mm ←→ 400 mm ←→ 500 mm ←→ >500 mm High Winter Precipitation				
	Low Precipitation during summer ETP >> P [*3] ←→ High Precipitation during summer P >> ETP [*3]				
Ground water	Ground water near surface (~1.5 m below) ←→ Ground water >2.5-3 m below surface				

[*1] Data:[3,23]; [*2] Data:[17, 29, 34]; [*3] ETP=Evapotranspiration, P= Precipitation

Fig. 1. Key parameters of the model for the prognosis of S deficiency (MOPS) on agricultural soils.

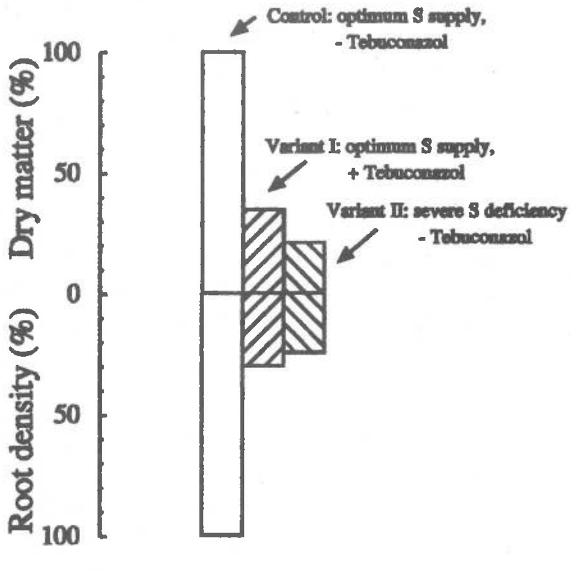


Fig. 2. Influence of a fungicide used for regulating growth (Tebuconazol) and S supply on relative dry matter production and root density of a single low spring oilseed rape variety (cv. NIKLAS). Experimental design: sand culture in Mitscherlich pots (10 kg/4 plants); S fertilization: 100 mg/pot; N

fertilization: 750 mg/pot); harvest and root density determination after 90 days.

The comparison of oxidized and elemental S sources applied in foliar form revealed high rates of uptake and transport of foliar applied S [32]. This does, however, not necessarily imply that the SO_4-S is physiologically available for plants as excess SO_4-S applied in oxidized form was mainly trapped in vacuoles from which only very little re-translocation is possible [e.g. 1,8]. Foliar applied elemental S released SO_4-S slowly due to the oxidation process and thus provided the plant with a smaller, but continuous amount of SO_4-S which could be utilized in metabolic processes.

The re-utilization of S bound in gluscosinolates (GSL) obviously plays an important role in plant metabolism under conditions of an insufficient S supply [28]. GSLs can be re-cycled whereby the ascorbate/glutathione cycle is involved in the trigger mechanism. The ascorbic acid concentrations in cells regulates the activity of the enzyme myrosinase [2] and thus the cleavage of GSLs. Increasing GSL and GSH levels in the plant tissue could be observed with increasing S supply [31]. The validity of this hypothesis on the bio-recyclisation of GSL is strongly supported by the fact that old, 0 oilseed rape varieties show a lower symptomatological value (3.0 mg/g S) than 00 varieties (3.5 mg/g S) [24,29; Fig. 1].

S deficiency will not only cause yield losses [6,29] but also has a great influence on crop quality parameters such as protein content and protein composition [9]. The baking quality of wheat is closely related to the S supply of the crops: elasticity and resistance against extensibility of the dough is related to concentration of S containing amino acids and glutathione in the gluten fraction since they are responsible for the linkages between protein molecules [15,27]. Especially in organic farming, where additives are not permitted in the baking process, farmers regularly cannot meet quality requirements for breadmaking wheat due to an insufficient S supply [13,14].

Non-protein N is accumulated in plant parts under conditions of S deficiency; Schnug [25] showed for instance that nitrate accumulated in leaf tissue of cabbage with decreasing S supply and increasing N level.

The S supply is closely related to the content of secondary S containing compounds, e.g. alliins and glucosinolates (GSL). (Iso)Alliins are secondary metabolites of garlic and onions and the alliine content - a criteria for taste and medical value - is positively correlated with the S supply [19]. For industrial production of natural medical health products it is important to maintain a high and constant level of the active agent. Tropaéolum május is used as a herbal product against infections of the urethra. In a collaborative research project with the Technical University Braunschweig (Prof. Dr. Selmar, Prof. Dr. Winterthaler) production techniques for Tropaéolum május are investigated in order to produce crops with a high and constant level of intact GSL for manufacturing phyto-pharmaceutics.

In other crops such as Brassica napus high GSL contents in the extracted rapeseed meals have a thyroid effect when used in animal nutrition [11,26]. In comparison high GSL contents in mustard are favourable [18] as they increase the sharpness of taste.

Cyclic disulphides are S containing secondary metabolites of Aspáragus officinális. First results of a collaborative research project (Prof. Dr. Mueller, Dr. Blankenburg, College Erfurt) reveal that the total S content in Asparagus was significantly increased by the S fertilization. Further organoleptic and chemical analyses (e.g. asparagic acid) shall reveal relationships with the taste of the crop.

The distribution of GSL in different plant organs (pods, seeds, stems, roots) of 0 and 00 oilseed rape varieties in dependence on the S supply is studied under field conditions. In a project with colleagues from the University of Essen (Prof. Dr. Pfanz) samples from these experiments are used in a feeding experiment with slugs whereby increasing GSL levels have a repellent effect on intake.

S supply and S metabolism of agricultural crops are supposed to play an important role in the natural resistance against pests and diseases. S metabolism provides several mechanisms by which plants are able to tackle with abiotic and biotic stress. For example, the release of volatile S compounds [e.g. 12], the glutathione pathway [21], the production of S rich proteins [5], localised deposition of elemental S [7], and the production of phytochelatines (S containing peptides) which detoxify heavy metals [33]. A better knowledge on the significance of S metabolites in crop resistance to diseases will be beneficial for the improvement of S fertilizer strategies and will therefore minimize the input of pesticides. First results on investigations of different oilseed rape genotypes revealed significant differences in the total S content and differences in the activity of L-cysteine desulfhydrogenase, an enzyme responsible for the release of H_2S in the living plant (Papenbrock et al., unpublished data).

References

1. Bell, R.W., Rerkasem, S.K.K., Phechawee, N., Hiranburana, S., Ratanarat, S., Pongsakul, P., Loneragan, J.F. 1990: Mineral nutrition of nofood legumes with particular reference to micronutrients. ACIAR Technical Reports 16, 39-41.
2. Bjoerkmann, R. 1976: Properties and function of plant myrosinases. In: Vaughan et al. (Ed.) The biology and chemistry of the cruciferae. Acad. Press London pp. 191-206.
3. Bloem, E. 1998: Schwefel-Bilanz von Agraroekosystemen unter besonderer Beruecksichtigung hydrologischer und bodenphysikalischer Standorteigenschaften. PhD thesis, TU-Braunschweig, Germany, 156 pp.
4. Bloem, E., Haneklaus, S., Daemmgen, U., Schnug, E. 1999: Sulphur Balance in Agroecosystems and its Implementation into a Model for the Prediction of Sulphur Deficiency. Z. Pflanzenernaehr. Bodenk. (submitted).
5. Bohlmann, H. 1993: Significance of sulfur rich proteins in seeds and leaves. In: Sulfur nutrition and assimilation in higher plants. (Ed. De Kok et al.), SPB Acad. Publ., The Hague, pp. 211-220.
6. Booth, E., Walker, K.C., Schnug, E. 1991: The effect of site, foliar sulfur and nitrogen application on glucosinalate content and yield of oilseed rape. Proc. Int. Rapeseed Cong., Saskatoon 2, 567-572.
7. Cooper, R.M., Resende, M.L.V., Flood, J., Rowan, M.G., Beale, M.H., Potter, U. 1996: Detection and cellular localization of elemental sulphur in disease-resistant genotypes of Theobroma cacao. Nature 379, 159-162.
8. Cram, W.J. 1990: Uptake and transport of sulfate. In: Sulfur nutrition and sulfur assimilation in higher plants (Ed. Rennenberg et al.) , SPB Acad. Publ., The Hague, pp. 3-11.
9. Eppendorfer, W.H., Eggum, B.O. 1994: Dietary fibre, starch and amino acids and nutritive value of potatoes as affected by sulfur, nitrogen, phosphorous, potassium, calcium and water stress. Acta Agric. Scand. Sect. B. Soil and Plant Sci. 44, 1-11.
10. Eriksen, J., Murphy, M.D., Schnug, E. 1998: The soil sulphur cycle. In: Sulphur in Agroecosystems (Ed. E. Schnug), Kluwer Academic Publ., Dordrecht, pp. 39-73.
11. Gruenewald, K.H., Spann, B., Obermaier, A. 1995: Einsatz von Rapssaat in der Milchviehfuetterung. VDLUFA-Schriftenreihe 40, 453-456.
12. Grundon, N.J., Asher, C.J. 1986: Volatile losses of sulfur by intact alfalfa plants. J. Plant Nutrition 9, 1519-1532.
13. Hagel, I., Schnug, E. 1999: Proteinfraktionen und Schwefelgehalte von Winterweizen aus konventionellem und biologisch dynamischem Anbau des Erntejahres 1997. Proc. XXXIV., DGQ-Tagung, Freising-Weihenstephan, 335-340.
14. Hagel, I., Wieser, H., Schnug, E. 1999: Wirkungen hoher Schwefelgaben auf Mineralstoffgehalte, Proteinfraktionierung und Kleberqualität von Weizen aus biologisch dynamischem Anbau. Proc. XXXIV. DGQ-Tagung, Freising-Weihenstephan, pp. 329-334.
15. Haneklaus, S., Evans, E., Schnug, E. 1992: Baking quality and sulphur content of wheat I. Influence of grain sulphur and protein concentration on loaf volume. - Sulphur in Agriculture Vol. 16, 31-35.
16. Haneklaus, S., Murphy, D.P.L., Nowak, G.A., Schnug, E. 1995: Effects of the timing of sulphur application on grain yield and yield components of wheat. Z. Pflanzenernaehr. Bodenk. 158, 83-85.
17. Haneklaus, S., Schnug, E. 1998: Minimum factors for the mineral nutrition of field grown sugar beet in northern Germany and eastern Denmark. Aspects of Applied Biology 52, 57-64.
18. Haneklaus, S., Paulsen, H.M., Gupta, A.K., Bloem, E., Schnug, E. 1999: Influence of sulfur fertilisation on yield and quality of oilseed rape and mustard. Proc. 10th Int. Rapeseed Congress, Sept. 26-29, 1999, Canberra, (CD-ROM).

19. Hoppe, L., Bahadir, M., Haneklaus, S., Schnug, E. 1996: Sulphur Supply and Alliin Content of Allium Species. In: Deutsche Gesellschaft fuer Qualitaetsforschung (Pflanzliche Nahrungsmittel) e.V. (Ed.): 31. Vortragstagung in Kiel, pp. 189-192.
20. Kuehn, H., Weller, H. 1977: 6 jaehrige Untersuchung ueber Schwefelzufuhr durch Niederschlaege und Schwefelverluste durch Auswaschung (Lysimeter). Z. Pflanzenernaehr. Bodenk. 140, 431-440.
21. Lamoureux, G.L., Rusness, D.G. 1993: Glutathione in the metabolism and detoxification of xenobiotics in plants. In: Sulfur nutrition and assimilation in higher plants. (Ed. De Kok et al.), SPB Acad. Publ., The Hague, pp. 221-237.
22. Paulsen, H.M., Haneklaus, S., Schnug, E. 1996: Use of SDA-products from coal fired power plants as a sulphur source in agriculture. Proceedings of the 10th International CIEC Symposium: Recycling of Plant Nutrients from Industrial Processes, pp. 215-223.
23. Paulsen, H.M. 1998: Produktionstechnische und oekologische Bewertung der landwirtschaftlichen Verwertung von Schwefel aus industriellen Prozessen. Dissertation, TU-Braunschweig.
24. Schnug, E. 1988: Quantitative und qualitative Aspekte der Diagnose und Therapie der Schwefelversorgung von Raps (*Brassica napus* L.) unter besonderer Beruecksichtigung glucosinolatarmer Sorten. Habilitationsschrift (Dsc thesis) Agrarwiss. Fakultät der Christian-Albrechts-Universität zu Kiel Dezember 1988.
25. Schnug, E. 1990: Sulphur Nutrition and Quality of Vegetables. Sulphur in Agriculture 14, 3-7.
26. Schnug, E. 1990: Glucosinolates-fundamental, environmental and agricultural aspects. In: Sulfur nutrition and sulfur assimilation in higher plants, (Ed. Rennenberg et al.), SPB Acad. Publ., The Hague, pp. 97-106.
27. Schnug, E.; Haneklaus, S., Murphy, D.P.L. 1992: Impact of sulphur supply on the baking quality of wheat. - Aspects of Applied Biology. Cereal Quality 36 (1993), pp. 337-345.
28. Schnug, E., Haneklaus, S. 1993: Regulation of glucosinolate biosynthesis in oilseed rape by nutritional factors. GCIRC Bull.
29. Schnug, E., Haneklaus, S. 1994: Sulphur Deficiency in Brassica Napus- Biochemistry- Symptomatology- Morphogenesis-. Landbauforschung Voelkenrode, Sonderheft 144.
30. Schnug, E., Haneklaus, S., 1994: Ecological aspects of plant sulphur supply. Proc.15th Int. Congr. Soil Sci. Acapulco/ Mexico, Vol. 5a, Comm.IV, Symposia, pp. 364-371.
31. Schnug, E., Haneklaus, S., Borchers, A., Polle, A. 1995: Relations between sulphur supply and glutathione and ascorbate concentrations in *Brassica napus*. - Z. Pflanzenernähr. Bodenk. 158, 67-69.
32. Schnug, E., Paulsen, H.-M., Untiedt, H., Haneklaus, S. 1995: Fate and physiology of foliar applied sulphur compounds in Brassica napus. Proc. IAOPN Symposium 10.-14.12.1995 in Cairo (Egypt), pp. 91-100.
33. Schnug, E. 1997: Significance of sulphur for the quality of domesticated plants. In: Sulfur Metabolism in Higher Plants (Ed. W.J. Cram), Backhuys Publishers, Leiden, The Netherlands, pp. 109-130.
34. Schnug, E., Haneklaus, S. 1998: Diagnosis of sulphur nutrition. In: Sulphur in Agroecosystems (Ed. E. Schnug), Kluwer Academic Publ., Dordrecht, pp. 1-38.
35. Schnug, E., Bloem, E., Haneklaus, S., 1999: Schwefelmangelsymptome in Zuckerrueben. Zuckerruebe (in prep).
36. Widdowson, J.P., Blakemore, L.C. 1982: The sulphur status of soils of the south-west Pacific area. Proc. of the Conference, London 2 (Internat. Sulphur Conference), pp. 805-819.
37. Zhao, F., McGrath, S.P., 1997: Importance of sulphur in UK agriculture. In: Sulfur Metabolism in Higher Plants (Ed. W.J. Cram), Backhuys Publishers, Leiden, The Netherlands, pp. 347-348.