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Meeting Initial Snap Bean Seedling Requirements with Starter Phosphorus or Bicarbonate to Solubilize Soil Phosphorus in High-phosphorus Soils

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Abstract. **Starter phosphorus (P) is often recommended for warm-season vegetables sown in cool soil, even if soil P index levels are already high. The cost and environmental risk associated with excessive P fertilization justify re-examination of the practice. The objective of the study was to confirm that performance of early plantings of snap bean (*Phaseolus vulgaris* L.) is improved by starter P application and to test whether solubilizing soil P with potassium bicarbonate ($KHCO_3$) can serve as an alternative in western New York soils. Addition of starter fertilizer at either recommended (15 kg·ha^{-1}) or supraoptimal (35 kg·ha^{-1}) P rates did not generally improve seedling tissue P concentration, early growth (biomass at flowering), or pod yield. Starter P application increased tissue P in only two of 11 experiments, and it never increased yield. Application of 6 kg·ha^{-1} $KHCO_3$ to release soil-bound phosphate was not phytotoxic to snap beans. In the two experiments in which starter P increased tissue P, $KHCO_3$ application had a smaller effect in one and no effect in the other. $KHCO_3$ application did not increase yield in any of the six experiments where it was tested. A direct test of the contribution of P limitation to the poorer performance of early plantings showed that neither starter P nor $KHCO_3$ application increased yield at early planting. Seasonal differences in crop performance could not be attributed to mineralization of soil phosphate after soil warmed. Water-extractable soil P was not lower in the spring than in summer, remaining constant at all 11 bean fields that were sampled from mid-April through mid-July. In these trials, P was likely not growth-limiting in the cool soils tested. Because starter P may not be necessary in vegetable soils testing high or very high for P, vegetables would also not likely benefit from bicarbonate application under high P conditions.**

In the northeastern United States (New England, New York, and northern Pennsylvania), starter P is often recommended for vegetable production in cold spring soils (Howell and Hazzard, 2014; Reiners and Petzoldt, 2014), even when soils have soil test P levels so high that additional fertilizer application can pose aquatic pollution hazards (Fixen, 2006). However, there is little primary literature on which to base adjustments to standard P recommendations. Furthermore, an alternative method to increase bioavailable P to vegetable seedlings in high P soils would have great agricultural value.

Phosphorus is a critical macronutrient required for many functions in plant growth and development. Symptoms of P deficiency in plants include decreased plant height, delayed emergence of leaves, and reduced seed production (Grant et al., 2001). Although P is present in a variety of chemical forms in soil, plants use only the orthophosphate (inorganic) form of P (Schachtman et al., 1998). Soil concentrations of orthophosphate are extremely low and rarely exceed 10 μM (Bieleski, 1973). Some plants have evolved strategies to optimize acquisition of P from soil, including modifications to root architecture to increase soil exploration, release of root exudates to solubilize P, association with microorganisms that increase bioavailable P, and production of transporter proteins directly involved in P uptake into root cells (Lynch and Brown, 2008; Richardson et al., 2011).

In the northeastern United States, market demands require that vegetable planting begin early in the spring, when air and soil temperatures are still cold. Because P uptake is temperature-dependent, P acquisition in cold spring soils poses a special challenge to plants. Satisfactory stands require high P availability to seedlings, but bioavailability to chilling-sensitive crops like snap bean is low in cold soil even when soil tests show excessive P (Grant et al., 2001; Lorenz and Vittum, 1980). The 1981–2010 mean temperature at 5-cm soil depth in Geneva, NY, was 7 °C in April, 12 °C in May, and 19 °C in June. Both diffusion and solubility of P are also decreased in colder soils (Grant et al., 2001). In addition, as a result of very low inorganic P concentrations in many soils, plants must acquire P against a steep concentration gradient because P concentration in root cells is ≈1000-fold higher than in soil (Yuan and Liu, 2008). The active transport system driving P uptake is also temperature-dependent (White, 2012). Phosphorus acquisition rates decrease as temperature decreases, as shown in experiments in bush bean and corn (Raeini-Sarjaz and Barthakur, 1995, and Bravo and Uribe, 1981, respectively). Analysis of P acquisition in several other crop species at three temperatures (18, 12, and 9 °C) showed that P uptake at 12 or 9 °C was only half that of P uptake at 18 °C (Singh and Subramaniam, 1997). Furthermore, P uptake is dependent on root growth, which is also sharply reduced in beans during and after exposure to chilling temperatures (El-Saht, 1998). Breeding for stronger seedling performance could have selected for reduced cold sensitivity of either root growth or uptake in recently released varieties. The soil orthophosphate concentration may need to be considerably higher in cold soils to compensate for the lower P uptake capacity of roots and thereby provide sufficient P for seedlings.

Low microbial activity may also reduce P availability in cold soils if planting precedes mineralization of organic P. Much of the P in cold high P soils is in the organic form, which is unavailable to plants. Effective uptake from this pool, should it occur, depends on both microbe and plant being metabolically active. In this climate, the process is reduced or inhibited in the spring (Bieleski, 1973). Therefore, P bioavailability may not be high until after the spring peak of microbial activity (Russell and Russell, 1950). In temperate climates, it has long been known that the peak of microbial activity typically occurs when soil temperature has warmed to 12 to 15 °C (Russell and Appleyard, 1915).

Spring planting of snap bean in the northeastern United States presents a dilemma between addressing the low acquisition rates of P from cold spring soils and mitigating the negative environmental impact of adding P fertilizer to already high P soils. Efforts are underway to identify and breed varieties of snap bean more efficient in acquisition and use of P (Bonser et al., 1996; Henry et al., 2010; Mourice and Tryphone, 2012). Recently, Björkman and Reiners (2014) described the use of $KHCO_3$ to increase bioavailable P in certain soils used for snap bean and other vegetable production in the northeastern United States. Potassium bicarbonate is an inexpensive (5 to $10/kg; Armand Products,

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Princeton, NJ) and non-toxic compound that desorbs phosphate from solid-phase binding sites (Kuo, 1996).

In the current study, we sought the answers to three questions: 1) How much starter P fertilizer is needed to compensate for cold soil for snap bean performance? We measured seedling tissue P concentration, early growth (biomass at flowering), and pod yield response to different starter P concentrations at various field sites; 2) Can bicarbonate solubilize enough phosphate in high P soils to avoid adding P fertilizer? We identified a safe application rate and formulation of bicarbonate by assessing phytotoxicity on snap bean for three different chemical forms of bicarbonate ($KHCO_3$, $NaHCO_3$, and NH_4HCO_3) and had previously identified an effective application rate (Björkman and Reiners, 2014). In field trials, we evaluated crop P uptake and growth and yield response to band-applied fertilizer and $KHCO_3$ in cool soil; and 3) To what extent is P limitation alleviated as a result of mineralization when soils warm in the spring?

Materials and Methods

Snap bean varieties. We used two similar snap bean varieties in the field experiments, both adapted to northeastern U.S. growth conditions, 'Hystyle' (Harris Moran Seed Co., Modesto, CA) and 'Zeus' (Seminis Vegetable Seeds-Asgrow, Oxnard, CA), a newer variety selectively bred for cold tolerance. 'Labrador' (Seminis Vegetable Seeds-Asgrow, Oxnard, CA), a widely grown variety, was used in the greenhouse experiments.

Determination of bicarbonate phytotoxicity in snap bean. We evaluated bicarbonate phytotoxicity in greenhouse snap beans to determine the maximum amount of bicarbonate that could be applied without injury to seedlings and thus confirm that bicarbonate application would not harm snap bean crops. Three commercially available chemical forms of bicarbonate were used, $KHCO_3$, sodium bicarbonate ($NaHCO_3$), and ammonium bicarbonate (NH_4HCO_3). Moist soil was placed in 5-cm-diameter, 15-cm-deep pots. Soil was collected from the Jon field site (Table 1), which was used in the subsequent bicarbonate field trial. A 2-cm-deep hole was made in the soil, bicarbonate was placed at the bottom of the hole followed by one snap bean seed, and the pot was then filled with soil flush to the surface. This method approximates the effect of placing bicarbonate in the seed furrow. The four bicarbonate application rates were 0, 50, 100, and 500 μmol/seed. Pots were kept in the greenhouse at 20 to 25 °C and scored for germination and growth after 7 d on a 4-point scale with 0 = unemerged, 1 = hook emerged, 2 = cotyledons open, or 3 = unifoliate leaves unfolded. Each treatment was replicated 10 times. Results were analyzed by ordinal logistic regression, allowing the treatment intensities and ratings to be ordinal values rather than continuous.

Snap bean response to starter P rates in cool soil. The experiment was conducted in May 2000 and May 2001 in two locations in New York, the Batavia and Geneva research farms. The Batavia site (lat. 42.027° N, long. 78.154° W) is located 35 km south of Lake Ontario at an elevation of 266 m. The Geneva site (lat. 42.856° N, long. 77.030° W) is located 46 km south of Lake Ontario at an elevation of 185 m. Both locations had a Honeoye silt loam soil (mesic Glossic Hapludalf). Soil P analysis was performed by the Cornell Nutrient Analysis Laboratory (CNAL; Ithaca, NY) on a composite sample of 30.5-cm-deep cores using Morgan extraction (Kuo, 1996). Morgan soil P values (in $mg \cdot kg^{-1}$) for snap bean crops were designated as less than 2, low; 3 to 5, medium; 6 to 12, high; and 13 or greater, very high (CNAL). The design consisted of three starter P treatments (no added P, 15 $kg \cdot ha^{-1}$, or 35 $kg \cdot ha^{-1}$ P as superphosphate) replicated six times each. Fertilizer was broadcast by hand with a rotary spreader (EZ Spreader; Republic, Carlsbad, CA) at 16N–0P–11.6K and 14N–0P–17.9K $kg \cdot ha^{-1}$ for each planting according to Cornell Vegetable Guidelines (Reiners and Petzoldt, 2014) such that nitrogen (N) and potassium (K) were not growth-limiting. Starter P application of 15 $kg \cdot ha^{-1}$ was intended to provide the recommended P rate, whereas starter P application of 35 kg P/ha was intended to saturate the P response. Phosphorus fertilizer was applied in a band placed 5 cm to the side of, and 5 cm below, the seeds at 6 and 14 $g \cdot m^{-1}$ (15 and 35 $kg \cdot ha^{-1}$, respectively). Plots were 15 m long and 3 m wide. Treatments were applied to the center two rows of the four-row plot. Snap bean seeds were sown 4.5 cm apart using a vacuum planter (Monosem, Edwardsville, KS). The seeds were treated with commercial fungicides (Captan; Drexel Chemical Co., Memphis, TN, and Demosan; Kincaid Enterprises, Inc., Nitro, WV) and an insecticide (Lorsban; Dow Agrosciences, Indianapolis, IN).

Tissue P content was measured in unifoliate leaves of snap bean seedlings at the time the first trifoliate was beginning to expand (less than 1 cm), a time early in growth and when P would have its greatest effect if growth-limiting. Selecting one leaf per plant, 20 representative leaves were collected from the plot. Leaves were rinsed free of soil with deionized water and then dried at 80 °C. Dried leaves were finely ground (largest piece less than 1 mm), weighed, and then ashed at 470 °C. The ash was dissolved in 6 M HCl and filtered into deionized water (Bickelhaupt and White, 1982). The resulting solution was assayed for P using the ascorbic acid method (Kuo, 1996). For tissue P analysis, means were calculated by analysis of variance (ANOVA) by experiment with block correction. Significance was calculated using Dunnett's means comparison against the unamended control (0). Early growth was measured by sampling biomass when flower buds were just forming. The exact timing varied among trials depending on temperature, but was typically 30 to 35 d after planting. Biomass was sampled in 0.5 m of a row (0.75 m^2 of soil surface) at each of two representative locations (average snap bean growth) in each plot. Harvest to determine pod yield occurred at commercial maturity for Hystyle and Zeus varieties. At commercial maturity, most snap beans were at sieve size four (8.3 to 9.7 mm) with a minority of snap beans at sieve size five (9.7 to 10.5 mm). Seeds inside the sieve size four snap beans were ≈8 mm in length.

Snap bean response to $KHCO_3$ or starter P in cool soil. The experiment was conducted in six locations in western New York, including the Geneva and Batavia research farms and four commercial snap bean fields on Geneva-area vegetable farms. Fertilizer N and K were broadcast like in the starter P experiments. Snap beans were planted in May 1999 and May 2001 with the exception of the early- vs. late-planting experiment, in which snap beans were planted in May 2002 and July 2002. Soil samples were collected and soil test P was determined using Morgan extraction as described in the starter P experiment. The design consisted of three treatments (no added P or $KHCO_3$; 35 kg P/ha; or 6 $kg \cdot ha^{-1}$ $KHCO_3$) replicated six times each. The contribution of $KHCO_3$ to K fertility (2 kg K/ha) was negligible. Plots were 15 m long and 3 m wide. Treatments were applied to the two center rows of the four-row plot. Granulated $KHCO_3$ was applied in the seed furrow using a planter-mounted metering unit (Monosem, Edwardsville, KS) dispensing 43 mg·m of row (6 $kg \cdot ha^{-1}$ or ≈100 μmol/seed). Phosphorus fertilizer was applied in a band placed 5 cm to the side of, and 5 cm below, the seeds at 14 $g \cdot m^{-1}$ (35 $kg \cdot ha^{-1}$). Snap bean seed planting, biomass sampling, tissue P analysis, and harvest (pod yield measurements) were performed like in the starter P experiments.

Table 1. Characteristics of western New York snap bean fields tested for response to starter phosphorus (P) treatment and/or potassium bicarbonate ($KHCO_3$) treatment.

Field[z]	Location	Planting date	Soil P[y] ($mg \cdot kg^{-1}$)	Interpretation[x]
CRF	Batavia	15 May 2001	20	Very high
Jon	Geneva	17 May 1999	23	Very high
Tile	Seneca Castle	25 May 2001	4	Medium
Toomey	Bellona	17 May 2001	47	Very high
VRF21E[w]	Geneva	29 May 2002	32	Very high
VRF21L[w]	Geneva	2 July 2002	32	Very high
VRF28	Geneva	7 May 2001	15	Very high
Whitney	Flint	24 May 2001	10	High

[z]All soils are silt loams (mesic Glossic to Oxyaquic Hapludalfs).
[y]Measured using the Morgan extraction method (Kuo, 1996).
[x]Based on Cornell Nutrient Analysis Laboratory, Ithaca, NY: 1 to 2, low; 3 to 5, medium; 6 to 12, high; and 13 or greater, very high.
[w]VRF21E = early (cool soil) planting at VRF21 site; VRF21L = late (warm soil) planting at VRF21 site.

Plant stands were counted in 7.5 m of a row in each plot.

The magnitude of treatment effects and their statistical significance were determined by ANOVA with location and treatment within location as predictors. The effect of variety and interaction between variety and treatment were tested and found nonsignificant, so the results from both varieties were consolidated (JMP 11; SAS Institute, Cary, NC).

Seasonal change in soil phosphate and nitrate availability. Soil samples were collected from 11 commercial snap bean fields in Genesee, Ontario, and Yates counties in western New York. Each field was fertilized by its respective grower with banded P and broadcast N at concentrations normally used in each field. The fields were each sampled nine times from 24 Apr. through 9 July 2001 at ≈10-d intervals. The bands with P applied at planting were avoided when collecting soil samples. The date range was chosen to cover the period from which the spring soil could first be worked through the time when snap beans typically no longer required starter P. The cooperating growers' perception was that soil is too cold for snap beans to establish when sown before 20 May and need starter P through ≈5 June. At each site and time, five soil cores were taken to a depth of 20 cm to sample the plow layer. The samples were stored frozen at –20 °C until analysis. Soil solution phosphate was assessed by water extraction of two replicate 2.0-g subsamples of soil as described in Björkman and Reiners (2014) and phosphate assayed with a spectrophotometric antimonate assay (Kuo, 1996). Water extraction assesses P immediately available to the seedling, in contrast to tests that are intended to predict season-long availability, and therefore reveals transient deficits. Nitrate was assayed by extraction of 50 g air-dried soil in 20 ppm potassium nitrate, filtered, and measured with a nitrate-selective electrode (Cardy C-141 nitrate meter; HORIBA, Kyoto, Japan) following the manufacturer's instructions.

Results are reported as the mean and SE for each location and sampling time. In addition, data were pooled for three periods, 20 Apr. to 21 May, 22 May to 15 June, and 16 June to 15 July and subject to ANOVA with location as a block effect and the variation among dates compared.

Results

Determination of bicarbonate phytotoxicity in snap bean. To find a material that could be applied at a useful rate in the field, bicarbonate with three alternative cations was tested at several rates covering the range of interest. Neither $KHCO_3$ nor NH_4HCO_3 was inhibitory at doses up to 500 µmol/seed (Fig. 1). $NaHCO_3$ inhibited seedling development ($P = 0.03$) at 500 µmol/seed relative to lower doses of 100 µmol/seed or less (Fig. 1). The cause of slower snap bean emergence in the absence of bicarbonate (Fig. 1) is unknown. Although NH_4HCO_3 was safe, it was somewhat hygroscopic and tended to clump when dispensed. We therefore selected $KHCO_3$ for field experiments as a result of its relatively low phytotoxicity to snap bean seeds and its ease of application. Based on our greenhouse phytotoxicity results, we chose a field application rate of 100 µmol/seed $KHCO_3$, which did not harm snap bean seedlings (Fig. 1).

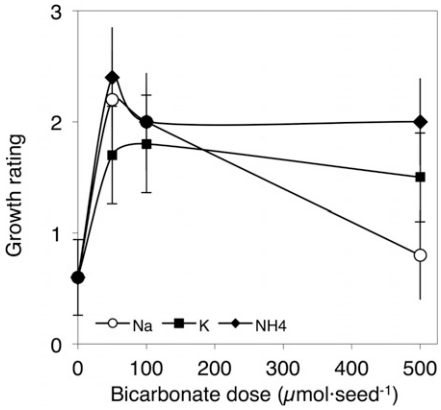

Fig. 1. Three forms of bicarbonate ($NaHCO_3$, $KHCO_3$, and NH_4HCO_3) were evaluated for phytotoxicity in greenhouse snap beans. Snap bean seeds were planted in the presence of 0, 50, 100, or 500 µmol/seed of one form of bicarbonate, and growth was assessed after 7 d on a scale of 0 = unemerged, 1 = hook emerged, 2 = cotyledons open, or 3 = unifoliate leaves unfolded. Each value is the mean of 10 seedlings; vertical bars represent the SE.

Snap bean response to starter P rates in cool soil. The experiment was conducted at two sites in 2 years each. The soil test *P* values for the Batavia research farm (field site CRF) and Geneva research farm (field site VRF21) were very high, 20 and 32 mg·kg^{-1}, respectively (Table 1). Providing starter P at either a recommended (15 kg·ha^{-1}) or supraoptimal (35 kg·ha^{-1}) rate did not increase P uptake (tissue P), early growth (biomass at flowering), or economic value (pod yield) in the starter P experiments (Table 2). After blocking for year and location, the means for 0, 15, and 35 kg·ha^{-1} were tissue P, 0.29%, 0.30%, and 0.30% ($P > 0.27$), and pod yield, 6.5, 6.9, 7.0 t·ha^{-1} ($P > 0.35$). Thus, there was no significant effect of starter P on any of the measured parameters in any of the four trials.

We also tested whether a newer snap bean variety bred to be more vigorous in spring growing conditions (Zeus) would respond differently to starter P application than an older variety (Hystyle) in case newer varieties have rendered obsolete the grower practice of using starter P in the spring. In the experiment described, the interaction between treatment and variety blocked for year and location was tested. We found no significant differences between the established snap bean variety (Hystyle) and the more robust variety (Zeus) in the starter P effect on pod yield ($P > 0.45$), biomass at flowering ($P = 0.78$), or tissue P ($P = 0.86$).

Snap bean response to $KHCO_3$ in cool soil. Soil test *P* values from snap bean fields used in the $KHCO_3$ field experiment ranged from medium (4 mg·kg^{-1} at the Tile site) to very high (47 mg·kg^{-1} at the Toomey site) (Table 1). If P is limiting growth, the expectation is that the tissue P is in the inadequate range and that adding P increases both the tissue P and growth; if bicarbonate liberates enough P, it will give the same result. The main alternative is that P is not limiting, in which case tissue P would be in the adequate range and addition of P would not increase growth. The various sites did not consistently fall into either of these models. In the positive control (35 kg P/ha), tissue P increased relative to the untreated control at both the Toomey and VRF28 field sites but had no effect at the other three sites (Table 3). At the sites where the positive control had an effect, $KHCO_3$ application did not nor did $KHCO_3$ application at the other sites (Table 3). Thus, starter P improved P status at two of seven sites and $KHCO_3$ at zero of two sites.

Early growth responded to the positive control at two of seven sites and to $KHCO_3$ at one of those two sites. $KHCO_3$ application had no effect on early growth at sites where the positive control was unresponsive. The positive early growth response occurred at only one of the two sites in which tissue P was increased by starter P.

Pod yield was not increased by starter P or $KHCO_3$ in any of the trials in which starter P application benefitted earlier. Starter P was associated with higher yield at one site (Table 3).

The soil test P did not predict whether tissue P was deficient nor whether it responded to starter P. The field with the least soil P (4 mg·kg^{-1}; medium) gave no response, whereas the field with the most soil P (47 mg·kg^{-1}) showed P deficiency and a strong response to starter P.

A direct test of whether the poorer growth in early plantings is a P response was conducted in VRF21 by doing an early and a late planting. The mean daily soil temperature at the seedling root depth (5 cm) was 21 °C for the early (May) planting and 30 °C for the late (July) planting at the VRF21 field. The relative progress of the season can also be described as accumulated degree-days of 10 °C ($DD_{10\ °C}$) at 5-cm soil depth. The early planting occurred at 154 $DD_{10\ °C}$ and the later planting at 572 $DD_{10\ °C}$. In untreated control soils, early planting resulted in a lower and less uniform (i.e., larger error) stand than late planting (Fig. 2). This poor establishment is what makes early plantings such a high risk. Neither $KHCO_3$ nor P treatment affected stand count (Fig. 2) or pod yield (Table 3) at either planting date.

Seasonal change in soil phosphate and nitrate availability. Potential mineralization of P as soil warmed seasonally was examined in 11 snap bean fields, which are described in Table 4. Soil P levels remained relatively constant (averaging ≈10 mg·kg^{-1}) from mid-April through mid-July 2001 (Figs. 3 and 4). In contrast, nitrate levels started low in mid-April, rose dramatically by mid-June, and continued to rise through mid-July (Figs. 3 and 4). Interestingly, bioavailable P

Table 2. Snap bean growth responses to starter P application.[z]

		Tissue P[y]			Biomass at flowering[x]			Pod yield[w]		
			Response to P at			Response to P at			Response to P at	
Field[v]	Soil P[v] (mg·kg^{-1})	Control[t] (%)	15 (Δ%)	35 (Δ%)	Control (g·m^{-2})	15 (Δg·m^{-2})	35 (Δg·m^{-2})	Control (t·ha^{-1})	15 (Δt·ha^{-1})	35 (Δt·ha^{-1})
CRF 00	20	0.310	0.000	0.070	ND[s]	ND	ND	ND	ND	ND
CRF 01	20	0.461	0.320	0.470	81	–5	4	6.2	–0.1	–0.5
VRF 00	32	0.167	0.030	0.110	114	3	7	7.3	0.8	1.3
VRF 01	32	0.222	–0.011	–0.006	95	9	20	6.0	0.6	0.7

[z]Treatments of recommended (15 kg·ha^{-1}) or supraoptimal (35 kg·ha^{-1}) phosphorus (P) were banded at planting. Responses are P uptake (leaf tissue P), early growth (biomass at flowering), and economic value (pod yield). At each site, the treatments were applied with four replications. None of the treatment effects were statistically significant at $P \leq 0.1$.
[y]Tissue P content of unifoliate leaves when the first trifoliate was beginning to expand, when P limitation would have its greatest effect on subsequent growth. Adequate P is 0.3% to 0.5% (Hochmuth et al., 2004).
[x]Biomass at flower bud formation, when P limitation to growth would be most apparent.
[w]Pod weight, the effect on crop value.
[v]Farm and year. Both soils are silt loams (mesic Glossic to Oxyaquic Hapludalfs).
[u]Measured using the Morgan extraction method (Kuo, 1996).
[t]Control is untreated soil.
[s]ND = not determined.

Table 3. Snap bean growth responses to treatments that potentially avert early season P limitation.[z]

		Tissue P[y]			Biomass at flowering[x]			Pod yield[w]		
			Response to			Response to			Response to	
Field[v]	Soil P[u] (mg·kg^{-1})	Control[t] (%)	$KHCO_3$[s] (Δ%)	P[s] (Δ%)	Control (g·m^{-2})	$KHCO_3$ (Δg·m^{-2})	P (Δg·m^{-2})	Control (t·ha^{-1})	$KHCO_3$ (Δt·ha^{-1})	P (Δt·ha^{-1})
CRF	20	0.415	–0.033	0.014	43	14*	23*	9.6	1.6	2.2
Jon	23	ND[r]	ND	ND	50	–5	–2	11.5	1.1	–0.3
Tile	4	0.127	0.007	0.013	ND	ND	ND	ND	ND	ND
Toomey	47	0.175	–0.002	0.095***	82	–3	7	ND	ND	ND
VRF21E[q]	32	ND	ND	ND	ND	ND	ND	4.4	1.7	1.2
VRF21L[q]	32	ND	ND	ND	ND	ND	ND	19	–4.3	0.8
VRF28	15	0.186	0	0.041**	95	4	28*	15.6	0	1.8
Whitney	10	0.147	0.007	–0.018	60	1	7	5.5	–0.1	1.2*

[z]Treatments of 6 kg·ha^{-1} potassium bicarbonate ($KHCO_3$) treatment or 35 kg·ha^{-1} phosphorus (P) were banded at planting. Responses are P uptake (leaf tissue P), early growth (biomass at flowering), and economic value (pod yield). At each site, the treatments were applied with four replications.
[y]Tissue P content of unifoliate leaves when the first trifoliate was beginning to expand, when P limitation would have its greatest effect on subsequent growth. Adequate P is 0.3% to 0.5% (Hochmuth et al., 2004).
[x]Biomass at flower bud formation, when P limitation to growth would be most apparent.
[w]Pod weight, the effect on crop value.
[v]All soils are silt loams (mesic Glossic to Oxyaquic Hapludalfs).
[u]Measured using the Morgan extraction method (Kuo, 1996).
[t]Control is untreated soil.
[s]$KHCO_3$ and *P* values expressed as change compared with control.
[r]ND = not determined. At VRF21 by design, at Tile and Toomey because growers ended the crop.
[q]VRF21E = early planting at VRF21 site (planted after seasonal accumulation of 154 $DD_{10\ °C}$); VRF21L = late planting at VRF21 site (planted after seasonal accumulation of 572 $DD_{10\ °C}$).
*Significant at $P \leq 0.05$; **significant at $P \leq 0.01$; ***significant at $P \leq 0.001$.

concentrations remained relatively constant in both the highest and lowest water-extracted P soils (Voak field site and VRF01 field site, respectively), despite increasing soil temperatures from spring to summer (Fig. 4).

Discussion

In temperate climates with high P soils, early plantings of snap beans typically receive substantial amounts of starter P fertilizer to avoid growth inhibition in the cool soil. We attempted to make soil P more bioavailable by using a band of bicarbonate to displace P from soil-binding sites and compared that with applying conventional starter P fertilizer.

Response to starter P

One set of experiments was designed to confirm a positive growth response to a recommended rate of banded fertilizer at planting to provide sufficient P (Table 2). In addition, a supraoptimal rate of starter P served as the positive, response-saturating control in these as well as in eight bicarbonate experiments (Table 3). The high P control in the bicarbonate experiments is used in some of the analyses below.

Positive evidence that starter P is necessary and beneficial consists of three results: a suboptimal tissue P in the control and starter P causing both higher tissue P and greater early growth. This pattern was obtained in only one of five sites where the complete comparison could be made (Table 2). Clearly contradictory results were obtained at the other sites: apparent P deficiency occurred on a soil with extremely high soil P and a positive response to P in a stand where the plants had sufficient P. Thus, the classic situation was rare, and a causal relationship between starter P application and better growth is difficult to assert.

Tissue P level was a weak predictor of P response. The accepted adequacy level of 0.3% to 0.5% leaf tissue P is well established for normal plant development (Hochmuth et al., 2004). However, we found strong growth and no response to fertilizer P at considerably lower levels. Seedling P concentration was sampled when the first trifoliate was beginning to expand, a time when a P deficit would have been most apparent if it were growth-limiting. Bean seeds typically contain ≈1 mg total P (Lolas and Markakis, 1975). P stored in the seed would be sufficient, at most, until the seeding has a dry mass of 0.25 g at 0.4% P. In the starter P experiment (Table 2), tissue P was in the adequate range at one site and in the deficient range at the other. Nevertheless, there was no growth response to starter P at either site. In the bicarbonate experiment (Table 3), the expected increase occurred at only one location (VRF28). Other sites had responses inconsistent with the model but also not in a consistent pattern. This lack of a consistent fit to anticipated models is not unusual (Hisinger et al., 2011).

Tissue P may be sufficient at less than 0.3%. Our results are consistent with earlier experiments at the VRF site where Peck et al. (1980) found that 0.24% to 0.27% tissue P was sufficient for maximal growth and could not be increased by supplying additional P. A positive P response occurred only when

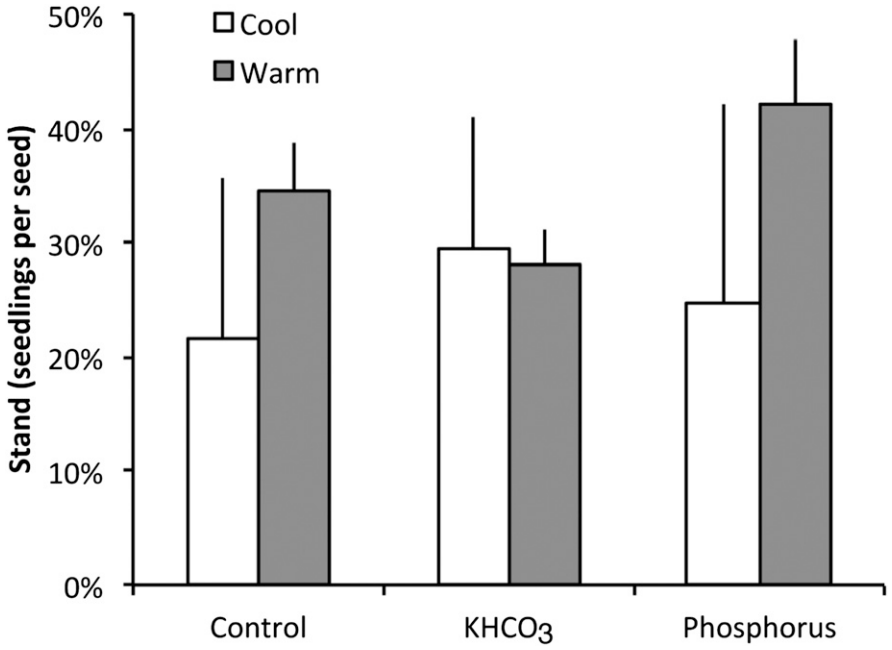

Fig. 2. Effect of early (29 May) vs. late (2 July) snap bean planting on stand count in potassium bicarbonate ($KHCO_3$)-treated or phosphorus (P)-treated soils in 2002. Mean heat accumulation at a 5-cm soil depth at the time of early (cool) planting was 154 DD_{10} °C and at and the late (warm) planting was 572 DD_{10} °C. Stand count is expressed as percent of seedlings that appeared relative to total number of seeds planted. Application rates for $KHCO_3$ and P were 6 kg·ha^{-1} and 35 kg·ha^{-1}, respectively. Control is untreated soil. Vertical bars represent the SE of six replicates.

Table 4. Characteristics of western New York snap bean fields tested for seasonal phosphate and nitrate levels.

Field[z]	Location	Soil P[y] (mg·kg^{-1})	Interpretation[x]
Asbury	LeRoy	12	High
CRF	Batavia	32	Very high
Fort	Seneca Castle	19	Very high
Mel	Seneca Castle	22	Very high
Post	Stanley	24	Very high
Prospect	Seneca Castle	18	Very high
Toomey	Bellona	24	Very high
Voak	Gorham	29	Very high
VRF01	Geneva	15	Very high
Wabash	Bellona	26	Very high
York	LeRoy	21	Very high

[z]All soils are silt loams (mesic Glossic to Oxyaquic Hapludalfs).
[y]Measured using Morgan extraction method (Kuo, 1996).
[x]Based on Cornell Nutrient Analysis Laboratory, Ithaca, NY.

tissue P was lower, 0.20%. In addition, where bean leaves were in the deficient range (0.19%), starter P increased growth without raising the tissue P concentration (Mourice and Tryphone, 2012). One possibility is that bean seedlings allocate additional P to new tissue rather than increasing the concentration. The subsequent analysis of the results is done without the assumption that the low tissue P was indicative of P limitation.

The evidence does not support starter P application on these medium-textured soils under cold conditions if none is indicated for warm conditions. If such an application were useful, a supraoptimal rate would consistently increase early growth. If the recommended amount of starter P were enough, then it would also have a consistent positive effect. For this analysis, we will not assume that low tissue P is a predictor of responsiveness to P application. In three starter P experiments (Table 2), neither recommended (15 kg·ha^{-1}) nor response-saturating (35 kg·ha^{-1}) starter P rates improved early growth (biomass at flowering) or pod yield over the untreated (no P) control. In the bicarbonate experiment (Table 3), the supraoptimal P rate increased early growth at two of five sites with a yield increase at only one of five early-planted sites.

Results here and in previous work are consistent in supporting standard P recommendations regardless of soil temperature. Cold makes beans grow slowly, but adding P provides no remedy. The CRF and VRF21 field sites had very high soil P levels (Morgan P of 20 and 32 mg·kg^{-1}, respectively), several times higher than the threshold for "high" (6 mg·kg^{-1}; Cornell Nutrient Analysis Laboratory, Ithaca, NY). For context, the most comparable previous reports have shown that Florida snap bean yields were 80% to 90% of maximal at a medium level (Mehlich-I 20 mg·kg^{-1}) and 90% to 100% of maximal at a high level (Mehlich-I 32 mg·kg^{-1}) in warm soils (McAvoy and Obreza, 2005). Tomato transplants, which are also chilling-sensitive, respond to starter P application in cool soil with greater yield, only at a low level (2 to 3 mg·kg^{-1} Morgan) but not at the low end of very high (14 mg·kg^{-1} Morgan) (Grubinger et al., 1993). At the same VRF farm, snap bean P requirements are satisfied with a low P rate: on a soil testing medium (3 mg·kg^{-1} Morgan), banded P gave maximal yield with only 30 kg·ha^{-1} (Peck et al., 1980). That experiment was planted on 8 June, when soils are just warm enough for bean planting by grower standards.

The effect of growth temperature on yield response was tested directly by comparing two planting dates in the same field. If starter P is helpful only in cold soil, there would be a positive response only at the early planting date (Table 3, Field VRF21E), but not when sown into warm soil (Field VRF21L). Although the early planting date has only one-fourth the yield of the later planting date, P application did not improve it. With a differential that large, this comparison should have easily detected growth limitation that could be overcome with additional P.

Thus, the preponderance of trial results show that extra P is not a helpful adjustment to normal P recommendations when planting in cold soil.

Response to bicarbonate

Phytotoxicity of amendments. Potassium bicarbonate was non-toxic to germinating seedlings when applied to soil in an amount that released a meaningful amount of phosphate. A dose of up to 500 µmol/seed was non-toxic in a greenhouse trial (Fig. 1). An application rate of 100 µmol/seed was selected to ensure safety while solubilizing P. A band is expected to affect ≈2 g of soil per seed, resulting in a bicarbonate dose of ≈50 µmol·g^{-1}, which approximately triples the water-extractable P (Björkman and Reiners, 2014).

Citrate is also of interest as an alternative to starter P by analogy with natural P uptake enhancement through citrate excretion (Gerke, 2007; Vance et al., 2003). Soil acidification by roots is a commonly considered strategy for improving crop P nutrition (Richardson et al., 2011). For instance, Ryan et al. (2014) generated wheat plants that constitutively secrete citrate anions in an attempt to enhance bioavailability of soil P. In terms of wheat biomass and yield, they found no consistent benefit of the citrate efflux trait to P uptake in field trials; in greenhouse trials, citrate secretion improved biomass only at the lowest soil P levels (Ryan et al., 2014). In an effort to determine specific soil treatments that might increase bioavailable P for snap bean without further increasing soil P, we evaluated the efficacy of citric acid. Citric acid was eliminated from further trials, because 10 µmol g/soil citric acid resulted in low snap bean emergence and necrotic root tips (unpublished data). Citrate might be useful only in specialized roots such as lupin proteoid roots

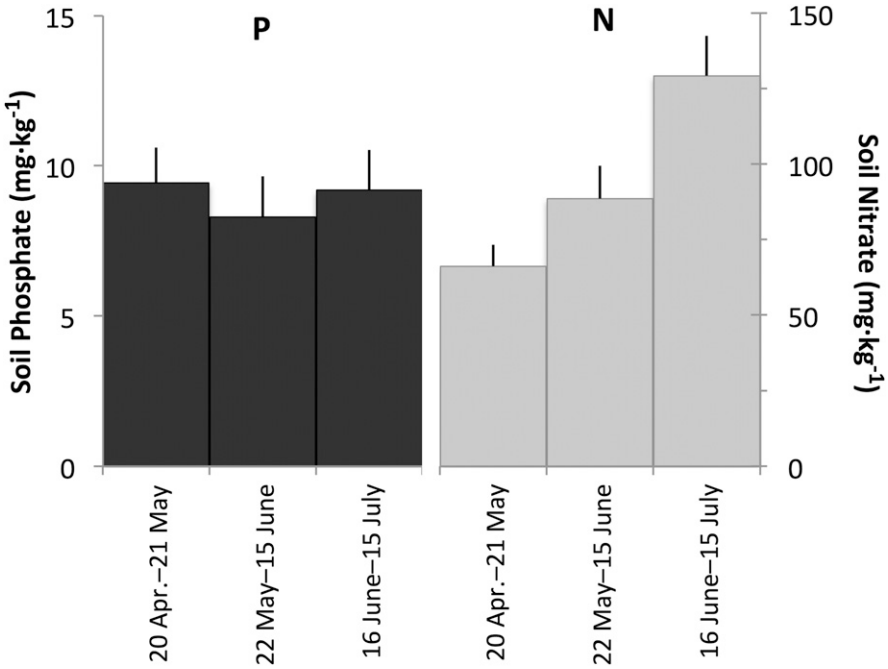

Fig. 3. Seasonal variation in plant-available soil nitrate and phosphate in 2001. Nitrate mineralized as soil temperature increased and microbial activity commenced, whereas phosphate concentrations remained relatively constant. Date ranges correspond to early cool soils when planting is risky (20 Apr. to 21 May), optimal planting time (22 May to 15 June), and warm soil with rapid subsequent plant growth (16 June to 15 July). Soil solution phosphate was assessed by water extraction. Vertical bars represent the SE of three sampling dates and eight (nitrate) or 11 (phosphate) locations.

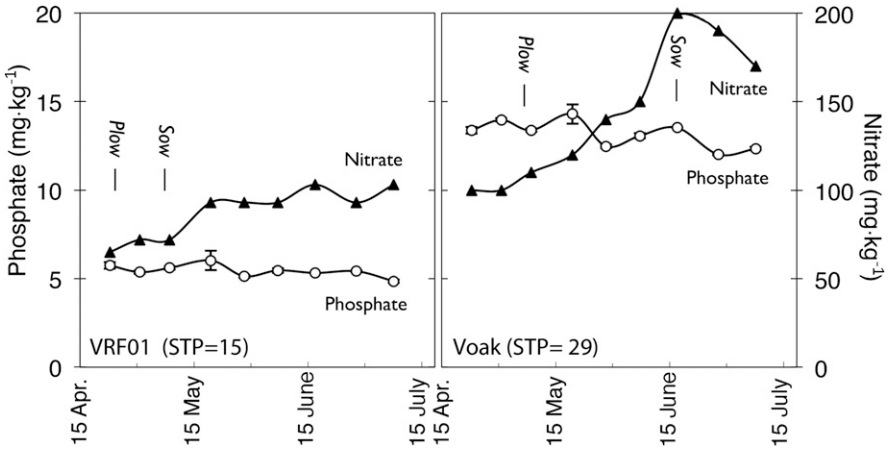

Fig. 4. Time course of water-soluble phosphate and nitrate in two representative snap bean fields with contrasting Morgan soil test phosphorus (P) levels. Soil test P levels in fields were high (VRF01, Morgan soil test $P = 15$ mg·kg^{-1}; left panel) or very high (Voak, Morgan soil test $P = 29$ mg·kg^{-1}; right panel). Timing of tillage and fertilizer application (plow) and planting (sow) are indicated; nitrogen (N) fertilizer broadcast at sowing affected post-sowing nitrate values. Dates correspond to early cool soils when planting is risky (20 Apr. to 21 May), optimal planting time (22 May to 15 June), and warm soil with rapid subsequent plant growth (16 June to 15 July). Vertical bars represent the SE of three replicates, where no bars are visible the error bar is smaller than the symbol.

(Dinkelaker et al., 1989) that tolerate the high extracellular citrate concentration. In a broad survey of bean genotypes, Lynch and Beebe (1995) found only one genotype that acidified the soil and tolerated the lower pH.

Response to field application of bicarbonate. Where starter P is currently used, an alternative that does not exacerbate excess P would be valuable. Bicarbonate is as effective at P solubilization in cool soils (15 °C) as in warm soils (25 °C) and is effective throughout the entire range of soil moisture conditions that might be encountered during the 2 weeks after early crop planting (Björkman and Reiners, 2014).

A band of bicarbonate granules applied at 100 µmol/seed is expected to approximately triple the water-extractable P in ≈2 g of soil per seed at a 5-cm spacing (Björkman and Reiners, 2014). The potential effect on tissue P can be calculated for a soil with a Morgan value of 25 mg·kg^{-1} and assuming that all the solubilized P is taken up. The increase in available P per plant would be 15 µg·g^{-1} in 2 g soil, distributed in 0.05 g of dry tissue, giving a potential increase in tissue P of 0.6 mg·g^{-1}. This value is necessarily a rough estimate but shows that the treatment could have a beneficial effect by supplying P during initial growth.

We tested the effect of banding granular K bicarbonate with the seed as a way of making a small amount of phosphate available to germinating seedlings to provide enough to grow until availability was higher. In our field trials, application of 6 kg·ha^{-1} $KHCO_3$ had little effect on the responses we measured. Although bicarbonate was expected to approximately double the soil solution concentration of inorganic phosphate (Björkman and Reiners, 2014), it did not increase either seedling P concentration or pod yield in any of the fields tested, although $KHCO_3$ did increase early growth (biomass at flowering) in one of the five fields tested. Because the bicarbonate treatment did not increase the amount of P in the leaves, it is unlikely to be useful as a starter P alternative on loamy soils such as those studied here.

There remains one scenario in which bicarbonate application may have use. Bicarbonate is particularly effective in soils with high sand content (Björkman and Reiners, 2014), possibly as a consequence of the higher P solubility in such soils (Kovar and Barber, 1988; Leinweber et al., 1999). Sandy soils have been attractive for early spring planting of beans because they dry first in the spring and, as former beaches, are often near P-sensitive salt water. Our previous survey (Björkman and Reiners) found several particularly high P sandy soils near the Chesapeake Bay. Thus, sandy high P soils near P-impacted water bodies are attractive for early bean plantings and are likely to be the most responsive to this treatment.

Seasonal variation in P mineralization. Phosphorus mineralization in the spring was assessed to determine when and whether P bioavailability increases. Soil P availability is usually regarded as stable through the year, but these soils have uncommonly large pools of P, whose susceptibility to microbial mineralization has not been described. Dates were chosen to correspond to the early period when planting into cool soils is risky (20 Apr. to 21 May), optimal planting time (22 May to 15 June), and warm soil with rapid subsequent plant growth (16 June to 15 July). These intervals were determined in consultation with processing snap bean growers based on their experience with snap bean growth at various planting dates. The water-extractable soil P level represents the mineralized fraction that can be taken up by roots (Sorn-Srivichai et al., 1988). That amount remained relatively consistent (averaging ≈10 mg·kg^{-1}) from mid-April through mid-July 2001. We used the rise in nitrate levels through nitrification as a proxy for determining when microbial activity increased as the soil warmed, a finding that it occurred in mid-June. Water-extractable P did not increase in the same timeframe, so the P

availability is normal despite the sometimes excessive P.

Conclusions

The practice of adding starter P when soils are cool, even if they have adequate soil test P, is not justified for snap beans under the conditions studied here. These conditions are soil P test levels from the top end of high to very high and silt loam soils.

The efficacy of releasing soil-bound P with bicarbonate as a substitute for starter P was assessed for silt loam soils; the results were not encouraging. Tissue P increased with starter P at two sites, but bicarbonates had no effect at either of those sites. Early growth was increased with starter P at two of five sites; bicarbonate had a small effect at one of those sites (CRF) and none at the other (VRF28). Starter P increased yield at only one of six sites where it was measured; at that site, bicarbonate had no effect. Thus, even where P was limiting, i.e., where starter P gave a positive response, bicarbonate failed to improve P nutrition and growth. Nevertheless, bicarbonate should also be tested on sandy high P soils, because sandy soils release much more phosphate with bicarbonate treatment and are commonly used for snap bean production in some pollution-impacted watersheds.

Mineralization of P is not normally considered a major contributor to seasonal improvement in P availability, yet these fields had such high soil P levels that the assumption of no change needed confirmation. Indeed, water-extractable soil P (i.e., dissolved phosphate) did not increase as the soil warmed in the spring and early summer.

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