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An evaluation of plant-borne factors promoting the solubilization of alkaline rock phosphates

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Summary Four experiments are described in which the uptake patterns of various crop species were shown to enhance the solubilization of alkaline rock phosphates. In most cases, such enhancements resulted from soil acidification brought about by the alkaline uptake patterns. In one case, the enhancement may have stemmed primarily from a high Ca-uptake rate, which might be responsible for a shift in mass-action equilibria favoring the solubilization of rock phosphates. High uptake of Ca is expected to serve two purposes: 1. it acts in creating alkaline uptake patterns causing a decline in soil pH, and 2. it promotes a shift in mass-action equilibria.

Introduction

Variations among plant species in ability to absorb soil and fertilizer phosphate have received ample attention in the literature and continue to attract the interest of many researchers. Each new discovery of a phosphate deposit, often in developing countries being in great need of phosphate fertilizers, again raises the question whether, and if so, under which conditions the phosphate rock can be used in agriculture without having to be submitted to a beneficiation procedure, apart from grinding.

It is evident that the usefulness of rock phosphates to crops can be influenced by soil-borne and plant-borne factors. Concerning the former, it is in the first place well-known that rock phosphates dissolve more readily in acid than in neutral and alkaline soils. Crops capable of yielding satisfactorily when grown on acid soils may, therefore, be in a position to utilize phosphate applied in the form of rock phosphate. Second, in submerged soils, as in the case of lowland rice production, the extensive body of water in contact with soil and added fertilizer allows the total quantity of dissolved phosphate (the phosphate intensity) often to be large enough to meet the phosphate requirement

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of the rice crop even when the P fertilizer is a sparsely soluble rock phosphate.

In addition, the large volume of soil moisture reduces the interference imposed by solid soil particles on the rate of diffusion of phosphate ions to the extent that translocation of phosphate ions by diffusion toward absorbing roots proceeds much more rapidly than in aerobic soils.

Regarding the plant-borne factors Black[3] distinguished three theories to account for the observed differences among plant species in ability to absorb phosphates, viz. the *root-character* theory, the *phosphorus-requirement* theory, and the *ionic-equilibrium* theory.

In the root-character theory emphasis is laid on differences in root system extensiveness and in P absorption characteristics among species. Gramineous plants are known for the extensiveness of their root systems. It can be reasoned that a specific ability to maximize contact between P-bearing soil constituents and absorbing root surface, and to lower the concentration of P in the liquid phase of a large fraction of the soil body is likely to promote the capacity of the species to withdraw phosphate from the soil. However, it has often been shown and will be shown again in the present investigation that, in spite of the extensiveness of the root system of gramineous species, these plants are not very effective P feeders when rock phosphate is the P source. Apparently, other characteristic features of these species overshadow the favorable effect of the extensiveness of the root system, with regard to mobilization of rock phosphates.

The phosphorus-requirement theory is based on observed differences in the rate with which various crop species absorb P. It is commonly observed that slow-growing species low in P content are better adapted to grow under conditions of phosphorus deficiency than are fast-growing species high in P content. In an attempt to account for the differential response of crop species to rock phosphate applications, Khasawneh and Doll[9] emphasized the importance of differences in relative growth rates and their effects on the quantities of both Ca and P required for normal growth. In accordance with this statement, to maintain a normal growth rate fast-growing plants are known to show a high rate of P uptake. If a plant species has an extensive root system, the P demand per unit length of root will be lower than for a species having a root system of limited extensiveness. Again, for a given level of P-intake per unit root length, the concentration of P in the soil solution needs to be above a certain critical value which is determined by the kinetics of P uptake for the species involved. If a rock phosphate cannot maintain such a concentration in solution, the rate of P absorption per unit of root will be insufficient and the relative growth rate will decline accordingly.

In their coverage of 'the use of phosphate rock for direct application to soils', Khasawneh and Doll did not mention any direct effect roots may have on the solubility of soil and fertilizer phosphates. Nevertheless, on this subject much research work has been conducted that can be included in the so-called ionic-equilibrium theory. Evidence that plants actively influence the external ionic environment governing phosphorus solubility in soil is to be found in the classical experiment demonstrating the etching of polished marble in contact with roots, presumably as a result of the action of protons originating from the carbonic acid exuded by the roots. Further evidence was provided by Johnston and Olsen[7] who observed a much larger P uptake when roots of squash, barley and wheat were in direct contact with Virginia fluorapatite than when they were confined to the supernatant liquid. These authors concluded that pH changes in the liquid phase of the growth medium, CO_2 excretion and exudation of chelates (except for squash) were not responsible for the observed increases in P uptake, but that the efficient feeders (squash and soybean) were most effective in removing calcium from the immediate environment of the solid rock phosphate with a concomitant shift in the mass-action equilibrium of the calcium phosphate compound. In other words, a decrease in Ca concentration (increase in pCa) will be accompanied by an increase in phosphate concentration (decrease in pPO_4). This is in agreement with Truog's[11] original ideas on variations in 'feeding power'. However, Johnston and Olsen concluded that the shift in Ca concentration would be insufficient to account for a significant solubilization of the phosphate unless the mass-action effects were confined to the immediate environment of the rock. In earlier work by Leggett *et al.*[10] with detached barley roots and by Wild[12] with plants grown on nutrient solutions, no effect of variations in Ca concentration upon the uptake of P was found.

The ionic-equilibrium theory can be extended to include those instances in which on an equivalence basis the uptake of cationic and anionic nutrients by plants is shown to be different. Such a difference will have consequences for the pH of the root environment and, by inference, for the solubilization of rock phosphate.

Imbalances in cationic and anionic uptake can be divided in cases of excess-cation-over-anion uptake and excess-anion-over-cation uptake. In a third category, plants absorb equivalent quantities of cations and anions. Such plants exert no influence on the pH of their root environment and, consequently, do not affect the rate of mobilization of rock phosphates.

When N is absorbed as NO_3, in most plant species anion uptake exceeds cation uptake. For maintenance of internal and external electroneutrality, plants are expected to compensate for the resulting imbalance in ionic uptake. The exact nature of this compensation is as yet unknown, but the effect of it is measurable. The equivalents of acid needed to neutralize the pH increase brought about in nutrient solutions by plants absorbing from these solutions more anions than cations, has been found[6] to equal the equivalents of excess anions absorbed. This finding has given rise to the supposition that to maintain electroneutrality OH-ion excretion by plant roots is in order. Such a situation can be represented by the following equation:

$$\text{OH efflux} = \Sigma \text{ anions absorbed} - \Sigma \text{ cations absorbed} \qquad (1)$$

Measurements of ion absorption in this type of experiments usually comprise the cations K, Ca, Mg and Na and the anions NO_3, H_2PO_4, SO_4 and Cl. Omission of minor elements usually leads to not more than acceptably small errors in balance estimation. Omission of NH_4 is acceptable only when experiments are conducted in water- and sand-cultures or when plants receive NO_3 fertilizer added to soils containing only negligibly small quantities of organic matter.

Cereals are representatives of the large group of species absorbing more anions than cations, when N is absorbed as NO_3. Plants in this category display a so-called 'acidic uptake pattern'.

The category of plant species absorbing more cations than anions, even when N is absorbed as NO_3, is small. For such plants, the following relationship holds:

$$\text{H efflux} = \Sigma \text{ cations absorbed} - \Sigma \text{ anions absorbed} \qquad (2)$$

Buckwheat is a well-known representative of this category. The pH decrease in the root environment resulting from such a H efflux can be expected to aid the solubilization of alkaline rock phosphates.

If the unusually high uptake of cations by such species is brought about mainly by higher than normal Ca-uptake rate, the resulting shift in the mass-action equilibrium of the added calcium phosphate may corroborate the solubilizing action stemming from the H efflux which, in turn, results from the excess-cation-over-anion uptake of equation 2. Such a pattern is called an 'alkaline uptake pattern'.

Plant species that normally display an acidic uptake pattern shift to an alkaline uptake pattern when N is absorbed as the cationic NH_4^+. It is known that many gramineous plants, although showing a slight preference for NO_3-N, grow reasonably well when all N is absorbed as NH_4. In water- and sand cultures, N added as NH_4 can be expected to also be taken up as NH_4. In soil cultures, such an expectation is justified only when the soil is extremely acid or completely anaerobic, or when nitrification inhibitors are used. When NH_4 nutrition is a consequence of extreme soil acidity, the resulting cationic uptake pattern of plants absorbing N as NH_4 will even aggravate such an acidity. However, absence of nitrification also means avoidance of the acidification arising from nitrification, although this acidification can be partially neutralized when the nitrate formed induces an acidic uptake pattern of plants utilizing the NO_3.

As stated earlier, it is known that gramineous plants showing an acidic uptake pattern, when N is absorbed as NO_3, switch to an alkaline uptake pattern when N is absorbed as NH_4, without serious damage being done to the health and productivity of these plants. The question then arises whether any dicotyledonous plants exist which already exhibit an alkaline uptake pattern under conditions of NO_3 nutrition, but which show an even more outspoken pattern of alkaline uptake when absorbing N as NH_4. In the present investigation, the characteristics of rape (*Brassica napa oleifera*) were tested.

It has already been established that legumes, when using symbiotically fixed nitrogen, can show an alkaline uptake pattern resulting in soil acidification and in mobilization of rock phosphates[2]. In the present work, the relative usefulness of two rock phosphates differing in hardness, to field bean (*Vicia faba,* var. Rato) was examined. *Vicia faba* is one of the few leguminous species presently of some importance in Dutch agriculture.

To summarize, the following experiments will be described in the present paper:

1. A comparison of the abilities of buckwheat and maize to utilize P supplied in the form of three rock phosphates.
2. An examination of the responses of two grass species to rock phosphate application under conditions of either NO_3- or NH_4 nutrition.
3. An evaluation of the uptake patterns, the growth and the rock phosphate-mobilizing capacity of rape when exposed to either NO_3 or NH_4 as N source.
4. An investigation of the effect of symbiotic nitrogen fixation on the uptake pattern and the rock phosphate-mobilizing capacity of field bean.

Materials and methods

Greenhouse experiments

For all but one of the experiments, use was made of a sandy loam taken from a depth of approximately 10 meters in a sand pit. This soil is extremely low in P and N and therefore useful as a medium for growth of plants that should make use of only one N source, namely NO_3, NH_4 or atmospheric N_2, and only one P source, namely fertilizer P. The virtual absence of organic matter on the one hand guarantees the absence of any N mineralization, but on the other hand is also responsible for very poor structural conditions. Due to the latter feature, rape failed to grow on this soil and had to be grown on another soil. This again was a sandy loam, also chosen for its extremely low P availability. However, being a topsoil, this soil contained organic matter (3%) and therefore released some inorganic N during the growth period of the rape. Less so than in the subsoil could therefore in this soil the form of N available to the plants be confined to strictly NH_4 or strictly NO_3.

The pots used for the various experiments contained either 3 kg or 7 kg of soil. Specific information on the type of pot and the number of plants per pot will be given for each experiment in the next section.

In total, 4 rock phosphates were tested. Their origins, P contents and percentages of total P soluble in 2% citric acid were, respectively: Morocco, 13.7% P, 40%; Mali, 13.3% P, 26%; Florida, 13.5% P, 24%; Mexico (Zimapan) 13.5% P, 16%. The performances of these rock phosphates in making P available to plants were compared with that of triple superphosphate (TSP). The rock phosphates were applied in the form of powder that had passed a 0.125 mm sieve.

Growth responses of the plants were measured in the form of dry matter produced. Only in the *Vicia faba* experiment were the dry-matter yields of the root systems included in the measurements. The plant material was dried for 48 hours at 70°C, weighed and ground. Plant subsamples were analyzed for K, Ca, Mg, Na, H_2PO_4, NO_3, Cl, SO_4 and total N.

Analytical techniques

Subsamples of dried plant material were wet-ashed in H_2SO_4 and H_2O_2 in the presence of salicylic acid. In the digest, Na, K, Mg and Ca were determined flamephotometrically, and H_2PO_4 and total N colorimetrically. In an aqueous extract, NO_3, Cl and SO_4 were determined. For NO_3 this was done colorimetrically after reduction of NO_2, for Cl potentiometrically with the use of a chlor-o-counter, and for SO_4 turbidimetrically.

Methods of calculation

The method for calculating acid and alkaline excretion by plants was described earlier[4]. For NO_3-fed plants, the total number of equivalents of cationic nutrients absorbed by the plants (C_a) is calculated directly from the analytical values of the K, Ca, Mg and Na determinations, and the number of equivalents of anionic nutrients (A_a) is calculated from the values of total N, total S, H_2PO_4 and Cl. Total S is taken to be the sum of SO_4-S, analytically determined, and organic S which is estimated at 0.05 times the equivalents of organic N[5]. In the case of NH_4-fed plants, the value of organic N is added to the values of the metallic cations to obtain an estimate of C_a, and A_a is estimated as being the sum of total S, H_2PO_4 and Cl.

Results and discussion

Buckwheat and maize

In this experiment, the relative abilities of buckwheat (*Fagopyrum esculentum*) and maize (*Zea mays*, var. LG 11) to utilize rock phosphates were compared. The rock phosphates employed were the ones obtained from Mali, Mexico and Florida. The quantities applied were 370 mg P per pot of 3 kg soil. The basal N application was 200 mg N as calcium nitrate, with two side dressings of 100 mg N each. K was added in either a low or a high quantity (150 mg or 450 mg K per pot). The variation was made to investigate whether the total cation uptake and, hence, the cation-anion uptake balance could be affected. Mg, Ca and minor elements were added in adequate quantities. Care was taken to ensure that the Mg- and SO_4 supplies were not influenced by variation in K supply.

The 5 buckwheat and 3 maize plants per pot were grown for a period of 2 months. Only above-ground plant parts were harvested, and after the harvest soil samples were taken for pH determinations. In Table 1, the yields and chemical compositions of the two crop species are presented. It is evident that even under circumstances of NO_3 absorption, buckwheat shows a strongly alkaline uptake. Maize, to the contrary, displays an acidic uptake pattern. In a comparison of ΣC_a and ΣA_a values for the two species, it is to be noticed that the differences occur mainly in the latter values, and especially in the N contents. It is evident that buckwheat has a low N requirement. With respect to the cation values, it is important to note that, comparatively speaking, buckwheat shows high Ca and Mg contents and low K contents.

The consequences of these large differences in uptake pattern are to be sought primarily in soil pH variations and through these in variations in solubilization of rock phosphates leading to variations in dry-

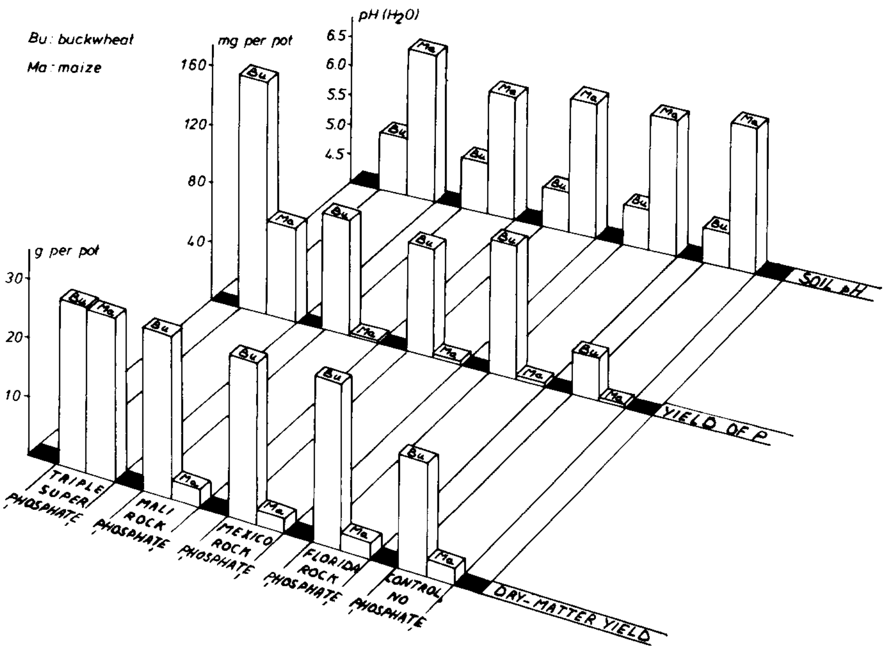

Fig. 1. The effect of variation in cation-anion uptake pattern on the ability of two crops to utilize rock-phosphate P.

matter yields. Information on these features is presented in Fig. 1. It can be seen that buckwheat yields are hardly influenced by variations in P source whereas under conditions of NO_3 feeding maize is unable to grow with P supplied as rock phosphate. That P is the factor limiting maize growth is borne out by the close correlation existing between yield of dry matter and yield of P. Only in the presence of TSP can maize reach a production level resembling that of buckwheat. When TSP is the P source, buckwheat absorbs so much P that the concentration reaches a luxury consumption level (0.57% P). With the rock phosphate sources, an adequate availability of P induces dry-matter yields as high as obtained with TSP.

The information on soil pH levels measured at the end of the experiment makes it clear that the alkaline uptake patterns of buckwheat cause considerable pH declines which are thought to be partially responsible for the solubilization of the rock phosphates. Rises in pH brought about by the alkaline uptake patterns of maize are small on account of poor growth of the maize with rock phosphates. Only with TSP, the satisfactory growth of maize gives rise to a sizeable pH increase.

The high rate of calcium uptake is partially responsible for the alkaline uptake pattern of buckwheat. As a result of this high Ca absorption rate, a shift in the mass-action equilibrium of a rock phosphate may account for a portion of the P solubilization. It was investigated whether an enhanced rate of K uptake, brought about by a raised K application, could widen the differences between cation- and anion uptake without affecting the rate of Ca absorption. If this can be accomplished, it is to be expected that the combined effects of accentuated alkaline uptake pattern and an ability to lower the Ca concentration in the soil solution would still further raise the ability of buckwheat to utilize rock phosphates. The data of Table 1 already indicate that such an attempt remained without success. It is evident that the increase in K uptake, resulting from the raised K supply, is achieved at the expense of the uptake of Ca and Mg, so that with extra K the total uptake of cations is slightly suppressed instead of raised. Averaged over the three rock phosphates, with extra K buckwheat lowered the soil pH to 5.0, whereas with the lower amount of K the pH was lowered to 4.8. In the former case, P absorbed by buckwheat amounted to 88 mg, in the latter to 83 mg per pot.

Three conclusions can be drawn:

1. The exceptional capacity of buckwheat to absorb Ca and Mg, combined with its low N requirement, affords this species a remarkable ability to lower the pH of the soil in which it grows.
2. The combined effects of an alkaline uptake pattern and an ability,

Table 1. Dry matter yield and chemical composition of buckwheat and maize grown with different P fertilizers, and the influence of the crops' cation-anion uptake patterns on the pH of the soil used in the pot experiment

Treatment	Yield g/pot	Chemical composition, meq/kg d.m.												Final soil pH
		Na	K	Ca	Mg	Org.N	NO_3	H_2PO_4	SO_4	Cl	ΣC_a	ΣA_a*	$\Sigma(C_a-A_a)$	
Buckwheat														
No P, low K	19	7	393	1690	1614	1285	121	49	122	68	3704	1710	1994	4.6
TSP, low K	28	19	341	900	1090	1012	12	184	118	43	2350	1420	930	5.0
Mali rock P, low K	28	9	337	1014	1072	1016	22	96	88	43	2433	1316	1117	4.9
Mexico rock P, low K	27	10	360	1168	1208	1124	19	87	86	45	2746	1418	1328	4.7
Florida rock P, low K	29	27	331	1176	1136	951	20	104	104	37	2670	1265	1405	4.9
No P, high K	21	3	574	1330	1264	1247	99	48	62	63	3172	1572	1600	4.8
TSP, high K	31	0	414	812	832	899	11	153	76	41	2058	1213	845	4.9
Mali rock P, high K	28	10	470	900	874	939	32	104	80	47	2254	1235	1019	5.0
Mexico rock P, high K	27	0	408	974	922	1094	15	96	70	54	2304	1384	920	4.9
Florida rock P, high K	27	19	532	988	930	1136	45	113	74	61	2467	1488	979	5.1
Maize														
No P, low K	2.8	19	1106	522	620	1841	804	30	36	185	2267	2988	−721	6.5
TSP, low K	28	5	312	230	450	840	5	77	118	29	996	1104	−108	6.5
Mali rock P, low K	3.0	0	1093	488	566	1992	750	37	44	191	2148	3114	−966	6.1
Mexico rock P, low K	2.8	1	971	610	640	1900	754	37	42	172	2222	3000	−778	6.3
Florida rock P, low K	3.1	4	1004	490	546	1900	618	39	22	108	2043	2782	−739	6.3
No P, high K	2.8	8	1135	476	564	1728	686	30	28	184	2182	2741	−559	6.3
TSP, high K	30	30	405	206	302	760	0	65	74	41	943	979	−36	6.4
Mali rock P, high K	2.7	46	1268	458	526	1739	734	32	20	234	2297	2846	−549	6.1
Mexico rock P, high K	3.3	20	1320	444	536	1723	670	28	28	193	2320	2729	−409	6.6
Florida rock P, high K	2.6	0	1362	494	596	1632	746	23	54	223	2350	2760	−410	6.4

* In this value is included organic S, estimated at 5% of organic N.

through high Ca uptake, to bring about a shift in the mass-action equilibrium of rock phosphates enables buckwheat to effectively utilize these rock phosphates as P sources.

3. When through a raised supply of K the uptake of Ca is suppressed, this effect does not impair the ability of buckwheat to utilize rock phosphates, thus showing that the exceptional feeding power of buckwheat for P is based on both an ability to lower the soil pH and an ability to lower the Ca concentration in the soil solution. The results of the present experiment seem to justify the conclusion that these two phenomena can substitute for each other in promoting the mobilization of rock phosphates.

Ryegrass and Rhodes grass

Most gramineous plants appear to have a slight preference for NO_3 over NH_4 nutrition, and often do best when the two nutrient ions are present in combination with each other. It is to be expected that with NO_3 nutrition the uptake pattern will be an acidic one and that the resulting rise in soil pH will not affect the P nutrition as long as P is supplied in the form of superphosphate or another water-soluble compound. When, however, rock phosphates are used an acidic uptake pattern will interfere with the solubilization of these alkaline phosphates, and consequently, the grass may suffer from P deficiency. With NH_4 as sole N source, an alkaline uptake pattern is to be expected, and the anticipated drop in pH might be large enough to facilitate the solubilization of alkaline rock phosphates.

In an experiment designed to test these expectations, use again was made of pots containing 3 kg of the subsoil described in the previous section. Every pot received 370 mg P, in the form of TSP, Mali rock phosphate or Mexico rock phosphate. Two grasses were grown, namely ryegrass (*Lolium perenne*) and Rhodes grass (*Chloris gayana*). During the growth period, lasting from mid-April to mid-July, the ryegrass was cut five times and the Rhodes grass four times.

Nitrogen was applied either as $Ca(NO_3)_2$ or as $(NH_4)_2SO_4$. In the latter case, a nitrification inhibitor (N-serve) was used for preventing the conversion of NH_4^+ to NO_3^-. The basal application of nitrogen was 140 mg N per pot. During the experiment, when deemed necessary for continued growth, additional portions of 140–210 mg N per pot were applied. K was also applied in small quantities with a frequency adjusted to the rate of removal of K by the grass.

The results obtained are presented in Fig. 2. The data are those on dry-matter yield, yield of P and soil pH measured at the end of the experiment. It can be seen that with the use of TSP for both grass

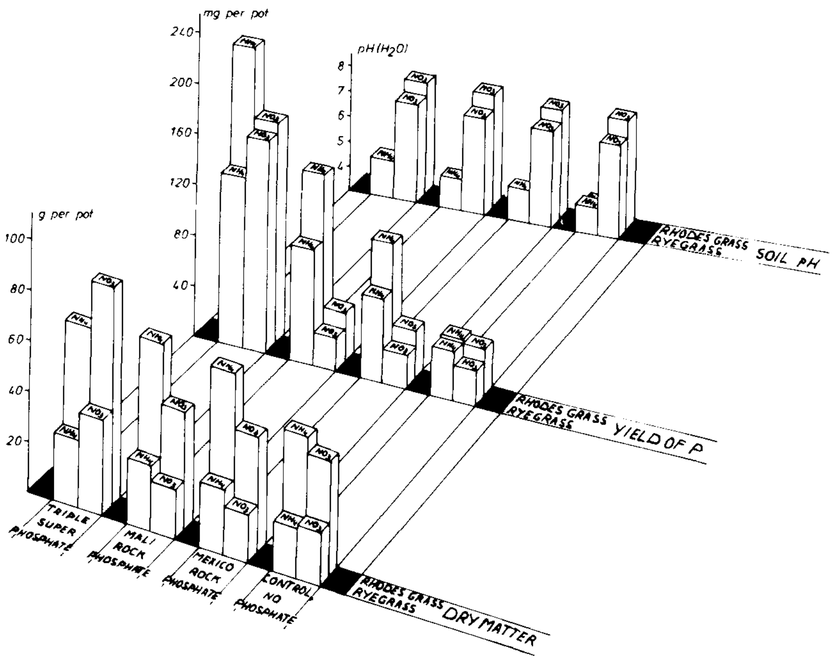

Fig. 2. The influence of variation in type of N nutrition (NO_3 or NH_4) on the ability of two grasses to utilize rock-phosphate P.

species the dry-matter yields obtained with NO_3-N indeed exceeded those obtained with NH_4-N. However, when rock phosphates were used, the yields obtained with NH_4-N surpassed those obtained with NO_3-N. With NO_3-nutrition, the yields in the rock phosphate treatments were so poor that they did not rise significantly beyond those in the control (no P) treatment.

In the TSP treatment, the yield of P in Rhodes grass was not correlated with dry-matter yield. In this species, the uptake of P apparently was so strongly enhanced by the fact that N was absorbed in the cationic form that luxury consumption of P resulted (0.6% P in dry Rhodes grass). In the rock phosphate treatments, dry-matter yields were strongly correlated with P-uptake values, which may serve as evidence that dry-matter yield was a function of the degree of availability of the rock phosphate.

The pH(H_2O) values measured in the soil at the completion of the experiment clearly show that the acidic uptake pattern resulting from NO_3 nutrition causes a strong rise in pH (values ranging from 6.7 to 7.5), whereas the alkaline uptake pattern associated with NH_4 nutrition brings about a sharp decline in soil pH (values ranging from 3.7 to 4.3).

The conclusions to be drawn from this experiment are the following:

1. When phosphate is present in readily available TSP form, both

grasses respond more favorably to NO_3- than to NH_4 nutrition. The yield level reached with NH_4, although lower than that obtained with NO_3, is still high enough to justify the statement that these grasses respond satisfactorily to NH_4 as N source.

2. When N is absorbed as NH_4, the dry-matter yields of both grasses are not affected by differences in solubility among phosphates: the yields obtained with rock phosphates are as high as those obtained with TSP.

3. The lowering of the soil pH brought about by the alkaline uptake pattern of NH_4-fed grass species promotes the solubilization of alkaline rock phosphates to the extent that these rock phosphates can sustain a growth rate of the grasses similar to that encountered with the use of TSP.

Rape

In the next experiment, it was investigated whether the known ability of rape to utilize sparsely soluble phosphates must be attributed to a specific cation-anion uptake pattern, or whether other characteristics of the crop are solely or partially responsible for this feature. In the original experiment conducted, it was found that rape failed to grow on the subsoil used for the other experiments. For that reason, in a second experiment rape was grown on the other sandy loam mentioned in 'Materials and methods'.

Six rape plants (*Brassica napus oleifera*) were grown on 3-kg quantities of soil. The soil had received 420 mg N applied either as $Ca(NO_3)_2$ or as $(NH_4)_2SO_4$. In the latter case, to compensate for the Ca applied when $Ca(NO_3)_2$ was used, $CaSO_4 . 2H_2O$ (2.6 g per pot) was added. In addition, these pots received a nitrification inhibitor (N-serve), of which a second application was made 15 days after germination.

The phosphates used were TSP, Morocco rock phosphate and Mali rock phosphate in quantities of 180 mg P per pot. K and Mg were applied as sulpomag (30% K_2O and 10% MgO as sulphates) in a quantity of 2770 mg per pot. Furthermore, each pot received 165 mg NaCl. Micronutrients were added in the form of a multi-nutrient solution.

The growth period was 43 days. To all pots eventually yielding more than 11 g of dry matter, on days 34 and 39 second applications of N and K + Mg, respectively, were made (140 mg N as $Ca(NO_3)_2$ or $(NH_4)_2SO_4$ per pot and 920 mg sulpomag per pot).

The dry-matter yield data (Table 2) show that even with NO_3 as N source, rape appears to be able to utilize rock phosphates. Even with the sparsely soluble Mali RP the yield and P content were well above those obtained in the control treatment. Still, this response

Table 2. Dry-matter yield and chemical composition of rape grown with different N- and P fertilizers, and the influence of the crop's cation-anion uptake pattern on the pH of the soil used in the pot experiment.

Treatment	Yield g/pot	Chemical composition, meq/kg d.m.												Final soil pH
		Na	K	Ca	Mg	Org. N	NO_3	H_2PO_4	SO_4	Cl	ΣC_a	ΣA_a*	$\Sigma(C_a-A_a)$	
NO_3, no P	3.80	7	1251	1551	590	2355	574	22	576	320	3399	3971	− 572	5.6
NO_3, TSP	21.94	30	1097	896	258	1520	76	62	261	643	2281	2644	− 363	5.8
NO_3, Morocco rock P	15.12	42	1475	973	444	1854	369	66	386	534	2935	3309	− 375	5.7
NO_3, Mali rock P	10.52	27	1453	1217	434	2023	486	58	448	668	3131	3792	− 662	5.8
NH_4, no P	3.77	0	1111	1463	535	3056	420	21	981	399	6585	1988	4597	5.1
NH_4, TSP	21.57	46	1101	651	262	1498	3	80	455	581	3561	1200	2361	5.0
NH_4, Morocco rock P	18.66	31	1322	724	355	1650	34	71	480	530	4117	1204	2913	5.0
NH_4, Mali P	12.22	38	1464	905	398	1853	102	70	589	757	4760	1618	3142	5.1

* In this value is included organic S, estimated at 5% of organic N.

to rock phosphates was not resulting from an alkaline uptake pattern inducing an acidifying effect. As can be seen from Table 2, the uptake pattern was an acidic one and, compared to the pH of the control pots, the pH values in the P-treated pots had increased slightly. On the basis of results obtained in their experiments, Hedley *et al.*[6] concluded that the high P-feeding power of rape was to be attributed to an acidifying effect arising from an alkaline uptake pattern. Due to the fact that their plants, growing under rather artificial circumstances, received no Cl, the Cl contents were extremely low. In the present experiment Cl accounted for a sizeable portion of the total anion uptake. The same holds for S, which is known to be absorbed in large quantities by all Brassica species.

It must therefore be concluded that the P-solubilizing ability of rape in this experiment did not result from soil acidification induced by an alkaline uptake pattern, but rather from the crop's ability to absorb much Ca. This latter ability is likely to lower the Ca concentration in the soil solution enough to induce the solubilization of alkaline rock phosphates.

It was further experienced in this experiment that, unlike most dicotyledonous plants, rape responds favorably to NH_4. The NH_4 nutrition induces an alkaline uptake pattern leading to soil acidification. NH_4 also reduces the Ca uptake, more so than it does the uptake of K and Mg. With NH_4, growth and P uptake of the rock phosphate-treated plants were significantly better than with NO_3. There are indications that in this case the solubilization of rock phosphate was induced more by the pH-lowering effect of an alkaline uptake pattern than by an unusually high Ca-uptake rate.

The presence of NO_3 in the NH_4-fed plants suggests that in this soil the nitrification inhibitor was not fully effective in preventing the formation of NO_3. Not all N was therefore taken up as NH_4 and, consequently, the values given for $\Sigma(C_a - A_a)$ might be overestimations of the real values. The acidifying effect of nitrification, especially when the NO_3 formed is not taken up by the crop, may have been responsible for the finding that the final soil pH in the control (no-P) pots was not similar to that in the pots to which P had been added.

On the one hand, this could account for the finding that the final soil pH in the control pots had fallen to about the same value as found in the pots that had received P and had produced much more dry matter. On the other hand, the average NO_3-N value (15 ppm) measured at the end of the experiment in the control pot from which plants withdrew only one-third of the initially available N, was only slightly higher than the original value (12 ppm), which certainly would not support an assumption that nitrification might have been substantial. The observed reduction in Ca uptake also leads one to believe that N was absorbed mainly as NH_4.

The following conclusions can be drawn from this experiment:

1. The ability of rape to utilize rock phosphate P when NO_3 is the available N source is to be attributed to the NO_3-induced high uptake rate of Ca, even though an under these circumstances slightly acidic uptake pattern causes a small rise in soil pH.
2. Rape seems to be one of the few dicotyledonous crops responding well to NH_4 nutrition.
3. When rape absorbs N as NH_4, the resulting soil acidification induced by an alkaline uptake pattern favors the solubilization of rock phosphates to the extent that the P in these phosphates becomes reasonably available to the crop.

Field bean

In this experiment, field bean (*Vicia faba* var. Rato) was grown on the sandy loam subsoil. Per pot, a quantity of 7 kg soil was used. Nitrogen nutrition of the beans was supposed to proceed either through symbiotic N_2 fixation or through NO_3 nutrition. All pots received a basal application of 140 mg N as $Ca(NO_3)_2$. Depending on the growth rates of the NO_3-fed plants, these received several top dressings of $Ca(NO_3)_2$ in total quantities ranging from 1820 mg N for the zero-P pots to 4340 mg N for the TSP pots. The plants making use of N_2 fixed from the atmosphere were inoculated with strain RBI of Rhizobium leguminosarum. Spontaneous infection of NO_3-fed plants was negligible.

The soil in each pot received 7 g sulpomag and 35 ml of a multinutrient trace element solution, including Co. On day 63 after seeding an additional quantity of 0.71 g K_2SO_4 was added to each pot. The phosphates used were TSP, Morocco rock phosphate and Mali rock phosphate in quantities of 1000 mg P per pot as basal applications.

The growth period of the beans was 85 days. At the end of this period, when the pod-filling stage was completed, the above-ground and below-ground portions of the three plants per pot were harvested. The results of measurements of dry-matter yield, yield of P and final soil pH are presented in Fig. 3.

In the TSP treatment, the rather cloudy weather during the growth period was responsible for yields of plants utilizing symbiotically fixed N_2(N_2 plants) to be lower than those of the NO_3-fed plants. The absence of NO_3 competing with H_2PO_4 for absorption sites caused the P content of the former plants to be significantly higher. The

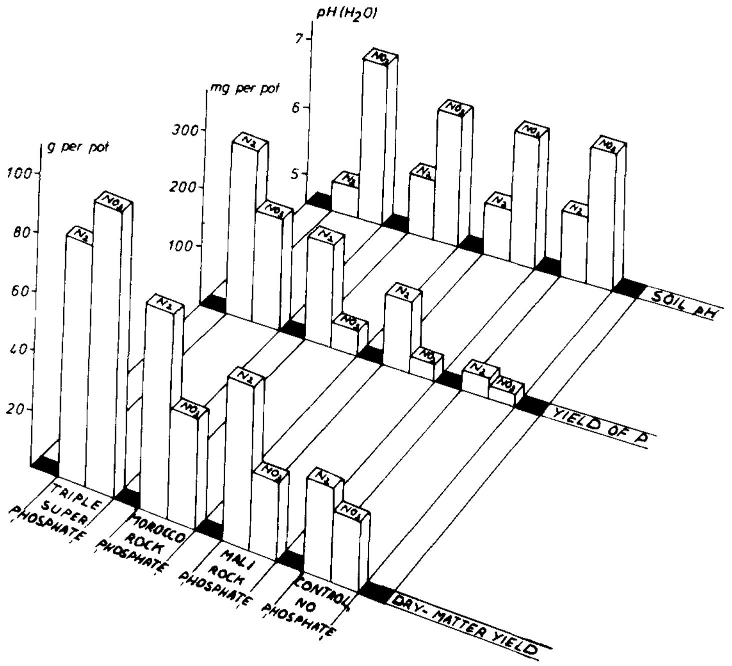

Fig. 3. The influence of variation in N source (fixed N_2 or NO_3) on the ability of field bean (*Vicia faba*) to utilize rock-phosphate P.

alkaline uptake pattern of the N_2 plants induced a considerable decline in soil pH, whereas the acidic uptake pattern of the NO_3-fed plants was responsible for a sizeable increase in soil pH. The shifts in soil pH values for plants utilizing rock phosphate were less impressive than those obtained with TSP. Nevertheless, the acidification stemming from the alkaline uptake patterns of the N_2 plants resulted in a mobilization of enough P from rock phosphate sources to sustain significantly higher dry-matter yields than obtained with the NO_3-fed plants which through their acidic uptake pattern caused the soil pH to rise.

Two conclusions can be advanced:

1. Utilization of symbiotically fixed N_2 by legumes causes a strongly alkaline uptake pattern resulting in soil acidification.

2. Although the extensiveness of root systems of legumes is usually small compared to that of cereals, the induced soil acidification affords these legumes a capacity to utilize alkaline rock phosphates.

General conclusions

In recent decades, the rate of utilization of alkaline rock phosphates in agriculture has not kept pace with the rate of discovery of these phosphates. Especially in developing countries, each time a new deposit is discovered it is advisable that the discovered material be tested for its potential usefulness in agriculture.

It has to be accepted that rock phosphates, even in finely ground form, are entirely ineffective when applied to high-pH soils. However, in neutral and acid soils, circumstances may exist under which such phosphates can make a contribution to crop growth. In many, but not in all cases the degree of effectiveness is influenced by the type of N-nutrition.

When plants can utilize rock phosphates, even under conditions of NO_3 nutrition, such an ability is usually associated with high Ca uptake. In the present experiments, this was the case for buckwheat and rape. It is recommended that a search for more crops of such ability be continued.

Under circumstances of NO_3 nutrition, rock phosphates are useless to gramineous plants which in such situations tend to raise the pH of their rhizosphere. In general, however, these plants respond rather favorably to NH_4. An added advantage is that the resulting decrease in soil pH favors the solubilization of alkaline rock phosphates. Since in comparison with NO_3, NH_4 is less subject to leaching, more attention should be paid in developing countries to potential advantages to be gained from the use of nitrification inhibitors in raising the efficiency of both nitrogenous fertilizers and alkaline rock phosphates in the culture of grasses and cereals.

Even more promising are the potential advantages of rock phosphates when applied to legumes. Here they might stimulate symbiotic N_2 fixation which, in turn, through an induced alkaline uptake pattern causes soil acidification which can promote a further solubilization of the rock phosphates. In earlier work[1] it was shown that a small quantity of readily soluble superphosphate, used as a starter fertilizer, may aid in setting this chain reaction into motion.

For the sake of completeness, one other situation should be mentioned in which the effectiveness of alkaline rock phosphates can be raised. It was shown earlier[1] that through their priming action in mobilizing rock phosphates, vesicular-arbuscular mycorrhizae promoted the growth of and the symbiotic N_2 fixation in a legume.

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