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Hans-Marten Paulsen

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Hans Marten Paulsen[1]

Abstract

Beyond the natural role of sulfur as plant nutrient, in organic farming it is an important fungicide and acaricide. S as plant nutrient has to be kept at a sufficient level because it can help in saving nitrogen and in reducing nitrogen leaching. S influences the nitrogen fixation of legumes, which is the essential microbiological process for plant production in organic farms. S is determining quality aspects of feedstuffs and other products. An adequate S nutrition of plants is therefore essential. But in organic farming practice negative S balances are found. To decide about fertilization needs, organic farmers need to know about S flows in soils, S supply to plants, necessary S contents in plants and also about S availability in soils, in organic materials and in different fertilizers. Various S-containing fertilizers are approved in organic farming and could be used to correct S imbalances. Due to its low S content and low S availability manure application is of low importance for the S nutrition of plants.

Keywords: Acaricide, elemental sulfur, fertilizers, fungicide, organic farming, sulfur fertilization, sulfur fertilizers

Introduction

In organic farming the input of chemo-synthetic fertilizers is forbidden. Sulfur (S) in organic farms can be supplied together with S containing approved fertilizers or raw S from natural sources. Even if S deficiencies in plant nutrition are reported in conventional agriculture, S fertilization in organic farms is not of practical importance up to now.

In organic farming the use of pesticides is strictly limited to natural sources and has to be certified by the control bodies in advance (IFOAM 2002; EU, 1991). S used as fungicide and acaricide is of special importance in organic vine- and pomefruit-production. In the following article the importance of S, S balances and S use in organic agriculture are reviewed and described. The legal base used for the discussion and description is the Council Regulation (EEC) No 2092/91 of 24 June 1991 on organic production of agricultural products and indications referring thereto on agricultural products and foodstuffs (EU, 1991).

Sulfur as fungicide and acaricide

Limiting legislation on pest-, disease- and weed-control in organic farming is given as guideline of worldwide validity by the IFOAM Basic Standards of Organic Production and in European law by the Council Regulation (EEC) No 2092/91 of 24 June 1991 (EU, 1991). Additional restrictions are given by different organic grower associations in the whole world, which are listed in Willer and Youseffi (2004). According to the EEC 2092/91 pests, diseases and weeds shall be controlled by a combination of the following measures: Choice of appropriate species and varieties, appropriate rotation program, mechanical cultivation procedures, protection of natural enemies of pests through provisions favorable to them (e.g. hedges, nesting sites, release of predators) and flame weeding. Only in cases of immediate threat to the crop may recourse be had to direct measures with products referred to in Annex II of the regulation. In organic viniculture, organic fruit and vegetable growing elemental S (S^0) is a main and essential agent of plant protection to keep the internal and external quality (Palm and Klopp, 2004; Kienzle, 2004; Hofmann, 2004; Table 1).

Table 1:
Target organisms for elemental S (S^0) application and common doses used in organic vine- and pomefruit production according to Palm and Klopp, 2004; Kienzle, 2004; Hofmann, 2004.

S^0 as fungicide:
Powdery mildew in vine (*Uncinula necator*, *Oidium tuckeri*) Powdery mildew in tomatoes (*Oidium lycopersicum*) Apple scab, pear scab (*Venturia spp.*) Cherry leaf spot (*Blumeriella jaapii*) Leaf rust on plum (*Tranzschelia pruni spinosae*)
S^0 as acaricide:
Pear bud, grape bud (*Eriophyes piri*, E. viti) Rust mite in vine (*Phyllocoptes vitis*)
S^0-dosage per year:
Pome fruits: 21-27 kg S^0 per meter crown height divided in up to 30 applications Vine: up to 9 applications between 3.6 an 4.8 kg ha^{-1}

[1] Institute of Organic Farming, Federal Agricultural Research Station (FAL),Trenthorst 32, 23847 Westerau, Germany

Winkler and Stein (2004) summarized risk assessments and findings for S^0 in the environment when used as plant protection agent as follows. S^0 has low toxicity for mammals, birds and fish and high no-observed-effect-concentration (NOEC) values for plants. Soil application of 10 and 100 kg ha^{-1} S^0 lowered N- and C-mineralization. The legislative limit of a level of 75 % of the N- and C-mineralization in S^0-treated soil in comparison to untreated soil after 100 days was reached after 14 and 66 days respectively. S^0 is relatively immobile in soils and is leached as sulfate (SO_4) after incorporation and oxidation in the soil sulfur cycle. S^0 is hydrophobic and nearly not watersoluble. When reaching surface waters it is incorporated in the soil after sedimentation. Additional SO_4-loads to waters from oxidation under aerobic conditions are irrelevant under consideration of natural water contents. S^0 is toxic for green algae (e.g. *Scenedesmus subspicatus*) and water fleas (e.g. *Daphina magna*). Therefore safe distances to waters are necessary when S^0 is applied. S^0 is toxic for different non-target terrestial arthropodes (e.g. *Trichogramma cacoecie*) but further studies on the toxicity of S^0 for arthropodes are necessary. Due to this restricted knowledge on the effects of S^0-application on non-tagret-terrestial arthropods, Winkler and Stein deduced, that a final risk assessment for S^0 in the environment according to the rules of the German plant protection law (PflSchG, 1998) is not possible at the moment. Several S^0-products have a new admission for the use as plant protection agent. Even if in organic farming legislation no limits in dosage is given, German organic farmers have to keep to the application restrictions of the German plant protection act. But a natural limit on S^0 application used as acaricide e. g. in organic apple production is set by biological balances because high S^0 doses are killing beneficial mites (e.g. *Amblyseius spp*.) as well. Those mites are natural predators of spider mites that are non controllable in organic farming (Palm and Klopp, 2003) and are urgently needed to keep a natural balance.

But still S^0 as fungicide is of high importance in organic pest management and is an essential tool in organic vine and fruit production. The legal restrictions are under discussion but the lacks in knowledge on environmental effects have to be filled to ensure a reasonable future use of S^0 in organic agricultural systems (Kühne and Friedrich, 2003). Research on alternatives to S^0 as fungicide is focusing on direct measures like different plant strengtheners based on SiO_2, different plant extracts, milk products, $NaHCO_3$, lactic acid bacteria and other microorganisms and on resistant plants. As indirect control measures supporting of soil antagonist populations and removal of plant residues are reported (Berkelmann-Löhnertz and Kauer, 2003; Hofmann, 2003). S^0 used as acaricide in organic farming can not be substituted up to now (Pfeiffer, 2003).

Sulfur as plant nutrient

S is an essential plant nutrient influencing internal and external quality, plant growth, health and nutrient efficiency of agricultural crops. In plants S is involved in the composition of amino acids, in the determination of the protein content, in aspects of baking quality, in the formation of secondary plant components and pharmaceutical components, in the nitrogen metabolism of plants and in the resistance of plants against pests and diseases.

According to the Council Regulation (EEC) No 2092/91 the fertility and the biological activity of the soil must be maintained or increased, in the first instance, by the cultivation of legumes, green manures or deep-rooting plants in an appropriate multi-annual rotation program, incorporation of livestock manure from organic livestock production and by incorporation of other organic material, composted or not, from holdings producing according to the rules of this regulation. Other organic or mineral fertilizers, mentioned in Annex II, may, exceptionally, be applied, as a complement to the extent that adequate nutrition of the crop being rotated or soil conditioning are not possible by the methods mentioned before. In organic farming S can be applied as a component of approved fertilizers (Table 2) to compensate expected or acute S deficiencies. S from sulfate (SO_4) sources is readily plant available whereas S^0 has to be oxidized in soil before plant uptake. The oxidation speed of S^0 is limited by high particle sizes (Fox et al., 1964, Gupta et al., 1998, Paulsen, 1999) and small populations of thiobacteria in soil (Schnug and Eckhardt, 1981).

Table 2:
Approved S containing fertilizers in organic farming according to the Council Regulation (EEC) No 2092/91.

Fertilizer	S content
Potassium sulfate	18 % SO_4-S
Kieserite*	22 % SO_4-S
Epsom salt	13 % SO_4-S
Gypsum (from natural sources)	14 % SO_4-S
Calcium carbonate with S (gypsum from natural sources)	2-4 % SO_4-S
Elemental S (from natural sources)*	80 % S^0-S

* Use has to be authorized by the inspection body

Table 3:
Dry matter- (DM), N- and S-contents of cattle slurry (n=14) and cattle farmyard manure (n=43) from organic farms in England (Shepherd et al., 2002).

	Slurry				Farmyard manure		
	Mean	Range	SD		Mean	Range	SD
DM (%)	7.9	1.0-12.0	3.57	DM (%)	21.0	13.0-38.0	5.83
Total N (kg m^{-3})	2.5	0.3-4.1	1.19	Total N (kg t^{-1})	5.2	2.9-7.8	1.16
S (kg m^{-3})	0,29	0.03-0.53	0.139	S (kg t^{-1})	0.8	0.3-1.8	0.30

Values expressed on a fresh volume or weight basis

Organic materials used in fertilization have low S contents and low S availability (Eriksen et al., 1995). Ranges of S and N contents of manure and slurry from organic farms in England were surveyed by Shepherd et al., 2002 (Table 3). The N/S ratios of slurry (1/0.12) and farmyard manure (1/0.15) are wide.

Furthermore the mineralization of organic S from organic materials added to soils is mainly dependent of the C/S ratio of the materials (Figure 1). From manures with C/S ratios between 430 and 735 between 47 % and 127 % from the organic S were mineralized to SO_4-S respectively. Mean values ranged between 5 % (horse manure) and 31 % (chicken manure). Digested materials had a relatively constant S mineralization of up to 97 %, decreasing with increasing C/S ratio (Tabatabai and Shae, 1991). According to the values given in Table 3 and figure 1 from 16 kg S applied together with 20 t farmyard manure per hectare only 2.6 kg S would be plant available. Farmyard manure and slurry therefore are only poor S sources in organic plant nutrition.

Due to the lower yield level in organic farms compared to conventional farming, S uptake and S demand of the crops are lower as well. Therefore S fertilization is not common in organic farms up to know. But S balances determined in a survey in Denmark (Table 4) are showing that normal organic crop rotations already have negative S balances (Erikson et al., 2002).

So it must be expected that in high S demanding crops or in years with favorable growth conditions and with high yield levels an insufficient S nutrition, at least in parts of the vegetation time, will likely to be occur in organic plant production as well. Because soil structure and water movement are determining the S supply to a large extent (Bloem et al., 1998) it is necessary to have a close look on site specific conditions influencing the S supply to plants.

Because organic farms rely on mineralized soil-nitrogen, temporary N-deficiency in early spring is widespread and can be mixed up with S deficiency symptoms (Schnug and Haneklaus, 1997). Therefore in organic farms for the identification of S deficiency expert knowledge is needed to avoid misinterpretations.

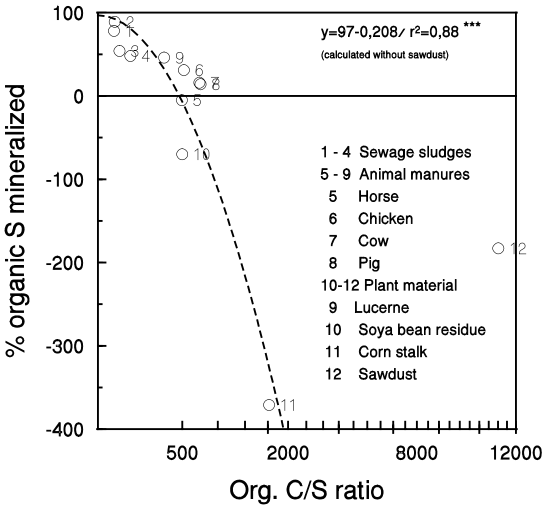

Figure 1:
Mineralization of organic S from waste materials with different C/S ratios added to soils. Mean values of five soils as difference between treated and untreated soil (after Tabatabai and Chae, 1991).

Additionally due to the lower yield levels in organic production critical nutrient thresholds for S and other plant nutrients extracted from field surveys and fertilization trials (Schnug et al., 1997, Haneklaus and Schnug, 1998; Bergmann 1993) have to be revised and must be adopted to yield expectations of organic production. Only an exact knowledge on S demands of crops grown in systems with lower yield expectations can result in an adequate S fertilization strategy in organic farms.

S and N nutrition of plants are metabolically linked (Hawkesford et al., 1994; Amâncio et al., 1998). In grassland and crops the application of S has been shown to increase the efficiency of N use by plants. Adequate S supply is increasing the N-recovery and reduces N losses from the system (Brown et al., 1999; Schnug and Haneklaus, 1994). So also in organic farming the control of the S nutri-

Table 4:
Sulfur balance (kg ha^{-1}) in an organic crop rotation as average of year, location and crop[a] (Eriksen et al., 2002).

	Input[b]			*Output*		*Balance*[c]
	Deposition	Manure	Irrigation	Plants	Leaching	
Year						
1997-1998	10	4	9	3	34	-13ab
1998-1999	10	3	6	3	34	-18ab
1999-2000	10	3	0	2	19	-7a
Location						
Jyndevand	10	4	15	2	32	-6a
Foulum	7	2	0	3	34	-28b
Flakkebjerg	13	5	0	2	20	-4a
Crop						
Barley	10	7	5	3	31	-12a
Grass-Clover	10	0	4	0	22	-8a
Winter Wheat	10	8	6	4	30	-11a
Parley/pea	10	0	5	4	33	-22b

[a]Main effects did not interact
[b]Assuming no variation between replicates
[c]Values with the same letter are not significantly different within the group ($P<0.005$)

tion of plants could help in saving nitrogen and in reducing nitrogen leaching. Also in nodule formation of legumes S has an important role (Howieson et. al., 2000). It is part of a metal-sulfur-cluster, acting as catalyst during nitrogen fixation (Schneider and Müller, 1999). So S deficiency can induce N-deficiency of legumes (Mason and Howieson, 1988). S as key component in nitrogen fixation, which is the essential microbiological process for plant production in organic farms, therefore should be carefully kept in mind in organic production.

The S balance of organic plant production also has consequences for organic animal production. Organic farming aims at the use of local feedstuffs in livestock production. Therefore oilcakes are valuable energy and protein sources and are used as substitute for imported soy (Zollitsch et al., 2000). S in excess can lead to increased glucosinolate concentrations in different oilseeds (Zhao et al, 1994) and may limit their use as component in feedstuffs (Jeroch et al., 1997).

On the other hand S-containing amino acids - mainly methionine - are limiting factors in home grown organic feedstuffs for monogastric animals, especially in rations for poultry (Zollitsch et al., 2000). The use of synthetic amino acids to correct imbalances of feed rations is not allowed in organic production. An adequate S nutrition of plants helps maintaining the methionine and cysteine content of plants (Eppendorfer et al., 1992).

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