Timing of P application for corn and soybean production

AFREC Project Report 3/31/2021 for

AFREC Project(s) R2019-L; R2020-U

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Summary Points

- Both Bray-P1 and Olsen soil P in June was impacted consistently by P application rate and timing. Soil test P was greater in June following spring P application as indicated by significant P timing main effects and significant rate by timing interaction in sites with high carbonates.
- Corn leaf P concentration were consistently impacted by P application rate in 2019 and impacted by timing in 2020.
- Soybean trifoliate P concentration was not consistently impacted by P application rate or timing.
- Corn and soybean yield were impacted by P application rate at 3 of 6 corn and 3 of 6 soybean locations.
- Corn grain yield was greater when P was applied in Spring and soybean grain yield was greater when P was applied in fall. Grain yield was increased when up to 60 lb P_2O_5 were applied for corn when applied in the spring, and 90 lbs P_2O_5 applied in the fall produced similar yield as 45 lbs P_2O_5 applied in spring.
- Soybean grain yield across the six location was linearly increased when up to 90 lbs P_2O_5 were applied.
- Corn grain yield was at maximum when June Olsen soil test P was 10 ppm while soybean grain yield was at maximum when June Olsen soil test P was 15 ppm.
- Grain P concentration and P removed in the harvested grain were inconsistently impacted by P application rate and timing.
- Soybean grain quality (protein and oil concentration) were not consistently impacted by P application rate and timing.

Introduction

Phosphorus is a plant nutrient which, if deficient, can significantly limit crop growth and development. Phosphorus is considered a primary macronutrient. Primary macronutrients are elements that are essential for plant growth which more commonly require fertilizers to be applied to satisfy crop requirements. Orthophosphate is the form of phosphorus taken up by plants. The concentration of orthophosphate in the soil solution is low as orthophosphate is highly reactive with metal elements. Iron, aluminum, and calcium all can react with orthophosphate creating compounds varying in solubility. The ion which reacts with orthophosphate depends greatly on the pH of the soil.

Soils in major cropping regions in Minnesota predominantly formed under calcareous parent materials. Carbonates deposited in the material left following glaciation are still present near the soil surface in areas of the state. These soils with greater carbonate and calcium contents present challenges when managing phosphorus as it is difficult to increase available soil test phosphorus of calcareous soils. Soils with high calcium contents can fix phosphorus. Fixation is a process where orthophosphate reacts with calcium forming compounds like di- and tri-calcium phosphate. While fixed phosphorus is not technically lost from the soil it is rendered unavailable for plant uptake.

The relative rate of phosphorus fixation is not known in soils. Short term P sorption tests can be run to determine the amount of P which a soil will sorb, which can be substantial for some calcareous soils. Management of fertilizer P is common in the fall which gives more time for P to react and potentially bind phosphorus. Studies have been conducted focused on timing of P application, but many were conducted in soils with a neutral to slightly alkaline pH which did not contain appreciable amounts of calcium carbonate.

In a previous study funded by AFREC, on-farm strip trials established to determine corn and soybean response to a single rate of phosphorous fertilizer showed that a high rate of P applied one year can have multiple years' benefits for crops in a two-year rotation. The exception was one location with a calcium carbonate equivalency of 20% where there was a yield benefit to P applied both years for a two-year corn-soybean rotation and P applied the previous year had not impact on the crop grown. Fall application provides more flexibility for farmers but there are questions as to whether spring is better under some circumstances.

Objective

The objective of this study is to establish whether there is a difference between fall and spring application of P fertilizer for corn or soybean production and whether potential differences may be tied to calcium carbonate content of the soil.

Materials and Methods

Table 1. Soil series information, planted crop at each location, and initial potassium soil test data from phosphorus studies conducted in 2019. Soil test data was collected in the Fall at trial establishment from each main plot.

			Soil Test P		Soil Test†			
Year	Location	Crop	Bray-P1	Olsen	K	pH	CCE	Soil Series
				ppm			%	
2019	Crookston	Corn	3	6	258	8.0	13.8	Colvin-Perella
	Lamberton	Corn	11	5	147	5.3	0.2	Normania
	Morris	Corn	12	7	253	7.4	0.9	Flom-Aazhahl-Hamerly
	Benson	Soybean	28	23	135	7.9	2.2	Arveson
	Morris	Soybean	5	3	245	7.4	0.7	Flom-Aazhahl-Hamerly
	Stewart	Soybean	2	10	183	7.7	16.2	Harps
2020	Crookston	Corn	3	4	262	8.1	2.1	Wheatville
	Lamberton	Corn	15	8	167	5.1	0.3	Amiret
	Morris	Corn	8	4	164	7.4	1.3	Aazdahl-Formdale-Balaton
	Danvers	Soybean	9	11	271	7.9	2.5	Bearden-Quam
	Morris	Soybean	7	5	194	7.8	1.9	Aazdahl-Formdale-Balaton
	Stewart	Soybean	3	8	245	7.8	6.7	Canisteo-Glencoe

† K, Soil test potassium (K-ammonium acetate); CCE, calcium carbonate equivalency.
‡Soil Texture: ClL, clay loam; FSL, fine sandy loam; L, loam; SCL, silty clay loam; SilL, silt loam.

Field trials were established in farmer fields and at ag experiment stations in Minnesota (Table 1). Locations were targeted to test Low by either the Bray-P1 or Olsen tests (< 10 ppm Bray-P1 or <8 ppm Olsen P). Sites with a calcium carbonate equivalency of >5% CCE were given preference due to a greater capacity for P fixation but the exact CCE was not known until after trial establishment.

A split plot design was used where main plots consisted of four P rates and sub-plots consisted of timing (Fall or Spring). The four P rates were 0, 30, 60, and 90 lbs P_2O_5 per acre applied as MAP (11-52-0). All treatments were replicated four times. Nitrogen supplied with MAP was balanced with AMS. Gypsum was used to balance sulfur applied by AMS such that all plots received similar rates of N and S when P treatments are applied. Calcium supplied by gypsum was not expected to impact corn or soybean yield due to excessive levels of calcium already in the soil.

Corn and soybean will be the two crops utilized for this study. Additional crop species are not used as corn and soybean should provide sufficient information on potential differences in responses based on fertilizer timing which can be translated to additional crops. A total of three trials were established for each crop each year (6 trials total per year).

Soil samples (0-6") were collected from each main block prior to fall treatment application, were air dried, ground, and analyzed for P by Bray-P1, Olsen, and Mehlich-3 P tests. Samples were additionally analyzed for calcium carbonate equivalency (modified pressure calcimeter method) and pH (1:1 soil:water). Additional 0-6" soil samples were collected in June from all plots to assess change in Bray-P1 and Olsen soil test P after treatment application.

Table 2. Summary of cultural practices for studies conducted in 2019 and 2020. Soil test data was collected in the Fall at trial establishment from each main plot.

				Date of		
Year	Location	Crop	Cultivar†	Fall Fert.‡	Spring Fert.	Planting
2019	Crookston	Corn	P 7632	2-Nov.	9-May	15-May
	Lamberton	Corn	P 0157	15-Nov.	17-May	17-May
	Morris	Corn	DK 44-80	9-Nov.	25-Apr.	14-May
	Benson	Soybean	DG 11LL48	9-Nov.	6-May	7-Jun
	Morris	Soybean	C 0716	9-Nov.	25-Apr.	17-May
	Stewart	Soybean	NS 6162	17-Oct.	6-May	13-May
2020	Crookston	Corn	DK 26-40	30-Oct.	18-May	21-May
	Lamberton	Corn	P 0157XMT	1-Nov	24-Apr.	27-Apr.
	Morris	Corn	DK 41-96	31-Oct.	11-May	8-May
	Danvers	Soybean	DG 13LL35	18-Nov.	23-Apr.	2-May
	Morris	Soybean	NK S06-T8L	31-Oct.	11-May	18-May
	Stewart	Soybean	P 15A65	29-Oct.	21-Apr.	20-Apr.

†C, Cropland; DG, Dyna-gro; DK, Dekalb; NK, Northrup King; NS, North Star; P, Pioneer.
‡ Fall fertilizer (fert.) was applied the fall the previous year in which the study was harvested.

Leaf samples were collected from each corn plot at V8-V10 (uppermost fully developed leaf) and R1 (leaf opposite and below the ear), and for soybean at the R1-R2 growth stage (uppermost fully developed trifoliate). All soybean plots will be harvested with a small plot combine. Corn will either be harvested with a plot combine or by hand. Soybean grain yield is reported at 13% moisture and corn grain yield is reported at 15.5%. Grain samples were collected from each location and analyzed for total P concentration for both crops while soybean was analyzed for protein and oil concentration in grain by NIR.

Results and Discussion

Location data are summarized in Table 1. Sites were selected to have low initial soil test P (STP) and measurable carbonate levels. The exception to this was Lamberton (both years) which was included due to a very acidic pH which is a good comparison to the remaining sites to determine the impact of free iron and aluminum on the retention of soil test P. The only location which tested above the medium STP class was Benson. To establish the location, we targeted high pH zones which tend to have low soil P, but that was not the case for Benson, Stewart 2019, and Danvers. The remaining sites were all within targeted parameters. Calcium carbonate equivalency (CCE) was highest at Crookston and Stewart, both in 2019. At the remaining four locations there was measurable CCE (except for Lamberton) but the levels were lower than anticipated.

2019 Data Summary

Table 2 and 3 summarizes main effects and main effect interactions for the ANOVA for the measured variables for the 2019 corn and soybean trials, respectively. Tables 4 and 5 summarize the phosphorous (P) rate and timing main effects for corn and soybean, respectively. Interactions were generally not significant, and the interaction data are not summarized for the majority of the measured variables. A lack of a significant interaction is an indication that there is no impact of P timing on fertilizer use by either crop. Exceptions however will be noted.

Soil samples were collected in June to assess potential loss of P availability following the fall application. In general, main effect significance was similar when P was analyzed by either the Bray P1 or Olsen P tests. The two exceptions were the corn location at Crookston and soybean location at Benson where the high level of carbonates neutralized the Bray solution and resulted in Very Low soil P tests which did not change with application rate. Benson was the only location where neither main effect was significant which could be due to greater variability in soil P due to the higher initial P soil tests. For Lamberton and both Morris sites, both main effects were significant for both soil tests while both main effects were also significant for the Olsen P test only at Crookston and Stewart. Since most sites were high pH where the Olsen P test is typically used, the Data in Figures 3 and 4 will be discussed for the corn and soybean locations, respectively.

The interaction between P source and rate was significant for the change in Olsen soil test P at the Morris corn and soybean locations. This indicates a difference in slope in the relationship between soil test P change and P application rate for the fall and spring applications. In all cases, Olsen soil test P was greater in June following spring application which is not surprising considering the greater time the P had to react with the soil from the fall application. From the relationships in Figures 3 and 4 it is surprising that more of the interactions were not significant. However, since most of the timing main effects were significant we have strong evidence that P is being tied up following fall application including at Lamberton which had an acidic pH. Sites like the soybean trial at Morris exhibited very little change in soil test P when up to 60 lbs P_2O_5 were applied.

Corn data are summarized in Table 5. Phosphorus application rate more consistently impacted measured variable compared to P application timing. Corn leaf P at V10 and R1 were generally increased linearly at most locations except for R1 leaf P at Morris which was no affected by P application. The only timing effect occurred for R1 leaf P concentration, which was greater for the fall application, but the difference was negligible. Expected concentration of P in corn leaves at R1 is between 0.2 and 0.4 %. All locations tested within that range with the lowest concentrations of P combing back at 0.23 %.

Corn grain harvest moisture was inconsistently affected by P application. Yield, however, was increased by P application at Lamberton and was impacted by timing at two locations, Lamberton and Morris. Corn grain yield favored spring application at both locations which were significant. The P rate by timing interaction was also significant at Morris indicating a significant impact of P rate that varied based on timing. The interaction is not shown in figures, but the analysis of data showed no yield difference between timing at the 0 and 90 lb application rates while spring application resulted in greater yield when 30 or 60 lbs P_2O_5 were applied. A regression was not run on the data but the ANOVA would indicate that application of 90 lbs would result in similar yield and that a small reduction in P could be taken if the P were applied at a rate greater than 60 lbs P_2O_5. The lack of a response to P at Crookston was likely due to high levels of Goss' Wilt which reduced yield potential in the trial. Overall yield potential was significantly lower at Crookston compared to the remaining sites. Corn grain P concentration and P removed in the harvested grain were also inconsistently impacted by P rate and timing effects.

Soybean data are summarized in Table 6. Phosphorus rate and timing did not affect the concentration in the uppermost fully developed trifoliate at R1. In addition, P concentration in the harvested grain, soybean protein and oil concentration were inconsistently impacted by treatments.

Soybean grain yield was affected by P rate at Morris and Stewart and was not impacted by timing. Soybean yield was increased when up to 60 lbs P_2O_5 were applied at both locations. Removal of P in the harvested grain was increased by P application rate at all three locations, even Benson where yield was not affected which contrasts with corn where P removal was seldom impacted. Yield increase to P was greater at Morris where yield was nearly doubled with the 60 lb P_2O_5 application rate compare to the control, and grain yield was increased 2 bu/ac at Stewart.

Table 3. ANOVA summary for measured variables (phosphorus rate and timing) for the three corn trials conducted in 2019.

Main Effect	Bray P Change	Olsen P Change	V10 Leaf	R1 Leaf P	Grain Moisture	Grain Yield	Grain %P	Grain P Removal
	------------------	------------------	------------------	*P*>F	------------------	------------------		
				Crookston				
P rate	0.42	**	*	***	0.56	0.45	*	0.44
Timing	0.22	*	0.15	0.07	0.11	0.68	0.34	0.94
P rt. x Time	0.49	0.23	0.89	0.63	0.52	0.90	0.18	0.29
				Lamberton				
P rate	*	*	***	**	**	*	*	0.10
Timing	0.10	0.07	0.36	0.57	0.46	0.08	0.37	0.14
P rt. x Time	0.64	0.58	0.71	0.59	0.07	0.42	0.09	0.07
				Morris				
P rate	***	**	0.09	0.28	0.19	0.39	0.88	0.72
Timing	**	**	0.23	0.63	**	*	0.38	*
P rt. x Time	0.17	*	0.63	0.31	0.71	**	0.68	0.18

Table 4. ANOVA summary for measured variables (phosphorus rate and timing) for the three soybean trials conducted in 2019.

Main Effect	Bray P Change	Olsen P Change	R1 Leaf P	Grain Yield	Grain %P	Grain P Removal	Grain Protein	Grain Oil
		--	--*P*>F	--				
				Benson				
P rate	0.27	0.20	0.15	0.31	0.36	0.10	0.82	0.16
Timing	0.33	0.89	1.00	0.74	0.11	0.28	0.26	0.71
P rt. x Time	0.78	0.44	0.95	0.08	0.98	0.40	0.73	0.68
				Morris				
P rate	***	***	0.29	**	***	*	*	0.19
Timing	**	**	0.74	0.81	*	0.90	0.10	0.29
P rt. x Time	**	**	0.40	0.11	0.55	0.71	0.91	0.77
				Stewart				
P rate	0.98	**	0.91	*	0.13	0.08	0.13	*
Timing	0.64	**	0.67	0.78	0.25	0.31	0.07	0.74
P rt. x Time	0.09	0.25	0.48	0.18	0.80	0.35	*	0.53

Table 5. Summary of treatment main effects for three corn locations where P fertilizer rates were applied in Fall or spring ahead of the 2019 cropping season. Treatments are considered significantly different at $P \leq 0.10$. Numbers followed by the same letter for individual site treatment main effects are not significantly different.

	P application rate (lb P_2O_5 ac^{-1})				Application Time	
Location	0	30	60	90	Fall	Spring
	V10 Upper Leaf %P					
Crookston	0.31b	0.32b	0.35a	0.34a	0.33	0.32
Lamberton	0.25c	0.30b	0.30b	0.32a	0.29	0.29
Morris	0.23a	0.24ab	0.25ab	0.27a	0.26	0.25
	R1 Leaf %P					
Crookston	0.23b	0.24b	0.28a	0.28a	0.26a	0.25b
Lamberton	0.23c	0.25bc	0.26b	0.28a	0.25	0.25
Morris	0.24	0.25	0.25	0.26	0.25	0.25
	Moisture in harvested grain %					
Crookston	26.0	25.4	26.1	24.6	25.1	26.0
Lamberton	20.2a	19.4b	19.3b	19.1b	19.6	19.4
Morris	19.3	19.7	19.5	19.8	19.3b	19.8a
	Corn grain yield at 15.5% bushels per acre					
Crookston	133	120	129	143	132	130
Lamberton	175b	192a	200a	194a	187b	193a
Morris	233	223	235	233	225b	238a
	Corn Grain %P					
Crookston	0.24b	0.24b	0.27a	0.27a	0.25	0.26
Lamberton	0.17b	0.18b	0.19ab	0.21a	0.18	0.19
Morris	0.19	0.18	0.19	0.18	0.18	0.19
	P Removed in Corn Grain (lb P_2O_5/ac)					
Crookston	34	33	36	38	35	35
Lamberton	34b	37ab	40a	42a	37	39
Morris	48	43	48	46	44b	48a

Table 6. Summary of treatment main effects for three soybean locations where P fertilizer rates were applied in Fall or spring ahead of the 2019 cropping season. Treatments are considered significantly different at $P \leq 0.10$. Numbers followed by the same letter for individual site treatment main effects are not significantly different.

	P application rate (lb P_2O_5 ac^{-1})				Application Time	
Location	0	30	60	90	Fall	Spring
	------ R1 Trifoliate %P ------					
Benson	0.37	0.38	0.40	0.42	0.39	0.39
Morris	0.42	0.35	0.44	0.45	0.41	0.42
Stewart	0.39	0.39	0.39	0.40	0.39	0.39
	------ Soybean grain yield at 13% bushels per acre------					
Benson	56.3	55.9	58.7	56.2	56.9	56.7
Morris	32.7c	39.3b	47.5a	43.0ab	40.8	40.4
Stewart	57.1c	58.2bc	59.8a	58.8ab	58.4	58.6
	------ Soybean Grain %P ------					
Benson	0.72	0.69	0.73	0.73	0.71	0.72
Morris	0.46b	0.47b	0.52a	0.54a	0.49b	0.51a
Stewart	0.56	0.57	0.58	0.60	0.57	0.58
	------ P Removed in Soybean Grain (lb P_2O_5/ac)------					
Benson	48ab	46b	51a	50a	48	49
Morris	16c	23b	27ab	28a	24	24
Stewart	38c	39bc	41ab	42a	40	41
	------ Soybean Grain Protein % ------					
Benson	45.7	45.7	45.8	45.9	45.9	45.7
Morris	45.1b	45.0b	45.8a	45.9a	45.3b	45.6a
Stewart	45.8	46.2	46.0	46.0	45.9b	46.1a
	------ Soybean Grain Oil % ------					
Benson	21.5	21.5	21.2	21.5	21.4	21.4
Morris	20.7	20.9	20.5	20.6	20.7	20.6
Stewart	22.8a	22.5b	22.4b	22.6b	22.6	22.6

2020 Data Summary

Table 7 and 8 summarizes main effects and main effect interactions for the ANOVA for the measured variables for the 2020 corn and soybean trials, respectively. Tables 9 and 10 summarize the phosphorous (P) rate and timing main effects for corn and soybean, respectively. Interactions were generally not significant for soybean and mostly for corn. The interaction data are not summarized for many of the measured variables. A lack of a significant interaction is an indication that there is no impact of P timing on fertilizer use by either crop. Exceptions however will be noted.

Soil samples were collected in June to assess potential loss of P availability following the fall application. In general, main effect significance was similar when P was analyzed by either the Bray P1 or Olsen P tests. There was only one location in 2020, Stewart, where carbonates were relatively high, and the Bray P test was not impacted. There were three significant interactions between time and rate for Bray P (Crookston, Lamberton, and Stewart) and there was a significant interaction for Olsen P only at Crookston and Stewart (Figures 3 and 4). The Bray-P interaction was a result of no change in June Bray-P when P for P applied in the fall. The same was true for the significant interaction for Olsen P at Crookston but for Stewart Olsen soil test change differed between timing for the 30 and 60 lb application rates but not for the 0 and 90 lb rate. Timing did differ but, in all cases, the two-way interaction was also significant as well.

Corn data are summarized in Table 9. Phosphorus application rate more consistently impacted measured variable compared to P application timing. Corn leaf P at V10 and R1 were impacted by timing but not by rate, which contrasts with 2019 where rate generally impacted leaf P concentration.

Corn grain harvest moisture was greater when P was applied in the Fall at Crookston and Lamberton but did not differ at Morris (Table 9). At Morris, grain moisture decreased with increasing P application rate. Grain yield as greater with spring application at both Crookston and Lamberton while P application rate increased yield at Morris with 60 lb P_2O_5 application rate. In all cases decreased moisture in the grain at harvest was accompanied by an increase in grain yield.

Soybean data are summarized in Table 10. Phosphorus timing did not affect the concentration in the uppermost fully developed trifoliate at R1, while trifoliate P concentration increased with increasing rate of P applied at Danvers. In addition, P concentration in the harvested grain, soybean protein and oil concentration were seldom impacted by treatments. The exception was grain P and protein concentration at Morris which was increased by the rates of P applied.

Soybean grain yield was affected by P rate at Danvers (Table 10). Rate and timing of P application did not affect soybean grain yield in all other cases. Yield was relatively low at Morris and Stewart. The low yield at Morris could not be explained while two separate hail events in July reduced soybean yield potential at Stewart. Grain P removal was increased by P application rate at both Danvers and Stewart. At Danvers, soybean grain yield and grain P removal were greater for the 90 lb and there was no difference among the remaining treatments. At Stewart, all rates of P increased P removal similarly compared to the no P control.

Year 2 Overall Summary and Conclusions

A summary of tissue P concentration did not result in a relationship between relative corn or soybean grain yield and corn leaf P concentration at V10 or R1 and soybean trifoliate P concentration at the R1 growth state. Relative yield was calculated by determining maximum yield at each location and dividing individual plot yield by maximum yield. The best relationship between tissue P and relative yield was for soybean. However, the R^2 value, which indicates how much of the variation in relative yield could be predicted by trifoliate P concentration, was low. The lack of a relationship between tissue P concentration and relative yield could be due to differences in tissue P concentration among the locations. I have not converted tissue P into relative concentrations, which may be needed to get a good relationship between the two values. It is also possible for P to accumulate in tissue in low P situations due to lack of growth of the plant.

A summary of corn and soybean P response across the six individual locations is given in Figure 5. In both cases P rate and timing significantly differed. In addition, the P rate by timing interaction was significant for corn only which was because timing differed but only for the two highest rates of P. For fall application, corn grain yield increased linearly to the 90 lb application rate which yield was increased up to 60 lbs of applied P for the spring application. The yield produced by the 90 lb fall rate was roughly equivalent to 45 lbs of P_2O_5 applied in the spring. The data indicates that for corn, P application in the spring should be favored with low P soils and that some of the P was likely tied up in the soil and rendered unavailable following application in the fall.

Soybean yield was greater for fall application compared to spring (Figure 5). Soybean grain yield was increased linearly up to the 90 lb P_2O_5 application rate across the sites. There was no interaction between rate and timing so the greater yield for fall application occurred regardless of the rate of P applied. This indicates that P in the fall is favored for soybean while P in the spring if favored for corn.

June Olsen soil test P (STP) was regressed with relative corn and soybean grain yield (Figure 6). There was a better relationship between June STP and corn yield as there was much greater variability in relative soybean grain yield. For corn, relative grain yield was at maximum when Olsen P was 10 ppm which is in the medium soil P classification. In contrast, soybean grain yield was at maximum when soybean grain yield was near 15 ppm which is the upper end of the high soil test classification. Responses were separated by fall and spring application but the soil test at maximum yield was similar for both corn and soybean.

Table 7. ANOVA summary for measured variables (phosphorus rate and timing) for the three corn trials conducted in 2020.

Main Effect	Bray P Change	Olsen P Change	V10 Leaf	R1 Leaf P	Grain Moisture	Grain Yield	Grain %P	Grain P Removal
	--------------------------------------			*P*>F	--------------------------------------			
				Crookston				
P rate	0.07	**	0.86	0.99	0.21	0.33	0.40	0.29
Timing	***	***	0.27	0.11	***	***	***	***
P rt. x Time	**	**	0.50	0.55	0.85	0.28	0.08	*
				Lamberton				
P rate	0.08	0.16	0.41	0.24	0.95	0.15	0.23	0.49
Timing	***	***	**	***	*	***	**	**
P rt. x Time	*	0.24	0.83	0.32	0.06	0.13	*	0.08
				Morris				
P rate	*	***	0.33	0.39	*	*	0.09	0.08
Timing	0.38	0.44	**	**	0.47	0.73	0.96	0.88
P rt. x Time	0.38	0.21	**	**	0.40	0.61	0.41	0.72

Table 8. ANOVA summary for measured variables (phosphorus rate and timing) for the three soybean trials conducted in 2020.

Main Effect	Bray P Change	Olsen P Change	R1 Leaf P	Grain Yield	Grain %P	Grain P Removal	Grain Protein	Grain Oil
		--	--	*P*>F	--	--		
				Danvers				
P rate	**	**	*	0.07	0.49	0.07	0.17	0.30
Timing	*	0.33	0.43	0.32	0.27	0.54	0.92	0.87
P rt. x Time	0.78	0.60	0.18	0.55	0.08	0.75	0.55	0.25
				Morris				
P rate	0.14	0.06	0.34	0.91	0.05	0.51	0.06	0.67
Timing	0.28	0.15	0.29	0.40	0.41	0.28	0.17	0.10
P rt. x Time	0.18	0.33	0.91	0.45	0.47	0.28	0.89	0.41
				Stewart				
P rate	*	**	0.22	0.28	0.15	*	0.35	0.33
Timing	0.12	0.32	0.26	0.13	0.63	0.27	0.86	0.34
P rt. x Time	**	0.10	0.39	*	0.54	0.30	0.25	0.99

Table 9. Summary of treatment main effects for three corn locations where P fertilizer rates were applied in Fall or spring ahead of the 2020 cropping season. Treatments are considered significantly different at $P \leq 0.10$. Numbers followed by the same letter for individual site treatment main effects are not significantly different.

	P application rate (lb P_2O_5 ac^{-1})				Application Time	
Location	0	30	60	90	Fall	Spring
	V10 Upper Leaf %P					
Crookston	0.27	0.27	0.28	0.32	0.29	0.27
Lamberton	0.33	0.36	0.34	0.36	0.33b	0.36a
Morris	0.27	0.32	0.27	0.31	0.32a	0.26b
	R1 Leaf %P					
Crookston	0.23	0.23	0.23	0.24	0.25	0.22
Lamberton	0.30	0.31	0.30	0.33	0.28b	0.33b
Morris	0.25	0.28	0.23	0.27	0.28a	0.23b
	Moisture in harvested grain %					
Crookston	13.6	13.3	13.5	13.0	13.8a	12.9b
Lamberton	18.1	18.0	17.9	18.1	18.3a	17.8b
Morris	17.0a	16.4ab	16.1bc	15.5c	16.1	16.4
	Corn grain yield at 15.5% bushels per acre					
Crookston	143	158	156	162	143b	166a
Lamberton	195	195	202	197	193b	202a
Morris	188c	201bc	207ab	223a	206	204
	Corn Grain %P					
Crookston	0.25	0.27	0.27	0.28	0.24b	0.29a
Lamberton	0.21	0.22	0.21	0.22	0.20b	0.22a
Morris	0.19b	0.19b	0.22a	0.23a	0.21	0.21
	P Removed in Corn Grain (lb P_2O_5/ac)					
Crookston	41	48	48	49	38b	55a
Lamberton	43	45	45	47	42b	48a
Morris	40b	40b	54a	55a	47	47

Table 10. Summary of treatment main effects for three soybean locations where P fertilizer rates were applied in Fall or spring ahead of the 2020 cropping season. Treatments are considered significantly different at $P \leq 0.10$. Numbers followed by the same letter for individual site treatment main effects are not significantly different.

	P application rate (lb P_2O_5 ac^{-1})				Application Time	
Location	0	30	60	90	Fall	Spring
	------ R1 Trifoliate %P ------					
Danvers	0.52b	0.48c	0.54ab	0.55a	0.52	0.53
Morris	0.39	0.37	0.39	0.42	0.40	0.39
Stewart	0.58	0.55	0.53	0.57	0.55	0.56
	------ Soybean grain yield at 13% bushels per acre ------					
Danvers	56.1b	54.5b	54.0b	60.7a	56.7	55.9
Morris	22.7	22.9	24.8	24.6	24.5	23.0
Stewart	42.2	44.2	44.0	44.0	44.2	43.0
	------ Soybean Grain %P ------					
Danvers	0.62	0.64	0.63	0.62	0.62	0.63
Morris	0.49b	0.52ab	0.54a	0.55a	0.53	0.52
Stewart	0.48	0.50	0.51	0.51	0.50	0.50
	------ P Removed in Soybean Grain (lb P_2O_5/ac) ------					
Danvers	41b	41b	40b	46a	42	42
Morris	13	14	15	17	15	14
Stewart	24b	26a	27a	27a	26	26
	------ Soybean Grain Protein % ------					
Danvers	36.2	36.0	35.7	35.7	35.8	35.9
Morris	35.0b	35.6a	35.8a	35.8a	35.4	35.7
Stewart	34.4	34.2	34.2	34.2	34.3	34.2
	------ Soybean Grain Oil % ------					
Danvers	16.5	16.1	16.4	16.4	16.3	16.4
Morris	16.4	16.4	16.3	16.5	16.4	16.3
Stewart	17.5	17.7	17.7	17.6	17.6	17.7

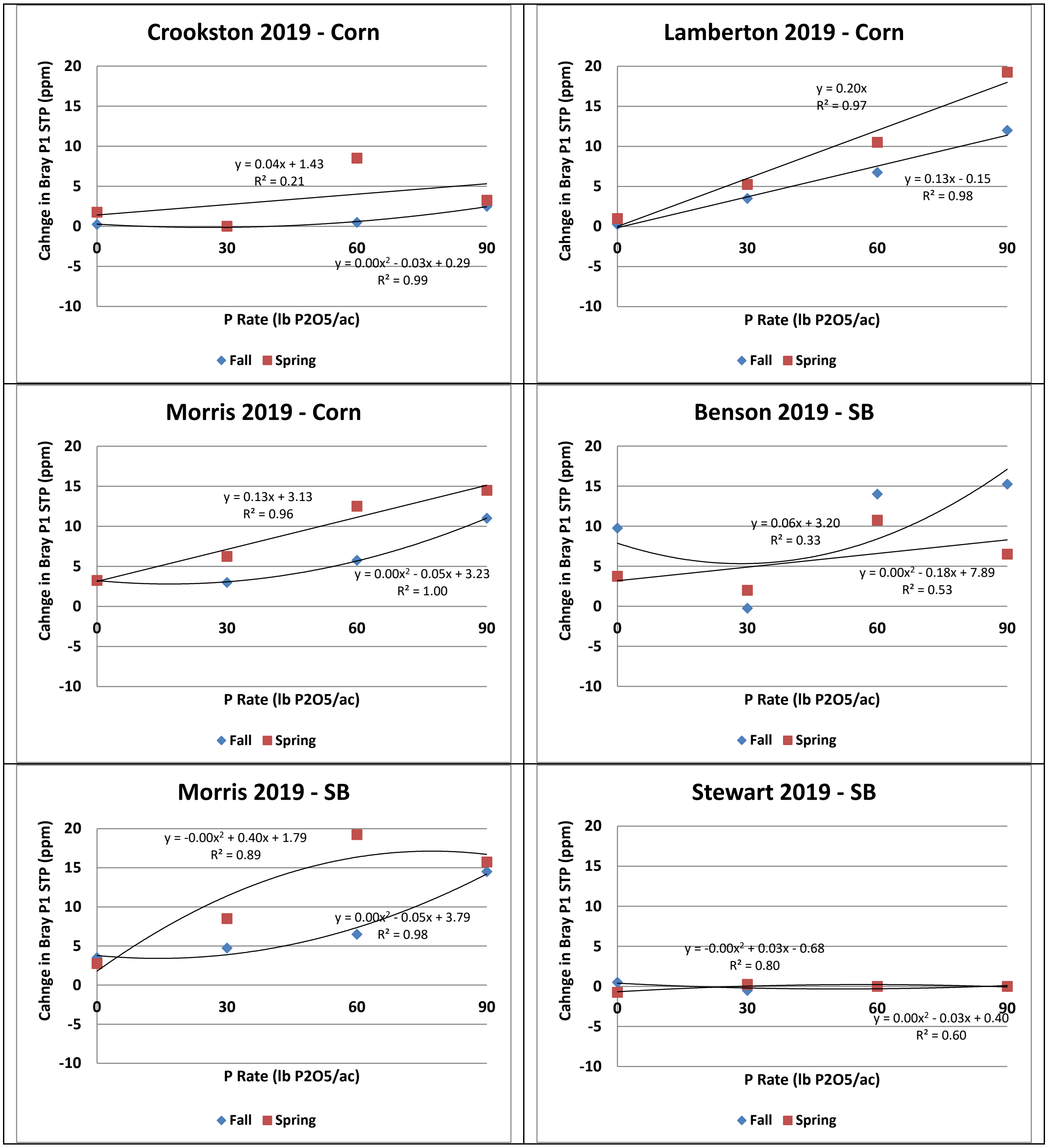


Figure 1. Summary of change in June Bray-B1 P following P application ahead of corn or soybean in Fall 2018 or Spring 2019.

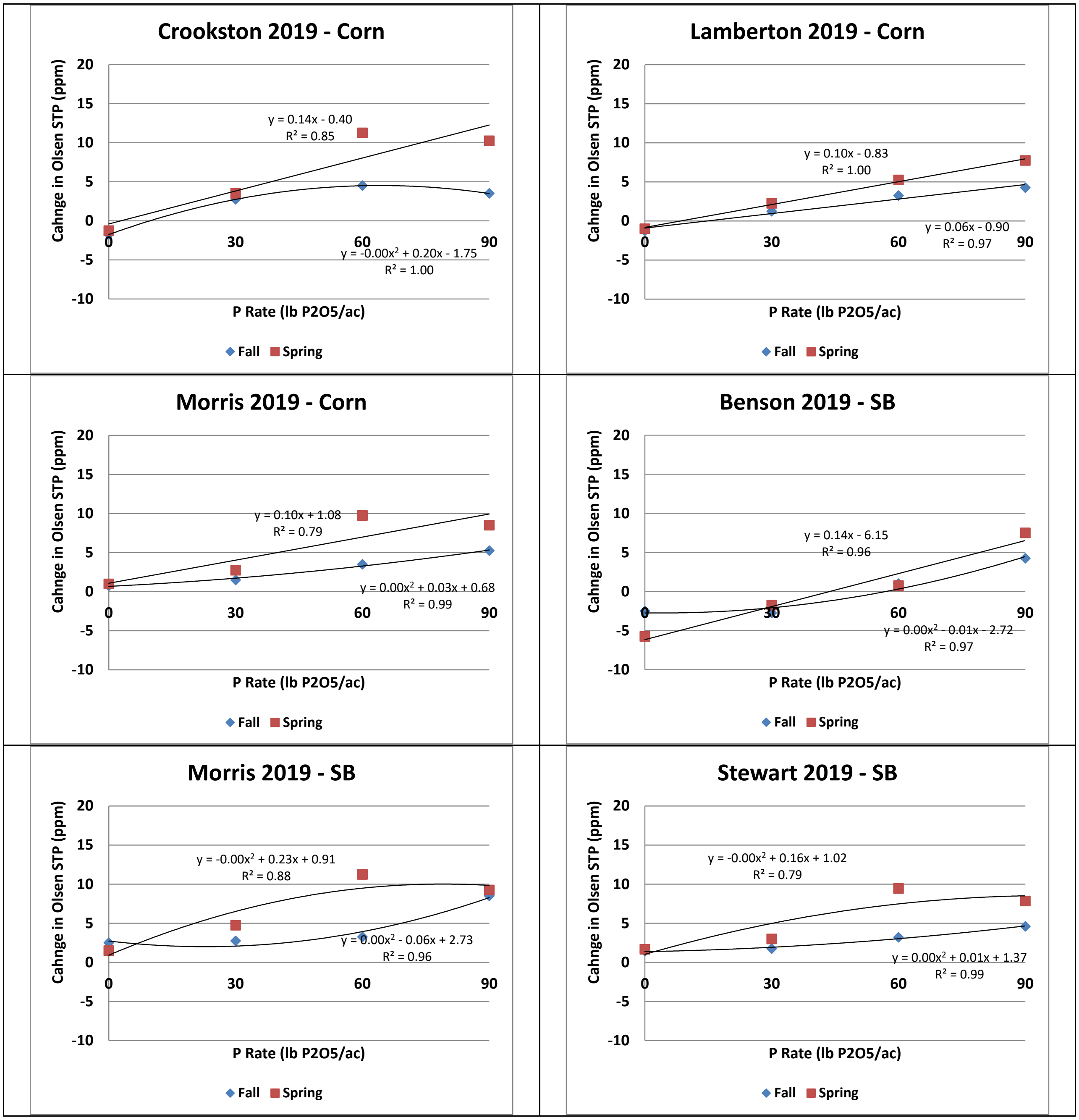


Figure 2. Summary of change in June Olsen P following P application ahead of corn or soybean in Fall 2018 or Spring 2019.

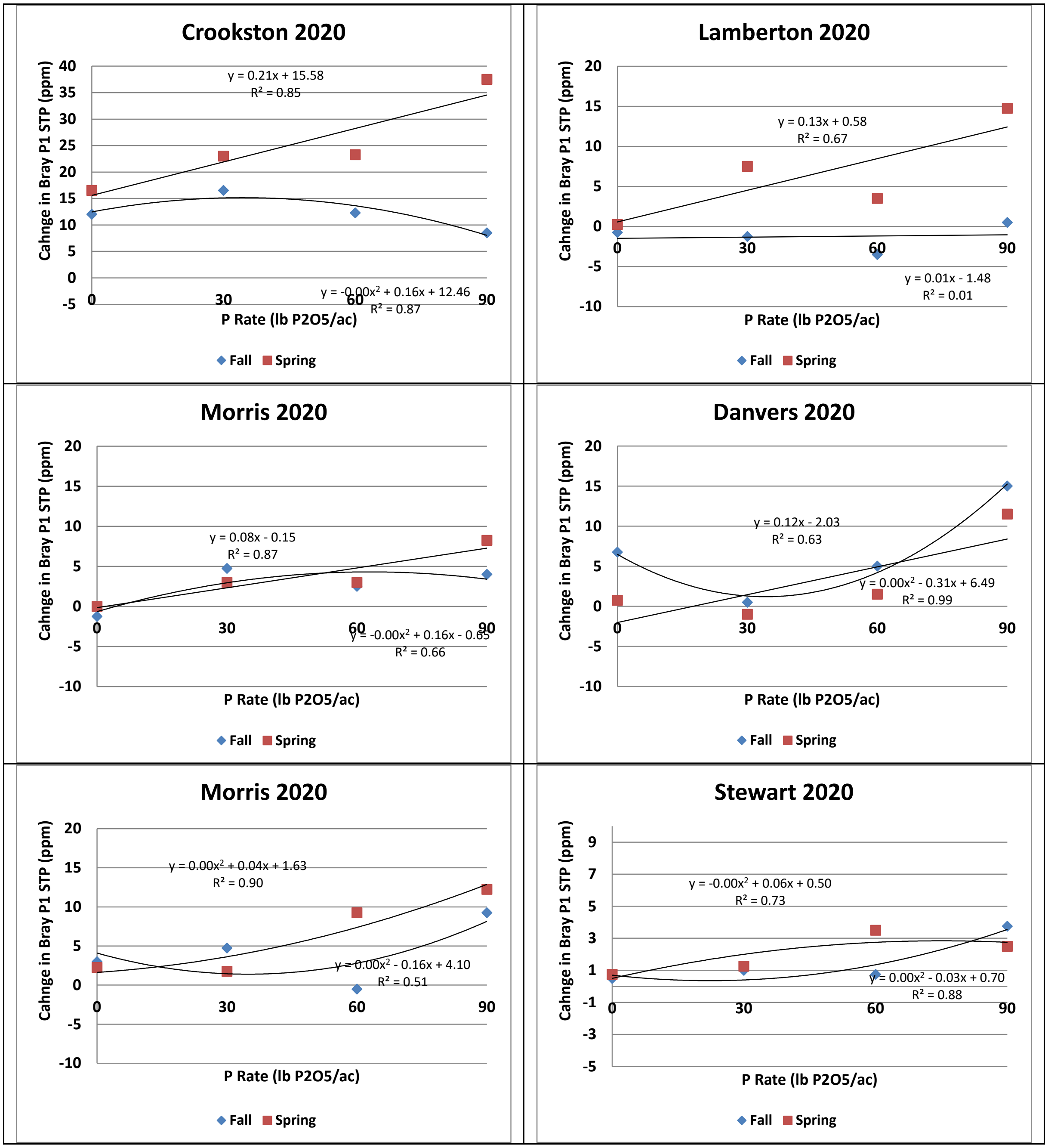


Figure 3. Summary of change in June Bray-B1 P following P application ahead of corn or soybean in Fall 2019 or Spring 2020.

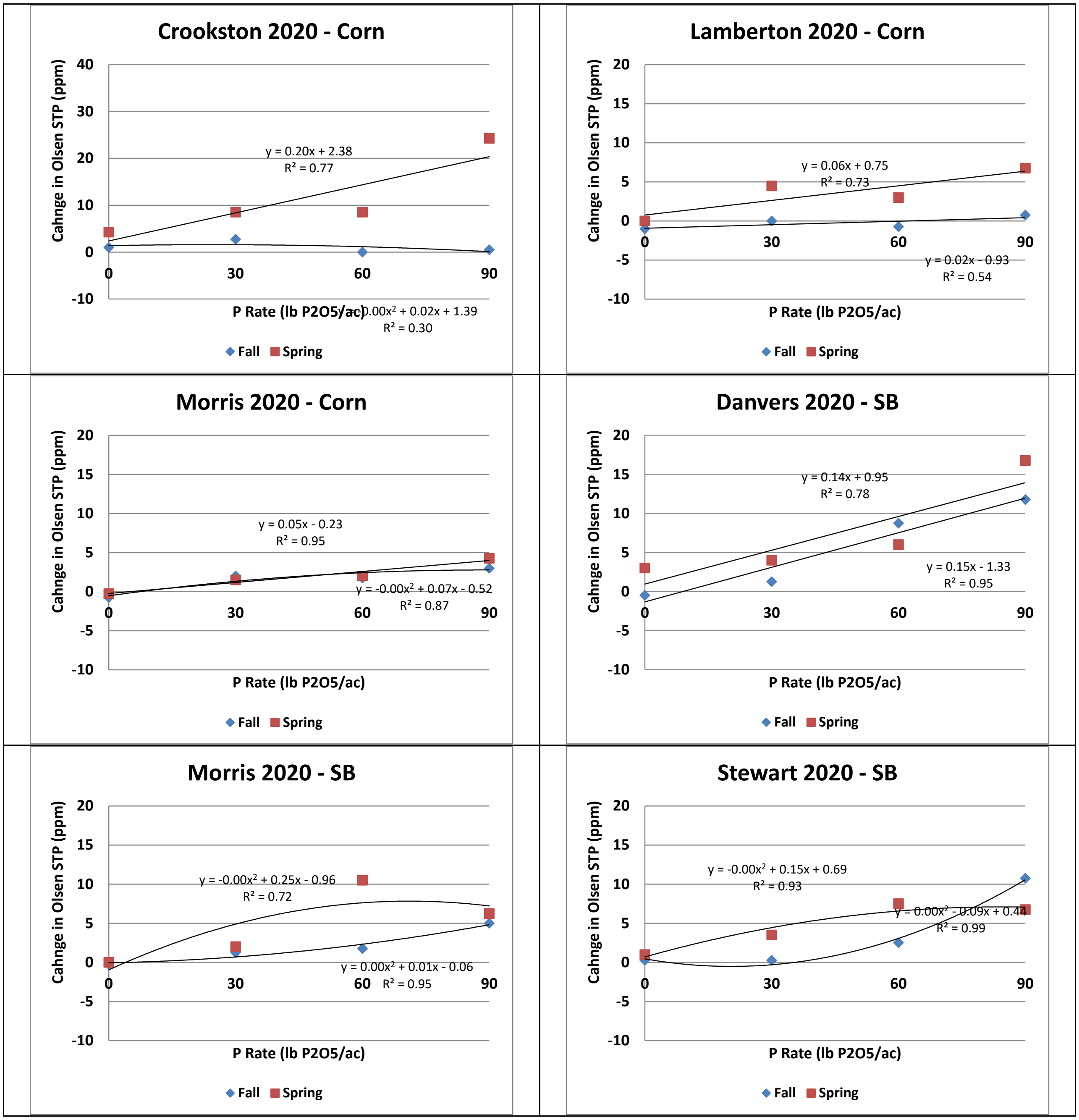
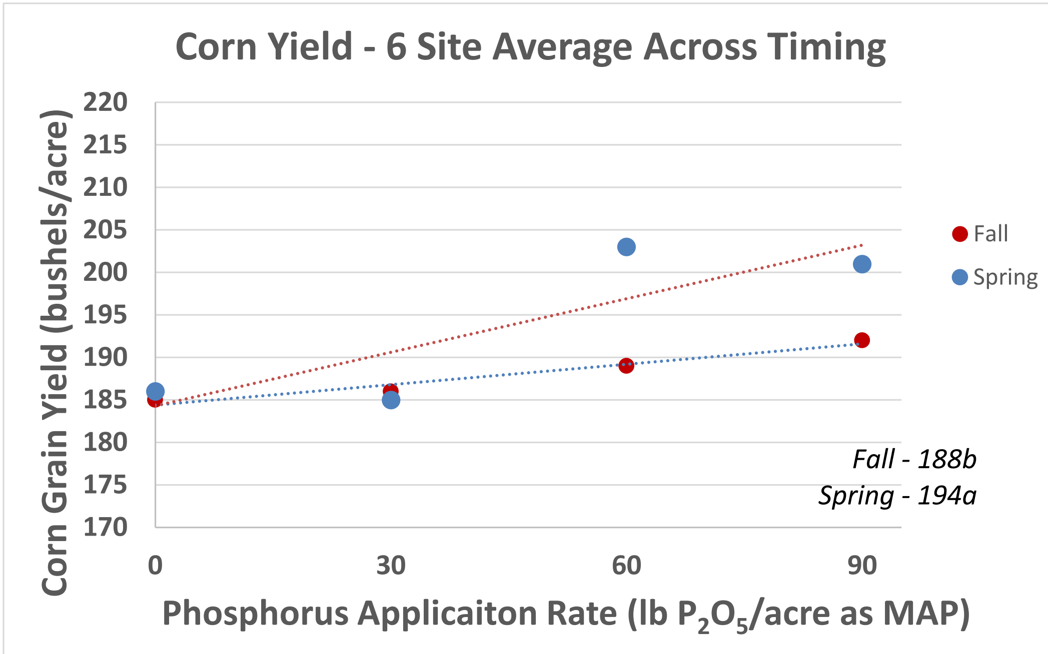


Figure 4. Summary of change in June Olsen P following P application ahead of corn or soybean in Fall 2019 or Spring 2020.



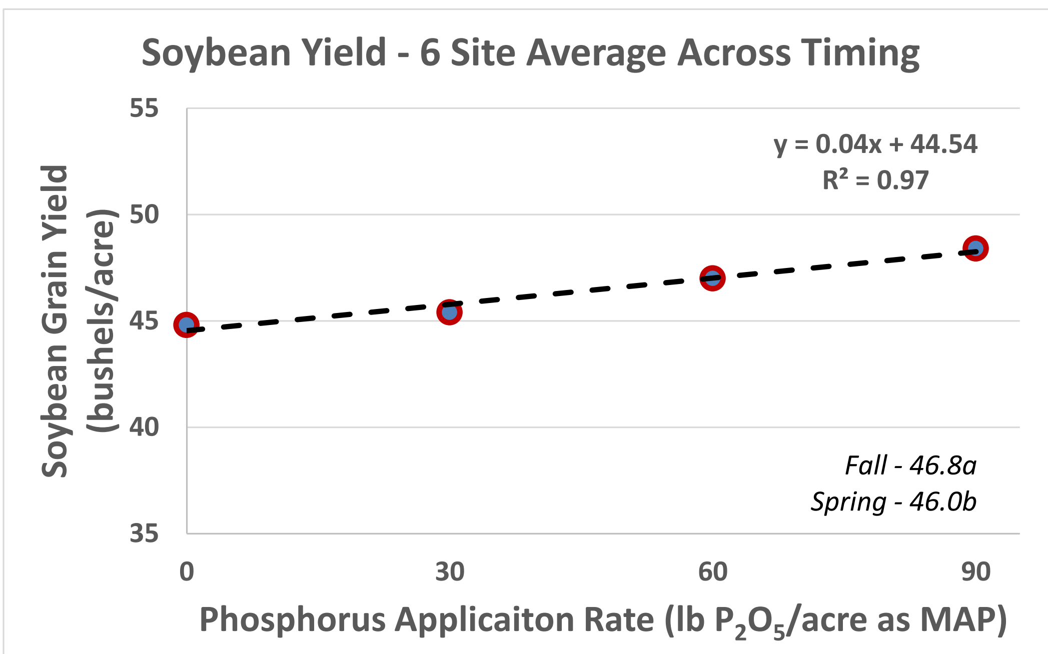
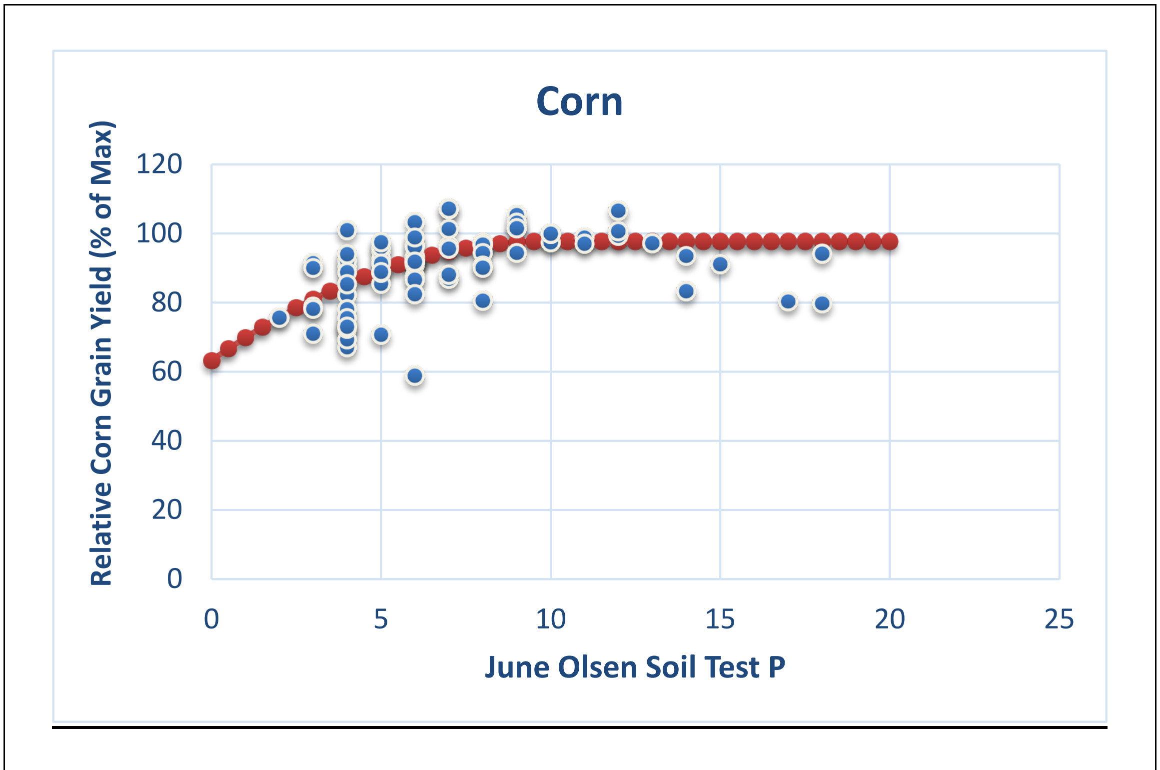


Figure 5. Summary of yield response to P across the six corn and six soybean locations conducted in 2019 and 2020.



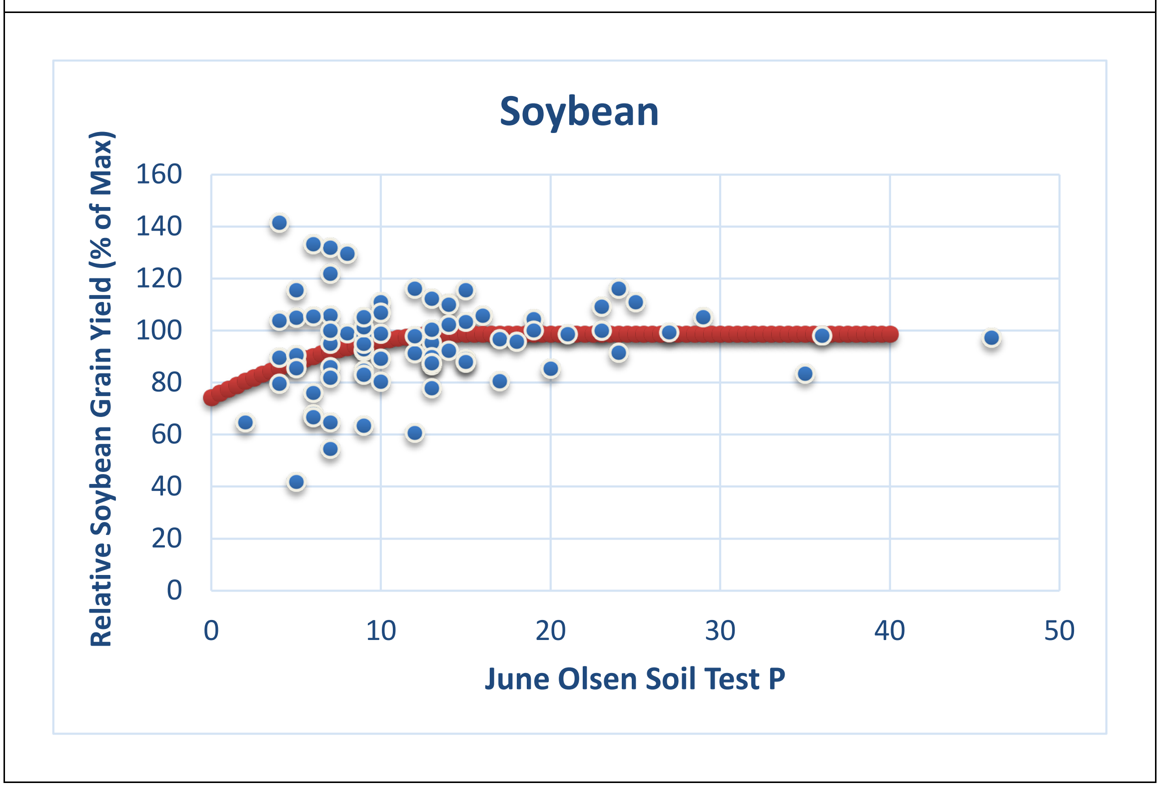


Figure 6. Summary of relative corn or soybean yield (% of maximum) based on June Olsen soil test P level.