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The role of sulfur in sustainable agriculture

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Abstract

The term 'sustainability' has been used so many times on facets of agriculture that it is meanwhile difficult to understand its true origin. "Sustainable development" has been defined in 1987 by *The Brundtland Commission* as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". For agriculture this implies primarily the sustainable use of natural resources such as water, soil and atmosphere. This contribution highlights the role of a single plant nutrient in achieving sustainability in agriculture. A sufficient sulfur supply secures level and quality of yields, improves plant health through stimulation of natural resistance processes and alleviates the ecologically hazardous side effects of nitrogen fertilization on surface and groundwater bodies as well as on the quality of the atmosphere. Beside this the sulfur supply of agricultural crops affects also neighboring compartments of agro-ecosystems by providing indirectly food for insects.

Key words: atmosphere, fertilization, food safety, food security, nitrogen losses, ozone, sulfur, sustainability

Introduction

Few words have been so often used and few words have been so often abused as the word 'sustainability'. In many cases claiming for 'sustainability' is simply claiming for 'profitability'. In a world where making profit is the key indicator for being successful, the true meaning of sustainable development is often forgotten. 'Sustainable development' has been defined in 1987 by *The Brundtland Commission* as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Fact is that our society is far away from being on the track towards sustainable development like Wendel Berry stated in 2002: "We currently live in the economy and culture of the "one-night stand". Industrialism has provided us innumerable commodities, amusements, and distractions, but these offer us little satisfaction. Instead we suffer ever-increasing alienation from our families, our communities, and the natural world.

In a way agriculture may be a special segment within human societies as its sustainability is intrinsic under any circumstances, simply because no food, no man! Fertilizers provide food for plants but still fertilizers are often named together with pesticides as 'agrochemicals' which is to a great extent misleading: fertilizers provide essential minerals without no plants can grow. In contrast, pesticides are as essential for plants as aspirin to man. Several authors have identified pesticides as key issues counteracting sustainability, for instance Friedrich Engels, who wrote already in 1876: "Schmeicheln wir uns nicht so sehr mit unseren menschlichen Siegen über die Natur. Für jeden solchen Sieg rächt sie sich an uns“, followed years later by the famous Rachel Carson who wrote in her famous book "Silent Spring“ (1954): "The chemical war can not be won, and a life is caught in its violent crossfire.“

But also fertilization has its black spots in view for sustainability like for instance the loss of nitrogen and phosphorous from agro-ecosystems, the pollution of atmosphere and water-bodies with nitrogen compounds, the waste of non-renewable P-resources through inefficient fertilization strategies, the charging of soils with heavy metals and radioactivity through fertilization of waste materials and P-fertilizers) and the charging of soils with hazardous organic compounds, pharmaceuticals and infectious materials.

This contribution highlights the role of a single plant nutrient in achieving sustainability in agriculture: sulfur. A sufficient sulfur supply secures level and quality of yields, improves plant health through stimulation of natural resistance processes and alleviates the ecologically hazardous side effects of nitrogen fertilization on surface and ground water bodies as well as on the quality of the atmosphere. Beside this the sulfur supply of agricultural crops affects also neighboring compartments of agro-ecosystems indirectly by providing food for insects.

Sulfur fertilization and agricultural economy

One often used criterion for justifying fertilization as a component of sustainable development in agriculture is the allegation that fertilization alleviates world hunger. Kimbrell (2002) reveals this as a

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great mistake, because "world hunger is not created by lack of food but by poverty and landlessness, which deny people access to food. Industrial agriculture actually increases hunger by raising the cost of farming, by forcing tens of millions of farmers off the land, and by growing primarily high-profit export and luxury crops".

The general contribution of fertilization to sustainability is addressed directly to the success of the farm enterprises and simply aims at improving the profit of production.

In this context sulfur plays an extraordinary role in the history of fertilization: free and in surplus, amounts delivered by atmospheric pollution until the beginning of the 1980s sulfur deficiency is today the most common nutrient disorder in Northern European crop plants. The reason are the stringent clean air acts introduced at the end of the last century, which caused atmospheric sulfur depositions to drop from over 100 kg ha^{-1} S down to 10 kg·ha^{-1} S within only 20 years. The positive effect of sulfur fertilization to a sulfur-starving crop can easily be demonstrated in field experiments. Difficulties arise when trying to upscale results from field experiments to assess the impact of sulfur deficiency on crop production in an entire country. Table 1 shows an assessment of potential yield losses and their monetary value for two federal counties of Germany, where extended soil survey and hydrogeological information allows the classification of the cropping area according to the potential risk for S deficiency. Applying the same calculation model to the 7.600 km^2 of grassland in this area (assuming a loss of 10% under moderate and 20% under severe S deficiency and an average N content of 2% in the dry matter the potential N losses for this type of farming amounts to an additional 19.8 million kg N. Those two counties comprise roughly 17% of Germanys cereal, and 27% and 12% of the entire oilseed rape and grassland area. Extrapolating the results from table 1 according to these figures, German agriculture faces a potential monetary loss (potential means a scenario without any sulfur fertilization) of about 1.200.000.000 € per annum alone from yield losses in oilseed rape and cereal cropping.

Contribution of sulfur to sustainability in agriculture

Crops not only provide food and profit for man, but also have also ecological functionalities. In the context of this paper ecological functionality is defined as the beneficial contribution of crops to ecosystems. As far as S is concerned, three examples shall be presented here: the contribution of crops to the degradation of surface ozone, non-point nitrogen losses from agriculture and the function of oilseed rape as a forage crop for honey bees.

Surface ozone concentrations

Over the last decade surface ozone concentrations in rural areas increased on average by 1.8 µg m^{-3} yr^{-1} (Schnug, 1997). At the same time S concentrations declined at a constant rate of 0.45 mg yr^{-1} (Schnug, 1997). Assuming that: a) H_2S emissions from plants decline together with the sulfur supply (Collins, 1997; Rennenberg, 1984) linearly on a rate of 0.57 nmol m^{-2} h^{-1} (calculated from data given by Schroeder (1993)); b) crops have an average leaf area index of 1; c) crops assimilate and reduce sulfur on average of 100 days a year and 10 h a day; and d) H_2S degrades O_3 in a 1:1 ratio; then up to 75% of the observed increase in surface ozone could be attributed to the decrease in the total amount of S turnover in the 'green part' of the ecosystem. The figures given here are only an estimate and may change depending on the factors considered, but they still outline the important function of sulfur assimilation and reduction in the ecosystem. Despite the importance of this for air quality, the higher sulfur inputs in the past century enabled plants to adapt to increasing environmental stress caused by increasing surface ozone concentrations and, vice versa, the decline of the sulfur supply within only one decade (Schnug, 1997; Schnug and Haneklaus, 1994) may have serious consequences for the stability of recent ecosystems. For example, sulfur deficiency is thought to be one of the reasons why 50% of all forests are damaged, although sulfur emissions have been cut down drastically over the past 10 years (Umweltbundesamt, 1993). The effect is thought to be due to the combination of reduced resistance (due to sulfur deficiency) and, at the same time, increased environmental stress (Will et al., 1997; Zhang and Rennenberg 1997).

Nitrogen losses to the environment

Via the metabolism of amino acids, the utilization of nitrogen and sulfur depend on each other, which means that for the efficient use of high nitrogen levels in agriculture, a sufficient sulfur supply is required. Therefore, increased ecological problems from agricultural crop production are expected because the utilization of fertilizer nitrogen is diminished in sulfur deficient crops (Schnug et al., 1993). This may result in increased nitrogen losses to the environment, particularly by nitrate leaching into the hydrosphere, or gaseous losses to the atmosphere. On average, each kg of sulfur unavailable to satisfy the plant's demand causes 15 kg of nitrogen with the potential to be lost to the environment. From the basic data presented in table 1 it was calculated that the potential annual loss of nitrogen due to insuffi-

Table 1:
Assessing the impact of sulfur deficiency on cop production in Brandenburg and Mecklenburg-Western-Pomerania (Germany).

		Brandenburg	Mecklenburg-Western Pomerania	Σ	Yield loss (10^3 t) [1]	Monetary loss (10^6 €)[2]	Potential N loss (10^6 kg)[3]
Cereals							
Total area	(km^2)	5650	5890	11540			
Potential yield	(t ha^{-1})	7					
Modelled yield	(10^3 t on 30% of area)						
no S deficiency		1316	1568	2884	0		
moderate S deficiency		1184	1411	2595	-289	-67	-11.5
severe S deficiency		1052	1254	2307	-577	-34	-5.8
Oilseed rape							
Total area	(km^2)	1110	2330	3440			
Potential yield	(t ha^{-1})	3	4				
Modelled yield	(10^3 t on 30% of area)						
no S deficiency		111	312	423	0	0	
moderate S deficiency		89	250	339	-84	-20	-3
severe S deficiency		67	187	254	-169	-40	-6

[1]calculated yield losses for cereals/oilseed rape: moderate S deficiency 10/20 and severe S deficiency 20/40 % of potential yield; [2]prices (€ t^{-1}): 116 for cereals and 235 for oilseed rape; [3]calculated for yield losses with 2% N in seeds

cient sulfur supply amounts to at least 300 million kg of nitrogen, which is equal 10% of the total nitrogen consumption of German agriculture.

Forage crops for honeybees

Although oilseed rape is self-pollinating (Saure 2002), the cross-pollination rate, predominately by honeybees, was estimated to be about 20% (Dan et al., 1980). According to Olsson (1960) the cross-pollination rate may vary in relation to genotype and climatic conditions between 5 % and 95 %. By comparison, on fields where composite hybrid oilseed rape varieties are grown or male-sterile lines for breeding of restored hybrid cultivars, these plants depend on pollination by vectors (Steffan-Dewenter, 2003). First observations in field-grown composite hybrids show increased problems with pollination of hybrids in low sulfur environments. This problem can be attributed to the processes discussed next. Oilseed rape provides an important source of nectar and pollen for honeybees, which are attracted by the bright yellow color of the crop in bloom (Pierre et al., 1999). Oilseed rape is one of the most important European melliferous crops for beekeepers as it is an important foraging plant in early summer. The main pollinators in oilseed rape are insects of the family Apidea (e.g. honey bees, wild bees and bumble bees) (Corbet, 1992; Williams, 1996) and the significance of honeybees as pollen vectors for seed set and yield has been described in the literature (Steffan-Dewenter, 2003).

Honeybees are attracted by scent, color and form of the honey-bearing plants, but it is the scent, which has the fastest and strongest impact (Menzel et al., 1993). Honey bees might assess the amount and concentration of nectar in each flower by employing different senses: directly by visual access to the nectar (Throp et al., 1975; Willmer et al., 1994), or by olfactory sensation (Heinrich 1979, Galen and Kevan, 1983); indirectly by an indicator of the reward for foraging such as color (Gori, 1983; Weis ,1991), flower size (Galen and Neport, 1987; Eckhart, 1991), or the particular floral structures (Bell et al., 1984; Gonzalez et al., 1995).

Volatiles released during flowering of plants facilitate flower recognition by the honeybee and thus increase their foraging efficiency. The chemical analysis of volatiles from various plant species revealed a multiplex composition of floral scents with more than 700 different compounds that were found in 60 families of plants (Knudsen et al., 1993). The mechanisms by which honeybees process this complex chemical information and adapt their behavior accordingly are as yet unknown (Wadhams, 1994). A total of 34 different compounds were found in volatiles of oilseed rape (Tollsten and Bergström, 1988, Robertsonet al., 1993; McEwan and Smith, 1998). The main volatiles from oilseed rape flowers were 3-hydroxy-2-butanone > 2,3-butanedione > dimethyl disulfide >> formaldehyde > 3-methyl-2-butanone > dimethyl trisulfide (Robertson et al., 1993). Omura et al. (1999) determined nitriles and isothiocyanates in large quantities in the floral volatiles of *Brassica rapa*. Honeybees use volatiles for discrimination whereby a conditioning threshold was determined for individual components (Pham-Delégue et al., 1993). Previous studies have shown that the S supply increases the glucosinolate in vegetative plant tissue, seeds and petals of oilseed rape (Schnug, 1988, 1993). Additionally, 2-phenylethyl isothiocyanate yielded limited conditioned responses in honeybees, but was an active component after being learned in a complex mixture of volatiles (Laloi et al., 2000). Thus a relationship between the S-containing compound, intensity of the scent and finally the attractiveness to honey bees seems possible.

Crops visited by bees show earlier petal fall, probably because they set flowers earlier, resulting in a more uniform pod ripening and ease of harvest. Nectar, however, is the bee's source of carbohydrate and their hovering is the one of the most energy expensive forms of flight. The reflective pattern of flowers provides visitors with clues as to the age of the flowers and presence of food rewards (Kevan and Baker, 1983). During senescence of rapeseed flowers, which begins immediately after pollination, the yellow petal color vanishes and the petals shrink quickly before falling to the ground. A pollinated and fading rapeseed flower is therefore similar to an unpollinated S deficient one and thus less attractive to honey bees. Barth (1982) reported that bees prefer yellow flowers to white ones and consequently in S deficient fields, much lower bee activity has been observed than in S sufficient crops, which are bright yellow.

Smaller, whiter flowers may be less attractive to bees only after previous experience and not because of a specific signaling. Even if sufficiently with S supplied rapeseed flowers would be 'instinctively' more attractive to honey bees, the animals are known to adapt their behavior rapidly, in this case in favor of white(r) and smaller flowers if the reward will be satisfying. De Jong (1998) emphasized that bees are extremely fast in associating relevant cues with a reward. S-deficiency in rapeseed, therefore, will probably only have the negative bee-related effects when the bees can not distinguish pollinated from non-pollinated flowers as reliable as they can in rapeseed that is sufficiently supplied with S.

Who could have imagined at the beginning of the 1980s that the reduction of SO_2 emissions from burning fossil fuels (Sendner, 1985) would have an impact on honey production twenty years later?

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