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Potential importance of the subsoil for the P and Mg nutrition of wheat

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Abstract

A method is described which allowed the quantification of the potential uptake of P and Mg from the subsoil (>30 cm) by spring wheat. Wheat was grown on an artificial topsoil (sand with no plant available P or Mg) which was superimposed on loess subsoils in N. Germany. The supply of P and Mg in the topsoil was varied by application of different quantities of P and Mg fertilizer. Uptake of P and Mg from the subsoil was calculated as the difference between total plant uptake (determined by plant analysis) and the quantities of P and Mg removed from the topsoil (determined by soil analysis). P uptake from the subsoil increased from 37% to 85% of total P uptake, with decreasing P supply in the topsoil. Calculations of potential supply by diffusion showed that, with a CAL-extractable P_2O_5 content in the subsoil of 9 mg 100 g^{-1}, supply from the subsoil was only possible if the influence of root hairs was considered. The method also showed that the total demand for Mg by spring wheat could be satisfied from the supply of Mg from the subsoil of typical loess soils. Mg uptake from the subsoil decreased to 33% of total uptake with increasing Mg supply in the topsoil.

Introduction

The importance of the subsoil below the plough layer (>30 cm) for the P and Mg nutrition of plants depends on the amount of plant-available P and Mg in the subsoil, on the length of roots present in the subsoil, and P and Mg supply in the topsoil.

The amount of plant-available P and Mg in the subsoil can vary greatly, as found by Witter (1964), Grosse and Hammer (1968), Grimme (1978), Steffens (1980), Baumgärtel (1988) and Kuhlmann (1988), and even on the same soil types.

The site-to-site variations in P content in the subsoil can be attributed to leaching with percolating drainage water, to the variable adsorption of P by the soils and to the transfer of P by earthworms (Graff, 1967). The much higher P contents in the topsoil, in comparison to the subsoil, are a result of the application of mineral and organic P fertilizers and manures over many years, in excess of that removed by crops.

The higher Mg contents which frequently occur in the subsoil compared to the topsoil can be attributed to the fact that crop removal and leaching of Mg from the topsoil have exceeded additions by fertilization. The average leaching of Mg in percolating water may amount to about 20 to 30 kg ha^{-1} year^{-1} (Köhnlein et al., 1966; Pfaff, 1963; Schröder and Zakosek, 1981).

The extent to which these nutrients in the subsoil contribute to the nutrition of plants depends essentially upon the fraction of roots in the subsoil. Up to 50% of wheat roots can be found below the plough layer (Barraclough and Leigh, 1984; Kmoch et al., 1957). Crop species, and soil chemical and physical characteristics, all influence the root distribution in the soil profile (Barraclough and Weir, 1988; Drew, 1975; Mohr, 1980).

Whilst there have been numerous studies on the contribution of the subsoil to the N nutrition of crops (e.g. Borst and Mulder, 1971; Wehrmann and Scharpf, 1986), there are very few on the P and Mg uptake from the subsoil. This is because while the change of NO_3-nitrogen in the subsoil is measurable by the N_{min} method (Scharpf, 1977), the annual variation of exchangeable P and Mg contents in the subsoil cannot be measured directly due to large buffer capacities, and to the small quantities removed.

The aim of this study, therefore, was to assess the potential importance of the subsoil for the P and Mg nutrition of wheat by using a balance method.

Materials and methods

A 'balance method' was developed for estimating the uptake of P and Mg from the subsoil under field conditions. This method is based on the measurement of the P and Mg taken up from the entire plant (by plant analysis) and the decrease in P and Mg in the topsoil (by soil analysis). The uptake from the subsoil is assumed to be the difference in these two amounts.

A sand, washed several times in distilled water, was used as topsoil. This sand contained no plant-available P and Mg as found in a preliminary experiment using the Neubauer technique (Neubauer, 1939) (Table 1). This experiment showed that after 21 days of growth from germination in unfertilized sand in a growth chamber, the spring wheat plants contained only P and Mg present in the original seed, and were therefore unable to remove any P and Mg from the sand. P- or Mg fertilization of the sand led to an increase in P- or Mg removal by the crop.

The experimental setup and the conditions of the 'balance method' for the estimation of the P- and Mg uptake from the undisturbed subsoil are illustrated in Figure 1.

Experimental method

The artificial topsoil, 16 kg washed sand, was compacted into 10-litre cylindrical containers. Prior to filling, the sand was mixed with 1.5 g N, 1.5 g K, 1.7 g Ca, and micronutrients.

In addition, 0.5 g of P (in the Mg experiment) and 0.5 g of Mg (in the P experiment) were added to the containers used to determine the

Table 1. Results of Neubauer experiments for the determination of plant-available (**I**) P and (**II**) Mg contents of a washed sand (100 g sand, 100 spring wheat seeds, growth period: 21 days from germination)

I

P applied (mg pot^{-1})	P in seeds (mg pot^{-1})	P content in dm (shoots + roots) (%)	P in plants (mg pot^{-1})	Dm yield (g pot^{-1})	P removed from soil and fertilizer (mg pot^{-1})
0		0.39	10.96	2.81	−1.54
5	12.5	0.49	13.33	2.72	+0.83
10		0.53	15.32	2.89	+2.82
LSD 5% Tukey		0.037	1.90	n.s.	1.90

II

Mg applied (mg pot^{-1})	Mg in seeds (mg pot^{-1})	Mg content in dm (shoots + roots) (%)	Mg in plants (mg pot^{-1})	Dm yield (g pot^{-1})	Mg removed from soil and fertilizer (mg pot^{-1})
0		0.13	3.37	2.63	−0.24
2		0.16	4.33	2.66	+0.72
8	3.61	0.27	7.36	2.71	+3.75
16		0.32	10.37	3.21	+6.76
LSD 5% Tukey		0.04	2.26	n.s.	2.26

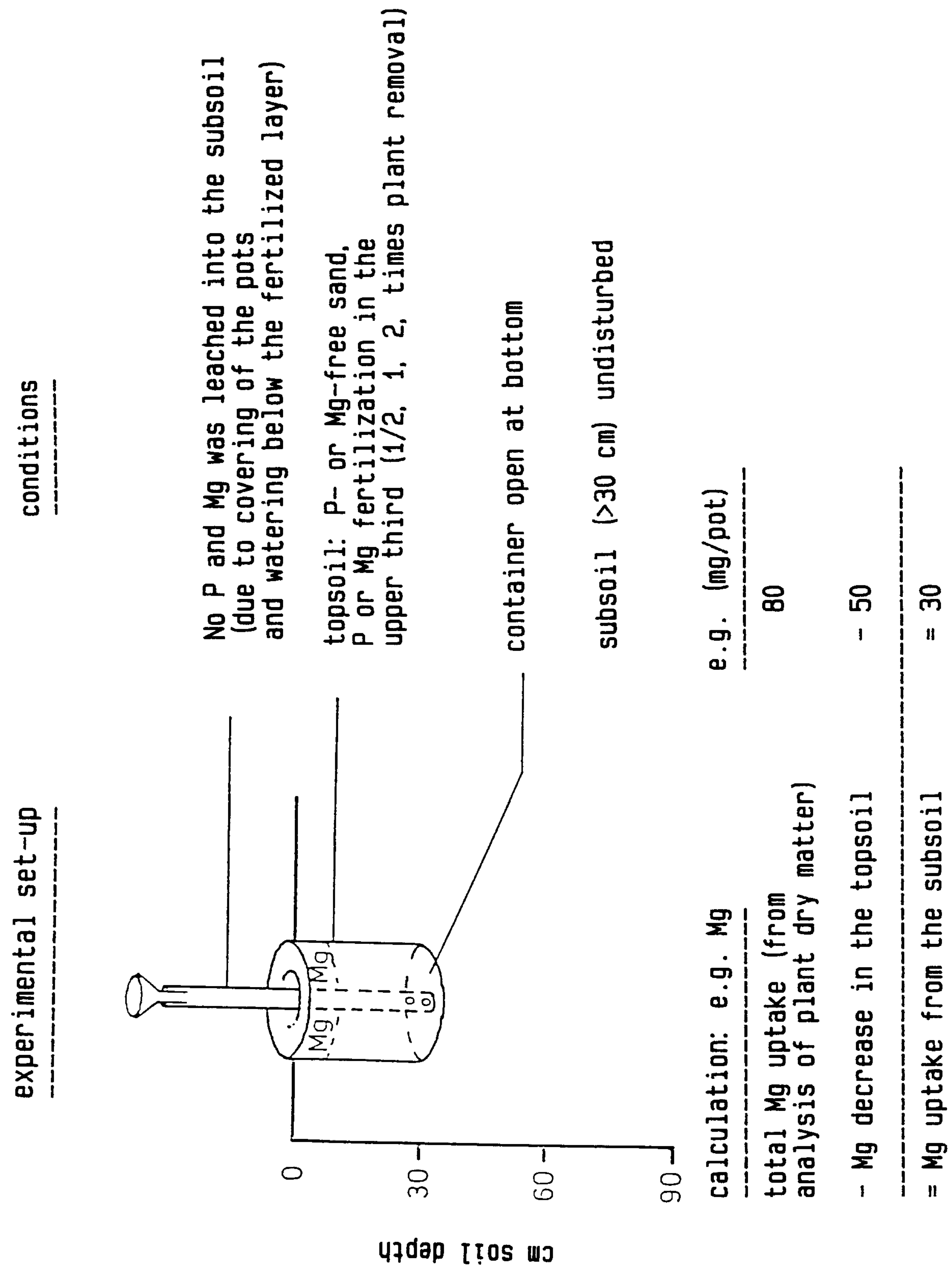

Fig. 1. Experimental set up.

uptake of Mg and P, respectively. P or Mg were added in varying amounts to the upper third of the containers for experiments to determine P- and Mg uptake, respectively. For the P-uptake experiments, there were 3 treatments in which P was added at rates of 40, 150, and 300 mg P per container. For the Mg-uptake experiments, there were 3 treatments in which Mg was added at rates of 30, 100, and 300 mg per container.

Each treatment was replicated four times. Twenty spring wheat (cv. Syros) plants were grown in each container. After germination the containers were inserted into the topsoil in the experimental fields. By removing the plate at the base of the container roots were able to penetrate the undisturbed subsoil.

Precautions were taken to avoid leaching of P or Mg out of the sand into the subsoil. Firstly, the experimental area was protected from rainfall, by a transparent covering. Secondly, the watering of the containers was carried out beneath the soil layer fertilized with P or Mg. An irrigation pipe in the middle of the container was used for this purpose (see Fig. 1). The upper third of the 'topsoil', which was fertilized with P or Mg, was kept moist by small additions of water 1–2 times day^{-1}. Analysis of different layers of the topsoil for P and Mg showed no evidence of leaching of P or Mg from the topsoil into the subsoil, so all P and Mg removed from the topsoil was attributed to uptake by crops. P in the topsoil and subsoil was analysed after extraction of the soil following the HCl and CAL methods, respectively; Mg was extracted with $CaCl_2$ (see below). Wheat was harvested at the anthesis and milk stages in the P and Mg experiments, respectively. Dry matter was analysed for P and Mg.

Since the plants were not grown in natural topsoils, the results can only give an indication of the natural situation. Only the potential uptake of P and Mg from the undisturbed subsoil can be estimated in relation to the P and Mg supply in the topsoil.

Soil analysis

Two different methods were used to extract P from the soil. The CAL method (Schüller, 1969) is routinely used in Germany to obtain a measure of plant-available P. Following this method, soil was shaken for 2 hours at room temperature in a soil solution ratio of 1:20, in a mixture of $0.05M$ calcium lactate, $0.05M$ calcium acetate, and $0.03M$ acetic acid. Using the HCl method, soil was shaken in $4M$ HCl for 2 hours at room temperature in a soil:solution ratio of 1:50. Mg was extracted in $0.025N$ $CaCl_2$ following the method of Schachtschabel and Heinemann (1974). Soil was shaken in solution (1:10 ratio) for 1 hour at room temperature.

Results and discussion

P uptake from the subsoil

Using the balance method, the uptake of P by wheat was estimated from black earth and parabrown subsoils containing 9 mg and 13 mg CAL-extractable P_2O_5/100 g, respectively. P uptake from the subsoil was similar in each treatment on both subsoils (Baumgärtel, 1988). Therefore, average values are presented in Table 2.

Yield and P uptake increased with increasing amount of P fertilizer applied, although the P content in the plant dry matter remained constant. The P uptake from the topsoil was increased from 17 to 125 mg P/container by the addition of P to this soil layer. The decrease of P in the topsoil (A) and the total P uptake by the plants (B) were used to calculate the percentage uptake from the subsoil $(=(B-A)\times 100/B)$. This value decreased with increasing P in the topsoil. When P supply in the topsoil was 40 mg/container, 85% of P uptake was supplied from the subsoil. With supplies of 150 and 300 mg/container, the contribution from the subsoil was reduced to 59 and 37% of total uptake, respectively.

The question remains whether the potential supply from the subsoil can be estimated from extractable P fractions of the soil. Calculations of P transport to the root by diffusion confirmed that such a supply from the subsoil was possible, only if root hairs were present. Details of the calculations are shown below.

Table 2. Balance sheet of P uptake by wheat from the subsoil (>30 cm) with varying P supply in the topsoil (field experiments, average of 2 sites with initial subsoil P contents of 9 and 13 mg P_2O_5/100 g soil (CAL); harvest at anthesis)

P supply in the topsoil (mg/container)		40	150	300
Residual P in the topsoil (mg/container)		23	86	175
P decrease in the topsoil (mg/container)	(A)	17	64	125
P uptake (entire plant) (mg/container)	(B)	114 a	156 b	199 c
% P uptake from the subsoil = (B − A) × 100/B		85 a	59 b	37 c
Dm yield (entire plant) (g/container)		52 a	75 b	97 c
P content at anthesis (% in Dm)		0.220 a	0.208 a	0.205 a

Different letters indicate significant differences at 5% level (Tukey test).

Theoretical calculations of P uptake from the subsoil

Using the model of Barraclough (1986) (Equation 1), it is possible to calculate the concentration of P in the soil solution (C_l) required to sustain the measured inflow (uptake rate/unit length of root). Use of this equation assumes transport of P to the root only by diffusion. This assumption is valid because transport of P by mass flow is minimal at low concentrations of P in the soil solution (Barber, 1984).

$$C_l = C_{la} - \frac{I}{4\pi D_l \theta f_l} \times \left[1 - \left(\frac{1}{1 - \pi a^2 L_v}\right) \ln\left(\frac{1}{\pi a^2 L_v}\right)\right] \quad (1)$$

C_l was calculated for the wheat crop grown on the black earth subsoil using parameter values measured in this field experiment. I, the mean measured inflow, was 0.01 pmol cm^{-1} s^{-1}. This was calculated from P uptake, and root length data (for both top and subsoil) for the wheat crop grown from the middle of May until the end of June (for details of measurements of root length and P uptake, see Kuhlmann, 1988). L_v, the mean root length density in the subsoil (30–60 cm) was 2 cm cm^{-3}. The value of a, the mean root radius was 0.015 cm, being the average of several measurements made using a microscope. The value of θ, mean volumetric water content of the soil was 0.3 cm^3 cm^{-3}, and that of f_l, the tortuosity factor, 0.3, a value derived from the equation of Barraclough and Tinker (1981). D_l, the diffusion coefficient of $H_2PO_4^-$ in water at 15°C was 0.74×10^{-5} cm^2 s^{-1}. C_{la}, P concentration in soil solution at the root surface, was assumed to be 0.5 μM (Breeze and Wild, 1984).

Substitution of these values into Equation 1 resulted in a value of C_l of 7μM. This is equivalent to a CAL-extractable P_2O_5 soil content (C) of 16.7 mg 100 g^{-1} of soil, which was calculated using a buffer power of 500 measured by Müller (1988) on very similar soils. C was calculated as follows:

$$\text{Since } b = \frac{\Delta C}{\Delta C_l} = \frac{C}{C_l}$$

$$C = C_l \times b$$

Substituting for b and C_l gives:

$$C = 7\ \mu M\ P \times 500$$
$$= 3500\ \mu M\ P$$
$$= 250\ mg\ P_2O_5\ dm^{-3}\ of\ soil$$
$$= 16.7\ mg\ P_2O_5\ 100\ g^{-1}\ of\ soil$$

(soil bulk density = 1.5 g cm^{-3}).

This value is higher than that measured in the black earth subsoil of the field experiment (9 mg P_2O_5 100 g^{-1}), and thus P could not have been transported at the required rate by diffusion. This calculation was made assuming the absence of root hairs. If it is assumed that densely packed root hairs were present, then the mean root radius is effectively increased by the mean length of root hairs, which for wheat is 0.029 cm (Itoh and Barber, 1983). Extending the mean root radius in Equation 1 by this value results in a decrease in C_1 to 4.5 μM (which is equivalent to 10.7 mg CAL-extractable P_2O_2 100 g^{-1}). Alternatively, if root hairs are considered as extensions of the root length system (as a lateral root) with a length of 16.2 cm per cm of root and an average radius of 5.7×10^{-3} mm (Itoh and Barber, 1983), then C_1 is further reduced to 1 μM (equivalent to 2.4 mg CAL-extractable P_2O_5 100 g^{-1}). This latter assumption, however, probably leads to an underestimation of the required P concentrations in the subsoil, because root hairs are not evenly distributed in the soil, and competition which occurs between densely packed root hairs was not allowed for.

Obviously, if the effect of root hairs is considered in Equation 1, the concentration of CAL-extractable P as measured in the field experiment would have been sufficient to sustain the required uptake rate by diffusion. In this situation, the subsoil which contained approximately 1/4 to 1/3 of total root length (Kuhlmann, 1988) could have supplied 20–30% of the total P uptake of the crop. Results, however, should be treated with caution, since the calculation of C from C_1 involved the use of b measured on different (although very similar) soils. If b is underestimated, then the corresponding value of C will be proportionally higher, and vice versa.

Results from Fleige et al. (1981), who also found 30% of P taken up from the subsoil, support the present findings that the subsoil is involved to a substantial extent in the P nutrition of the crop. Their experiment was carried out with spring wheat on a parabrown soil in an area south of Hannover on soil containing less CAL-extractable P (11.5 mg and 4 mg CAL-extractable P_2O_5/100 g in the top and subsoil (30–60 cm), respectively) than the present black earth soil.

Using an isotope dilution method with ^{32}P, Haak (1977) established that the subsoil contributed 10–50% to the P nutrition of spring cereals on sites in Sweden. This large range was attributed to various factors, such as P content of the soil, seasonal influences, seeding date, crop growth, crop species and varieties.

Mg uptake from the subsoil

The contribution of the subsoil to the Mg nutrition of wheat was estimated by the balance method on 3 soil types: a sandy brown, a parabrown, and a black earth soil with $CaCl_2$-extractable Mg contents in the subsoil of 4, 6 and 8 mg/100 g, respectively.

The results of these three experimental sites are presented in Table 3 as average values for each treatment, since there were no appreciable differences in uptake of Mg from the subsoil between the sites (Kuhlmann, 1988).

Addition of Mg to the topsoil led to a significant increase in Mg concentration in the dry matter from 0.093 to 0.103%. Since yield did not increase, a Mg concentration of 0.093% was sufficient for optimum growth.

Almost all Mg in the plants grown at the lowest Mg level in the topsoil (30 mg/container) originated from the subsoil (97%). The contribution of the subsoil decreased to 33% with increasing Mg supply in the topsoil. In the treatment with the lowest Mg supply in the topsoil, Mg deficiency symptoms appeared on all three sites during tillering. However, these disappeared as soon as the roots grew into the subsoil.

The measured Mg uptake of 97% from the subsoil can be compared with the results of theoretical calculations under field conditions. The potential transport of Mg by mass flow to the roots in the subsoil can be calculated from a theoretical calculation of mass flow which is the product of total water used from the subsoil up to the milk stage and Mg concentration in the soil solution of the subsoil. The value of water used was assumed to be 50 mm (Renger et al., 1981), and the Mg concentration was the lowest measured of the sites studied (500 μM). This results in a potential supply of Mg by mass flow of 0.6 g m^{-2} which is equivalent to 6 kg ha^{-1}. This amount is equivalent to about 50% of the usual Mg uptake by spring wheat up to the milk stage (Renger et al., 1981). The remainder of

Table 3. Balance sheet of Mg uptake by wheat from the subsoil (>30 cm) with varying Mg supply in the topsoil (field experiments; average from three sites with subsoil Mg contents of 4, 6 and 8 mg Mg/100 g soil ($CaCl_2$); harvest at milk stage)

Mg supply in the topsoil (mg/container)		30	100	300
Residual Mg in the topsoil (mg/container)		27	78	226
Mg decrease in the topsoil (mg/container)	(A)	3	22	74
Mg uptake (entire plant) (mg/container)	(B)	101	96	110
% Mg uptake from the subsoil = (B − A) × 100/B		97 a	77 b	33 c
Dm yield (entire plant) (g/container)		109 a	100 a	107 a
Mg content at milk stage (% in Dm)		0.093 a	0.096 a	0.103 b

Different letters indicate significant differences at 5% level (Tukey test).

Mg was probably delivered to the roots by diffusion. Seggewiss (1986) has shown that this is possible under the given conditions.

The Mg contents of the soils from the three experimental sites (4, 6 and 8 mg 100 g^{-1} in the subsoil) are lower than those of most typical loess sites, which average 8 mg and 10 mg 100 g^{-1} in the top- and subsoil, respectively.

It can be assumed that on loess sites, with almost the same Mg contents in the top and subsoils (Kuhlmann, 1988), Mg uptake from the subsoil is approximately equal to the proportion of the root system present in the subsoil, which is 20–30% (Kuhlmann, 1988).

The results have shown that wheat is capable of taking up significant amounts of P and Mg from the subsoil. This fact should be considered when planning P and Mg fertilization.

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