Using Silicon Fertilizers to Improve Soil Phosphorus Availability in High Phosphorus Soils

Final Report
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Project Purpose and Objectives: The overall goal of this project is to identify and evaluate possible BMPs to mitigate the potential for P losses from legacy P soils. The specific objective of this research is to evaluate the ability of Si fertilization to enhance soil P availability from legacy P soils. Overall, we seek options to help farmers reduce inorganic P application and enhance crop yields. We believe that Si fertilization may speed soil P drawdown and the associated risk of legacy P losses from sites with a long history of poultry litter and/or fertilizer P application.

Materials and Methods: Composite soil samples were randomly collected to a depth of 15 cm from three identified "legacy P" field sites (all loamy sand texture) using a bucket auger to obtain soil for use in a soil only incubation study. Each soil sample was analyzed, in duplicate, using standard soil testing procedures (Table 1).

Table 1. Properties of three Delmarva soils selected for a silicon fertilization incubation study.

Soil Series	**pH**	**OM**	**M3-P**	**M3-Al**	**M3-Fe**	**M3-Ca**	**AA-Si**
		(%)	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
Ft. Mott-Henlopen	6.6	1.7	198	714	137	225	4.03
Ingleside-Hammonton	6.2	2.0	360	650	123	584	6.09
Mullica-Berryland	5.7	5.5	684	1487	180	697	5.04

Switchgrass residue ash, commercially available calcium silicate ($CaSiO_3$) lime alternative (AgrowSil), and silicic acid were used as Si fertilizer materials and incorporated into each of the selected legacy P soils (in triplicate) at 0, 0.25, 0.50, 1.0, and 2.0 Mg ha^{-1} total Si rates. Subsamples were collected at seven intervals (2 through 150 d) and analyzed for water extractable P (WEP) and acetic acid extractable Si (AA-Si). Soil samples collected from each cup at 56 and 150 days were also analyzed for pH, organic matter, Mehlich 3 extractable P (M3P), Al, Fe, K, Ca, Mn, and Mg. The ratio of WEP to M3P was calculated to evaluate the solubility of soil P for each cup (i.e., higher ratio suggesting higher P solubility).

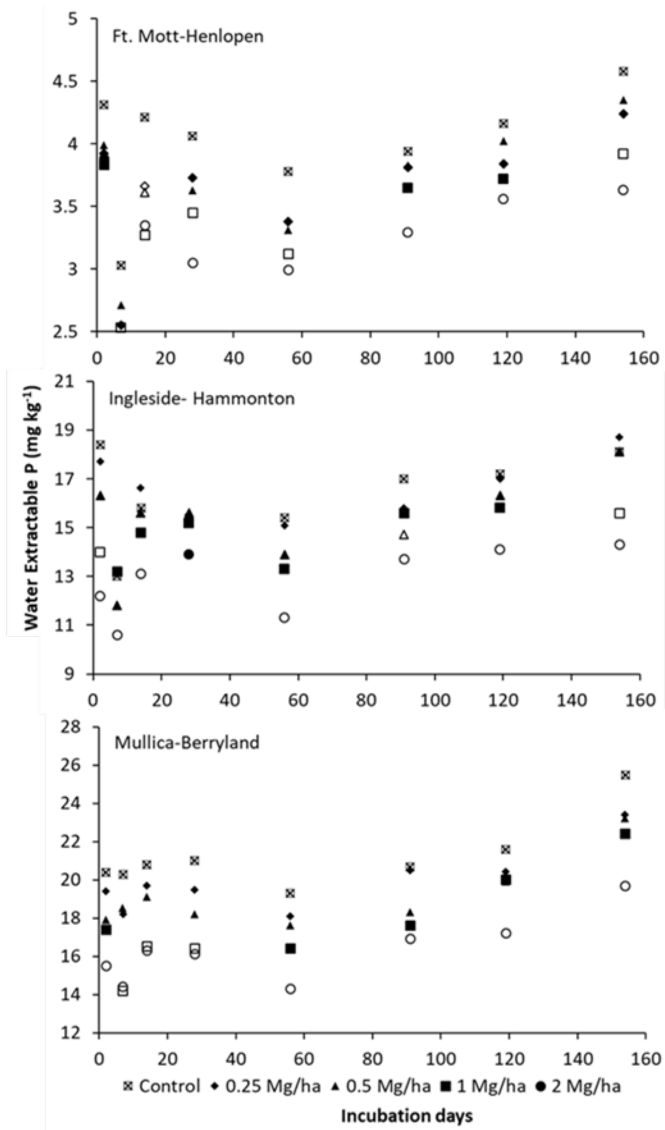

Figure 1. Effect of switchgrass ash application on soil water extractable P (WEP) during the soil only incubation study. Data points shown as hollow were significantly different than the controls using Tukey's honestly significant difference test at P<0.05.

Results and Discussion

Switchgrass ash. We found that application of switchgrass ash consistently and significantly reduced soil WEP concentrations compared with the unamended soils despite supplying Si (total Si applied at 0.25—2 Mg ha^{-1}) to soils (Figure 1). We suspect that the high surface area of the ash materials (a result of the fine texture and porous surface) provided ample binding sites for soluble P, which masked the effect of Si addition in improving soil P availability. The burning of plant residues, like switchgrass, under high temperature is a process similar to pyrolysis, which is used to produce plant-based biochar. Pyrolysis of plant tissues results in biochar materials with high binding capacity for chemicals. As a result, switchgrass ash would not be a viable Si amendment for farmers seeking to improve P uptake by winter small grains. However, it is possible that this type of material could be used as a soil amendment to reduce P solubility in soils with excessive soil test P.

Silicic acid. Application of silicic acid at a total Si rate of 1 or 2 Mg ha^{-1} increased soil WEP concentrations compared with the unamended control when applied to the Ft. Mott-Henlopen and Ingleside-Hammonton soils (Figure 2). The Ingleside-Hammonton soils generally showed a quicker response to Si addition (soil WEP increases noted as early as 7 d) than the Ft. Mott-Henlopen soils (soil WEP increases noted by 56 d). Silicic acid applied at a total Si rate of 0.5 Mg ha^{-1} also periodically (14, 28, and 119 d of incubation) resulted in higher soil WEP concentrations compared with the unamended Ingleside-Hammonton soils (Figure 2). For both soil types, soil WEP concentrations tended to increase with increasing rate of silicic acid (Figure 2). In

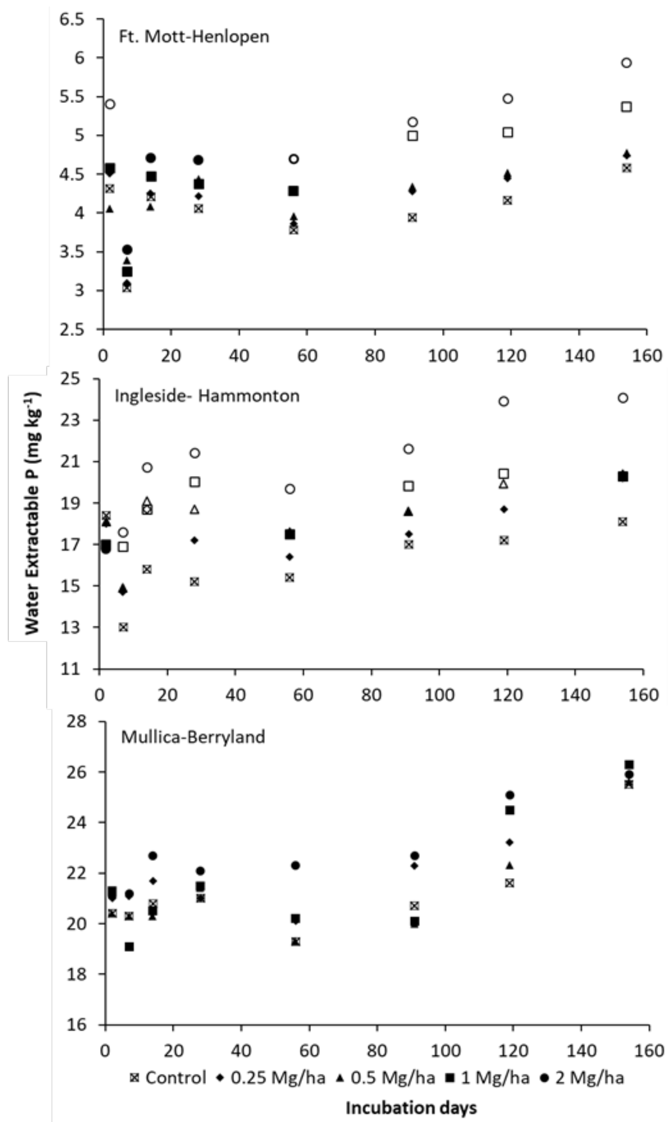

Figure 2. Effect of silicic acid application on soil water extractable P (WEP) during the soil only incubation study. Data points shown as hollow were significantly different than the controls using Tukey's honestly significant difference test at P<0.05.

contrast, there was no significant effect of silicic acid on soil WEP concentrations when applied to Mullica-Berryland soils, regardless of total Si application rate (Figure 2). Routine soil analysis performed at 56 (early stage) and 154 d (end of the study) after application showed that silicic

Table 2. Effect of Si fertilization on soil pH, Mehlich-3 extractable P (M3P), and the ratio of water extractable P (WEP) to M3P when three legacy P impacted soils were incubated with Si amendments for 56 and 154 d.

Source	**Total Si rate**	**pH**		**M3P**		**WEP/M3P**	
		56 d	**154 d**	**56 d**	**154 d**	**56 d**	**154 d**
	Mg ha^{-1}			——mg kg^{-1}——		———%———	
			Ft. Mott-Henlopen				
Control	0	5.87	5.97	220	238	1.72	1.94
$CaSiO_3$	0.25	6.07	6.23 *	213	209	1.76	2.10
	0.5	6.27	6.33 *	219	212	1.77	2.36
	1	6.67 *	6.70 *	195	191 *	2.24 *	2.96 *
	2	7.03 *	7.27 *	194	205	3.58 *	3.85 *
Silicic acid	0.25	5.73	5.73 *	221	201	1.75	2.40
	0.5	5.80	5.67 *	199	222	2.00	2.17
	1	5.73	5.80	197	191	2.18 *	2.82 *
	2	5.47 *	5.83	201	197	2.35 *	3.02 *
			Ingleside-Hammonton				
Control	0	5.53	5.90	557	542	2.76	3.33
$CaSiO_3$	0.25	6.03	6.23 *	553	516	2.25 *	3.06
	0.5	6.40 *	6.47 *	538	518	2.18 *	2.84
	1	6.87 *	6.80 *	511 *	523	2.32 *	2.71
	2	7.27 *	7.40 *	507 *	509	2.47 *	2.89
Silicic acid	0.25	5.70	5.80	553	526	3.01	3.85
	0.5	5.73	5.60 *	475 *	534	3.71 *	3.82
	1	6.07 *	5.67 *	522	535	3.35 *	3.81
	2	6.00	5.57 *	532	529	3.71 *	4.56 *
			Mullica-Berryland				
Control	0	5.63	4.77	791	752	2.44	3.38
$CaSiO_3$	0.25	5.83	5.00 *	775	755	2.23	3.02
	0.5	5.23 *	5.03 *	785	774	2.11 *	2.80 *
	1	5.43	5.40 *	769	772	1.85 *	2.46 *
	2	5.73	5.73 *	746 *	787	1.74 *	1.91 *
Silicic acid	0.25	5.47	4.63	783	819	2.56	3.16
	0.5	5.03 *	4.67	810	777	2.38	3.30
	1	4.90 *	4.77	812	799	2.48	3.29
	2	4.90 *	5.07	788	847 *	2.83 *	3.07

* values within each soil were statistically different than the control using Tukey's honestly significant difference test at P<0.05; pairwise comparisons were made by the Si source and by soil.

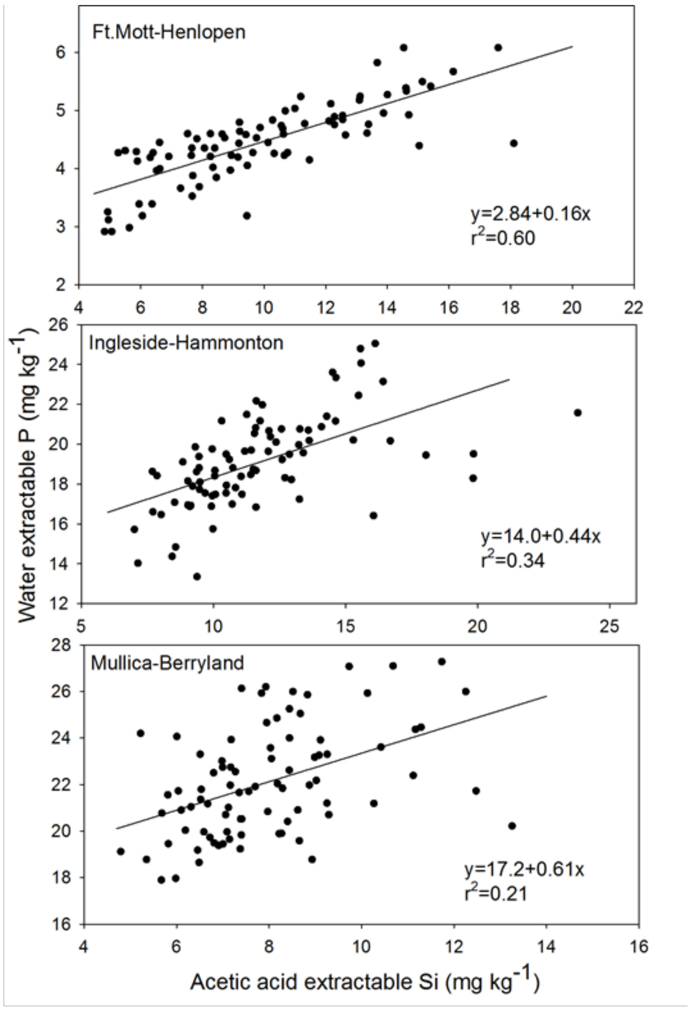

Figure 3. Relationship between acetic acid extractable Si and water extractable P when silicic acid was applied as the Si source to three legacy P impacted agricultural soils during the soil only incubation study. All relationships were significant at α level of 0.001.

acid had little to no impact on soil M3P concentrations (Table 2). However, application of silicic acid (especially at 1 or 2 Mg ha^{-1}) tended to increase the ratio of WEP to M3P (i.e., increased soil P solubility) in all three evaluated soils (Table 2).

Overall, we believe that application of silicic acid tended to improve soil P solubility by increasing soil WEP concentrations and the WEP to M3P ratio, which was driven by the competition between dissolved Si with P for soil sorption sites. In fact, we found that soil WEP concentrations increased with increasing AA-Si concentrations when silicic acid was applied to all three evaluated soils (*P* value <0.0001 for all three soils; Figure 3); the relationship between soil WEP and AA-Si was stronger for Ft. Mott-Henlopen soils (r^2 = 0.60) compared with the other two soil series (r^2 = 0.34 and 0.21 for Ingleside-Hammonton and Mullica-Berryland soils, respectively). The lack of Si treatment effects on soil WEP concentrations for the Mullica-Berryland soils may be related to the low soil pH (which was often lower than 5), which reduced competition of Si for soil sorption sites. Application of silicic acid tended to further decrease soil pH at the early stage of the incubation (56 d; Table 2), which could further reduce Si efficacy.

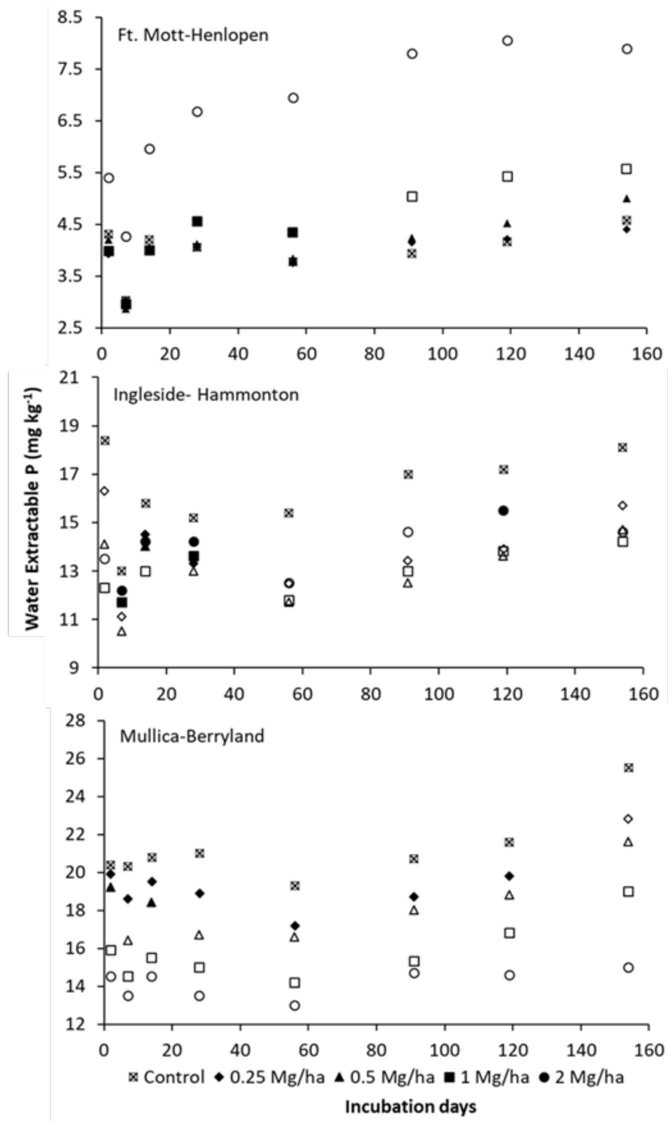

Figure 4. Effect of $CaSiO_3$ application on soil water extractable P (WEP) during the soil only incubation study. Data points shown as hollow were significantly different than the controls using Tukey's honestly significant difference test at $P<0.05$.

Calcium silicate lime alternative. Application of $CaSiO_3$ lime alternative to the Ft. Mott-Henlopen soil at a total Si rate of 2 Mg ha^{-1} significantly increased soil WEP concentrations compared with the unamended control during the entire 156 d incubation study (Figure 4). Similarly, application of $CaSiO_3$ to the Ft. Mott-Henlopen soils at the 1 Mg ha^{-1} total Si rate also significantly increased soil WEP concentrations compared with the unamended control from 91 through 156 d of the incubation (Figure 4). Concentrations of soil WEP tended to increase with increasing application of $CaSiO_3$ in Ft. Mott-Henlopen soils (Figure 4). In contrast, application of $CaSiO_3$ at rates exceeding 0.5 Mg ha^{-1} total Si often significantly reduced soil WEP concentrations compared with unamended controls when applied to the Ingleside-Hammonton and the Mullica-Berryland soils (Figure 4). In fact, application of $CaSiO_3$ to the Ingleside-Hammonton soils at a total

Si rate as low as 0.25 Mg ha^{-1} also resulted in lower soil WEP concentrations than the unamended control throughout much of the study.

Routine soil analysis on incubated soils at 56 (early stage) and 154 d (end of the study) showed that application of $CaSiO_3$ at a total Si rate of 1 Mg ha^{-1} significantly decreased M3P concentrations compared with the unamended control at the end of the incubation for Ft. Mott-Henlopen soils (Table 2). However, $CaSiO_3$ applied at a total Si rate of 1 or 2 Mg ha^{-1} significantly increased the ratios of WEP to M3P for Ft. Mott-Henlopen soils at 56 and 154 d compared with the unamended control when soils were incubated (Table 2). In comparison, application of $CaSiO_3$ at a total Si rate of 1 or 2 Mg ha^{-1} significantly reduced M3P concentrations and the ratios of WEP to M3P relative to the unamended control when Ingleside-Hammonton soils were incubated for 56 d. Application of $CaSiO_3$ at lower rates also significantly reduced the ratios of WEP to M3P compared with the unamended control when Ingleside-Hammonton soils were incubated for 56 d. However, all these effects disappeared when Ingleside-Hammonton soils were incubated for 154 d (Table 2). For Mullica-Berryland soils, application of $CaSiO_3$ at a total Si rate of 2 Mg ha^{-1} only significantly decreased M3P concentrations relative to the controls when soils were incubated for 56 d. Application of $CaSiO_3$ at a total Si rate higher than 0.25 Mg ha^{-1} also resulted in lower ratios of WEP to M3P than the controls when soils were incubated for 56 and 154 d (Table 2).

The effect of $CaSiO_3$ application on soil P dynamics is likely controlled by a variety of factors including soil pH and the presence of Ca and Mn in soils; many of these parameters were directly affected when $CaSiO_3$ was introduced to the soil system. Specifically, application of

Table 3. Effect of $CaSiO_3$ application on Mehlich-3 extractable Ca, Mg, and Mn when three legacy P impacted agricultural soils were incubated for 56 and 154 d.

Source	Total Si rate	Mehlich-3 Ca		Mehlich-3 Mg		Mehlich-3 Mn	
		56 d	**154 d**	**56 d**	**154 d**	**56 d**	**154 d**
	Mg ha^{-1}	mg kg^{-1}					
		Ft. Mott-Henlopen					
Control	0	340 c†	382 e	140 c	151 d	11.5 d	14.2 d
$CaSiO_3$	0.25	487 c	519 d	163 bc	174 cd	13.9 cd	16.2 cd
	0.5	710 b	659 c	170 bc	184 bc	17.9 bc	19.0 c
	1	845 b	871 b	208 b	207 b	19.3 b	23.5 b
	2	1380 a	1576 a	321 a	343 a	26.6 a	32.9 a
		Ingleside-Hammonton					
Control	0	783 d	768 d	132 d	114 d	20.4 c	18.6 b
$CaSiO_3$	0.25	962 c	881 d	166 cd	148 d	21.9 b	19.6 b
	0.5	1063 c	1113 c	187 c	178 c	22.9 b	22.8 b
	1	1319 b	1354 b	232 b	230 b	23.7 b	27.4 a
	2	1903 a	1829 a	343 a	330 a	30.0 a	30.9 a
		Mullica-Berryland					
Control	0	652 d	633 e	111 e	115 c	6.46 d	6.42 c
$CaSiO_3$	0.25	747 d	800 d	135 d	149 c	6.82 cd	6.11 c
	0.5	938 c	980 c	171 c	218 b	7.38 c	7.39 bc
	1	1185 b	1262 b	229 b	259 b	10.0 b	8.73 b
	2	1628 a	2031 a	327 a	449 a	12.2 a	13.3 a

†Values within each soil with different letters were statistically different using Tukey's honestly significant difference test at $P<0.05$.

$CaSiO_3$ increased soil pH (Table 2), as well as the concentrations of AA-Si and Mehlich-3 extractable Ca, Mg, and Mn (Table 3). While the increase in Si concentrations can enhance P desorption and soil P solubility (as in the case of silicic acid), the concomitant increase in Ca, Mg, and Mn with the application of $CaSiO_3$ can lead to the adsorption or precipitation of P by these elements, thereby reducing soil P availability. The Ingleside-Hammonton and Mullica-Berryland soils had M3P concentrations that were about seven and ten times the agronomic optimum and were much higher than the Ft. Mott-Henlopen soils (Table 1). It is possible that the high P concentrations in Ingleside-Hammonton and Mullica-Berryland soils further drove the precipitation or sorption of solubilized P with Ca, Mg, or Mn, thereby masking the effects of the Si application in improving soil P availability. In comparison, this effect may be lower in Ft. Mott-Henlopen soils because of the lower P concentrations. As a result, we were still able to see a net positive effect of $CaSiO_3$ addition on soil P availability when applied to the Ft. Mott-Henlopen soils. Moreover, the Mullica-Berryland soils also had relatively higher organic matter content compared with the other two soils (Table 1). Organic matter-Al soil complexes play an important role in P adsorption in acid soils and could potentially influence the effects of Si application on soil P availability for the Mullica-Berryland "black" soils.

Although the application of $CaSiO_3$ was not effective at improving soil P availability when applied to Ingleside-Hammonton and Mullica-Berryland soils in this soil only incubation study, it tended to increase soil P availability for these two soils when evaluated in a separate pot study with active growth of winter wheat (funded by the Northeastern Sustainable Agriculture Research and Education Program). In the latter case, plants were available to absorb nutrients from soils, including soil P and P binding elements (i.e., Ca, Mg, and Mn) supplied by $CaSiO_3$ liming alternative. As a result, the P sorption or precipitation reactions may be largely suppressed in the pot study, thereby leading to a more significant effect of $CaSiO_3$ application in improving soil P availability.

Conclusions: Our results suggested that Si fertilization is a promising BMP that can improve early-season soil P availability and reduce the use of starter fertilizer for the growth of winter wheat on high P legacy soils on the Delmarva Peninsula. Silicic acid was the most effective Si source in improving P availability in our study; however, it is not commercially-available and would be cost-prohibitive for farmers to purchase. Locally-available $CaSiO_3$ liming alternative can simultaneously adjust the soil pH and supply Si. However, $CaSiO_3$ may only be a sufficient Si source for low pH soils with relatively high buffer capacity and may not be providing enough Si for other soils due to its liming effect. However, ashed plant material, like switchgrass, may not be a good choice to increase soluble P due to the absorptive nature of the materials. Yet, plant residue-based biochars may be effective at reducing P solubility in soils with excessive soil test P concentrations.

Financial Summary: Of the budgeted amount of $8,500, a total of $8,500 has been spent to date, with $4,650 for soil testing and analysis, $74.17 for travel, and $3,775.82 for laboratory supplies.

MGPUB Funding Recognition: 2017 Maryland Commodity Classic, 2016 University of Delaware Undergraduate Research and Service Symposium