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

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 KHCO₃ 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.
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 KHCO3 kg−1 soil for 4 d at 15°C. For analyzing the dose response, KHCO3 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 KHCO3 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 KHCO3 addition; each treatment was replicated three times.

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, CaCl2 extraction, H2SO4 extraction, water extraction, AEM extraction, and HCl extraction. Release of P by KHCO3 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, CaCl2, H2SO4, and AEM by sieving soil through a 2-mm screen, then air drying and storing until use. For water, CaCl2, and H2SO4 extractions, 2 g of soil was placed in a 125-mL Erlenmeyer flask with 20 mL of either deionized water, 0.01 mol L−1 CaCl2, or 0.5 mol L−1 H2SO4, 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 cm2 of an AEM that had been equilibrated in 0.5 mol L−1 NH4OAc and shaken for 1 h. The membrane was removed, rinsed, and shaken in 20 mL of 0.5 mol L−1 NH4OAc 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 H2SO4 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 KHCO3.

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 (CaCl2-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 KHCO₃ resulted in greater P release across the range studied (Fig. 3). Water-extractable P was <5 mg kg⁻¹ at low doses of KHCO₃, with appreciable plant-utilizable release starting at about 50 mmol KHCO₃ kg⁻¹ soil (Fig. 3). Preliminary trials indicated that doses of <50 mmol KHCO₃ 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 KHCO₃ 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 KHCO₃ (50 mmol kg⁻¹ soil) resulted in a rapid release of P (Fig. 4). Powdered KHCO₃ 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 KHCO₃ 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 KHCO₃ 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.

Identifying Responsive Soils

To better understand which soils were most bicarbonate responsive, we assayed the soils for various measures of soil P and...
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 KHCO₃ 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).

**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

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

<table>
<thead>
<tr>
<th>Variable†</th>
<th>Weight (eigenvector)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PC1</td>
</tr>
<tr>
<td>CaCl₂ extract</td>
<td>-0.472</td>
</tr>
<tr>
<td>Modified Morgan‡</td>
<td>-0.415</td>
</tr>
<tr>
<td>Bray P1</td>
<td>-0.517</td>
</tr>
<tr>
<td>H₂SO₄ extract</td>
<td>-0.411</td>
</tr>
<tr>
<td>Soil pH</td>
<td>0.025</td>
</tr>
<tr>
<td>Organic P</td>
<td>0.126</td>
</tr>
<tr>
<td>Sand content</td>
<td>-0.228</td>
</tr>
<tr>
<td>Clay content</td>
<td>0.316</td>
</tr>
<tr>
<td>Variance, %</td>
<td>40.5</td>
</tr>
</tbody>
</table>

† 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).
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-P 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-P 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 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.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Water Coefficient† SD</th>
<th>P</th>
<th>Coefficient SD</th>
<th>AEM Coefficient SD</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>3.42</td>
<td>0.166</td>
<td>***</td>
<td>1.75</td>
<td>0.13</td>
</tr>
<tr>
<td>PC1</td>
<td>0.125</td>
<td>0.094</td>
<td>0.194</td>
<td>-0.021</td>
<td>0.071</td>
</tr>
<tr>
<td>PC2</td>
<td>-0.757</td>
<td>0.111</td>
<td>***</td>
<td>-0.234</td>
<td>0.084</td>
</tr>
<tr>
<td>PC3</td>
<td>-0.057</td>
<td>0.156</td>
<td>0.719</td>
<td>-0.222</td>
<td>0.117</td>
</tr>
</tbody>
</table>

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.

### 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.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Water Coefficient† SD</th>
<th>P</th>
<th>Coefficient SD</th>
<th>AEM Coefficient SD</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>30.4</td>
<td>2.4</td>
<td>***</td>
<td>26.3</td>
<td>3.1</td>
</tr>
<tr>
<td>PC1</td>
<td>-9.76</td>
<td>1.38</td>
<td>***</td>
<td>7.95</td>
<td>1.73</td>
</tr>
<tr>
<td>PC2</td>
<td>8.34</td>
<td>1.63</td>
<td>***</td>
<td>-8.96</td>
<td>2.05</td>
</tr>
<tr>
<td>PC3</td>
<td>4.59</td>
<td>2.28</td>
<td>0.055</td>
<td>1.52</td>
<td>2.88</td>
</tr>
</tbody>
</table>

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.

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Soil texture was examined directly, showing that soils with high sand content were the most responsive to KHCO₃ treatment. The higher P solubility in sandy vs. clay soils (Leinweber et al., 1999) may explain the higher P release from sandy soils following KHCO₃ treatment in our study. For soils containing <50% sand, KHCO₃ 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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REFERENCES


