The importance of low mobile soil water for the S supply of plants

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Summary

Sulphur (S) deficiency is a serious nutrient disorder in European agriculture and there is a need for reliable methods to predict the S nutritional status of crops under various conditions. Former studies have shown that the soil water content is of special relevance for the S supply because soil sulphate mainly follows the water movement in agricultural soils with a pH > 5. Groundwater can contribute with high amounts of S for plant uptake when ascension takes place. On the other side, precipitation can leach plant available S out of the rooting zone. S that is stored in the low mobile water fractions is thought to be protected from leaching but still available for plant uptake. The significance of this important pool for plant nutrition is usually neglected in modelling. A simulation model was developed to describe the size and meaning of the low mobile soil water pool. It was the aim of this study to calculate the amount of plant available S stored in the low mobile water fraction using varying model parameters for soils under humid conditions. Additionally, the capability of the model to provide accurate data was tested by means of measured input data. The simulation results showed that HySuMo (Hydrological Sulphur Model) was able to calculate the S nutritional status of crops sufficiently accurate under different climatic scenarios and different soil conditions. Besides that the model proved to be suitable to predict S deficiency under different soil conditions. Another result of the presented study was that the low mobile soil water fraction is supposedly a highly significant S pool for plants.

Keywords: *HySuMo (**Hy**drological **Su**lphur **Mo**del,)low mobile water, mobile water, solute transport, sulphur supply*

Zusammenfassung

Schwefel(S)mangel hat sich in den letzten Jahrzehnten in Europa zu einer der wichtigsten Ernährungsstörungen bei landwirtschaftlichen Kulturen ausgeweitet und bis heute fehlen immer noch zuverlässige Methoden, um den S-Versorgungszustand einer Fläche sicher zu prognostizieren. Studien haben ergeben, dass das Bodenwasser von besonderer Bedeutung für die S-Versorgung ist, da die pflanzenverfügbare S-Form, das Sulfat, in landwirtschaftlichen Böden mit pH-Werten über 5 der Wasserbewegung im Boden folgt. Das Grundwasser kann zu wesentlichen Einträgen in Agrarökosysteme führen, wenn ein kapillarer Aufstieg von Bodenwasser möglich ist, während hohes Regenaufkommen zu einer starken S-Auswaschung führt. Ein Teil des Bodenwassers, das in Mikroporen gespeichert ist, ist nahezu immobil, und das darin gelöste Sulfat ist vor Auswaschung geschützt. Die Bedeutung dieses Pools für die Pflanzenernährung wurde bislang weder berücksichtigt, noch quantifiziert.

In diesem Beitrag wird ein Simulationsmodell vorgestellt, das Größe und Bedeutung dieses nur geringfügig mobilen Wassers für die Pflanzenernährung kalkulieren sowie eine Vorhersage über die S-Versorgung am Standort erlauben soll. Ziel der Untersuchung war es, die Menge an pflanzenverfügbarem S in der mobilen und geringfügig mobilen Wasserfraktion unter verschiedenen Umweltbedingungen zu berechnen und zu testen, ob das Model HySuMo in der Lage ist, den Nährstoffversorgungszustand einer Fläche zu prognostizieren. Die Ergebnisse zeigen, dass das Modell unterschiedliche Bedingungen sehr gut abbildet und darüber hinaus brauchbar ist, den S-Versorgungszustand einer Fläche vorauszusagen. Des Weiteren konnte anhand des Modells gezeigt werden, dass geringfügig mobiles Bodenwasser anscheinend eine wichtige Reservefraktion für S im Boden darstellt.

Schlüsselwörter: *geringfügig mobiles Bodenwasser, HySuMo (**Hy**drological **Su**lphur **Mo**del), mobiles Bodenwasser, Nährstofftransport, Schwefelversorgung*

Introduction

Although most nutrients are excessively abundant in northern European agricultural systems, sulphur (S) is one of the most important yield-limiting factors since clean air acts came into force (Richards, 1990; Booth et al., 1991; Pedersen, 1992; Knudsen & Pedersen, 1993; Kjellquist & Gruvaeus, 1995). Besides the drastic reduction of atmospheric S depositions since the beginning of the 1980s, an increasing use of S-free fertiliser products were the main reasons for this trend (Schnug & Haneklaus, 1994).

S deficiency can cause yield losses (Booth et al., 1991; Schnug & Haneklaus, 1994), may have a great influence on crop quality parameters such as protein content and composition (Eppendorfer & Eggum, 1994) and influences the baking quality of wheat

(Haneklaus et al., 1992; Schnug et al., 1993a). Also, environmental factors such as the efficiency of nitrogen utilisation by plants are related to the S status of plants (Schnug et al., 1993b) and the susceptibility of crops against some diseases was observed to be influenced by the S nutrition (Schnug et al., 1995; Bourbos et al., 2000; Klikocka et al., 2004). Severe S deficiency is still an important problem in agricultural production and thus, reliable fertiliser recommendations are required. The most common methods for the determination of the S nutritional status are soil and plant analysis (e.g. Anderson et al., 1992; Eriksen et al., 1998), and the assessment of a site-specific S balance. Soil analysis (plant available sulphate) is, in general, not reliable because of a high spatial and temporal variability of sulphates in soils (Schnug & Haneklaus, 1998; Bloem et al., 2001; Haneklaus et al., 2002). The high variability results from the high mobility of sulphate in agricultural soils with a pH > 5 (Curtin & Syers, 1990; Ajwa & Tabatabai, 1995) thus, following the water movement. Leaching (Kühn & Weller, 1977; Widdowson & Blakemore, 1982) and ascension of sulphate from subsoil or shallow groundwater sources (Bloem, 1998; Eriksen et al., 1998) may change the amount of plant available sulphate within short time intervals. Therefore, the analysis of soil sulphate delivers only a temporary value in most humid soils, which can change quickly (Bloem et al., 2001). In tropical soils, like those prevailing in the south-eastern parts of Brazil, soil sulphate adsorption is more important, because of the lower pH values resulting from the higher acidity in the soil solution (Prochnow et al., 1998; Lara et al., 2001; Da Rocha et al., 2003).

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 contaminations by foliar application of S containing products and the short time gap between sampling and fertilisation (Haneklaus et al., 1995; Schnug & Haneklaus, 1998).

S balances are a promising possibility for farmers to estimate the nutritional status of a site. Sources and sinks commonly included in S balances are inputs by atmosphere, fertilisers, plant residues and mineralisation. Outputs are represented by S off-take and S losses due to leaching. A frequent problem when establishing S balances is that the budget does not correspond with the observed S supply. The main reason is that under temperate conditions the spatio-temporal variation of hydrological soil properties controls most of the plant available sulphate content. The significance of plant available soil water as a source and storage pool for S has been disregarded or underestimated so far. Especially under humid growth conditions, plant available soil water can be the largest contributor to the S balance (Bloem, 1998) because groundwater is a large pool for S with concentrations of 5 - 100 mg L^{-1} S (Isermann, 1993; Bloem, 1998). A site-specific S budget, which includes hydrological information, is a more promising way for the evaluation of the S supply. HySuMo (**Hy**drological **Su**lphur **Mo**del) was developed to combine water flow patterns in the soil-plant system and the availability of soil sulphate for plants with the aim to deliver an assessment of the S supply.

S deficiency occurs more often on sandy soils because soils rich in clay minerals can store more water and consequently more sulphate (Bloem, 1998; Schnug & Haneklaus, 1998). Clay soils contain a higher quantity of micro-pores, storing water under higher potentials in a less mobile form. The mobile soil water pool is defined as the water-filled pore space which transports water and chemicals, while the low mobile fraction is the water-filled pore space that apparently contains stagnant water and chemicals (Okom et al., 2000) and this fraction is often addressed as immobile water from a hydrological point of view. In the present study this fraction is further addressed as the low mobile water because the nutrients which are bound in this fraction are not immobile but only low mobile. The understanding of the importance of this micro-pore space as a pool for storing nutrients, protecting them from excessive leaching and making them available for plant nutrition, is still insufficient. The retention of S in surface soils is strongly dependent on soil pH and mineralogy. Rapid leaching may, however, also be observed under tropical soil conditions by preferential flow under non-equilibrium conditions that usually occur during and shortly after rainfall.

The mobile, and low mobile water fractions and the transport of solutes are usually followed up by using tracer ions (e.g.: Cl^- or Br^-) in soil columns under field saturated or unsaturated conditions (Flühler et al., 1985; Angulo-Jaramillo et al., 1996; Shukla et al., 2000). Different models (mobile-immobile model - MIM, pulse breakthrough curves, frontal breakthrough curves, single tracer method, or sequential tracer experiments) were used to describe the transport of solutes in soils (Clothier et al., 1992; Jacobsen et al., 1992; Jaynes et al., 1995; Oliver & Smettem, 2003), but no method delivered satisfactory results under varying field conditions for S (Oliver & Smettem, 2003).

HySuMo simulates the S cycle in the soil, the soil water fractions and plant uptake, including the mobile and low mobile soil water fraction. In HySuMo a combination of the convection-dispersion equation for the evaluation of solute flow and the mobile-immobile model (Van Genuchten & Wierenga, 1976; Vogeler et al., 1998) was expected to significantly improve the prognosis of S fluxes and the modelling of soil S balance for different soil and climatic conditions and therefore was chosen as a basic input. Usually, solute transport and the different water fractions are calculated to simulate nutrient leaching, or contamination with harmful solutes (Flühler et al., 1985). The possible protective function of the low mobile fraction (against leaching) with respect to mobile nutrients was not discussed before.

The aims of this paper were to show the relevance of the mobile/immobile soil water concept for S balance modelling and to evaluate the suitability of the model to predict the S status for soils under humid condions by verifying if the model is sensitive to factors that are known to influence the S balance in agricultural systems.

Model Description

HySuMo was designed to predict the risk of S deficiency and to calculate the S content of different soil water fractions. HySuMo combines a hydrological, a plant growth, and a soil S model. In the following section the corner marks of HySuMo are described.

The S balance was simulated for a soil depth of 50 cm, defined in terms of its hydraulic properties. Plant development was simulated using the heat unit approach. (Wilson & Barnett, 1983). Carbon assimilation was estimated by the method proposed by Goudriaan and Laar (1978) and Van Heemst (1986). S requirement was defined by a fixed C:S ratio.

Initial water and S content of both, mobile and low mobile fractions were defined and a simulation was performed using a time step Δt. During each time step (Δt) the water and S balances were calculated subsequently.

Water balance

The water balance is composed of drainage, transpiration, evaporation, capillary ascension and rainfall, considered in this order. Drainage was calculated by

$$f_D = f_{D,\max}\left(\frac{\theta - \theta_{nd}}{\theta_s - \theta_{nd}}\right)^k$$

with f_D (m^3 m^{-2} s^{-1}) being the drainage rate,

$f_{D,\max}$ (m^3 m^{-2} s^{-1}) the drainage rate at saturation,

θ_s (m^3 m^{-3}) the soil water content at saturation,

θ_{nd} (m^3 m^{-3}) the soil water content at which drainage ceases and

θ (m^3 m^{-3}) the current soil water content.

Drainage was subtracted from the mobile water fraction.

Daily transpiration and evaporation were estimated by the FAO-Penman-Monteith equation (FAO, 1998). Transpiration and evaporation rates were calculated separately for both, mobile and low mobile water, based on extractability factors that are defined as a function of soil water content. Mobile and low mobile water fractions have individual critical soil water contents (θ_{lm} and θ_{li}), which were used to calculate the corresponding extractability factor F_{em} and F_{ei} (Fig. 1). The total extraction was weighted according to these extractability factors.

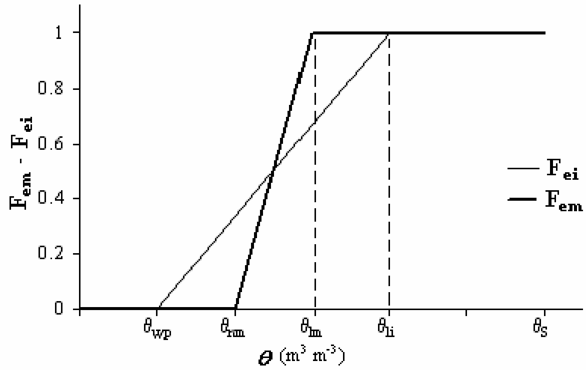

Fig. 1: Extractability factors as a function of soil water content

Ascension was calculated as a function of the soil water content by

$$f_A = f_{A,\max}\left[\cos\left(\pi\frac{\theta - \theta_{\text{na}}}{\theta_{ba} - \theta_{\text{na}}}\right)\right]^2$$

with f_A (m^3 m^{-2} s^{-1}) being the ascension rate,

$f_{A,max}$ (m^3 m^{-2} s^{-1}) the maximum ascension rate,

θ_{ba} (m^3 m^{-3}) the soil water content at which ascension starts,

θ_{na} (m^3 m^{-3}) the soil water content at which ascension ceases and

θ (m^3 m^{-3}) the current soil water content. Ascension was added to the mobile water fraction.

Rainfall data was based on hourly measurements; no runoff was supposed to occur, and rainfall was added to the mobile water fraction.

In the model the low mobile water content is filled up to saturation by the mobile water, if enough water is available.

Sulphur balance

S in- and outputs from pores can occur by mass flow with water, mineralisation and active plant uptake. Mass flow with water was estimated as the product of water flows calculated in the water balance and the concentration of S in this water. The mineralisation rate was assumed to be constant, and mobilisation and immobilisation processes in these fractions are balanced. Active uptake of S by plants was estimated as a function of S concentration (S_{soil}, kg m^{-3} S) for each S pool. Below a critical concentration of plant available sulphate in the soil (S_{crit}) S uptake becomes less than required for optimum plant growth ($U_{S,max}$). It was assumed to be reduced according to,

$$U_S = U_{S,\max}\left(\frac{S_{soil}}{S_{crit}}\right)^r$$

where the exponent r allows simulation of different shapes of S-uptake reduction. For $S_{soil} > S_{crit}$, U_s equals $U_{s,max}$ at a maximum S uptake rate (Fig. 2).

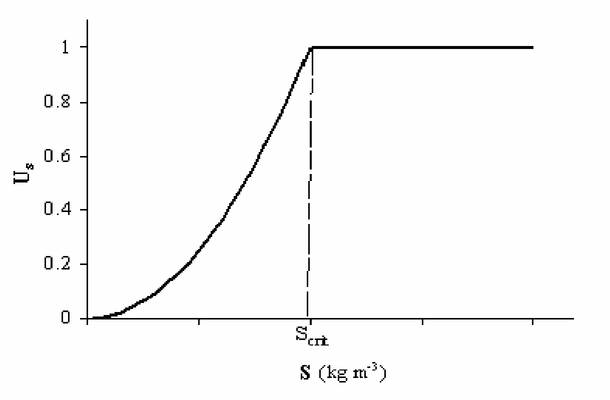

Fig. 2: Sulphur uptake factor (Us) in relation to the soil sulphur concentration

At last, the S transfer (Q, kg) between mobile and low mobile fractions was estimated by Fick´s equation of diffusion:

$$Q = D_s \frac{\Delta S}{l} A_i . \Delta t$$

with D_s ($m^2 s^{-1}$) being the diffusivity of S in water,

ΔS (kg m^{-3}) the difference of S concentration between low mobile and mobile fractions,

l (m) the boundary layer thickness,

A_i (m^2) the interface area between both fractions and

Δt (s) the time interval.

The model HySuMo calculates the S content in the different soil water fractions, and in soils and plants on a daily basis. The result is influenced by the different input parameters of the model like soil texture, groundwater influence and climatic conditions.

Evaluation of model input parameters and simulation scenarios

Calculations of the immobile water fraction delivered values ranging from up to 40% to less than 1% of the total water content (De Smedt et al., 1992; Okom et al., 2000; Oliver & Smettem, 2003). The mobile water was generally found to range from 70 to 95% of the total water content (Van Wesenbeck & Kachanowski, 1991; Izadi et al., 1993; Clothier et al., 1995; Okom et al., 2000) with an average of 85% for several soils ranging in texture from sand to clay (5.5 – 50.2 % clay). Oliver and Smettem (2003) found immobile water contents of 10% for sandy soils. In the simulations presented in this study for a sandy soil (lS) a low mobile water content of 0.07 m^3 m^{-3} was assumed and for loamy soils (sL) a corresponding value of 0.135 m^3 m^{-3}. The actual storage capacity of nutrients in the low mobile water is not yet known. Theoretically, nutrients in the low mobile water fraction are protected from leaching, but available for plants. Therefore the higher the fraction of low mobile water, the higher will be the storage of nutrients in this pool. This is of special importance for highly mobile and limited nutrients like sulphate. Field experiments have already shown that soil texture is an important parameter for the S supply of crops: the higher the clay content of a soil, the higher was the S content in younger leaves of oilseed rape (Y = 0.141·X + 2.186 with Y = S [mg g^{-1} S] content in leaves of oilseed rape and X = clay content [%]; (Bloem, 1998). Deeper soil layers from 60 to 150 cm soil depth were of special importance for the S supply of the crop because of the high mobility of the soil sulphate: leaching of S and capillary rise of S are important processes and deeper soil layers contribute significantly to the S nutrition of crops (Bloem, 1998). HySuMo calculates the S contents in the upper 50 cm of the soil, because the immobile water and its relevance for plant nutrition is thought to be highest in the rooted soil horizon where the nutrients can be depleted by the crops and differences in the nutrient content are highest between the different water fractions. The S input from deeper soil layers by capillary rise is, however, considered in the model.

The study of Bloem (1998) also showed that under humid conditions the amount of precipitation during winter was of great relevance for the S supply in the main growth season as most sulphate was leached from the soil, resulting in a low concentration of plant available sulphate. Another important factor was the access of plants to groundwater as this stores significant amounts of sulphate that can supply S for crop growth. Therefore, the influence of soil texture, groundwater level and precipitation over winter on the S supply of agricultural crops was calculated by HySuMo for plants grown under humid conditions (Tab. 1).

The calculations were made for two years with distinct amounts of precipitation. Climate data from an extremely rainy year (948 mm in 1961) and a dry year (443 mm in 1973) were chosen from Braunschweig (Germany) (Fig. 3). The calculations were done for maize (*Zea mays* L.) from February, 1 until October, 26. The S input through precipitation and mineralisation was set very low, therefore changes in the S content of the different water fractions were mainly caused by hydrological factors and plant uptake. In table 2 the most important simulation parameters are summarised.

Tab. 1: Different scenarios tested by HySuMo

Scenario Soil texture	Access to groundwater	Amount of precipitation	Expected S nutritional status based on empirical data
Sandy	no	High (948 mm)	Extreme S deficiency
Sandy	no	Low (443 mm)	S deficiency
Sandy	yes	High (948 mm)	S deficiency only when the groundwater table is deeper than rooting depth
Sandy	yes	Low (443 mm)	S deficiency only when the groundwater table is deeper than rooting depth
Loamy	no	High (948 mm)	S deficiency
Loamy	no	Low (443 mm)	Sufficient S supply possible
Loamy	yes	High (948 mm)	Sufficient S supply
Loamy	yes	Low (443 mm)	Sufficient S supply

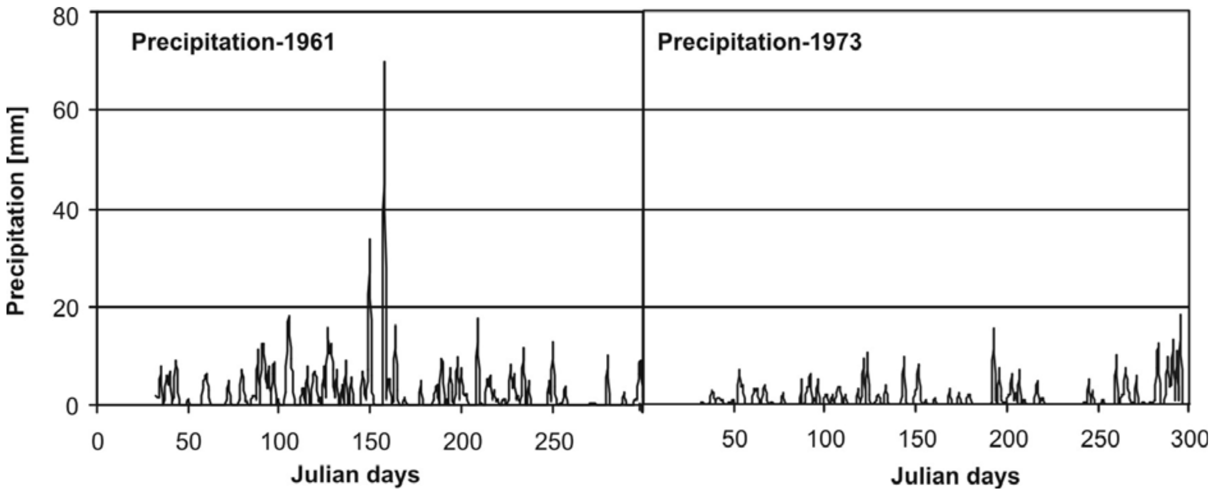

Fig. 3: Comparison of the precipitation in 1961 and 1973 in Braunschweig (Germany) during the simulation period from day 32 (February, 1) until day 300 (October, 26)

Tab. 2: Input parameters for the simulation of the S supply in the mobile and low mobile water fraction with HySuMo

Input parameter		Input value	Unit
Groundwater S concentration		50	mg L^{-1}
Initial S content of mobile water		20	mg L^{-1}
Initial S content of immobile water		20	mg L^{-1}
Initial soil water content mobile fraction	sandy soil	0.180	m^3 m^{-3}
	loamy soil	0.265	m^3 m^{-3}
Initial soil water content immobile fraction	sandy soil	0.07	m^3 m^{-3}
	loamy soil	0.135	m^3 m^{-3}
Profile thickness		50	cm
Start of simulation		01. Feb	Day 32
Sowing date		01. Apr	Day 91
End of simulation		26. Oct	Day 300[1]

[1]Julian day

Model results of the simulation scenarios

With the model HySuMo different important hydrological data were calculated (soil water content, low mobile and mobile water content, evapotranspiration) as well as the S content in the different compartments (water fractions, soil, plant), leaching of S, capillary rise, erosion, mineralisation and plant uptake. In figure 4 the results from the HySuMo-simulation which were carried out for the different scenarios shown in table 1 are summarised. In figure 4 the S content in the low mobile water fraction during time course is shown and the cumulative value for the S content in the mobile and low mobile fraction. In all four scenarios the S content was higher in the dry season 1973 than in the wet year 1961 where leaching was obviously the predominant process. Without ascending soil water the S content in both water fractions was decreasing continuously in both years but the process was faster in the rainy year and leaching was higher and faster in sandy soils compared to loamy ones because less water could be stored.

The S-contents in the water fractions were distinctly higher when ascension of soil water occurred. In the loamy soil in 1973 groundwater ascension was important and led to an S input of 38 kg ha^{-1} S (Tab. 3).

The shapes of the cumulative curves in figure 4 were mainly influenced by the mobile fraction, which was reacting fast to precipitation events and ascension and which was the first to be depleted by the crops. The model is calculating the different parameters for homogeneous soils but natural soils are often more or less heterogeneous. In such heterogeneous soils, preferential flow of water and chemicals is often observed (Van de Pol et al., 1977; Scotter & Kanchanasut, 1981; White, 1987; Ghodrati & Jury, 1990; Heng et al., 1999a) which is not considered by the model HySuMo. The cause of such preferential flow may include density or viscosity differences between resident and invading fluids, existence of structural voids, layering, discrete lenses in sandy soils, as well as the existence of two or more distinct flow domains (Jury & Flühler, 1992).

The S content in the low mobile water is generally changing more smoothly because of the slow diffusion process (Oliver & Smettem, 2003). Leaching of S occurs in the first place from the mobile fraction.

Therefore, even when starting with the same S content in both fractions the low mobile fraction contained higher S concentrations after a short period of time. The results in figure 4 clearly reveal that in the dry year a significant amount of S was transported into the soil profile from the groundwater. This increase took place mainly in the mobile fraction. The model seems to reflect these processes in a realistic and predictable way. The protection of nutrients in the low mobile fraction from leaching is the reason why this fraction can become important for plant nutrition. In table 3 S drainage, S ascension and S uptake by the plant from the water fractions are shown.

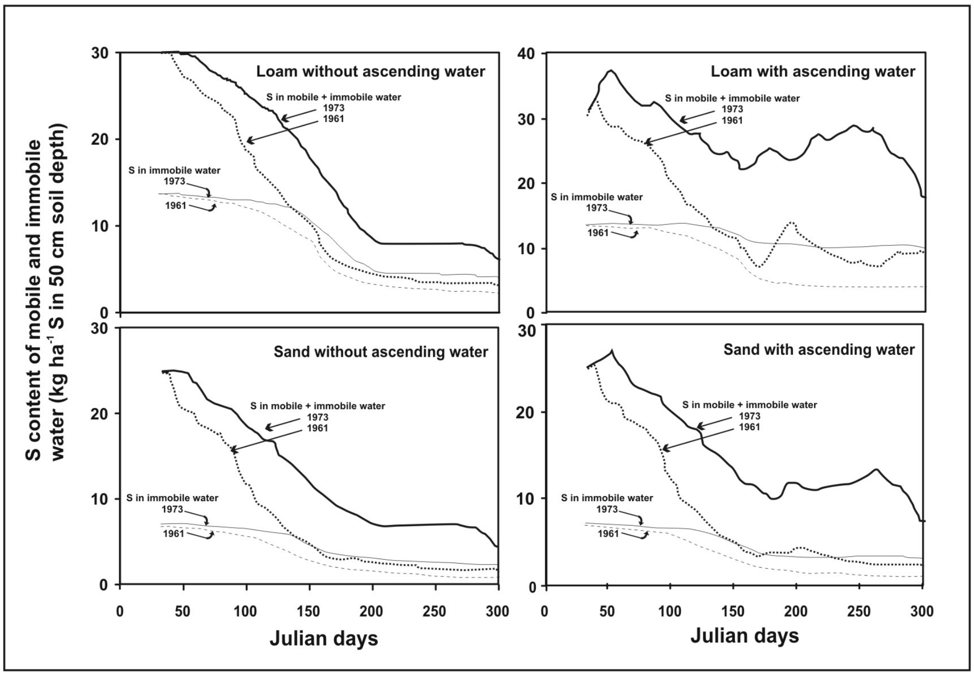

Fig. 4: S content in mobile and low mobile water in relation to soil texture, access of plants to groundwater and amount of precipitation

Additionally, the S nutritional status is characterised and the day is reported when the S content in both water fractions dropped below 10 kg ha^{-1} S. Most agricultural crops have high S demands, e.g. oilseed rape 45 to 100 kg ha^{-1} S or cereals about 30 kg ha^{-1} S (Haneklaus et al., 2003). Therefore a plant available soil S content of about 10 kg ha^{-1} will induce S deficiency in most crops.

Under sandy soil conditions without ascension and a high precipitation the S content in the soil profile dropped below 10 kg ha^{-1} on day 107, in the middle of April only two weeks after sowing. In the dry year (1973) the same happened at day 165 (middle of June) without ascension or at day 290 (after harvest) considering ascension. In the rainy year, S deficiency occurred independently of ascension because it accounted only for 2 kg ha^{-1} S as a result of the high amount of rain during the growth period. In the dry year, no S deficiency occurred when the plant had access to the groundwater while S deficiency was expected when no ascension occurred and the S content was below 10 kg ha^{-1} during main crop growth. The S status in table 3 was estimated on basis of the period when the S content fell below 10 kg ha^{-1} S. Plant S uptake was low in all simulations, as a result of the selected low input parameter, to focus the simulation on soil hydrological parameter. The value of 10 kg ha^{-1} was chosen as an extreme value and most crops will already show S deficiency at higher values.

In the loamy soil the S uptake by the plant was comparatively high in the dry year 1973 with a value of up to 19 kg ha^{-1} S. But also in the loamy soil S can become a limiting factor. Only 7.8 kg ha^{-1} S were available for the crop in the rainy year without ascension. In the rainy year with ascension there was only a short time period of two weeks when the available soil S content fell below 10 kg ha^{-1}. After that, ascending soil water increased the S content again. Ascension of S was of special meaning for the nutritional status of crops in years with high amounts of precipitation interrupted by dry periods. High amounts of precipitation during the vegetative growth can lead to S deficiency, but if plants can overcome a short time of S deficiency the S supply can normalize again after a hot and warm period which allowed ascension of S rich soil or groundwater. This phenomenon can sometimes be observed in oilseed rape. Up to approximately one week after blooming, even severe S starving oilseed rape plants are able to restart and continue with flowering, pod insertion and seed filling and regain full yield if sufficient S is supplied by S rich ascending soil water (Schnug, 1988). This performance is also well reflected by the model estimations. The comparison of the calculated S status of the crop (Tab. 3) with the expected S nutritional status (Tab. 1) reveal that HySuMo could describe the expected plant performance realistically and that the main model parameter and input values are in the right order of magnitude.

Nevertheless, it is necessary to measure the nutrient transport in soils under different conditions of adsorption and drainage to evaluate if HySuMo is able to describe the S nutritional status of a site even under very different hydrological and physical conditions.

Tab. 3: Input parameters for S drainage and S ascension, plant uptake and the S status and HySuMo calculations for different scenarios

Soil	Ascension of ground-water	Soil water content	Low mob. water	Year	S Drainage	S ascension	Plant uptake from different pools			S status	Day when plant available S was
							mob.	low mob.	total		<10 kg ha^{-1} S
		------ (m^3 m^{-3}) -----			(kg ha^{-1} S)						
Sand	No	0.25	0.07	1961	21	0	0.3	2.7	3.0	Strong S deficiency	107
		0.25	0.07	1973	14	0	2.5	4.7	7.2	S deficient	165
	Yes	0.25	0.07	1961	22	2	0.4	2.8	3.2	Strong S deficiency	108
		0.25	0.07	1973	18	9	4.4	5.1	9.5	Sufficient	290
Loam	No	0.30	0.135	1961	19	0	0.4	7.4	7.8	S deficient	151
		0.30	0.135	1973	12	0	2.5	10.0	12.5	Sufficient	188
	Yes	0.30	0.135	1961	30	19	2.7	8.0	10.7	Sufficient	155-178; 216
		0.30	0.135	1973	32	38	10.4	8.6	19.0	High S supply	Never

Heng et al. (1999a) showed that drainage and retention of sulphate in soil cores changed under varying water flow rates: in fast flow cores the solutes by-passed most of the soil matrix and appeared in the effluent very soon after they were applied. Good simulation results of cation and anion leaching could only be calculated at flow rates of 3-20 mm h^{-1}; at high flow rates of 350 mm h^{-1} the results were not satisfactory. Oliver and Smettem (1999) found differences in the immobile water content with soil depth ranging from 11-13% in the topsoil and 4.5-21% in the subsoil.

The results of the model show, that the immobile water can contribute significantly to plant nutrition in sandy and loamy soils (Tab. 3) with a plant S uptake from this fraction of 3-5 kg ha^{-1} S in the sandy and 7-10 kg ha^{-1} S in the loamy soil. Because of the fine texture more water and therefore more S is stored in the immobile water fraction of the loamy soil. Especially in the rainy year the nutrients in the immobile water are of importance when leaching is the predominant process in the mobile water fraction (Tabel 3) and S uptake from the mobile fraction is extremely low.

Conclusions

Values for the low mobile water content in relation to soil texture were adopted from data reported in literature. With these values HySuMo delivered reasonable values to describe expected plant performance. Sandy soils could store less plant available S and show faster symptoms of S deficiency because of high drainage and low water contents. Wet years led to S deficiency in sandy and loamy soils, while ascending soil water contributed significantly to S balance under dry conditions. HySuMo was able to describe the expected S dynamic at a site considering hydrology, plant growth and soil parameters together.

The simulation results also showed that the low mobile water contributed to the S balance in an important way. On an average, 9 - 14 mg L^{-1} S were prevented from leaching in the low mobile soil water fraction in the sandy soil accounting for 3 - 5 kg ha^{-1} S in the 0 – 50 cm soil layer. In the loamy soil this value was distinctly higher because of the higher water storage capacity (11 - 17 mg L^{-1} S equivalent to 7 - 12 kg ha^{-1} S).

Therefore the immobile soil water is most likely an important storage pool for S in the soil and can be an important source of S for crop nutrition.

The model delivered reasonable theoretical values, so that in a next step simulation data need to be verified by field experiments.

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