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Lime Effects on Phosphorus Availability in a Calcareous Soil

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ABSTRACT

Crop yields are sometimes reduced on irrigated calcareous soils with elevated lime concentrations. This study was conducted to determine the influence of lime on P availability. The effects of acid-equivalent lime concentrations and P fertilization rates on $NaHCO_3$-soluble P, anion resin-extractable P, P-adsorption isotherms in 0.01 *M* $CaCl_2$, and P uptake by sudangrass [*Sorghum bicolor* (L.) Moench] and potato (*Solanum tuberosum* L.) were investigated in the greenhouse on soil samples from the Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthid). Plant P uptake was increased by P fertilization and decreased by increasing lime concentration. Phosphorus uptake was curvilinearly related to solution P (extracted by 0.01 *M* $CaCl_2$). Solution P concentrations increased linearly as the resin-extractable P/equilibrium buffer capacity (EBC) ratio increased, where EBC is the slope of the P-adsorption isotherm at the indigenous equilibrium P concentration. The EBC increased as the lime concentration increased. Phosphorus applications increased solution P and resin-extractable P and decreased EBC within a given lime concentration. These data indicate that the soil-test P concentration or P fertilization rate should increase as the lime concentration increases to provide the same degree of P availability and plant P uptake in this calcareous soil.

MANY AGRICULTURAL SOILS in the western USA contain a lime-enriched layer that is often exposed during irrigation development from land leveling to aid water distribution. Serious erosion caused by furrow irrigation also reduces the topsoil depth (A and Bw horizons) sufficiently for tillage operations to mix a portion of the lime-enriched layer with the remaining topsoil (7). The lime-enriched layer often exceeds 200 g lime kg^{-1} ($CaCO_3$ equivalent), while the surface soil horizon of the native soil contains <10 g kg^{-1} (27).

Crop yields depend on the topsoil depth on irrigated soils (7). Yield reductions have occurred where the top 1.2 m of soil was mixed by deep tillage (8). These yield reductions were not associated with water stress or high concentrations of soluble salts (7,8). Subsoils in these soils are low in plant-available Zn, P, and N (19); however, above-normal fertilizer application rates did not compensate for the reduced crop yields (7,8). Attempts to identify other nutrient deficiencies or toxicities were not successful (19). Plants in these areas often show reduced vigor and growth in the seedling stages and delayed maturity. Plant P concentrations are often low even though soil-test P concentrations are above adequacy (19). In addition, the average soil temperatures are generally lower than normal until full plant cover because of a lighter colored soil surface due to the high lime concentration (8). These observations suggest that P availability may be a factor limiting plant growth and yields.

Soil factors affecting plant P uptake are the P concentration at the root surface and the ability of the soil solid phase to replenish it (23). These are partially controlled by soil water content, pH, $CaCO_3$ and clay concentrations, and the amount of readily labile P. One common characteristic of these eroded or land-leveled irrigated soils is a high lime concentration (>50 g kg^{-1}). Phosphorus availability is known to be affected by $CaCO_3$ (9, 15, 20, 28) and to react on its surfaces (10, 11), however neither P fertilization rates nor critical soil-test concentrations are commonly adjusted for the $CaCO_3$ concentration.

A study was initiated to evaluate the P nutritional relationships of irrigated crops grown on calcareous soils. This study investigated the effect of lime on the relationship between selected P-availability parameters and P uptake by plants grown in the greenhouse.

MATERIALS AND METHODS

The soil used in this study is a Portneuf silt loam. This soil contains a lime-cemented layer between 0.4- and 1-m soil depth. It restricts downward root penetration by annual plants but is permeable to water. Soil texture is uniform down to ≈1.2 m (18% sand, 62% silt, 20% clay). The surface soil has a pH of 7.5 (saturated paste) and a cation-exchange capacity of 200 $mmol_c$ kg^{-1} soil (27). Organic matter is usually ≈10 g kg^{-1}.

Four greenhouse experiments were conducted as follows.

Experiment 1. Six soil samples (0–20 cm) were obtained from a field study established in 1972 (8) that included P fertilization rates: three from deep-tillage, "high" lime treatments and three from traditional tillage, "low" lime treatments (Table 1). The soil was air dried and 5-kg subsamples were placed in an individual pot. Three sudangrass (cv. Trudan no. 8) plants were grown in each pot in a greenhouse maintained at 22 ± 4°C with natural lighting. Both the tops and roots were harvested after 45 d for determining P uptake.

Experiment 2a. A bulk soil sample (0–20 cm) was obtained from a Portneuf A horizon soil in crested wheatgrass [*Agropyron desertorum* (Fisher ex Link) Schultes] and sagebrush (*Artemisia tridentata* Nutt.) vegetation. Four different lime-concentration treatments were established by mixing CaO with the soil. The CaO–soil mix was subjected to repeated wetting and drying cycles, and intermittently mixed for 13 wk. The CaO was assumed to be completely converted to freshly precipitated lime when the soil pH (saturated paste) reached 8 or below. Sufficient weight of each soil–lime mix was used so that each pot contained the equivalent of 6 kg of untreated soil (e.g., 6.38 kg for the 6 g lime kg^{-1} treatment). This procedure eliminated the inherent soil variability that would occur in samples from different locations. Phosphorus, as $Ca(H_2PO_4)_2 \cdot 2H_2O$, was then added at rates of 0, 25, and 75 mg kg^{-1} across lime concentrations (Exp. 2a, Table 2). A single potato (cv. Russet Burbank) seed ball (1.5–cm diam.) was planted in each pot. The tops and roots were harvested after 35 d of growth for P-uptake determinations. After removing the roots, the soil was retained for use in Exp. 2b.

Experiment 2b. An additional application of $Ca(H_2PO_4)_2 \cdot 2H_2O$ was made on selected treatments from Exp. 2a after removing the potato plants in an attempt to obtain similar soil-test P concentrations within each lime

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Abbreviations: EBC, equilibrium buffer capacity; ANOVA, analysis of variance.

Table 1. Treatments†, lime, selected soil P characteristics, plant dry-matter yield, and P uptake for sudangrass in Exp. 1.

P application	Soil characteristics					Plant	
	Lime	$NaHCO_3$-P	Resin-P	Solution P	EBC‡	Yield	P uptake
kg ha^{-1}	g kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg L^{-1}	L kg^{-1}	g pot^{-1}	mg pot^{-1}
0	156	4.4	14.6	0.020	210	5.34	8.2
67	160	15.6	28.9	0.033	175	13.75	27.1
268	178	57.6	67.1	0.379	66	24.04	43.5
0	28	4.5	15.8	0.024	90	7.60	11.7
67	18	24.9	39.6	0.222	41	23.96	39.3
268	52	63.4	88.8	0.838	24	30.43	62.6
Significance							
Lime		**	***	***	***	***	***
Phosphorus		***	***	***	***	***	***
Lime × P		**	***	***	***	**	**
CV (%)		16.7	13.2	2.9	11.2	10.3	11.8

*,**,***Significant at the 0.05, 0.01, and 0.001 levels, respectively.
† Fall soil samples (0–20 cm) from field plots spring fertilized with $Ca(H_2PO_4)_2 \cdot 2H_2O$.
‡ EBC = equilibrium buffer capacity.

concentration (Exp. 2b, Table 2). Sudangrass (Trudan no. 8), three plants per pot, was grown for 55 d before harvesting tops and roots for P-uptake determinations.

Experiment 3. Chemical-reagent-grade $CaCO_3$ (Lot no. 23200, J.T. Baker Co., Phillipsburg, NJ) was added to 4 kg of the Portneuf A horizon soil at concentrations of 0, 68, and 110 g kg^{-1}. After several wetting–drying cycles, P, as $Ca(H_2PO_4)_2 \cdot 2H_2O$, was added to provide similar P availabilities at the different lime concentrations (Table 3). Sudangrass (Trudan no. 8) was grown (three plants per 4 kg soil plus lime) for 45 d before harvesting roots and tops for P-uptake determinations.

The P-fertilizer material was mixed with the soil in each pot. This mix was subjected to at least one wetting–drying

Table 2. Treatments, selected soil P characteristics, plant dry-matter yield, and P uptake for potato and sudangrass in Exp. 2a and 2b†, respectively.

Experiment	Treatments		Soil characteristics				Plant	
	Lime	P application	$NaHCO_3$-P	Resin-P	Solution P	EBC‡	Yield	P uptake
	g kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg L^{-1}	L kg^{-1}	g pot^{-1}	mg pot^{-1}
2a Potato	6	0	19.6	35.6	0.277	48	12.45	42
	6	25	32.8	61.0	0.455	38	14.29	62
	6	75	58.7	113.6	1.094	21	14.06	74
	30	0	12.5	43.3	0.172	104	8.65	25
	29	25	23.3	63.2	0.260	78	11.95	41
	28	75	45.8	104.1	0.763	53	12.95	59
	75	0	9.5	29.9	0.139	182	7.43	17
	75	25	19.5	48.3	0.172	129	10.88	33
	75	75	42.0	81.7	0.251	94	11.47	43
	126	0	7.2	20.1	0.020	624	6.52	10
	125	25	14.9	29.4	0.022	540	6.94	14
	126	75	32.7	51.2	0.030	338	7.53	20
Significance								
Lime			***	***	***	***	***	***
Phosphorus			***	***	***	***	***	***
Lime × P			***	***	***	***	**	**
CV (%)			5.0	33.3	0.1	10.5	7.2	10.6
2b Sudangrass	6	0	17.3	35.1	0.138	48	19.38	35
	6	0	28.2	51.1	0.280	35	22.38	52
	6	0	46.9	86.1	0.767	24	24.47	84
	30	16	20.9	56.7	0.125	70	7.18	14
	29	21	32.1	77.9	0.260	51	14.51	32
	28	29	52.2	127.5	0.682	38	20.46	54
	75	23	21.9	38.4	0.086	100	3.74	7
	75	30	32.5	54.0	0.189	74	9.74	21
	75	38	51.6	96.5	0.400	52	20.65	48
	126	31	23.4	39.5	0.055	196	1.86	2
	125	45	35.9	57.3	0.076	190	5.04	8
	126	65	54.8	90.2	0.194	130	10.59	20
Significance								
Lime			***	***	***	***	***	***
Phosphorus			***	***	***	***	***	***
Lime × P			NS	***	***	***	***	***
CV (%)			8.4	13.9	0.1	16.2	13.8	19.6

*,**,***Significant at the 0.05, 0.01, and 0.001 levels, respectively. NS = nonsignificant, at $P = 0.10$.
† Experiment 2b used the same soil pots as Exp. 2a, with additional fertilizer P added as indicated.
‡ EBC = equilibrium buffer capacity.

Table 3. Treatments, selected soil P characteristics, plant dry-matter yield, and P uptake for sudangrass in Exp. 3.

Treatments		Soil characteristics				Plant uptake	
Lime	P application	$NaHCO_3$-P	Resin-P	Solution P	EBC†	Yield	P Uptake
g kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg L^{-1}	L kg^{-1}	g pot^{-1}	mg pot^{-1}
5	0	21.4	36.5	0.144	56	22.96	28
5	20	31.9	59.8	0.309	40	25.56	34
68	0	22.1	32.0	0.030	207	8.2	13
68	40	43.3	58.0	0.152	115	18.88	26
110	0	22.9	24.0	0.008	457	4.11	6
110	80	69.9	73.8	0.129	208	23.43	32
Significance							
Lime		***	*	**	***	***	***
Phosphorus		***	***	***	***	***	***
Lime × P		***	***	NS	***	***	**
CV (%)		22.6	6.9	0.1	4.4	4.1	16.3

*,**,*** Significant at the 0.05, 0.01, and 0.001 levels, respectively. NS = not significant at $P = 0.10$.
† EBC = equilibrium buffer capacity.

cycle before sampling the soil from individual pots. The samples (≈100 g) were air dried and crushed with a soil pulverizer (flail type) before analysis for $NaHCO_3$-extractable P (24, 25), Cl-saturated resin-extractable P (2), and acid-equivalent lime (22). Phosphorus-adsorption isotherms were determined as follows: 3 g of air-dried soil was added to 0.03 L of 0.01 *M* $CaCl_2$ with 200 μL of toluene, shaken continuously for 24 h at 22°C, centrifuged and filtered. Phosphorus was determined on the filtrate (21). The initial P concentrations in the $CaCl_2$ solutions were 0, 1.0, 2.5, 5.0, and 10.0 mg kg^{-1}. The P in the $CaCl_2$ extraction was also compared with the P concentration in a solution obtained by centrifuging soil samples (only for soil samples used in Exp. 1) that were equilibrated for 6 d at the soil's field moisture capacity (1). The P buffer capacity was estimated as the EBC, defined as the slope of the P-adsorption isotherm at the indigenous natural equilibrium P concentration, i.e., $y = 0$ (12).

Adequate amounts of N, K, Zn, Fe, and S were applied in all experiments for maximum plant growth. Distilled water was added daily to maintain soil moisture near field capacity. At harvest, the plant tops were excised at the soil surface and the soil was then removed from each pot. The easily recoverable roots were physically separated from the soil and washed in distilled water. This procedure did not recover all the fine roots or root hairs. All plant materials were dried at 60°C, ground to pass a 425-μm^2 screen, digested in HNO_3–$HClO_4$, and analyzed for total P (17). The plant dry-matter yield and P uptake per pot is the sum of the tops and roots. All experiments contained three replicates. Data were analyzed by standard ANOVA procedures and regression analysis where appropriate.

RESULTS

The lime, P, and lime × P interaction effects on soil P characteristics and plant responses were significant in all experiments (Tables 1, 2, and 3). Applying P increased $NaHCO_3$-extractable P, resin-extractable P, solution P, plant dry-matter yields, and P uptake and decreased EBC. Increasing lime concentration at an equivalent P application generally decreased $NaHCO_3$-extractable P, resin-extractable P, solution P, plant dry-matter yield, and P uptake and increased EBC. Plant P concentrations (data not shown) and dry-matter yields were similar to P-uptake differences.

The P uptake by sudangrass in Exp. 1 was influenced by the $NaHCO_3$-extractable P and lime concentration (Fig. 1 and Table 1). Similar P uptake and dry-matter yields occurred in treatments with significantly

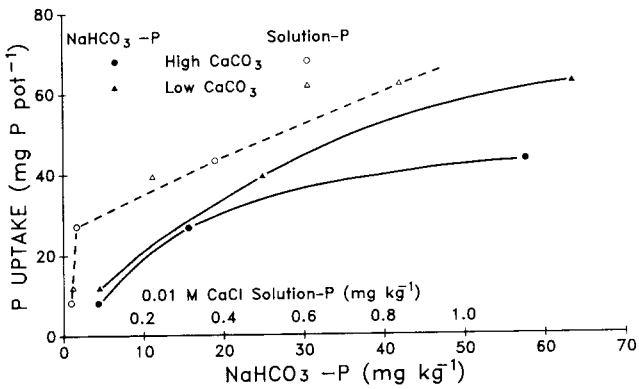

Fig. 1. The relationship between P uptake by sudangrass and soil solution P in 0.01 *M* $CaCl_2$ or P extracted by $NaHCO_3$ in Exp. 1. Lines hand-fitted to data points.

different $NaHCO_3$-extractable P and lime concentrations (i.e., 24.9 vs. 57.6 mg P kg^{-1}, and 18 vs. 178 g kg^{-1}, respectively, Table 1). Closer examination of data indicated that P uptake was probably related to the solution P concentration by two linear lines (Fig. 1).

Equivalent amounts of soil were included in each lime treatment in Exp. 2 to reduce any intrinsic soil differences that could affect the results. The relative increase in $NaHCO_3$-extractable P, resin-extractable P, and solution-P concentrations from P application decreased as the lime concentration increased (Table 2, Exp. 2a). Plant dry-matter yield and P uptake were related to $NaHCO_3$-extractable P and resin-extractable P within a lime concentration, but not across lime concentrations. Phosphorus uptakes were dependent on solution-P concentrations and independent of lime concentrations, similar to Exp. 1. Even the highest P application (75 mg kg^{-1}) on the 126 g lime kg^{-1} treatment had plants with severe P-deficiency symptoms, even though the $NaHCO_3$-extractable P concentration (32.7 mg kg^{-1}) would normally be considered adequate for plant growth.

Additional P applications were made on selected Exp. 2a treatments in an attempt to obtain equivalent $NaHCO_3$-extractable P concentrations at different lime concentrations (note no significant lime × P interaction in $NaHCO_3$-extractable P for Exp. 2b, Table

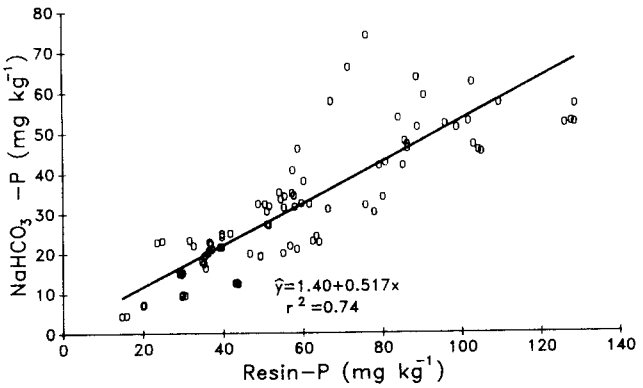

Fig. 2. The relationship between the soil P extracted by anion resin and $NaHCO_3$ in Exp. 1, 2a, 2b, and 3. Relationship significant at the P = 0.001 probability level.

2). Overall treatments trends were similar to Exp. 2a. Phosphorus uptake, dry-matter yield, and solution P decreased as lime concentration increased at nearly equivalent $NaHCO_3$-extractable P concentrations (Table 2). Solution P and P uptake were curvilinearly related. At similar solution-P concentrations, plant P uptake was slightly higher in the lowest lime concentration than in the other lime concentrations. The EBCs were lower than in Exp. 2a, partially because of additional P applications, and possibly because the lime's surface reactivity was decreasing. Solution P, $NaHCO_3$-extractable P, and resin-extractable P concentration decreased where additional P was not applied (i.e., 6 g lime kg^{-1}), reflecting P removal by the potato plants and slow fixation. Results were similar from an application of reagent grade $CaCO_3$ to the 'native' Portneuf soil (Exp. 3) as those obtained from precipitating lime from CaO (Table 2 vs. Table 3). Solution-P, plant dry matter yield, and P uptake decreased, and EBC increased as lime increased. Phosphorus uptake was related to solution-P across all lime concentrations (Table 3).

The $NaHCO_3$ extracted 55% of the P fertilizer applied in Exp. 3 with no significant effect of lime concentrations. Apparent recoveries by $NaHCO_3$ of the P fertilizer applied in Exp. 2a were 52, 44, 44, and 34% as lime increased from 6 to 126 g kg^{-1}. $NaHCO_3$-P averaged 52% of the resin-P across all experiments (Fig. 2) and was not affected by lime concentration. A multiple linear regression analysis that included lime or EBC did not account for more experimental variability. The resin-extractable P, as a percentage of the P fertilizer applied, decreased linearly as the lime increased in Exp. 2a and 3 ($\hat{y} = 103.5 - 4.81x$, $r^2 = 0.89$).

Simple linear correlation coefficients (Table 4) between selected variables were all significant (0.05 level), except for the relationship between lime and $NaHCO_3$-extractable P or resin-extractable P. Phosphorus uptake was negatively correlated with lime concentration and EBC, and positively correlated with $NaHCO_3$-extractable P, resin-extractable P, and solution P. Solution-P concentrations were positively correlated with resin-extractable P, $NaHCO_3$-extractable P, and P uptake, while negatively correlated with EBC and lime concentrations. The solution P was also exponentially related to EBC ($r = -0.87$) and to resin-extractable P ($r = 0.83$). Lime and EBC were positively correlated.

Table 4. Linear correlation coefficient matrix† for selected soil and plant P parameters in Exp. 1, 2a, 2b, and 3.

	Lime	$NaHCO_3$-P	Solution P	Resin-P	EBC†
			r		
$NaHCO_3$-P	−0.03				
Solution P	−0.49**	0.66**			
Resin-P	−0.27	0.86**	0.80**		
EBC	0.60**	−0.38*	−0.53**	−0.48**	
P uptake	−0.53**	0.61**	0.87**	0.69**	−0.58**

*,**Significant at the 0.05 and 0.01 probability levels, respectively.
† EBC = equilibrium buffer capacity.

Table 5. Relationships between selected independent variables and plant P uptake in Exp. 1, 2a, 2b, and 3.

Model	F-ratio	R^2
15.1 + 67.4 (solution P)	305.3	0.75
69.7 (solution P)$^{0.532}$	148.0	0.60
564.2 (EBC†)$^{-0.695}$	109.5	0.52
54.8 + 48.6 (solution P) − 7.74 ln(EBC)	198.1	0.80
24.4 + 0.72 ($NaHCO_3$-P) − 10.12 ln($CaCO_3$)	113.2	0.69

† EBC = equilibrium buffer capacity.
All models are significant at the 0.001 probability level.

The P-uptake data were also evaluated in a stepwise regression analysis. The solution P and a natural-log transform of the EBC were selected for the final regression model (Table 5). Attempts to improve this relationship with other variables or models were not successful. A similar model using $NaHCO_3$-extractable P and the natural log of the $CaCO_3$ equivalence as independent variables gave an intermediate fit.

DISCUSSION AND CONCLUSIONS

Adsorption isotherms are usually developed from relatively long equilibrations to simulate field soil conditions. In this study, they were determined after 24 h of continuous shaking. The solution-P concentrations (0.01 M $CaCl_2$) for all treatments in Exp. 1 were closely related to the P concentrations in soil solutions obtained by centrifugation (Cent-P = 0.931[solution P] − 0.014, $r^2 = 0.99$). The P in the soil solution should be representative of that found under field conditions since these soils were equilibrated for 6 d at their field-capacity moisture content before centrifugation.

Lime decreased the relative P uptake of both sudangrass and potato, and of bean (*Phaseolus vulgaris* L.) in a previous study (19). Significantly different plant-species responses to P buffer capacities are also reported (4). This suggests that the critical soil-test P concentration for a given extractant may also be dependent on plant species. Different critical soil-test concentrations are sometimes used for making P-fertilizer recommendations for different plant species. This is caused by species' differences in external-P requirement, root length and hairs, and infection by vesicular-arbuscular mycorrhizal fungi (26).

The P-uptake rate by roots is directly proportional to the P concentration at the root–soil interface (23). This concentration is largely controlled by the amount

of labile (adsorbed) P as related to the P buffering capacity (16, 18) and it can be estimated by the resin-extractable P/EBC ratio. This ratio was linearly related to the soil solution-P concentration (Fig. 3). A similar relationship existed between solution P and the $NaHCO_3$-extractable P/EBC ratio ($\hat{y} = 0.05 + 0.362x$, $r^2 = 0.86$). At a given resin-extractable P concentration, an EBC increase decreased the solution-P concentration. The EBC significantly increased as the lime concentration increased in this study (Table 4), lowering the solution-P concentration and reducing P uptake. A small but significant correlation occurred between resin-extractable P and EBC (Table 4). As expected, a P application at a given lime concentration increased P uptake because it increased resin-extractable P and reduced EBC. A higher EBC at a given labile-P concentration would reduce the solution-P concentration and the effective distance that P moves to the roots by diffusion (23). This effect will be intensified under field conditions because root densities are smaller than in greenhouse pots. If P uptake is less than optimal, plant growth rates will be reduced, delaying crop maturity or increasing the susceptibility of the crop to diseases. Yields may also be reduced if normal crop maturity is not reached by the end of the growing season.

Phosphorus adsorption in calcareous soils correlates with dithionite-soluble Fe and the surface area of the lime (12, 15). Every deep-tillage operation on an eroded calcareous soil has the potential to expose fresh calcareous subsoil material. This material is probably more reactive than lime subjected to cropping and management practices for a number of years. Organic materials and inorganic anions are adsorbed on the surfaces of lime materials with time, reducing their P-adsorption capacities (15). The lime in the deep-tilled soil samples (Exp. 1) was recently exposed to the cropping environment (8). Its P reactivity was similar to freshly precipitated lime (Exp. 2a or 2b) or reagent-grade $CaCO_3$ (Exp. 3), where equal amounts of "native" soil were used across lime concentrations. This suggests that the surface area of the lime was the major factor affecting P availability on these soils; however, neither surface area nor dithionite-soluble Fe was estimated in these soils. Other forms of carbonate minerals, carbonate minerals coated with nonreactive materials, or limed acidic soils may not follow the relationships found in this study. Increasing lime concentrations also reduce the residual value of P fertilizers (9, 28).

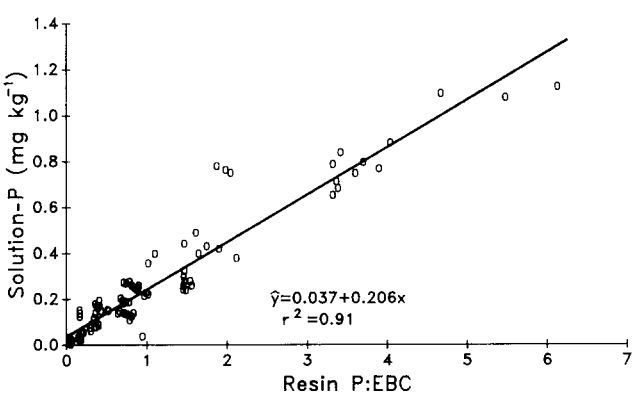

Fig. 3. The relationship between the soil solution P in 0.01 *M* $CaCl_2$ and the resin-extractable P/equilibrium buffer capacity (EBC) ratio in Exp. 1, 2a, 2b, and 3. Relationship significant at the *P* = 0.001 probability level.

The portion of labile P extracted by an effective soil test should be dependent on the P buffering capacity. Lime concentration or reactivity is generally not considered in P-fertilizer recommendations based on the $NaHCO_3$ soil test. The $NaHCO_3$ test is based on solubility-product principles in $CaCO_3$–soil systems (24). In this study, it averaged 52% of that extracted by the anion-exchange resin, similar to that reported for other calcareous soils (6). For a wider range of soil types, the portion of labile P extracted by $NaHCO_3$ decreased from 58 to 5% as the buffer capacity increased (14), suggesting that the critical concentration of $NaHCO_3$-extractable P may not change. However, this study and others (3, 5, 13) shows that the critical soil-test P concentration should increase as the buffer capacity increases to provide the same degree of P availability and plant uptake if the soil-test extractant is not sensitive to the buffering capacity. Additional studies are needed to further characterize the reactivity of the lime materials in calcareous soils and the effect of exposure and farming practices on their reactivity, and to identify the effect of the soil's P buffer capacity on the critical soil-test P concentration under field conditions.

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