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USE OF A SIMULATION MODEL TO QUANTIFY THE AMOUNT OF PHOSPHATE RELEASED FROM ROCK PHOSPHATE BY RAPE

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INTRODUCTION

In earlier papers it was established that rape (Brassica napus L.) is, in contrast to other species, an effective user of sparsely soluble rock phosphates (Hoffland et al. 1989a). It was demonstrated that rape acidifies its rhizosphere along a root zone of about 1.5 cm behind the root tip by exudation of organic acids as a reaction to P deficiency (Hoffland et al. 1989b). This rhizosphere acidification was assumed to be the cause of increased solubilization of rock phosphate.

In this paper we estimate the amount of P released from rock phosphate by rape as the difference between results of model simulations of P uptake without considering solubilization of rock phosphate by root exudation with experimentally determined P uptake by rape grown on rock phosphate.

Therefore, first the validity of the model for the simulation of nutrient uptake described by Hoffland et al. (1990) is checked with respect to its ability to predict uptake of dissolved P by a growing root system of rape at low P levels. Most other simulation models (Nye et al. 1975; Claassen and Barber 1976; Cushman 1979) underestimate the uptake of P from low P soils, even in case of non-rock phosphate-mobilizing plant species. This underestimation is attributed to lack of inclusion of the effect on P uptake of root hairs (Brewster et al. 1976; Schenk and Barber 1979; Fontes et al. 1986) or of the effects of inter-root competition in the model (Brewster et al. 1975). In the model of Hoffland et al. both phenomena are accounted for.

In a pot experiment the amount of P absorbed by rape grown on quartz sand mixed with a nutrient solution containing soluble P (KH_2PO_4) has been measured. The experiment provided plant and soil parameters for the simulation model. The P uptake measured in the pot experiment and the P uptake calculated by the model are compared and the differences are discussed in this paper.

METHODS

Experiment

Rape plants (Brassica napus L. cv. Jetneuf) were grown for 16 days after germination on cylindrical pots (10 plants per pot; Ø 12 cm) filled to a height of 20 cm with 3.1 kg quartz sand mixed with 560 ml nutrient solution. To make the quartz sand as inert as possible it was previously washed in 1.5 M

HCl, rinsed with water and subsequently heated at 900 °C for a few hours. The nutrient solution consisted of 5.0 mM $Ca(NO_3)_2$; 5.0 mM KNO_3; 2.0 mM $MgSO_4$ and trace elements (Hoffland et al. 1989a). In the 0.01 mM P and the 0.05 mM P treatment 0.01 mM and 0.05 mM KH_2PO_4 was added, respectively. In the rock phosphate (rock P) treatment 560 mg Mali rock phosphate (13.4 % P) was mixed with the quartz sand. The moisture content was adjusted daily for each treatment. Growth conditions were: temperature: 20 °C; light period: 16 h (70 W/m^2); relative humidity: ± 80%.

Plant material from part of the pots was dried and analyzed for P at each harvest. Other pots were deep frozen and divided into five layers of 4 cm height, referred to as layer I to V, from top to bottom. Root length and volumetric moisture content were determined in each layer.

The initial P concentrations in the soil solution of each layer were determined at t=0 (moment of germination) and t=16 after collecting the soil solution by extraction under vacuum from pots without plants. Evapotranspiration was measured daily. The tortuosity factor as dependent on the volumetric moisture content was determined as described by Hoffland et al. (1990).

Simulation

The main part of the simulation model used was described earlier (Hoffland et al. 1990). Only essential characteristics are given here. The root is located in the centre of a soil cylinder from which a limited amount of nutrients can be withdrawn. The root surface behaves like a zero-sink, i.e. each phosphate ion arriving at the root surface is absorbed, resulting in a zero P concentration at the root surface. Therefore, uptake of phosphate is the resultant of phosphate supply to the root surface by mass flow and diffusion, described according to Nye and Tinker (1977; eqn 1.5). Interaction of phosphate with the soil is not described in the model.

Inter-root competition is accounted for in the model similarly as in Cushman (1979): the wall of the considered soil cylinder surrounding a root is impermeable to nutrients. This results in a decreasing phosphate concentration at the cylinder wall in consequence of uptake.

To describe the effect of increasing root density on phosphate uptake the soil cylinders are divided into a number of shells. Each time the root length exceeds the length of the current soil cylinder, the outer shell of the cylinder is stripped off and its material is used to form a new soil cylinder, assigned to the newly grown roots. The new soil cylinder is divided into the same number of shells as left over in the stripped cylinders. Initially the phosphate concentration in the newly formed soil cylinders equals the weighted mean concentration of the shells from which they originate.

Root hairs are considered as an extension of the root radius.

To predict P uptake from rock phosphate without considering rhizosphere acidification, the model was extended. It is assumed that the P concentration in the soil solution of each shell remains constant as long as the amount of rock phosphate in that shell is not depleted. The amount of phosphate trans-

ported from a shell towards the root is replenished from the rock phosphate immediately, i.e. the chemical equilibrium which keeps the phosphate concentration at a certain constant level is adjusted without delay. The zero-sink concept is maintained, resulting in a concentration gradient of zero at the root surface to the equilibrium concentration within the innermost shell.

The soil parameters necessary to run the simulation model are: the volumetric moisture content, the diffusion coefficient of phosphate in water, the tortuosity factor, and the initial concentration of phosphate in the soil solution and in rock phosphate. Required plant parameters are: root length and water uptake per unit root length as a function of time, root radius and root hair length. No spatial gradients in volumetric moisture content and root density are accounted for in the model.

The CSMP-III model was run on a VAX computer using the variable time step integration method of Runge-Kutta Simpson. The initial number of shells was set to 20.

RESULTS

Experiment

The initial P concentrations in the soil solution and the root lengths determined in the experiment are given in Table 1 and 2, respectively. The volumetric moisture contents were 0.15, 0.21, 0.25, 0.28 and 0.31 in layer I to V in all treatments due to redistribution of water by gravity. The initial P concentration differed considerably from one layer to another. Part of the phosphate added with the nutrient solution is apparently adsorbed on the quartz sand. If the amount adsorbed per gram sand would be the same in each layer, the different initial concentrations could partly be caused by the different volumetric moisture contents.

The amounts of P absorbed by the plant as a function of time are shown in Figure 1. In the 0.01 mM P and 0.05 mM P treatment growth was strongly limited by P: the tissue concentration of P declined

Table 1: Initial phosphate concentration (mM) in the soil solution of each layer for all treatments in pots without plants. Results are means of two.

	Treatment		
Layer	0.01 mM P	0.05 mM P	rock P
I	0.003	0.009	0.004
II	0.007	0.029	0.001
III	0.010	0.041	0.001
IV	0.011	0.042	0.001
V	0.012	0.044	0.001

Table 2: Root length (m) per layer as a function of time for each treatment. Values are means of two.

	0.01 mM P					0.05 mM P					rock phosphate				
Time (days)	0	4	7	11	16	0	4	7	11	16	0	4	7	11	16
Layer															
I	0.3	2.7	5.2	8.6	11.9	0.3	2.7	5.8	7.7	9.5	0.3	2.6	7.4	12.5	25.2
II	0.1	1.2	5.3	7.3	11.8	0.1	1.9	4.0	9.0	11.6	0.1	0.6	3.6	11.7	24.5
III	0.0	0.6	2.0	4.8	9.7	0.0	0.2	1.2	7.4	12.9	0.0	0.4	1.3	8.8	17.3
IV	0.0	0.0	0.4	1.7	4.0	0.0	0.0	0.1	2.4	11.3	0.0	0.0	0.1	3.3	13.7
V	0.0	0.0	0.0	0.2	0.7	0.0	0.0	0.0	0.1	3.3	0.0	0.0	0.0	0.7	3.9

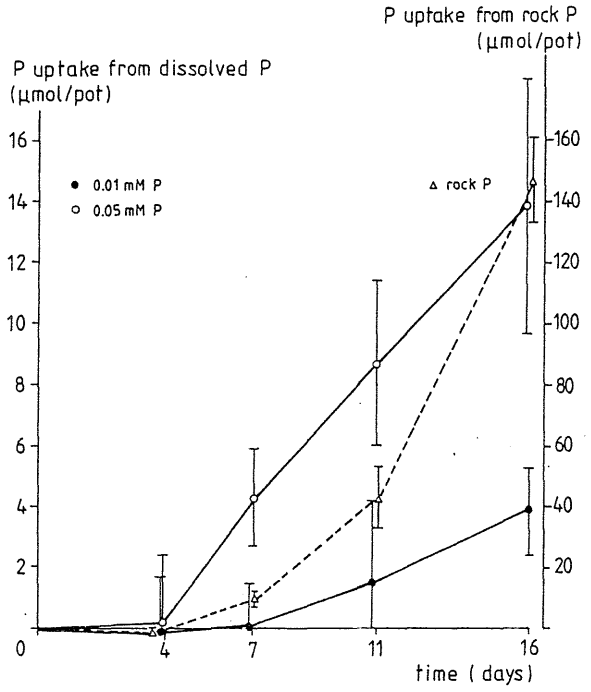

Figure 1: P uptake (means ± s.d.; n=3) by rape plants grown on quartz sand as a function of time. Note the different scales for the different treatments.

in both treatments from about 90 mmol/kg dry matter after 4 days of growth to about 25 mmol/kg dm after 16 days. In case of the rock P treatment the tissue concentration of P remained constant at about 85 mmol/kg dm throughout the experiment.

Simulation

Soil and plant parameters derived from the pot experiments were used to run the model. In case of the rock P treatment the concentrations of dissolved P as given in Table 1 were taken as the equilibrium concentrations.

The simulation model was run for each of the considered soil layers. Total P uptake was calculated by summation.

Predicted and observed P uptake are shown in Figure 2.

DISCUSSION and CONCLUSIONS

The results of the experiments show that there are considerable differences in initial P concentration (Table 1), root length (Table 2) and volumetric moisture content between the five layers of one pot. Since the model does not account for

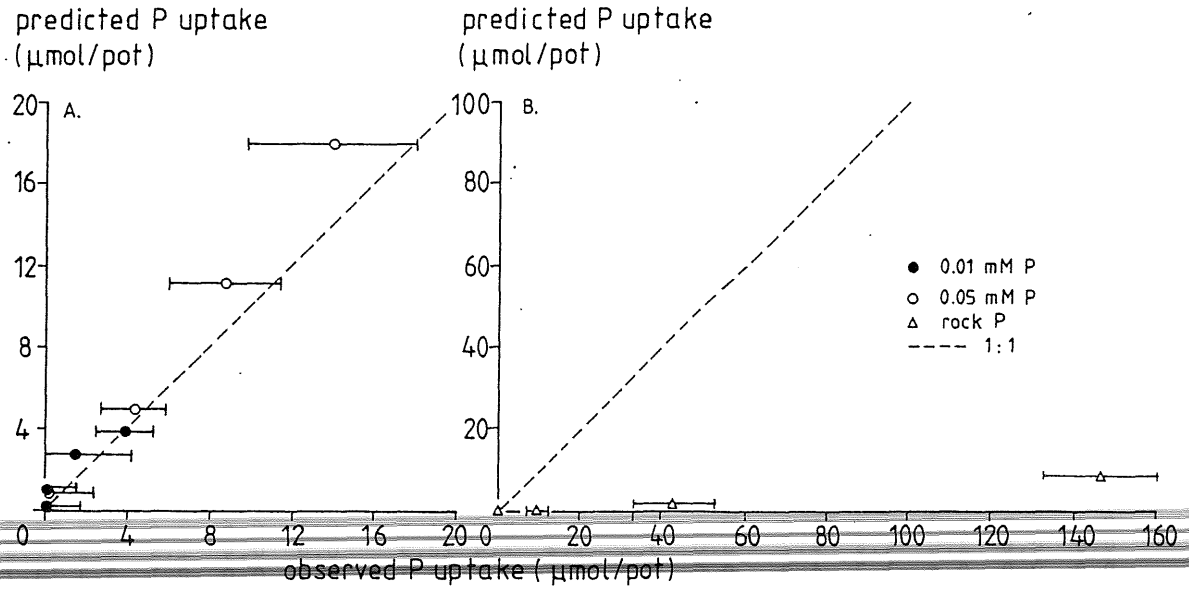

Figure 2: Comparison of observed P uptake (means ± s.d.; n=3) by rape with predicted uptake for the 0.01 and 0.05 mM P (A) and the rock P treatment (B).

spatial gradients in these parameters, the necessity to distinguish five layers instead of one for simulations is evident.

There is a relatively large scatter in the observed P uptake (Fig. 1). This is partly due to the fact that from the small amounts of P in the plants the amounts already available in the seeds (11.41 ± 1.14 umol) had to be subtracted to calculate P uptake.

Figure 2A shows good agreement between predicted and observed P uptake in case of the 0.01 mM P and the 0.05 mM P treatment although the model tends to overestimate P uptake slightly. This may be caused by the model assumption that at any time the roots are regularly distributed within one layer. In the experiment the roots will exploit the upper part of a layer first before penetrating into the lower part. Distinguishing more layers would be an improvement in this respect. In case the roots would be distributed random in the experiment instead of regular as supposed in the model, this could also cause an overestimation by the model (De Willigen and Van Noordwijk 1987). The model descriptions of the effect of root hairs, inter-root competition and increasing root density seem powerful.

Figure 2B shows that the model underestimates P uptake from rock phosphate by rape considerably. This must be due to the fact that the effect of organic acid exudation on rock phosphate solubility was not included into the model. From Fig. 2A it can be concluded that the model would predict P uptake well in case no interaction with rock phosphate would occur. Therefore, the amount of P absorbed in the rock phosphate experiment diminished by the predicted amount absorbed must be the amount of P dissolved as a result of exudation of organic acids. Sixteen days after germination this is about 140 umol P per pot, equivalent to 94 % of the total amount absorbed.

REFERENCES

Brewster J.L., K.K.S. Bhat and P.H. Nye. The possibility of predicting solute uptake and plant growth response from independently measured soil and plant characteristics. III. The growth and uptake of onions in a soil fertilized to different initial levels of phosphate and a comparison of the results with model predictions. Plant Soil 42, 197-226; 1975.

Brewster J.L., K.K.S. Bhat and P.H. Nye. The possibility of predicting solute uptake and plant growth response from independently measured soil and plant characteristics. V. The growth and phosphorus uptake of rape at a range of phosphorus concentrations and a comparison of results with the predictions of a simulation model. Plant Soil 44, 295-328; 1976.

Claassen N. and S.A. Barber. Simulation model for nutrient uptake from soil by a growing root system. Agron.J. 68, 961-964; 1976.

Cushman J.H. An analytical solution to solute transport near root surfaces for low initial concentration: I. Equations development. Soil Sci.Soc.Am.J. 43, 1087-1090; 1979.

De Willigen, P., M. van Noordwijk. Uptake potential of non-regularly distributed roots. J. Plant Nutr. 10, 1273-1280; 1987.

Fontes P.C.R., S.A. Barber and G.E. Wilcox. Prediction of phosphorus uptake by two tomato cultivars growing under insufficient and sufficient phosphorus soil conditions using a mechanistic mathematical model. Plant Soil 94, 87-97; 1986.

Hoffland E., G.R. Findenegg and J.A. Nelemans. Solubilization of rock phosphate by rape. I. Evaluation of the role of the nutrient uptake pattern. Plant Soil 113, 155-160; 1989a.

Hoffland E., G.R. Findenegg and J.A. Nelemans. Solubilization of rock phosphate by rape. II. Local root exudation of organic acids as a reaction to P stress. Plant Soil 113, 161-165; 1989b.

Hoffland E., H.S. Bloemhof, P.A. Leffelaar, G.R. Findenegg and J.A. Nelemans. Simulation of nutrient uptake by a growing root system considering increasing root density and inter-root competition. In: Van Beusichem, M.L., editor. Developments in plant and soil sciences. Dordrecht: Kluwer Academic Publishers; 1990: in press.

Nye P.H., J.L. Brewster and K.K.S. Bhat. The possibility of predicting solute uptake and plant growth response from independently measured soil and plant characteristics. I. The theoretical basis of the experiments. Plant Soil 42, 161-170; 1975.

Nye P.H. and P.B. Tinker. Solute movement in the soil-root system. Blackwell Scientific Publications, Oxford, 342 pp; 1977

Schenk M.K. and S.A. Barber. Root characteristics of corn genotypes as related to P uptake. Agron.J. 71, 921-924; 1979.

SUMMARY

The simulation model described by Hoffland et al. (1990) was used to predict P uptake by rape from inert quartz sand mixed with nutrient solution. The model was evaluated by comparing observed and predicted uptake of dissolved P, which agreed well. In case P uptake from rock phosphate was simulated without considering the effect of rhizosphere acidification on rock phosphate solubility, predicted P uptake was only about 6 % of the observed P uptake after 16 days of growth. It was concluded that about 94 % should originate from the rock phosphate that dissolves as a result of exudation of organic acids by roots of rape.