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ABSTRACT

Fertilizer systems that use an exchange medium in combination with slightly soluble phosphate rock could provide a slow, sustained release of P and avoid the potential problems (e.g., fixation) associated with a large, single application of an element. Consequently, the effectiveness of one NH_4-exchanged zeolite (clinoptilolite) in increasing phosphate-rock solubility in two soils (Red Feather loamy sand, a Lithic Cryoboralf and Weld loam, an Aridic Paleustoll) was evaluated by measuring increases in dry matter, nutrient content, and nutrient uptake by sorghum-sudangrass [*Sorghum bicolor* (L.) Moench–*S. sudanese* (Piper) Stapf, 'NB280S']. Two phosphate-rock application rates of 170 and 340 mg P kg^{-1} soil were used in factorial combination with zeolite/phosphate-rock ratios of 0, 1.5, 3, 4.5, 6, and 7.5:1. The largest dry-matter yields through four plant cuttings from the Weld soil generally were found with the 340 mg P kg^{-1} rate and with increasing zeolite/phosphate-rock ratio (linear response). Increasing zeolite/phosphate-rock ratio in this soil generally increased plant P concentrations and uptake. The exchanger fertilizer system increased P availability in the Weld soil by producing lower soil pH (nitrification of NH_4 released by the zeolite) than the 0:1 zeolite/phosphate-rock ratio control and by the adsorption of Ca in the zeolite. The Red Feather soil, which was deficient in K, did not provide definite yield responses because the zeolite sequestered K, thereby reducing plant K concentrations and uptake even though the zeolite increased total P uptake. The NH_4-exchanged zeolite/phosphate rock combination used in the present study seems to be a promising P-fertilizer system in nonalkaline soils if K or other plant-essential cations are not limiting.

The addition of soluble fertilizers initially exploits the intensity factor when used to supply essential nutrients to plants. Using a capacity-factor approach could maintain adequate nutrient levels, provided they are replenished at a sufficient rate. One method of utilizing the capacity factor is to fertilize with phosphate rock rather than with the relatively more soluble superphosphate. Unfortunately, the agronomic effectiveness of untreated phosphate rock is limited in many soils by its slow dissolution rate (Leon et al., 1986; Anderson et al., 1985). The effectiveness of phosphate rock can be increased by adding an exchanger that contains a monovalent exchange ion such as NH_4 or K. The exchanger serves to sequester Ca released from the phosphate rock, thereby shifting the equilibrium (Eq. [1]) toward releasing more P to the soil solution (Lai and Eberl, 1986; Chesworth et al., 1988):

$$\text{phosphate rock} + NH_4 \text{ exchanger} \rightleftharpoons \text{Ca exchanger} + NH_4^+ + H_2PO_4^- \quad [1]$$

By use of this technique, P concentrations can be buffered in the soil solution, the rate of P and N (and K using a K-exchanger) release can be controlled by varying the exchanger/phosphate-rock ratio, and the system can be renewed by adding additional exchanger, or by recharging the exchanger with NH_4 or K (Lai and Eberl, 1986). Furthermore, the exchanger can promote release of trace nutrients from sparingly soluble minerals by the exchange process (Bunzl, 1981; Eberl and Landa, 1985). Fertilizers with ion exchangers as essential ingredients are known as exchange fertilizers.

Certain clinoptilolites may serve as an exchanger in such a fertilizer system because they are very abundant in nature (Mumpton, 1984), they are silica-rich zeolites and should be relatively stable in soils, they are easier to handle than other exchangers such as bentonite and peat, and they have provided good results in previous chemical experiments by increasing the quantity of P released from Florida phosphate rock by more than an order of magnitude (Lai and Eberl, 1986). Use of a perennial plant such as sorghum–sudangrass in greenhouse experiments would allow multiple plant harvests with consequent removal of soil P and fertilizer P. The potential advantages of using sparingly soluble fertilizers include more efficient use of nutrients by plants (e.g., less P fixation), less pollution to ground and surface waters (e.g., by N; Ferguson et al., 1986), and less fertilizer processing (e.g., cheaper to manufacture).

Our hypothesis for this study was that increasing the zeolite/phosphate-rock ratio in the fertilizer would permit P to become more available to plants via an exchange mechanism according to reactions indicated by Eq. [1]. Dry-matter yields should be increased where exchange fertilizer is used in P-deficient soils. Additionally, we hypothesized that, because of the system's slow-release characteristics, exchange fertilizers should have long-term effectiveness in the release of P and N.

MATERIALS AND METHODS

Samples of Weld loam and Red Feather loamy sand surface soil to a depth of 15 cm (Table 1) were air dried and crushed to pass through a 4-mm screen. For field-produced irrigated sorghum-sudangrass, 20 and 40 kg P ha^{-1} would be recommended for the Weld and Red Feather soils, respec-

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tively, to achieve a 14 Mg ha^{-1} yield goal (Soltanpour et al., 1985). Various ratios of an NH_4-exchanged clinoptilolite (see Weber et al., 1984 for zeolite properties) containing 21 g N kg^{-1} zeolite, and a phosphate rock from North Carolina were used. The phosphate rock (by International Fertilizer Development Center, Muscle Shoals, AL), 99% of which passed through a 0.15-mm screen, contained 11.2% P and 35.1% Ca, and is considered a highly reactive P source (Leon et al., 1986). The zeolite/phosphate-rock combinations were pelletized by adding Wyoming bentonite (2% by weight) and corn starch (1% by weight dissolved in boiling water). Granules were passed through a 1-mm screen.

Zeolite/phosphate-rock ratios of 0, 1.5, 3, 4.5, 6, and 7.5 to 1 were used in this study. Factorial combinations of the six ratios and two P application rates of phosphate rock (170 and 340 mg kg^{-1} soil) replicated three times were used with each soil. These combinations resulted in zeolite application rates equivalent to field application rates of 0 to 52 Mg ha^{-1}. Each zeolite/phosphate-rock treatment was added to 1.5 kg of each soil. The treatments plus soil were mixed in a twin-shelled blender for approximately 1 min, and then added to 15-cm-diam. plastic pots that were lined with a plastic bag to prevent drainage losses.

The pots were arranged in randomized complete blocks (three replications), and border pots were established at the front and rear of the treatments along the direction of air flow in the greenhouse. The pots (1.5 kg of soil) were fertilized with a 0.21 mol KNO_3 L^{-1} solution. Quantities and timing of N and K applications are provided in Table 2.

Six sorghum–sudangrass seeds were planted in each pot. The pots were placed under Na-vapor lamps to provide light 14 h d^{-1} at a photon flux density of about 750 mol m^{-2} s^{-1}. After 28 d of growth, each pot was thinned to contain only the three largest plants. During the growing period, the Weld and Red Feather soils were brought to 0.20 and 0.12 kg H_2O kg^{-1} soil moisture content, which provided a matric potential of about −0.03 MPa, by weighing the pots and adding the required quantity of distilled water at least once per week.

The top growth was harvested 10 cm above the soil surface at 46, 73, 109, and 157 d. The plants were rinsed in distilled water, dried at 105 °C for 24 hr, weighed to determine dry-matter yield, and ground in a Wiley[1] mill to pass a 0.85-mm stainless steel screen. Each sample was digested with HNO_3 and the digests were analyzed for P, Ca, and K on a Jarrel-Ash Model 975 Inductively Coupled Plasma Optical Emission Spectrometer (Havlin and Soltanpour, 1980).

To determine if P was still available after four cuttings, the zeolite/phosphate-rock-treated soils were crushed and replanted. Two additional cuttings were taken 95 and 160 d after replanting (referred to as fifth and sixth cuttings). All plant analyses were conducted as mentioned above.

Soil pH was determined after the first four cuttings. The final pH (after six cuttings) and NH_4HCO_3–DTPA-extractable P also were measured (Workman et al., 1988).

A P-release study was completed using separate samples of 25 g of the zeolite/phosphate-rock or soil-plus-zeolite/phosphate-rock treatments and shaking 48 hr in 50 mL deionized water. Each sample then was centrifuged and P concentrations (Watanabe and Olsen, 1965) and pH were determined in the supernatant solution.

Analyses of variance were calculated for all measured plant and soil parameters. Regression analyses for predicting dry-matter yields, P uptake, and release of P to solution for each soil also were conducted (Steel and Torrie, 1980; Ryan et al., 1982).

Table 1. Soil properties of Weld loam and Red Feather loamy sand prior to fertilizer addition.

Property	Weld loam	Red Feather loamy sand
Paste pH	5.5	5.3
Cation-exchange capacity (cmol kg^{-1})	23.3	13.4
Electrical conductivity (DS m^{-1})	0.9	0.2
Organic Matter (g kg^{-1})	13	26
NH_4HCO_3–DTPA extractable	mg kg^{-1}	
NO_3–N	20	11
P	11	3
K	493	72
Zn	1.0	1.5
Fe	3	77
Mn	4	17
Cu	1.2	0.7

RESULTS AND DISCUSSION

We hypothesized that increasing the zeolite/phosphate-rock ratio in a fertilizer material should release more P for plant growth and subsequently increase yields. Therefore, this paper focuses on total dry-matter yields, plant P and K concentrations, and P uptake for soils treated with exchange fertilizer. Additional results are discussed in Barbarick et al. (1988) and will be mentioned briefly below.

Data for the accumulative dry-matter yields for the 340 mg P kg^{-1} rate for the Weld soil (Fig. 1) support

[1] Use of trade names is for identification purposes only and does not constitute endorsement by Colorado State University or the U.S. Geological Survey.

Table 2. Nitrogen and K additions to each treatment.

		N applied after								K applied after							
P rate	Zeolite/ phosphate rock ratio	From zeolite	Initially	1st cut	2nd cut	3rd cut	4th cut	5th cut	Total	From zeolite	Initially	1st cut	2nd cut	3rd cut	4th cut	5th cut	Total
mg kg/$^{-1}$		mg pot^{-1}															
170	0	0	150	150	150	75	150	75	750	0	416	416	416	208	416	108	1980
	1.5	74	150	150	150	75	150	75	824	0	416	416	416	208	416	108	1980
	3	148	150	150	150	75	150	75	898	1	416	416	416	208	416	108	1980
	4.5	222	150	150	150	75	150	75	972	1	416	416	416	208	416	108	1981
	6	296	150	150	150	75	150	75	1046	2	416	416	416	208	416	108	1982
	7.5	370	150	0	150	75	150	75	970	2	416	0	416	208	416	108	1566
340	0	0	150	150	150	75	150	75	750	0	416	416	416	208	416	108	1980
	1.5	148	150	150	150	75	150	75	898	1	416	416	416	208	416	108	1981
	3	296	150	150	150	75	150	75	1046	2	416	416	416	208	416	108	1982
	4.5	444	150	0	150	75	150	75	1044	3	416	0	416	208	416	108	1567
	6	592	150	0	0	75	50	75	1042	4	416	0	0	208	416	108	1152
	7.5	740	150	0	0	75	0	75	1040	5	416	0	0	208	416	108	1153

the hypothesis that increasing the zeolite/phosphate-rock ratio would increase dry-matter production, at least at the greater P-application rates in the Weld soil. This response was obvious in the first four cuttings (slope = 1.6; Fig. 1), which represent the initial, one-time response (first planting). The slope of the equations for cuttings five and six (after replanting) decreased to 1.1 and 0.9, respectively, indicating that the initial response did not continue at the same level.

In addition to the effect of the zeolite/phosphate-rock ratio, the total dry-matter yields of sorghum–sudangrass produced in the Weld soil were significantly increased by increasing the P rate from 170 to 340 mg P kg^{-1} (Barbarick et al., 1988). Accumulative dry-matter yield responded linearly, after the first cutting, to increasing zeolite/phosphate-rock ratio for the 340 mg P kg^{-1} rate in the Weld soil.

The accumulative dry-matter yields for the first four cuttings for the 340 mg P kg^{-1} rate are shown in Fig. 2. A significant P rate × zeolite/phosphate-rock ratio interaction occurred with respect to the accumulative dry-matter yield through four cuttings in the Weld soil, whereas only P rate affected the production in the Red Feather soil (Barbarick et al., 1988).

With respect to plant P concentrations and P uptake from the Weld soil, generally, the larger rate of P affected both P concentration and P uptake, while increasing the zeolite/phosphate-rock ratio increased P concentration and P uptake. The 340 mg P kg^{-1} rate produced significantly larger P concentrations in the first cutting, but significantly smaller concentrations in the third cutting, a nutrient dilution effect (Table 3). The larger yields associated with the 340 mg P kg^{-1} rate were the major cause of the larger P uptake (Barbarick et al., 1988). Also, increasing the zeolite/phosphate-rock ratio significantly increased P concentrations in the first, third, and fifth cuttings, and significantly increased total P uptake. The total P uptake was influenced more by the higher P concentrations than by the dry-matter production associated with the increasing zeolite/phosphate-rock ratio. A linear response in total P uptake through four cuttings was found for the Weld soil as shown in Fig. 3.

With respect to plant P concentrations and P uptake from the Red Feather soil, P rate and zeolite/phosphate-rock ratio had an interactive effect on P concentrations in the second, third, and fourth cuttings, and on total P uptake (Table 4). Consequently, inter-

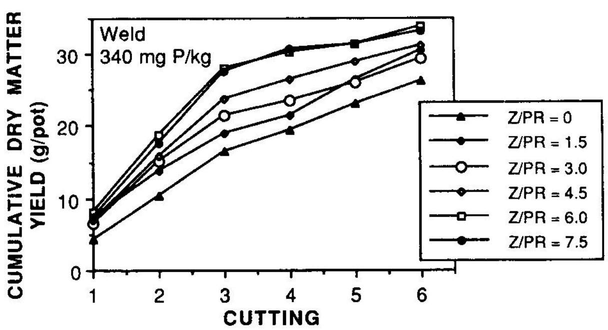

Fig. 1. Accumulative dry-matter yields for the Weld soil at the 340 mg P kg^{-1} rate. Z/PR is the zeolite/phosphate-rock ratio.

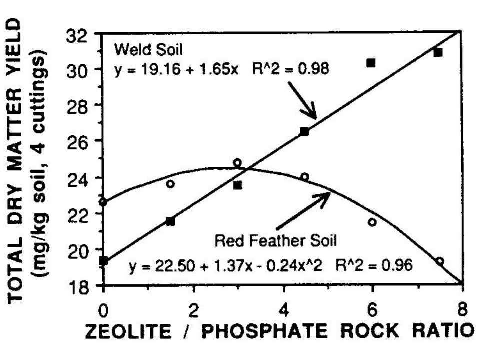

Fig. 2. Accumulative dry matter yields for (first four cuttings) at the 340 mg P kg^{-1} for both soils as a function of zeolite/phosphate-rock ratio.

Table 3. Plant P concentrations and uptake for zeolite/phosphate-rock treatments in the Weld soil.

P rate	Zeolite/ phosphate rock ratio	Cuttings† 1	2	3	4	5	6	Total uptake
mg kg^{-1}		g P kg^{-1}						mg P pot^{-1}
170	0	2.1	2.8	3.6	5.1	2.6	4.9	74
	1.5	2.8	3.9	3.9	6.1	2.8	4.4	97
	3	4.1	4.0	4.7	7.0	3.5	3.1	85
	4.5	5.2	4.9	5.0	8.7	3.5	2.2	106
	6	5.4	4.6	5.2	8.1	3.9	3.5	99
	7.5	6.4	4.5	5.1	9.6	4.1	4.3	122
	Avg.	4.3	4.1	4.6	7.4	3.4	3.7	97
340	0	2.3	2.4	2.7	3.9	3.1	3.9	113
	1.5	3.7	3.2	3.9	5.5	2.8	5.6	145
	3	6.3	3.8	4.0	6.7	3.6	2.5	116
	4.5	6.9	4.3	3.8	5.7	3.4	3.8	154
	6	7.4	5.4	3.9	6.4	5.1	3.5	147
	7.5	7.9	6.6	4.3	4.8	5.3	3.9	194
	Avg.	5.8	4.3	3.8	5.5	3.9	3.9	145
Avg. for both P rates	0	2.2	2.6	3.1	4.5	2.6	4.4	94
	1.5	3.3	3.6	3.9	5.8	2.8	5.0	121
	3	5.2	3.9	4.3	6.8	3.6	2.8	101
	4.5	6.1	4.6	4.4	7.2	3.4	3.0	130
	6	6.4	5.0	4.6	7.2	4.5	3.5	123
	7.5	7.1	5.6	4.7	7.2	4.7	4.1	158
Coefficient of variation (%)		16.7	7.5	13.0	17.5	21.5	52.2	13.7
F test significance								
P rate		**	NS	**	**	NS	NS	**
zeolite/rock ratio		**	**	**	**	**	NS	**
P rate × zeolite/rock ratio		NS	**	NS	*	NS	NS	NS

*,** Significant at the 0.05 and 0.01 probability levels, respectively. NS = not significant.

† Fifth and six cuttings were taken after replanting.

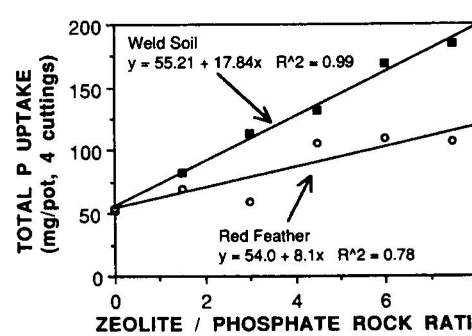

Fig. 3. Total P uptake (first four cuttings) at the 340 mg P kg^{-1} rate for both soils as a function of zeolite/phosphate-rock ratio.

Table 4. Plant P concentrations and uptake for zeolite/phosphate-rock treatments in the Red Feather soil.

P rate	Zeolite/ phosphate rock ratio	Cuttings† 1	2	3	4	5	6	Total uptake
mg kg^{-1}		g P kg^{-1}						mg P pot^{-1}
170	0	2.6	2.0	2.9	4.2	2.2	4.2	53
	1.5	2.5	1.8	2.4	3.6	2.5	5.9	61
	3	2.9	2.3	2.7	4.2	1.5	6.1	56
	4.5	3.5	3.4	2.7	4.0	2.8	7.9	67
	6	3.4	3.1	2.1	2.1	1.9	5.1	49
	7.5	3.4	4.3	2.8	2.7	2.4	2.2	69
	Avg.	3.1	2.8	2.6	3.4	2.2	5.2	59
340	0	2.9	2.4	2.0	2.9	1.7	5.4	62
	1.5	3.3	2.7	2.8	3.7	2.7	4.7	82
	3	4.4	2.9	1.8	2.7	2.1	7.2	78
	4.5	4.5	5.5	3.3	3.5	2.3	3.6	113
	6	4.4	5.8	4.9	4.3	2.5	5.7	116
	7.5	4.4	6.3	6.3	3.3	2.5	4.6	118
	Avg.	4.0	4.3	3.5	3.4	2.3	5.2	95
Avg. for both P rates	0	2.8	2.2	2.4	3.5	2.0	4.8	58
	1.5	2.9	2.2	2.6	3.6	2.6	5.3	71
	3	3.7	2.6	2.3	3.4	1.8	6.7	67
	4.5	4.0	4.5	3.0	3.7	2.5	5.8	90
	6	3.9	4.5	3.5	3.2	2.2	5.4	82
	7.5	3.9	5.3	4.6	3.0	2.5	3.4	94
Coefficient of variation (%)		18.1	12.4	10.5	18.6	35.2	44.8	14.2
F test significance								
P rate		**	**	**	NS	NS	NS	**
zeolite/rock ratio		**	**	**	NS	NS	NS	**
P rate × zeolite/rock ratio		NS	**	**	**	NS	NS	**

** = significance at the 0.01 probability level, NS = not significant.
† Fifth and sixth cuttings were taken after replanting.

Table 5. Plant K concentrations and uptake for zeolite/phosphate-rock treatments in the Red Feather soil.

P rate	Zeolite/ phosphate rock ratio	Cuttings† 1	2	3	4	5	6	Total uptake
mg kg^{-1}		g K kg^{-1}						mg K pot^{-1}
170	0	34	20	20	21	33	18	448
	1.5	31	20	19	21	33	24	520
	3	31	29	20	17	23	14	469
	4.5	30	20	18	18	26	16	414
	6	30	21	20	21	24	17	410
	7.5	26	14	15	16	21	12	345
	Avg.	31	19	19	19	27	17	434
340	0	31	21	19	21	34	19	536
	1.5	28	20	19	21	28	22	556
	3	34	26	16	17	22	13	610
	4.5	25	11	13	14	15	21	476
	6	25	11	8	8	19	15	395
	7.5	27	11	8	7	17	11	302
	Avg.	28	17	14	15	22	17	479
Avg. for both P rates	0	33	20	19	21	33	19	492
	1.5	30	20	19	21	30	23	538
	3	32	23	18	17	23	14	540
	4.5	28	15	15	16	20	18	445
	6	28	16	14	14	22	16	402
	7.5	26	12	11	12	19	11	323
Coefficient of variation (%)		15.9	15.6	12.6	17.1	17.5	21.1	13.0
F test significance								
P rate		NS	*	**	**	**	NS	*
zeolite/rock ratio		NS	**	**	**	**	**	**
P rate × zeolite/rock ratio		NS	**	**	**	NS	NS	NS

*,** Significant at the 0.05 and 0.01 probability level, respectively. NS = non significant.
† Fifth and six cuttings were taken after replanting.

preting the effects of P rate or zeolite/phosphate-rock ratio on P concentration was difficult. Through four cuttings, a significant linear effect for the total P uptake associated with the 340 mg P kg^{-1} rate was determined (Fig. 3).

Although increasing dry-matter yield in the Weld soil was correlated with increasing zeolite/phosphate-rock ratio (R^2 = 0.98; Fig. 2), the quantity of N added with each treatment (Table 2) also must be scrutinized for its potential effect on plant dry-matter yields. The total quantity of N added to all treatments was not equal (Table 2). Some N was added initially as adsorbed NH_4 on the clinoptilolite, and some N was added subsequently as a soluble salt. All of the zeolite N could be added initially because NH_4-exchanged zeolite performs as a slow-release fertilizer (Barbarick and Pirela, 1984). A single N application of a soluble N source at 740 mg N pot^{-1} (zeolite N supplied by the 340 mg P kg^{-1}–7.5:1 zeolite/phosphate-rock treatment) possibly could have produced a deleterious effect on the plants due to the greater soluble-salt concentration. Soluble N, therefore, had to be added as needed. According to field fertilizer recommendations (Soltanpour et al., 1985) for the Weld soil, the sorghum-sudangrass crop should have received 75 mg N pot^{-1} for each harvest. Even though fertilizer recommendations for field conditions cannot be exactly equated to the fertilizer needs in a greenhouse study, more than twice the recommended amount of N for field applications was added to all pots. No N deficiencies were noted for any treatments throughout the study; also, the average N content of the plants from the Weld soil was not significantly correlated to the amount of N added (Barbarick et al., 1988). Consequently, the yield response for the 340 mg P kg^{-1} rate in the Weld soil through four cuttings was attributable to the increased P provided by increasing the zeolite/phosphate-rock ratio and not to differences in N supplied.

The differential application rate of NO_3–N as KNO_3 and NH_4–N from the zeolite may have contributed to the yield response. The preference of sorghum–sudangrass for one of these forms is not known. Consequently, the overall effect of the NO_3–N/NH_4–N cannot be ascertained.

The K added with all treatments also was not equal in all pots (Table 2). For the Weld soil, no K fertilizer was required according to fertilizer recommendations. The Red Feather soil, however, needed 22 mg K pot^{-1} for each harvest. Much larger quantities of K than the recommended amount were added to all pots (Table 2). For the Red Feather soil, however, increasing quantities of NH_4-exchanged zeolite significantly reduced most plant K concentrations and the total K uptake (Table 5). Increasing the zeolite/phosphate-rock ratio in the Red Feather soil decreased total K uptake (Fig. 4) and yield (Fig. 2) in a quadratic fashion through four cuttings. Many clinoptilolites have a great affinity for K (Barbarick and Pirela, 1984). Consequently, the adsorption and reduction in availability of K by the clinoptilolite resulted in an overall decreased effectiveness of the zeolite/phosphate-rock fer-

Table 6. Soil pH and final extractable P for zeolite/phosphate-rock treatments in the Weld and Red Feather soil.

P rate	Zeolite/phosphate rock ratio	Weld pH—after 4 cuttings	Weld pH—final	Weld Extractable P	Red Feather pH—after 4 cuttings	Red Feather pH—final	Red Feather Extractable P
mg kg^{-1}				mg kg^{-1}			mg kg^{-1}
170	0	6.5	7.1	11.9	7.4	6.3	6.2
	1.5	6.2	6.9	11.7	5.7	6.4	6.9
	3	5.4	6.8	11.7	4.7	6.1	7.8
	4.5	4.7	6.5	12.3	4.8	6.0	9.8
	6	4.4	6.3	14.5	5.5	5.5	12.4
	7.5	4.8	5.5	17.8	5.1	5.2	15.4
	Avg.	5.3	6.5	13.3	5.5	5.9	9.8
340	0	6.5	7.2	13.1	6.5	6.7	8.1
	1.5	6.0	6.8	13.1	6.0	6.2	9.0
	3	5.3	6.3	15.5	6.3	5.8	11.7
	4.5	5.4	5.6	20.1	5.1	5.1	15.5
	6	5.1	5.1	26.7	4.1	4.8	24.1
	7.5	4.8	4.7	33.2	4.4	4.6	26.6
	Avg.	5.5	6.0	20.3	5.4	5.5	15.8
Avg. for both P rates	0	6.5	7.1	12.5	7.0	6.5	7.2
	1.5	6.1	6.8	12.4	5.8	6.3	7.9
	3	5.4	6.5	13.6	5.5	5.9	9.8
	4.5	5.0	6.1	16.2	5.0	5.6	12.6
	6	4.8	5.7	20.6	4.8	5.2	18.3
	7.5	4.8	5.1	25.5	4.8	4.9	21.0
Coefficient of variation (%)		5.3	17.8	53.7	31.8	4.3	19.2
F test significance							
P rate		NS	**	**	NS	**	**
zeolite/rock ratio		**	**	**	NS	**	**
P rate × zeolite/rock ratio		NS	**	**	NS	**	**

** Significant at the 0.01 probability level; NS = not significant.

tilizer system. For K-deficient soils, a K-exchanged zeolite or a naturally occurring K zeolite probably needs to be used in place of, or as a supplement to, an NH_4 zeolite.

The effectiveness of the exchange fertilizer in improving P uptake and plant yields (through four cuttings) in the Weld soil as the zeolite/phosphate-rock ratio increased may be attributed to two soil reactions that increased phosphate rock solubility. The first reaction was related to a lowering of soil pH (Table 6) compared with the control (0:1 zeolite/phosphate-rock ratio). The NH_4 released from the exchange fertilizer was nitrified and the resulting acidity decreased soil pH and dissolved phosphate rock as reflected by the extractable-P levels found at the end of the study (Table 6). However, only the soil pH of the 340 mg P kg^{-1} rate in combination with the 6 and 7.5:1 zeolite/phosphate-rock ratios in the Weld soil were less than the initial soil pH (5.5). The same was true for the 170 mg P kg^{-1} rate in combination with the 7.5:1 zeolite/phosphate-rock ratios and for the 340 mg P kg^{-1} rate in combination with the 6 and 7.5:1 zeolite/phosphate-rock ratio of the Red Feather soil. The addition of phosphate rock tended to increase soil pH, thereby balancing the effects of nitrification. For the control (0:1 zeolite/phosphate-rock ratio) for the Weld soil, the pretreatment pH of 5.5 (Table 1) was increased to 7.2 (Table 6) by the addition of phosphate rock at the 340 mg P kg^{-1} rate.

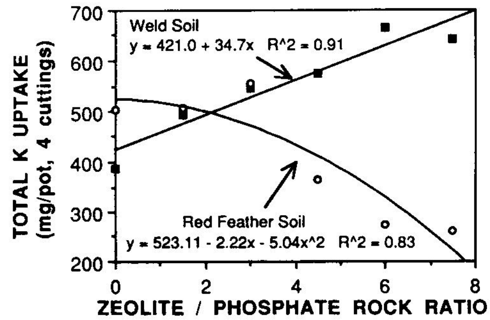

Fig. 4. Total K uptake (first four cuttings) at the 340 mg P kg^{-1} rate for both soils as a function of zeolite/phosphate-rock ratio.

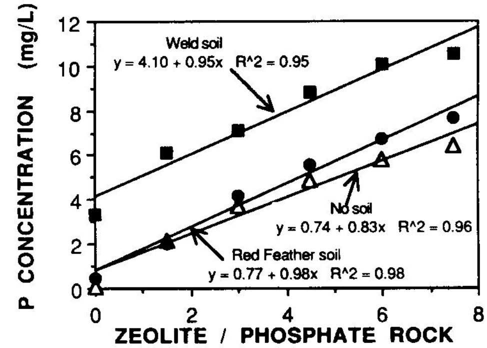

Fig. 5. Phosphorus release from shaking study for soil-plus-zeolite/phosphate-rock combinations and the no-soil control.

The second reaction that may have improved P availability was related to the sequestering of Ca by the zeolite (Eq. [1]). In order to separate this reaction from the pH effect, a 48-h shaking study (2:1 deionized water/soil ratio with phosphate rock added at the rate of 340 mg P kg^{-1}) was undertaken where pH did not affect phosphate-rock dissolution. The linear relation between the zeolite/phosphate-rock ratio and the P released is shown in Fig. 5. From the 0:1 to the 7.5:1 zeolite/phosphate rock, solution P in the control (no soil) increased 64-fold and pH increased from 7.3 to 8.6; in the Weld soil, solution P increased threefold and pH changed from 6.5 to 6.6; in the Red Feather soil, solution P increased 15-fold and pH changed from 6.1 to 6.3.

Other results for the same series of greenhouse experiments, not described here in detail but reported by Barbarick et al. (1988), can be summarized as follows. The presence of the zeolite influenced micronutrient availability, which may have also contributed to improved plant growth. For the Weld soil at the 340 mg P kg^{-1} rate over the range from 0 to 7.5:1 zeolite/phosphate-rock ratio, the mean plant concentrations of Cu, Fe, Mn, and Zn for all cuttings increased by a factor of approximately 2, 1.5, 5, and 1.5, respectively. A companion study for both soils that involved application rates of 0 to 480 mg P kg^{-1} soil of soluble P fertilizer (monocalcium phosphate) indicated that the NH_4-exchanged zeolite treatments produced significantly larger (as much as four times larger through four cuttings) plant yields. The reason for this difference in response is unknown. A study comparing the pelletized and unpelletized exchange fertilizer at the 4.5:1 zeolite/phosphate-rock ratio also indicated that pelletizing provided no advantage in terms of plant production or nutrient uptake.

CONCLUSIONS

An exchange fertilizer composed of NH_4-exchanged clinoptilolite and phosphate rock increased greenhouse-grown sorghum–sudangrass production by a factor of about 1.6 from the 0:1 to the 7.5:1 zeolite/phosphate-rock ratio for the 340 mg P kg^{-1} rate in the Weld soil. At this P rate, the plant P uptake in the Weld soil for the 0 and 7.5:1 zeolite/phosphate-rock ratio removed 22 and 38% of the applied P, respectively. Both the decreased soil pH (compared with the 0:1 zeolite/phosphate-rock ratio) that resulted from nitrification of NH_4 from the zeolite and the adsorption of Ca from the phosphate rock by the zeolite produced the improved P availability. Unfortunately, the extent to which each reaction affected P release from the phosphate rock could not be isolated. The exchange fertilizer, regardless of which mechanism is dominant, does provide promise as a slow- but sustained-release P-fertilizer system.

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