Application of Bicarbonate to High-Phosphorus Soils to Increase Plant-Available Phosphorus

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Vegetable growers in the northeastern United States often have soils with P levels so high that fertilizer applications have environmentally detrimental effects. However, growers raise crops that require P fertilizer in cool soils regardless of soil P levels. A method to increase bioavailable P to vegetable seedlings in cool soils would have great value. Bicarbonate is a safe and inexpensive material that solubilizes some pools of adsorbed phosphate. Incubation of 50 mmol $KHCO_3$ kg^{-1} soil increased water-extractable P three- to eightfold in soils characteristic of P-impacted vegetable soils in the northeastern United States. A banded treatment at this rate is equivalent to 28 kg ha^{-1}. Multivariate analysis of soil characteristics revealed that the most responsive soils were those high in sand content. The response increased linearly with sand content >50%. A bicarbonate application technique would therefore have particular promise on sandy, high-P soils such as those found on the Atlantic seaboard.

Abbreviations: AEM, anion exchange membrane; M-3P, Mehlich-3 extractable phosphorus; PC, principal component.

Phosphorus accumulation is common in agricultural soils, and an excessive soil P load creates a pollution hazard to aquatic systems (Carpenter et al., 1998; Carpenter, 2008). There must be a balance between short- and long-term agricultural goals and potential excess fertilization and subsequent eutrophication of waterways (Simpson et al., 2004). Many soils in the primary vegetable-growing areas of the northeastern United States are "grossly excessive in P relative to the crop requirements" (Sims, 1998), and in the northeastern United States, P levels are much higher than in the rest of North America (Fixen, 2006). Vegetables are among the most intensively managed crops, and market demands require that planting begin early in the spring. Satisfactory stands require high P availability to seedlings, but bioavailability to plants is low in cold soil even when soil tests show excessive P (Lorenz and Vittum, 1980; Grant et al., 2001). Phosphorus must therefore be added as fertilizer, exacerbating the high P load in the soil. Many states in the northeastern and mid-Atlantic United States, as well as the USEPA, have instituted stricter regulation of agricultural P use (Sims and Coale, 2002; USEPA, 2010) that requires new methods of providing vegetable crops with needed P. Bicarbonate is an inexpensive and nontoxic compound that desorbs phosphate from solid-phase binding sites (Kuo, 1996). We examined the potential of applying small amounts of bicarbonate to mobilize plant-available P in selected high-P vegetable soils of the northeastern United States.

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MATERIALS AND METHODS

Soil was collected by cooperative extension field staff and commercial crop consultants in New Hampshire, Massachusetts, New York, Pennsylvania, New Jersey, and Maryland. Participants were asked to collect soil from fields that were slated for early vegetable production in the spring, preferably snap bean (*Phaseolus vulgaris* L.) or sweet corn (*Zea mays* L.), and that were high in P. A total of 31 soil samples were collected from the plow layer in April 2000 and 2001 and stored until use (2–8 mo) in sealed plastic bags at 4°C to simulate continued late-winter conditions before the onset of microbial activity.

To determine the effect of dose, granulation, moisture, and temperature, a representative soil having a Mehlich-3 P (M-3P) content of 53 mg kg^{-1} was selected from among those described above. At a gravimetric moisture content that was friable (15.9%), the soil was screened through 2-mm mesh at 4°C. For each experiment, 25 g of soil was placed in a 100-mL beaker with the appropriate treatment and covered in paraffin film. After incubation (see below), P was extracted from the soil at room temperature with water or with an anion exchange membrane (AEM; AR204, Ionics Inc.), and the sample as assayed for P by the ascorbic acid method (Kuo, 1996). Unless otherwise specified, the soil had a moisture content of 15.9% and as incubated with 50 mmol $KHCO_3$ kg^{-1} soil for 4 d at 15°C. For analyzing the dose response, $KHCO_3$ was mixed with the soil to give 5, 10, 20, 50, or 100 mmol kg^{-1} dry soil. For analyzing granulation, soil mixed with either powdered or granulated $KHCO_3$ was incubated for different time periods (0, 1, 2, 4, 8, or 15 d). For analyzing soil moisture, the water content was adjusted to 10 g water g^{-1} dry soil (very dry), 15 g water g^{-1} (friable), 20 g water g^{-1} (near field capacity), and 25 g water g^{-1} (between field capacity and saturation). For temperature, the incubation was done at 15 and 25°C. Granulation, soil moisture, and temperature experiments included a control without $KHCO_3$ addition; each treatment was replicated three times.

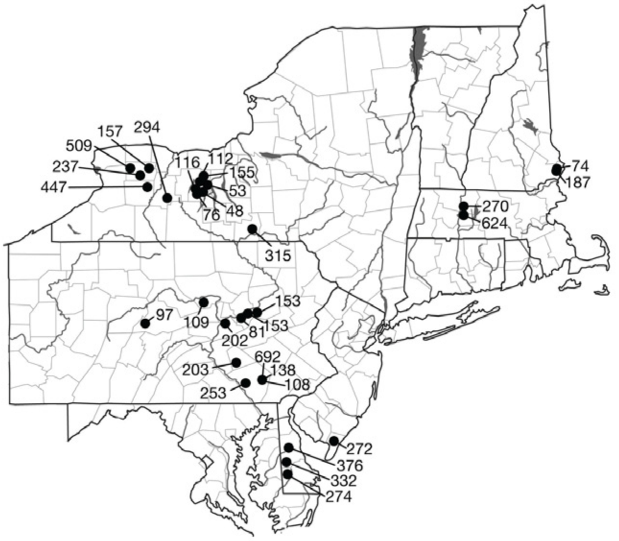

Fig. 1. Geographical distribution of soil samples collected for analysis in 2000 and 2001. The values are Mehlich-3 soil test P (M3-P) values (in mg kg^{-1}) for each site. No P addition is needed if M3-P > 50 mg kg^{-1}; remediation is recommended if M3-P > 150 mg kg^{-1} (Sims and Coale, 2002) due to potential negative environmental impact.

The 31 representative soils were characterized by P availability using the following analyses that solubilize different soil-P pools: M-3P, modified Morgan (Kuo, 1996), Bray-1, Bray-2, $CaCl_2$ extraction, H_2SO_4 extraction, water extraction, AEM extraction, and HCl extraction. Release of P by $KHCO_3$ was measured using water extraction to estimate the leaching potential and AEM extraction to estimate seedling P availability (Wang et al., 2012). Phosphorus from M3-P, modified Morgan, Bray-1, and Bray-2 extractions was assayed by A&L Eastern Laboratories, Richmond, VA. Phosphorus was extracted with deionized water, $CaCl_2$, H_2SO_4, and AEM by sieving soil through a 2-mm screen, then air drying and storing until use. For water, $CaCl_2$, and H_2SO_4 extractions, 2 g of soil was placed in a 125-mL Erlenmeyer flask with 20 mL of either deionized water, 0.01 mmol L^{-1} $CaCl_2$, or 0.5 mol L^{-1} H_2SO_4, shaken for 1 h, then centrifuged to remove soil particles. For AEM, 2 g of soil was placed in 20 mL of deionized water with 6.25 cm^2 of an AEM that had been equilibrated in 0.5 mol L^{-1} NH_4OAc and shaken for 1 h. The membrane was removed, rinsed, and shaken in 20 mL of 0.5 mol L^{-1} NH_4OAc to desorb the phosphate. All extractions were performed in duplicate on each soil. The extracts were assayed for P by the ascorbic acid method (Kuo, 1996). The soils were also characterized by their physical properties. Organic P was defined as the amount of P extractable in 0.5 mol L^{-1} H_2SO_4 after ignition of the soil at 550°C (Olsen and Sommers, 1982). Soil pH was measured with a surface electrode in a slurry of 2.5 parts distilled water after a 30-min equilibration. The fraction of sand and clay in the soil was assayed with a hydrometer using the density of a soil suspension as it settled (Day, 1965).

A principal components analysis was performed on the full set of P availability and physical property variables on the 31 soils using JMP software (version 9, SAS Institute). Mehlich-3 P and Bray-2 were excluded from the predictive analysis because they were >90% correlated with Bray-1 and therefore added no additional information. The first three principal components were used as predictors in a regression analysis of the relative and absolute increase in water- or AEM-extractable P following incubation with $KHCO_3$.

RESULTS

The soils used to test the applicability of bicarbonate addition were collected to represent high-P soils throughout the northeastern United States (Fig. 1; Table 1). We compared these vegetable soils with extensively studied dairy soils of the Delaware watershed (Kleinman et al., 2000). The relationship between the amount of plant-available P (M-3P) in the soil and the leaching risk ($CaCl_2$–extractable P) was comparable between these vegetable soils and other northeastern U.S. dairy soils (Fig. 2), with a similar change point for P saturation.

Dose

Increasing amounts of KHCO$_3$ resulted in greater P release across the range studied (Fig. 3). Water-extractable P was <5 mg kg^{-1} at low doses of KHCO$_3$, with appreciable plant-utilizable release starting at about 50 mmol KHCO$_3$ kg^{-1} soil (Fig. 3). Preliminary trials indicated that doses of <50 mmol KHCO$_3$ kg^{-1} soil were not phytotoxic to snap bean seedlings. A larger pool of P was available at lower bicarbonate doses with AEM extraction (Fig. 3). The membrane extracted more P than did water at KHCO$_3$ doses <100 mmol kg^{-1} soil, while both extraction methods yielded similar P levels at approximately 100 mmol kg^{-1} soil (Fig. 3).

Granulation

Incubation of soil with KHCO$_3$ (50 mmol kg^{-1} soil) resulted in a rapid release of P (Fig. 4). Powdered KHCO$_3$ acted essentially instantly (the time resolution of the assay is a few minutes). When the bicarbonate material was compounded into a granule of approximately 1 mm for ease of application, most of the release happened immediately and was complete in <2 d (Fig. 4).

Moisture

If the soil was moist enough for germination and growth (i.e., >15% soil moisture), release of P by KHCO$_3$ was relatively constant at approximately 30 mg P kg^{-1} soil (Fig. 5). In drier soil, P released during incubation could not dissipate and rebound to soil binding sites (McBeath et al., 2012).

Temperature

Release of P by KHCO$_3$ was similar at 15 and 25°C. When all incubation durations were pooled, P release was 18.3 ± 1.0 g P kg^{-1} soil at 15°C and 17.6 ± 0.7 g P kg^{-1} soil at 25°C compared to the untreated (no bicarbonate added) controls at 2.4 ± 0.4 g P kg^{-1} soil and 2.3 ± 0.4 g P kg^{-1} soil, respectively. The difference in P release between temperatures was not statistically significant.

Table 1. Description of soil sampling locations.

Location	Soil type	Previous crop
Annville, PA	Clarksburg silt loam	pea and sweet corn
Batavia, NY	Ontario loam	field corn
Bellona, NY	Lima fine silt loam	sweet corn
Bergen, NY	Ontario loam	cabbage
Centre Hall, PA	Dunning silt loam	snap bean
Denton, MD	Hanbrook sandy loam	soybean
Denton, MD	Hanbrook sandy loam	soybean
Denton, MD	Woodstowne sandy loam	sweet corn
Geneva, NY	Odessa silt loam	snap bean
Geneva, NY	Lima silt loam	alfalfa
Hadley, MA	Agawam fine sandy loam	butternut squash
Hadley, MA	Agawam fine sandy loam	butternut squash
Holtwood, PA	Chester silt loam	field corn
Jersey Shore, PA	Hagerstown silt loam	sweet corn
Mifflinville, PA	Hartleton channery silt loam	sweet corn
Mifflinville, PA	Chenango gravelly sandy loam	soybean
Milton, PA	Barbour-Linden complex (Silt loam)	soybean
Morganville, NY	Ontario loam	pea
Nescopeck, PA	Pocono sandy loam	sweet corn
New Holland, PA	Clarksburg silt loam	field corn
New Holland, PA	Duffield silt loam	field corn
New Holland, PA	Hagerstown silt loam	field corn
Owego, NY	Howard gravelly loam	rye and hairy vetch
Peoria, NY	Nunda silt loam	dry bean
Seneca Castle, NY	Palmyra fine sandy loam	wheat
Sparta, NY	Wooster gravelly loam	pea
Stanley, NY	Kendaia loam	snap bean
Stanley, NY	Lima silt loam	alfalfa
Stratham, NH	Boxford silt loam	sweet corn
Stratham, NH	Boxford silt loam	dry bean
Woodbine, NJ	Fort Mott loamy sand	melon

Identifying Responsive Soils

To better understand which soils were most bicarbonate responsive, we assayed the soils for various measures of soil P and

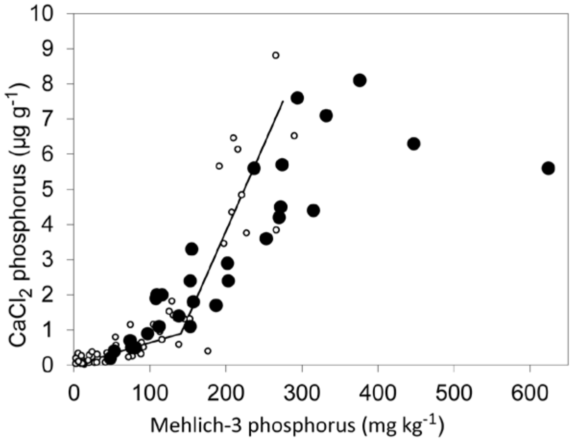

Fig. 2. Soils in which vegetables are grown have the same continuity in P release as do dairy soils relative to the soil P content. Soil P content was assayed by the Mehlich-3 P assay, whereas solution P, representing the leaching risk, was assayed by CaCl$_2$ extraction. Solid circles indicate vegetable soils of the northeastern United States; light gray circles and the line are dairy soils of the Delaware River watershed (Kleinman et al., 2000).

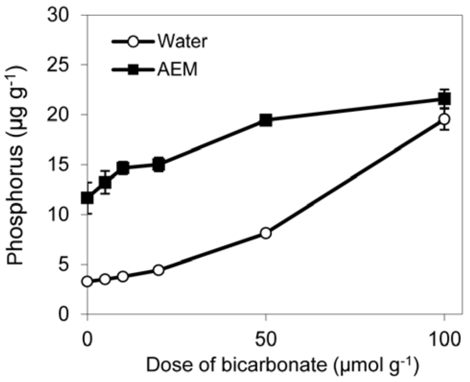

Fig. 3. Effect of bicarbonate dose on the release of P from soil during an 8-d incubation using water and anion exchange membrane (AEM) extraction methods. The soil had a Mehlich-3 P value of 53 mg kg^{-1}. Vertical bars represent the standard error of three replicates; where no bars are visible, the error bar is smaller than the symbol.

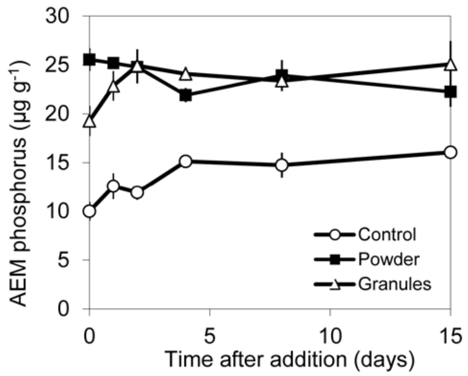

Fig. 4. Effect of granulation on the speed of P release from soil incubated with $KHCO_3$ (50 mmol kg^{-1} soil). Phosphorus levels were measured using anion exchange membrane (AEM) extraction. The soil had a Mehlich-3 P value of 53 mg kg^{-1}. Vertical bars represent the standard error of three replicates; where no bars are visible, the error bar is smaller than the symbol. The control was soil with no $KHCO_3$ added.

characterized the soil physical properties. The physical properties included organic matter, sand content, clay content, and soil pH. To identify soil properties that provided the strongest bicarbonate-responsive predictive power in this group of soils, we initially characterized the soils by principal component analysis, with those principal components then tested for predictive potential.

The first three principal components (PC1, PC2, and PC3) described 84% of the variation among soils (Table 2), with PC1 heavily weighted for P content, PC2 weighted for soil texture, and PC3 weighted for pH (Table 2). Soil responsiveness to bicarbonate was analyzed as either the relative (Table 3) or absolute (Table 4) increase in water- and AEM-extractable P following a 24-h incubation of soil with 50 mmol $KHCO_3$ kg^{-1} soil. The relative increase in P was due to PC2 (Table 3). The absolute increase in P was also associated with texture-related PC2, as well as with P-related PC1 (Table 4). The most heavily weighted component of PC2 was sand. Immediate P availability and leaching risk (water extraction) were better predicted than short-term nutrient availability (AEM extraction). The sand content of the soils provided a strong predictor of P release in the presence of bicarbonate (Fig. 6).

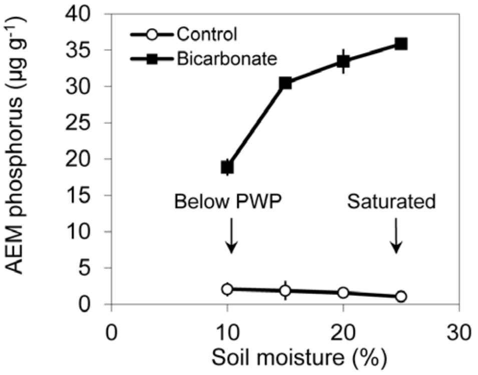

Fig. 5. Effect of soil moisture on release of P by 50 mmol $KHCO_3$ kg^{-1} soil. Phosphorus levels were measured using anion exchange membrane (AEM) extraction. The soil had a Mehlich-3 P value of 53 mg kg^{-1}. Vertical bars represent the standard error of three replicates; where no bars are visible the error bar is smaller than the symbol. PWP is the permanent wilting point. The control was soil with no $KHCO_3$ added. A soil moisture content of 15 to 20% is required for normal plant growth.

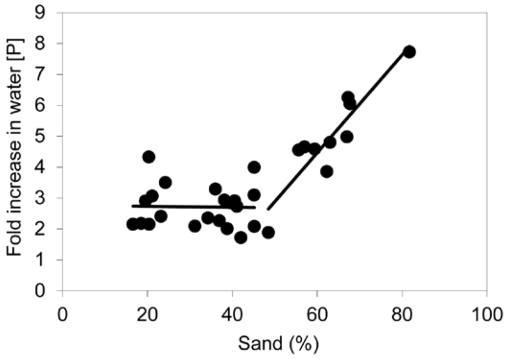

Fig. 6. The effect of sand content of northeastern U.S. vegetable soils on the increase in water-extracted P following incubation with 50 mmol $KHCO_3$ kg^{-1} soil.

DISCUSSION

A management alternative is needed for banded P application on land on which current excessive soil-P concentrations make additional P application undesirable or illegal. Application of a bicarbonate band has the potential to locally raise the solution phosphate concentration during seedling establishment. The appropriate method for bicarbonate application and the effect on P availability from relevant soils were determined.

Soils with high or excessive P were found in specific regions of the northeastern United States. Samples used in this study were comparable to high-P soils identified in previous unselected sampling (Ketterings et al., 2005). Soil water from our sampling sites drained mostly to fresh water, in which eutrophication is P limited; even the selected coastal sites drained into creeks and brackish estuaries before reaching salt water.

To provide an appropriate procedure for applying bicarbonate to soil, it was necessary to find the appropriate dose and formulation and to determine the effect of soil temperature and moisture on P solubilization. We found that a field application

Table 2. Principal components (PCs) describing 31 high-P vegetable soils from the northeastern United States.

Variable†	Weight (eigenvector)		
	PC1	PC2	PC3
$CaCl_2$ extract	−0.472	−0.173	0.078
Modified Morgan‡	−0.415	−0.371	0.101
Bray P1	−0.517	−0.002	−0.040
H_2SO_4 extract	−0.411	−0.251	−0.200
Soil pH	0.025	−0.214	0.797
Organic P	0.126	−0.409	−0.549
Sand content	−0.228	0.556	−0.070
Clay content	0.316	−0.497	0.030
Variance, %	40.5	29.0	14.7

† Mehlich-3P and Bray P2 extracts were not included in the analysis because they were >0.9 correlated with Bray P1 extracts; water and anion exchange membrane (AEM) extractions were excluded because they contributed to the response measure. Two extractions of each kind were performed on each soil.

‡ Modified Morgan extraction; described by Kuo (1996).

Table 3. Contribution to the relative increase in water-extractable or anion exchange membrane (AEM) extractable P by 50 mmol $KHCO_3$ kg^{-1} soil from each principal component describing 31 high-P vegetable soils from the northeastern United States.

Predictor	Water			AEM		
	Coefficient†	SD	*P*	Coefficient	SD	*P*
Constant	3.42	0.166	***	1.75	0.13	***
PC1	0.125	0.094	0.194	−0.021	0.071	0.764
PC2	−0.757	0.111	***	−0.234	0.084	**
PC3	−0.057	0.156	0.719	−0.222	0.117	0.070
R^2, %	64.2			29.7		

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Parameter coefficient. The response variable was the P value in a water or AEM extract of soil incubated with 50 mmol $KHCO_3$ kg^{-1} soil (treated) divided by the P value in a soil extract with no $KHCO_3$ added (untreated). Two extractions of each kind were performed on each soil.

rate should produce a local concentration of approximately 50 mmol bicarbonate kg^{-1} soil. In a moderately fine-textured soil, bicarbonate granules would be distributed in a band with a radius of approximately 1 cm. Such a band would contain approximately 425 g soil m^{-1} of row, resulting in a bicarbonate application rate of 2 g m^{-1} or, in 0.75-m rows, 28 kg ha^{-1}.

Granulation is essential for dispensing bicarbonate with agricultural equipment. Powder is difficult to dispense in accurate doses, and it tends to not flow consistently under field conditions. Granules overcome these problems, and existing planters are designed to dispense them accurately in or adjacent to the seed furrow. However, granulation can slow the effectiveness of a similar material, limestone; limestone particles of 0.2 mm react twice as quickly as 0.4-mm particles to neutralize soil acidity, and those >1.2 mm are relatively inert (Meyer and Volk, 1952). Bicarbonate granulation resulted in no significant delay in P release. In our in vitro experiments, most P release happened within minutes and was complete well before seed germination would normally occur.

The requirement for extra bioavailable P in early plantings is associated with low soil temperature (Lorenz and Vittum, 1980). The soil temperature at which early vegetable crops are normally planted in the northeastern United States is near 15°C. For bicarbonate to be useful in practice, then, it would need to be effective at 15°C. Our experiments showed that bicarbonate release of P was as effective in cool (15°C) soil in which the extra P is needed as it was in warm (25°C) soil. Therefore, bicarbonate would be effective even in the coolest soil into which warm-season vegetables would be sown.

Bicarbonate was effective across the entire range of soil moisture conditions that might be encountered during the 2 wk following early crop planting, at which time P bioavailability would be most relevant. In very dry soil, P release was reduced, but moisture would also limit seed germination and plant growth under very low soil moisture conditions.

It is important to predict the aquatic pollution potential of high-P soils to appropriately mitigate environmental effects. It is not yet known whether predictors developed for manured agronomic soils can be applied to highly fertilized vegetable soils. The M-3P test has been proposed as the predictor for the mid-Atlantic region (Sims et al., 2002). Kleinman et al. (2003) developed reliable predictors of soil P sorption capacity in dairy soils of different pH levels relative to M-3P test values, and M-3P is already the standard soil-P test in many northeastern U.S. states (Sharpley et al., 2003). Mehlich-3 P is an excellent predictor of leaching potential, matching the desorption curve of dairy soils (Kleinman et al., 2000), although fertilizer forms used, crops grown, soil texture, and pH (5.9–6.7) would be different in vegetable soils than in dairy soils.

Soil characteristics predictive of a large release of P by bicarbonate were determined by measuring a diverse group of soil parameters to find a set of parameters with the greatest predictive power. Many parameters were rejected using principal component analysis, followed by closer examination of the component with the greatest predictive power. Principal Component 1 and PC3 had no predictive power for relative P release (Table 3), therefore soil characteristics that do not determine the suitability of bicarbonate use are weighted in these components; PC1 is largely a reflection of the amount of P in the soil (Table 2). The *relative* amount of P released was not predicted by PC1 because the relative amount inherently normalizes for soil P content. As expected, PC1 was strongly associated with the *absolute* amount of P released by bicarbonate incubation (Table 4). This result is predicted if bicarbonate is affecting a fraction of soil P that increases in conjunction with the major pools of soil P. Principal Component 3 is largely associated with pH. Bicarbonate is known to solubilize P especially well in high-pH soils, a fact utilized by the bicarbonate-based Olsen extraction method (Olsen and Sommers, 1982). The prediction that bicarbonate would be effective in increasing P concentration in high-pH soils was not borne out in our soil samples.

Relative P release was predicted primarily by PC2, so this PC contains one or more of the determining soil characteristics. Principal Component 2 was most heavily weighted for soil texture and soil organic P (Table 2). When organic P was analyzed individually, it was inversely associated with P released by $KHCO_3$ ($r = -0.60$); therefore $KHCO_3$ was not releasing organic P.

Table 4. Contribution to the *absolute* increase in water-extractable or anion exchange membrane (AEM) extractable P by 50 mmol $KHCO_3$ kg^{-1} soil from each principal component describing 31 high-P vegetable soils from the northeastern United States.

Predictor	Water			AEM		
	Coefficient†	SD	*P*	Coefficient	SD	*P*
Constant	30.4	2.4	***	26.3	3.1	***
PC1	−9.76	1.38	***	7.95	1.73	***
PC2	8.34	1.63	***	−8.96	2.05	***
PC3	4.59	2.28	0.055	1.52	2.88	0.60
R^2, %	74.9			60.0		

*** Significant at the 0.001 probability level.

† Parameter coefficient. The response variable was the difference in P value in a water or AEM extract of soil incubated with 50 mmol $KHCO_3$ kg^{-1} soil vs. untreated (no $KHCO_3$ added) soil. Two extractions of each kind were performed on each soil.

Soil texture was examined directly, showing that soils with high sand content were the most responsive to $KHCO_3$ treatment. The higher P solubility in sandy vs. clay soils (Leinweber et al., 1999) may explain the higher P release from sandy soils following $KHCO_3$ treatment in our study. For soils containing <50% sand, $KHCO_3$ treatment increased water-extractable P approximately threefold; the proportion increased to eightfold at 80% sand (Fig. 6). Therefore, the high-P soils most likely to be candidates for bicarbonate treatment are those with sand content >50%.

In the northeastern United States, high-sand soils have some of the greatest excesses of soil P as well as high P indices (Sharpley et al., 2003). These soils are often chosen for the earliest vegetable planting because they are well drained and friable while still cool. Vegetable production with high fertilizer application combined with a large nearby poultry industry with land spreading of poultry manure have resulted in soil P becoming an acute environmental issue on the Delmarva peninsula and in southeastern New Jersey (Goodman, 1999; Simpson, 1998). It is on these Atlantic seaboard soils that bicarbonate shows particular promise as a means of replacing or reducing starter P application, thereby reducing grower time and expense, as well as decreasing the potential for aquatic eutrophication.

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