Change in soil test P following long term P fertilization strategies

Year 10 (Final) Report AFREC 2011-Project B; R2013-U; R2014-5, PO 14912, PO 22925 PO 22925
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Project Summary PO 26833 (Crop Year 2018) 3/31/2019

Objectives

1. Determine optimum phosphorus fertilizer application rates for corn and soybean over a long-term rotation.
2. Evaluate if timing of broadcast phosphorus fertilizer application impacts corn and soybean yield.
3. Determine if starter fertilizer for corn after broadcast P for soybean can maintain optimal yield of both crops.
4. Study the impacts of P application rate and P removal in grain on long term trends in soil test levels
5. Evaluate critical soil test P levels (soil test where, on average, 95% of maximum yield is achieved)
6. Determine if sub-soil P concentration is being affected by removal of P in corn and soybean grain

Data Summary

- The optimum fertilizer rate to maintain maximum yield varied by location and block within location and varied from year to year.
- Over years, the economic optimum rate of P or K based on a two-year application within the corn-soybean rotation varied from site to site
  - Lamberton: Optimum P rate varied from 55-60 lbs P_2O_5
  - Morris: Optimum P rate varied from 60-100 lbs P_2O_5
  - Saint Charles: The optimum P rate was zero but some response to P has been found following nine years of cropping where 20 lbs P_2O_5 resulted in maximum yield.
- Timing of application of P and K has not shown to impact yield potential of soybean but application before corn tended to result in better corn grain yield at the two responsive locations.
- Application of P and K at rates of exact crop removal result in an increase in soil test P over time. After 10 years of cropping, application of P fertilizer at 32-65% of crop removal has maintained STP.
- Evidence suggests soil P tests around 20 ppm should result in corn and soybean yield at or near maximum yield potential.
- The amount of P needed to increase soil test by 1 ppm varied by location.
- Application of P can result in soil test changes below to soil sampling layer (0-6”). It is not clear if application rates less than crop removal result in a draw-down of soil P.

INTRODUCTION

Large amounts of P can be removed when grain is harvested off the field. In terms of a 2-year rotation, corn grain harvest can remove a large quantity of phosphorus compared to soybean. Applying the correct rate at the appropriate time is important to make sure yield potential is maximized. Phosphorus can be a limiting nutrient for soybean and previous research has shown a benefit for a direct application of P to soybean. Research has shown that soybeans respond better to broadcast fertilization than banded fertilizer, and banding fertilizer is not always a feasible method for all producers. One form of banded fertilizer is in-furrow starter applied with the planter. In Minnesota many farmers utilize starter fertilizer for corn and seldom for soybeans since potential for response is low and potential for damage from fertilizer placed near soybeans is high. Often starter is applied only for early growth benefits while the amount of fertilizer is not regarded when planning broadcast fertilization. The combination of starter fertilizer with broadcast fertilizer in a rotation could potentially benefit soybean producers by obtaining yield increases from broadcasting P for soybean and maintaining high yields in corn with starter P.

Many research projects have been conducted focused on single year application of P. However, most farmers prefer to apply rates for more than one cropping year in order to save on application costs. With a drop in commodity prices there have been more questions related to the appropriate rate of P needed for corn and soybean to maximize economic productivity. Application of P can present a significant cost to the farmer if they are trying to maintain a specific soil test value. Most farmers trying to maintain soil tests will apply removal based P which varies from year to year based on the yield of the crop. Some farmers may target the previous year's yield which is easier to do with yield maps generated with a combine yield monitor. Long-term research studies can provide valuable information on trends in soil test P over time from repeated application of fertilizer in the same plots. This data can help farmers to decide whether applying exact crop removal is worth the expense or if a lower rate can still maintain optimal soil test levels while maximizing grain yield.

Traditionally, soil tests for P only measure the concentration of P in the top 6 to 8 inches from the soil surface. If the amount of P removed is not supplied back to the soil with fertilizer then the net effect should be a decrease in P over time. Sub-soil P levels are not always measured as changes may not be found in some soils at depths of 6 to 8 inches or greater. There have been some questions regarding the impact of sub-soil P on P response. Since the impact of P removal on sub-soil P is hard to determine in short term trials, long-term research studies can provide valuable information on changes in soil P at depths of 6 inches or more in the soil profile.

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MATERIALS AND METHODS

Research studies were initiated at 3 locations across Minnesota in 2009. Phosphorus trials were established at the West Central Research and Outreach Center at Morris and Southwest Research and Outreach Center at Lamberton. Along with these on-station studies, a third location was established in a farmer field near St. Charles. At each location, side by side plots were established with corn and soybean. Phosphorus rates from 0 to 240 lbs P_2O_5 /ac are applied at different times during the corn-soybean rotation. Application is made before corn, before beans, and a split of 2/3 rate for corn and 1/3 rate for soybean. In addition to broadcast P, 5 gallons of 10-34-0 was applied to corn directly on the seed followed by all broadcast P applied to soybean. All treatments are replicated four times at each location. Treatments are to be reapplied to the same plots according to an annual or biennial application. All fertilizer is broadcast either in the fall weather permitting. Additional crop nutrients (nitrogen, potassium, and or sulfur) are applied based on crop needs.

Table 1. Average, minimum and maximum soil test data at phosphorus trials from 0-6" samples collected in spring 2009.

		Bray P1			Olsen P			Soil Test†		
Location	Crop	Avg	Min	Max	Avg	Min	Max	K	pH	OM
		----------------------ppm----------------------						ppm		-%-
Lamberton	Corn	21.7	11	42	10.2	3	21	109	5.4	4.1
	Beans	16.7	10	28	7.7	4	14	109	5.5	3.9
Morris	Corn	10.4	2	31	6.2	2	17	156	8.0	4.0
	Beans	18.6	2	40	9.9	4	25	171	8.0	4.2
St. Charles	Corn	12.8	8	27	5.4	2	11	77	6.2	2.6
	Beans	14.2	10	25	6.1	3	14	81	6.4	2.7

† K, ammonium acetate K; pH, 1:1 soil pH; OM, soil organic matter (LOI).

Soil samples were collected from each individual plot prior to the initial treatment application from the surface six inches (Spring of 2009). In the fall before treatments are reapplied, soil samples are again collected from all plots in order to track incline and decline of soil test P. Grain samples were collected at harvest and analyzed for total P in order to determine the nutrient uptake in the harvested grain. Harvesting is completed with a research grade plot combine at all locations.

The purpose of this study is to gather grain yield, grain uptake, and soil test change data in corn-soybean rotations. For each plot within each site, the calculated P removal over the entire rotation was subtracted from the amount of total P applied and will be compared to the change in soil test P from initial soil samples collected before the first cropping year. The net P applied can be used to calculate the amount of P needed to maintain soil P test in the top 6" and the effect on soil test P if the exact removal were to be applied. Both values are important information for farmers looking for information as to the amount of P required to maintain soil test. Both the Bray-P1 and Olsen P tests will be analyzed on all soil samples.

Selected plots were sampled in early June from the soybean plots at depths of 0-6, 6-12, and 12-18" to determine impacts of the fertilizer application rates have had on soil test P below the traditional sampling depth (0-6"). Plots were sampled which did and did not receive fertilizer the previous fall. The Bray-P1 and Olsen tests were used to analyze all samples.

2018 Yield Data Summary

Table 2. Summary statistics for the 2018 yield data for the P and K trials. Main effects studies were fertilizer timing (all before corn, all before beans, split, and starter), 2-year total application rate, and the interaction between the two. Main effects are considered significant at $P \leq 0.05$.

		Timing	Rate	Timing x Rate
		---------------------------*P*>F--------------------------		
LTP	Lamberton Corn	0.03	<0.001	0.85
	Lamberton Soybean	0.55	0.02	0.80
	Morris Corn	0.38	<0.01	0.04
	Morris Soybean	0.44	<0.001	0.58
	St Charles Corn	0.81	0.01	0.46
	St Charles Soybean	0.40	0.28	0.61

Table 2 summarizes the statistical significance of yield data collected in 2018. Phosphorus fertilizer rate affected corn yield at Lamberton, Morris, and Saint Charles. There was no clear trend for increasing corn grain yield at Saint Charles (Figure 1) and it cannot be determined that P actually increased yield as no treatment resulted in greater yield compared to the non-fertilized control. Soybean yield was impacted by P fertilizer rate at Lamberton and Morris, but not at Saint Charles. It was anticipated that as time progressed more of the sites would respond to P. Through the life of this trial some blocks within sites have shown more consistent response, particularly at Morris. In 2018, wet field conditions limited yield at Morris which resulted in erratic and poor yield. Corn grain yield response was linear at Morris (Table 3). Corn yield increased through the highest application rate without a clear plateau. Corn and soybean grain yield did plateau at the remaining locations within the rates which were applied.

Summary of the amount of P required to maximize corn and soybean grain yield

Table 3. Summary of phosphorus response of corn or soybean from each plot at each study location.

			2009†		2010†		2011†		2012†		2013†	
	L‡	ST§	CR	CL	CR	CL	CR	CL	CR	CL	CR	CL
		ppm		lb/ac		lb/ac		lb/ac		lb/ac		lb/ac
Lamberton	N	10	C	***65***	S	ns	C	ns	S	ns	C	ns
	S	8	S	ns	C	ns	S	***180***	C	ns	S	ns
Morris	N	6	C	***80***	S	ns	C	***60***	S	***120***	C	***143***
	S	10	S	ns	C	ns	S	ns	C	ns	S	***40***
St. Charles	E	5	C	ns	S	ns	C	ns	S	ns	C	ns
	W	6	S	ns	C	ns	S	ns	C	ns	S	ns
			2014†		2015†		2016†		2017†		2018†	
		ST§	CR	CL	CR	CL	CR	CL	CR	Cl	CR	Cl
		ppm		lb/ac		lb/ac		lb/ac		lb/ac		lb/ac
Lamberton	N	10	S	ns	C	***92***	S	***64***	C	***242***	S	***31***
	S	8	C	***lin***	S	ns	C	ns	S	ns	C	***168***
Morris	N	6	S	***64***	C	***36***	S	***100***	C	***146***	S	***60***
	S	10	C	***204***	S	***20***	C	ns	S	ns	C	***lin***
St. Charles	E	5	S	***17***	C	ns	S	ns	C	ns	S	ns
	W	6	C	***30***	S	ns	C	***20***	S	ns	C	ns

†CR, crop; CL, fertilizer rate that produced the greatest yield if response to P was significant.
‡Designates the trial area location within each study: E, east; N, north; S, south; W, west half.
§ST, Olsen soil test value for each half of the study at a single location.

The amount of fertilizer required for a two-year rotation to maximize yield within a single year is summarized in Table 3. Since there were two blocks at each site in order to have both crops each year, each block was studied separately in order to determine if blocks at each location differed in their responsiveness to P. The starting soil test for each block is given in Table 3. Average soil test values were somewhat similar but did differ between blocks. For instance, the P site a Morris tested 6 ppm for the North block while the south block averaged 10 ppm. The difference between the soil test values for each block was evident when studying responses at the North block responded to P application in nine of the ten years studied.

The amount of fertilizer needed to maximize agronomic yield is far different that the amount required achieving the greatest economic benefit. Figures 2 and 3 in the appendix show the relative response of yield at the given locations to fertilizer rate based on four year data averaged across the two blocks at each location. Soil test should decline in some of the low rate treatments over time to which all sites should eventually respond to P. What is surprising is the lack of response at Saint Charles. At Saint Charles soils tested low but there has been no indication of a yield response at this site. High subsoil P levels could explain some of the lack of response at the locations. We are planning on taking deeper samples in upcoming years to determine the effect of subsoil fertility.

A full economic analysis was conducted for the corn and soybean rotation for four year segments. Years 1 and 2 were not used in the analysis as the first two years were required to set up the treatment structure in the rotation. Timing was not considered in the economic analysis. The economic optimum rates of P application are summarized assuming a fixed price ration of 0.10 according a cost of $0.40 per pound of P_2O_5 and a corn value of $4 per bushel and $10 per bushel for soybean. The EOPR values in Tables 4 represent the 2-year application rate that produced the maximum net return to P based on the data in Figures 2 and 3 in the Appendix.

Table 4. Economic response to phosphorus based on location and block studied summarized for a 2-year application of P in a corn-soybean rotation.

Location	EOPR†	
	Years 3-6	Years 7-10
	-lb P_2O_5/ac-	
Lamberton	55	59
Morris	60	96
Saint Charles	0	0

†EOPR, economic optimum phosphorus rate for a 2-year application based on a 0.10 price ratio ($/lb P_2O_5 / $/bu corn)

Application of P over the eight cropping years did provide a positive economic response at Lamberton and Morris and never produced an economic response at Saint Charles in spite of low P soil tests. In general, there was little yearly response to P at Saint Charles until the 7th and 8th crop year where only a small rate, 20 lbs P_2O_5, was enough to achieve maximum yield (Table 4). At Lamberton the maximum economic rate of P was 55 lbs P_2O_5 from years 3-6 then was slightly greater at 59 lbs in years 7-10. The amount of P required was relatively similar at Morris compared to Lamberton from years 3-6 but was substantially greater the last four years of the study at nearly 100 lbs P_2O_5. Splitting the data was done to determine if application of P below removal would result in declines in soil test P where response to P would be much greater as time progressed. It did appear that the response to P was increasing with time at Morris more compared to Lamberton. A greater potential for p response at Morris does follow the fact that the soils at Morris had a greater potential to fix and retain P. While the EOPR increased at both sites, the EOPR was still less than P removal at each site.

A second component of the study was to determine if timing of P application would impact corn or soybean grain yield. An analysis was conducted across blocks for both crops at each site for years 3-10 (Table 5). The first rotation in years 1 and 2 were omitted as not all treatments were established until the end of the first rotation. Data was not summarized for Saint Charles as the site did not respond to P and the only possible impact from treatments could have been a yield increase for corn due to starter effects (which did not occur). For Lamberton and Morris, soybean yield was not impacted by P fertilizer timing. Corn yield was impacted by timing at both sites. At Lamberton, corn grain yield was nearly 4 bu/ac less when P was split applied but was similar when P was either applied all before corn or soybean or starter was applied to corn and broadcast P was applied to soybean. At Morris, there was a clear advantage to P applied prior to corn, which included P applied as starter. Corn yield was reduced when P was applied before soybean or split applied. Even though both sites did not exhibit consistent results, it does appear that P application ahead of corn is a better option as soybean was not impacted by timing. A reduction in yield due to split application was interesting as 2/3 of the total P was applied before corn. The fact that starter to corn plus broadcast to soybean did not reduce yield also may indicate a better efficiency of the banded P application. The band application would give farmers an option to apply P to corn without having to pay application costs for broadcasting P to both crops.

Table 5. Summary of statistical difference for P application timing over 8 cropping years (years 3-10) at two P responsive locations in Minnesota considering treatments where similar amounts of P were applied over two cropping years. Timing of application within a 2-year corn-soybean rotation include all P before corn (B4 Corn), all P before soybean (B4 SB), 2/3 P broadcast before corn and 1/3 before soybean (Split), and 5 GPA of 10-34-0 applied in-furrow to corn plus broadcast P applied before soybean (Starter).

	Corn†			Soybean†		
Timing	B4 SB‡	Split	Starter	B4 SB	Split	Starter
	--*P*>F--					
	Lamberton					
B4 Corn	ns	4.3***	Ns	ns	ns	ns
B4 SB	--	3.9**	Ns	--	ns	ns
Split	--	--	Ns	--	--	ns
	Morris					
B4 Corn	5.5*	5.6*	ns	ns	ns	ns
B4 SB	--	Ns	ns	--	ns	ns
Split	--	--	ns	--	--	ns

† Asterisks indicate significance at $P \leq 0.05$ (*), 0.01 (**), and 0.001(***). ns, timings of P application were not significantly different.
‡ Letters in cells represent the average difference between with column treatment minus the row treatment based on linear contrast statements.

Impact of Crop Removal on Soil Test Maintenance

Table 6. The average amount of P fertilizer (in lbs P_2O_5/ac) that was needed to increase soil test by 1 ppm over a ten-year period for the Bray-P1 and Olsen P soil tests.

	Lamberton	Morris	Saint Charles
	-------------------------lb P_2O_5/ppm-------------------------		
Bray P-1	20	13	33
Olsen P	33	23	77

Table 6 summarizes the amount of P required to increase the Bray-P1 or Olsen tests by 1 ppm. The total amount of P applied over the ten years was factored into this soil test change. Overall, it took more P to raise soil test levels at St Charles. However, soil loss due to runoff from this site resulted in some plots returning to 2009 soil test levels for the western block following the 2017 growing season. Thus, the data after year 9 likely is inflated and over estimates the amount of P needed to increase soil test levels. Between 14 to 20 lbs P_2O_5 is generally expected to be needed to raise the Bray-P1 test by 1 ppm. The data obtained from this trial has varied over time but the amount after ten years shows a slightly higher requirement at two of the three locations.

Average soil test change based on total P application rate over ten years is summarized in Appendix Figure 4a. One interesting result is the curvilinear response of soil test increase to P application rates at Morris and Saint Charles. Throughout this study the relationship between soil test change and total P applied has been linear but with decreases in soil P over time now it appears that adjustments in removal due to poor yield may be levelling off soil test values for the sub-optimal rates. Figure 4a includes all data points while figure 4b includes data from Morris and Saint Charles summarized only for treatments which showed a positive increase in soil P. The slope of the linear regression lines in figure 4b was used to calculate soil test change over time for Morris and Saint Charles as including the points near the lower end of the application rates resulted in an underestimation of soil test change. At Morris, soil test values tended to increase when 80 lbs P_2O_5 were applied over a two year period which is roughly the average EOPR over the last eight years of the study at Morris. This indicates that P rates which maintain or slightly increase P should be sufficient to maximize yield and profitability at Morris. The same claim cannot be made at Saint Charles where there was no yield response, on average, across the ten years of the study. The relationship between soil P increase and P application rate was linear at Lamberton but the only treatment where soil test generally was less than the initial soil test in 2009 was the no P control.

One item of interest in this study was to determine the effect of crop removal of P or K on change in soil test. Many growers are interested in removal based application in order to maintain fertility within their fields. Since soils can vary in their chemical properties there can be some differences in how P or K levels build over time. Within most maintenance systems it is not recommended to use the past year's yields to determine how much fertilizer to apply. Even though it is seems logical, variation in yield and nutrient uptake in grain create great uncertainty on the exact numbers to use to where over-application of nutrients is highly likely if removal is based on previous yields. Typically, long term averages work better in order to determine include and decline of soil test.

Table 7. Summary of annual soil test change based on crop removal of P or K following nine years for fertilizer application and removal. Data are calculated from Figure 5.

Location	Soil Test Change when applying P or K based on crop removal	Annual P or K application required to Maintain Soil Test	% Crop Removal required for maintenance
	------ppm yr^{-1}-----	----lb P_2O_5 ac^{-1} yr^{-1}---	
Lamberton	1.9	-31	32%
Morris	0.6	-16	65%
Saint Charles	0.6	-31	43%

The net amount of P removed was calculated following nine cropping years at all locations and is summarized in Figure 5. Table 7 summarizes the annual rates of change based on if exact crop removal is targeted as well as the amount of fertilizer needed on an annual basis to maintain soil test levels. A removal based approach resulted in an increase in soil test P in the top 6" at all sites. The increase was the greatest at Lamberton at 1.9 ppm per year and least at

Morris and Saint Charles averaging 0.6 ppm per year. In order to maintain soil test 31 lbs P_2O_5 per acre per year could be removed at Lamberton and Saint Charles, followed by 16 lbs at Morris. Considering crop removal, only 32% of the annual removal total was needed to maintain soil test P at Lamberton, 65% at Morris, and 43% at Saint Charles.

Table 8. Summary of change in Bray-P1 and Olsen P from initial soil samples collected prior to treatment application in 2009 over time based on 2-year P application rates for P applied all before corn, all before soybean, and split applied before corn and soybean.

2-yr P application	Yearly Change in Bray-P1 P			Yearly Change in Olsen P		
	Lamberton	Morris	St. Charles	Lamberton	Morris	St. Charles
lb P_2O_5	ppm					
0	-0.62	-0.58	0†	-0.43	-0.71	-0.3
20	0†	-0.69	0†	0†	-0.73	-0.4
40	0.58	-0.55	0†	0.22	-0.73	-0.26
80	1.7	0†	0†	0.79	-0.25	0†
120	3.09	1.18	0.93	1.4	0†	0.36
160	5.31	2.55	1.37	2.53	1.1	0.66
240	7.52	4.93	3.18	3.66	2.51	1.57

†Linear regression analysis indicated no significant relationship between changes in soil test value over years

Table 8 summarizes the change is soil test P over time based on 2-year P application rates when P was broadcast before corn, before soybean, or split applied before both crops. Starter fertilizer treatments were not summarized due to questions when sampling banded treatments. Only data collected at the end of a full 2-year cycle was summarized in Table 8, and the data in Table 8 can be used to summarize points in Figures 4a where soil P is increasing or decreasing over time. Comparing the Bray-P1 and Olsen P tests, there was agreement in the amount of P needed to maintain the initial soil test values only at Lamberton. At Lamberton a small rate of 20 lb P_2O_5 every two years was able to maintain both soil tests over ten years. At Morris, the Bray-P1 test was maintained by 80 lb P_2O_5 applied ever two years but the Bray-P1 teste decreased and increased with rates were applied above and below 80 lbs P_2O_5, respectively. It took a slightly higher application rate (120 lbs P_2O_5) to maintain the Olsen soil P test at Morris. The 120 lbs P_2O_5 application rate would be closer to what is suggested for the rotation at Morris. At Saint Charles, the Bray-P1 test did not increase until 120 lbs P_2O_5 were applied. However, 80 lbs P_2O_5 were enough to maintain the Olsen test at Saint Charles and the test decreased when less than 80 lbs P_2O_5 were applied. It is not clear as to the reason for the discrepancy in tests which occurred at Saint Charles. Since soils were not alkaline at Saint Charles a response similar to Lamberton would have been expected. It is plausible that continual topsoil erosion at Saint Charles may have been contributing to some of the issues in differences between the soil tests and also may have resulted in more erratic changes in soil P over time at Saint Charles. The Saint Charles locations was tilled similar to the other locations to be consistent with practices used but the slop and erodibility of the soil would warrant no-till at this site which may have helped reduce the impact of erosion on soil P change over time.

Since we are only measuring the top 6", and given the fact that plants typically use 30% or less of fertilizer P applied, an increase in surface P could be happening at the expense of subsoil P. Soil test values for the top 0-6, 6-12, and 12-18" depths are summarized in Figures 6, 7, and 8 for Lamberton, Morris, and Saint Charles, respectively. The figures only represent soil test data for samples collected in June 2017 and 2018 from soybean plots and do not reflect change in soil test values as depths greater than six inches were not samples at the initial establishment of these trials in 2009. Thus, the data can only prove that the application, or lack thereof, can impact soil P at deeper depths and cannot prove the mining of P from the sub-soil. Previous treatment application tended to increase all soil test depths at Lamberton and two of the three depths at Morris and Saint Charles. At Morris, there was no difference in soil P due to previous P application at the 12-18" depth in 2017 while at Saint Charles there was no difference at the 6-12" but differences were found at the shallower and deeper depths. It is most likely that there were differences at all depths at Saint Charles but there was more variation among values within treatments resulting in difficulties assessing significance. Plots which did not receive P ahead of the soybean were primarily sampled.

The high rate before soybean was sampled and the increase in soil P was greater for freshly applied P versus P applied ahead of the previous crop. One routine question I receive is whether field can be sampled after recent fertilizer application. Since P can react slowly it is more likely that sampling too soon after application can result in inflation of P test results. While the data are limited it would support the fact that sampling following high rates of P applied would likely result in over estimation of soil test P availability. Since there was little difference between the soil test increase for rates of P applied ahead of corn versus the split applied treatment which applied only 1/3 the total P before soybean, fields where lower rates of P are applied may be safer to sample.

The impact of the deeper soil test values has not been fully studied. Past research has shown that the 0-6" soil test has been generally accurate to predict where a response to P may occur. One exception to this may be the Saint Charles location which should respond to P but has not consistently over the life of this study. Figure 8 shows that soil P levels were much higher in the 12-18" depths and it has not been uncommon to find higher levels of P and K in subsoils of some of the deep loess soils in southeastern Minnesota. One possible cause for the lack of yield response and lack of soil test change could be erosion bringing higher P testing soils closer to the soil surface. The silt loam soils have also been shown to mineralize organic nutrients at greater quantities compared to poorly drained soils with similar organic matter concentrations. While it cannot be determined that the soil critical P level is less in silt loam soils in southeastern Minnesota, the data does indicate that P deficiencies may be of less concern for southeastern Minnesota corn and soybean growers.

CONCLUSIONS

Medium testing P sites were selected to study the effect of timing of application and fertilizer rate in 2-year corn-soybean rotations. Corn and soybean yield was significantly increased by P over the years. Increase in soil test P varied by location and typically occurred more frequently within individual blocks within locations. It took less fertilizer P to increase soil P at Morris and the most to increase soil P at Saint Charles. However, greater rates of fertilizer could be removed at the previously mentioned sites in order to maintain soil test P.

The data has shown no direct evidence that application of all the P before either corn or soybean affects soybean yield, but there may be a benefit to supplying P directly ahead of corn. There has not been a significant yield advantage for using starter fertilizer as a substitute for broadcast P and any of the locations and the data indicates that if growers wish to apply P ahead of soybean a small rate of P in-furrow can result in a similar yield potential for corn compared to a high rate of broadcast P applied ahead of corn for both crops.. Rate of fertilizer applied within a two-year rotation appears to be the most significant consideration within a fertilizer application program. The rate required for maximum economic yield and to maintain soil test values in the top six inches is less than the amount of P or K removed over the 2-years in a corn-soybean rotation. Thus, growers do not have to continually apply higher removal based P rates to ensure maximum yield potential for two year corn-soybean rotations.

ACKNOWLEDGMENTS

The authors would like to thank the Minnesota Agricultural Fertilizer Research and Education Council for the support of this project. We would also like to thank our cooperators for their current and future support on the project along with the crop consultants which also were instrumental in helping locate and establish the trials. We also would like to thank the field crew from the Department of Soil, Water, and Climate for their technical support on the research project.

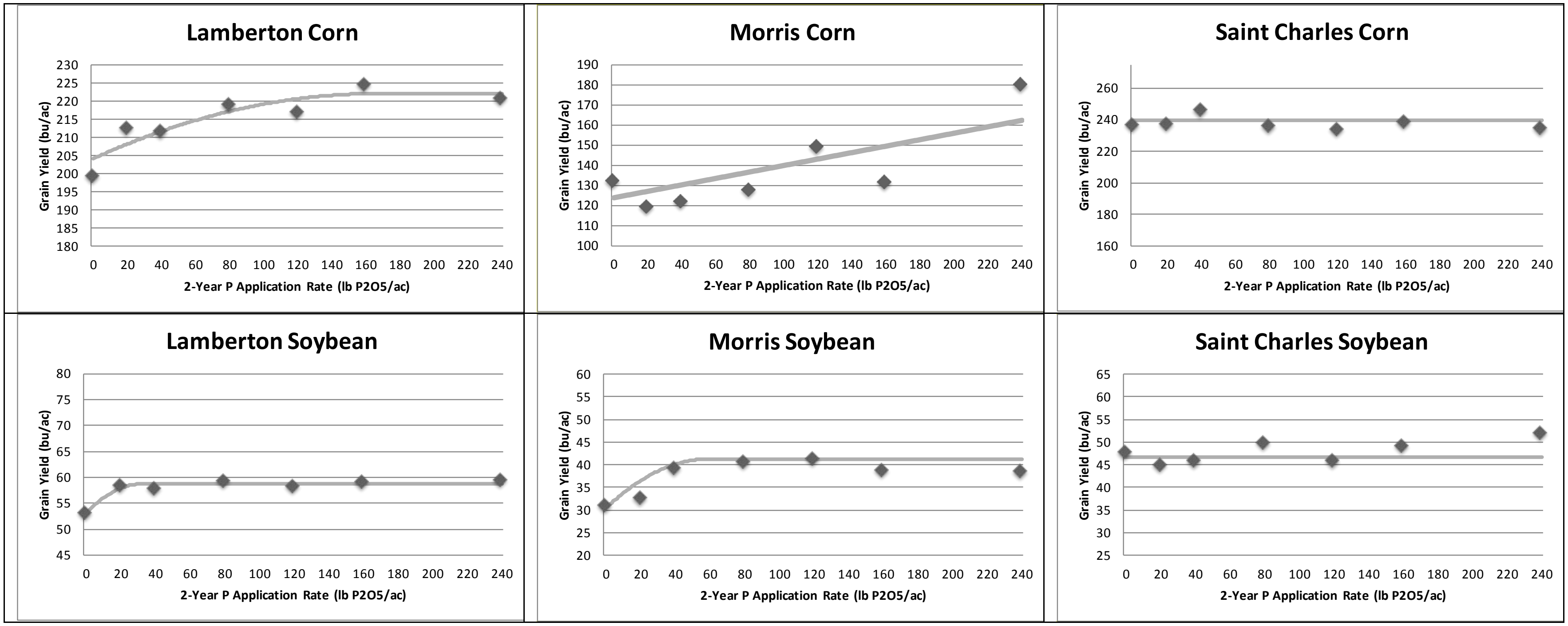

Figure 1. Corn and soybean yield summary for 2-year total P applications at three Minnesota locations in 2018.

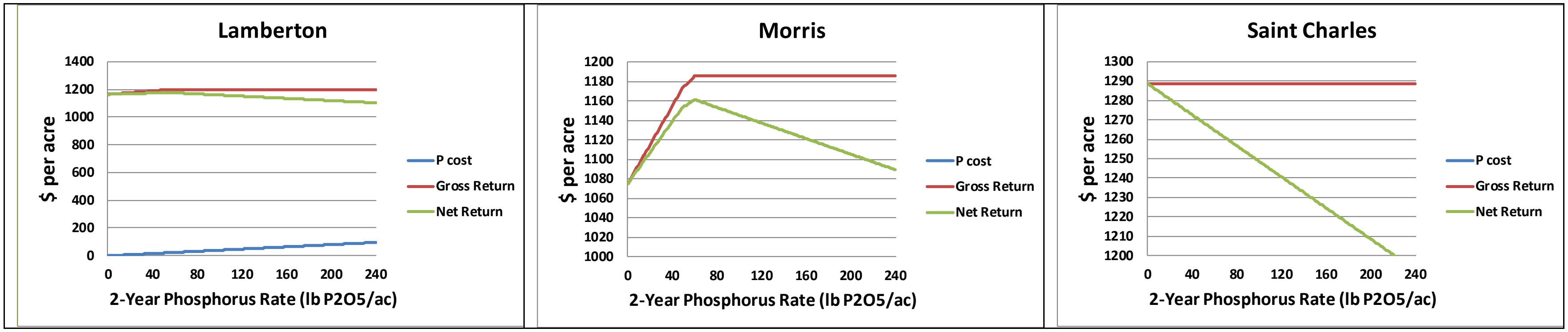

Figure 2. Summary of gross and net return to phosphorus application for three locations in Minnesota. Data are summarized based on average crop response for corn and soybean over two blocks at each site over three cropping cycles (4 corn and 4 soybean crops from years 3 to 6 of a ten year cropping sequence).

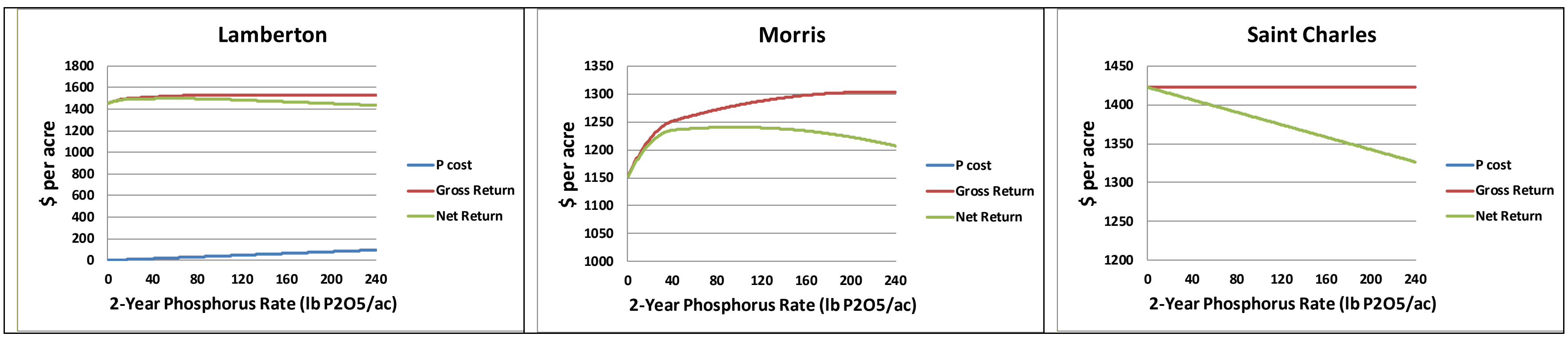

Figure 3. Summary of gross and net return to phosphorus application for three locations in Minnesota. Data are summarized based on average crop response for corn and soybean over two blocks at each site over three cropping cycles (4 corn and 4 soybean crops from years 7 to 10 of a ten year cropping sequence).

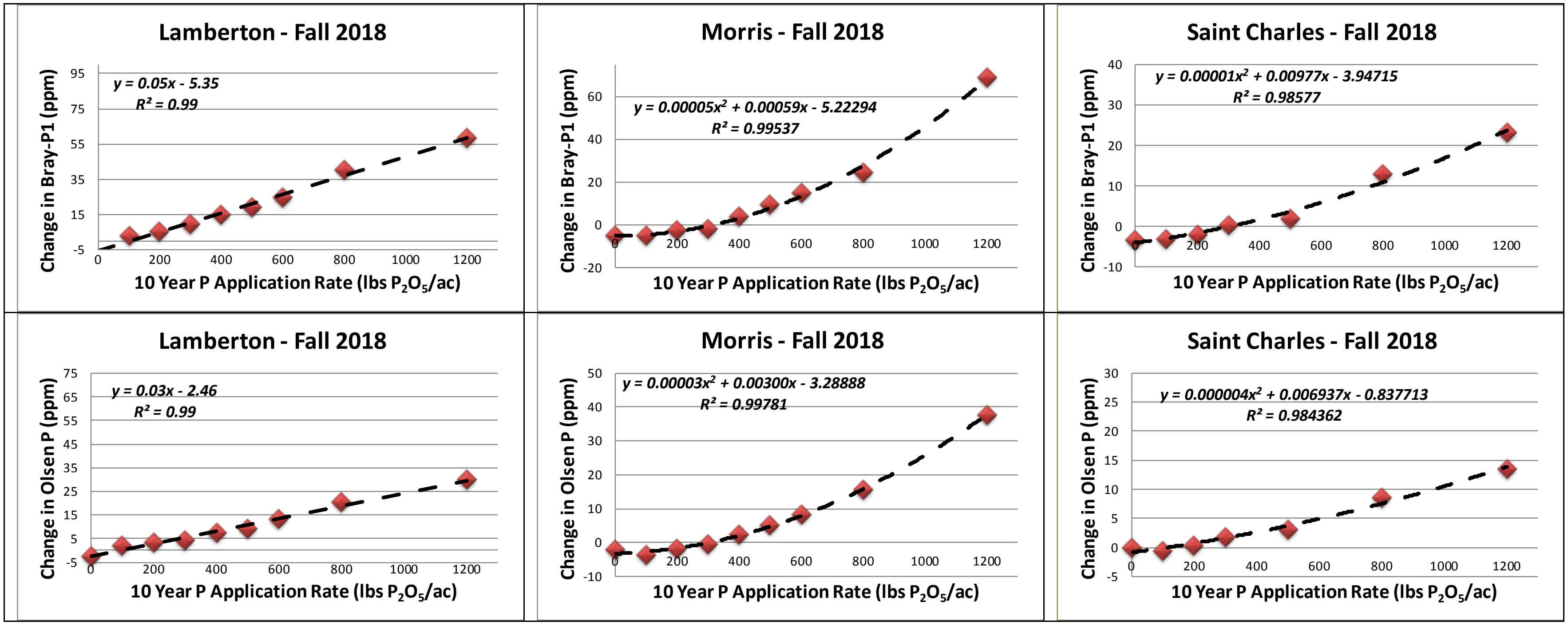

Figure 4a. Change in soil test P for the Bray-P1 and Olsen-P tests after eight cropping seasons for three Minnesota locations.

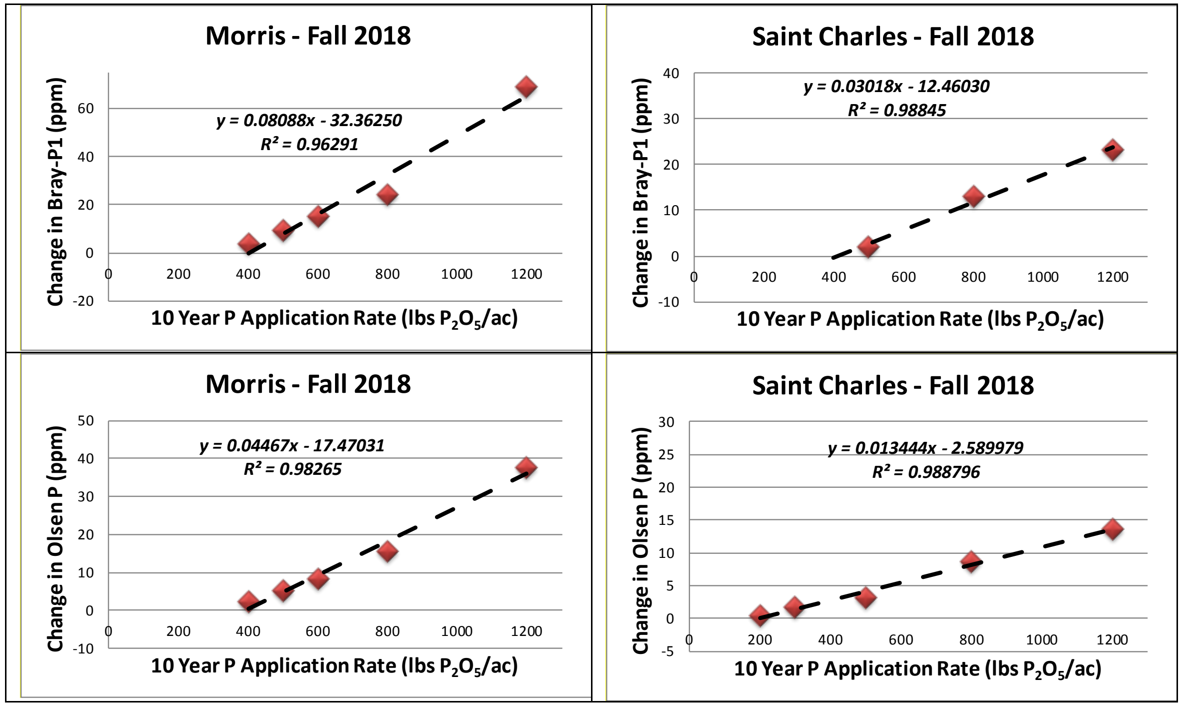

Figure 4b. Change in soil test P for the Bray-P1 and Olsen-P tests after eight cropping seasons for two Minnesota locations accounting for treatments where soil test was increased by P application.

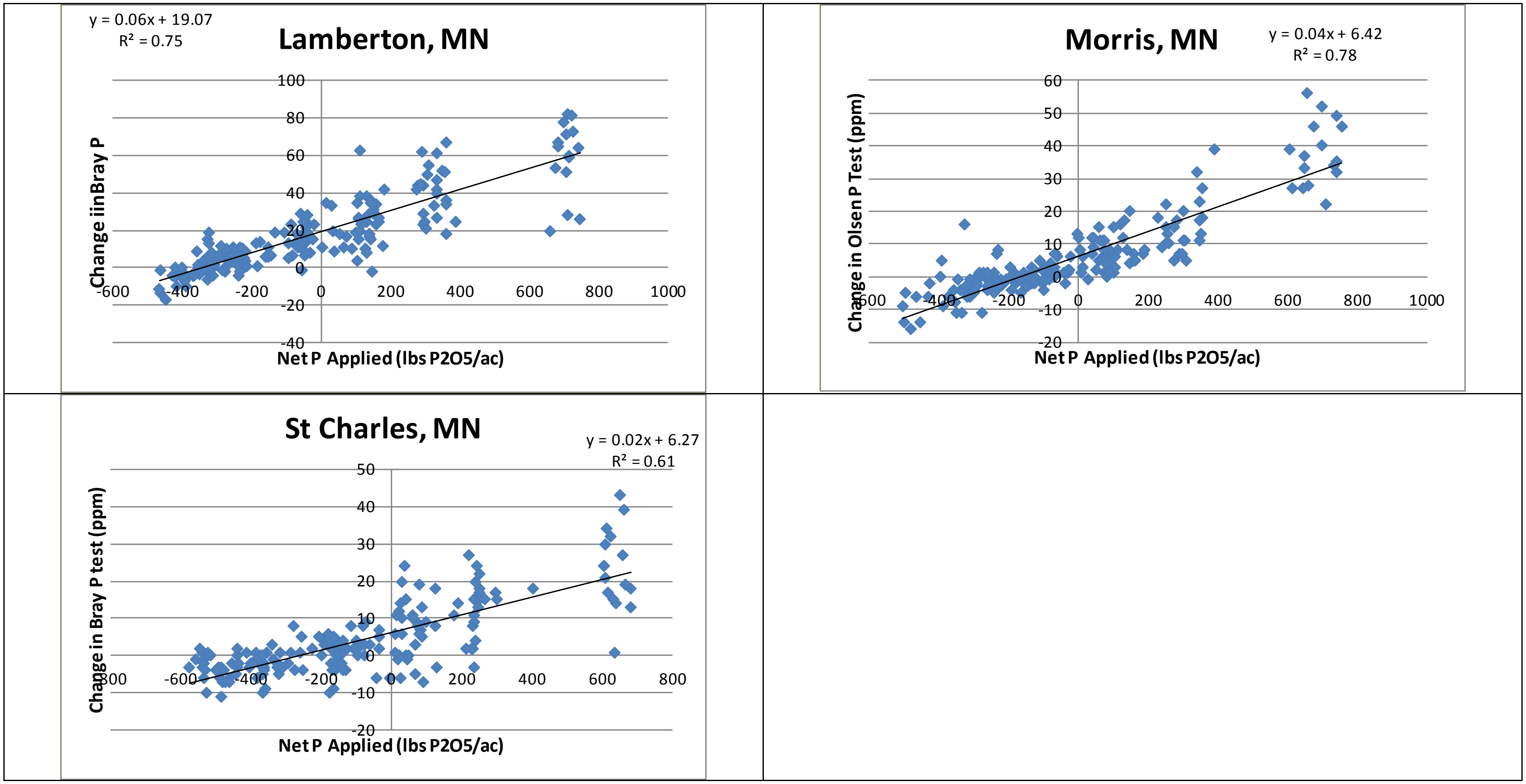

Figure 5. Summary of net P applied over ten growing season (applied P minus P removed in grain) versus the change in the Bray-P1 or Olsen soil tests.

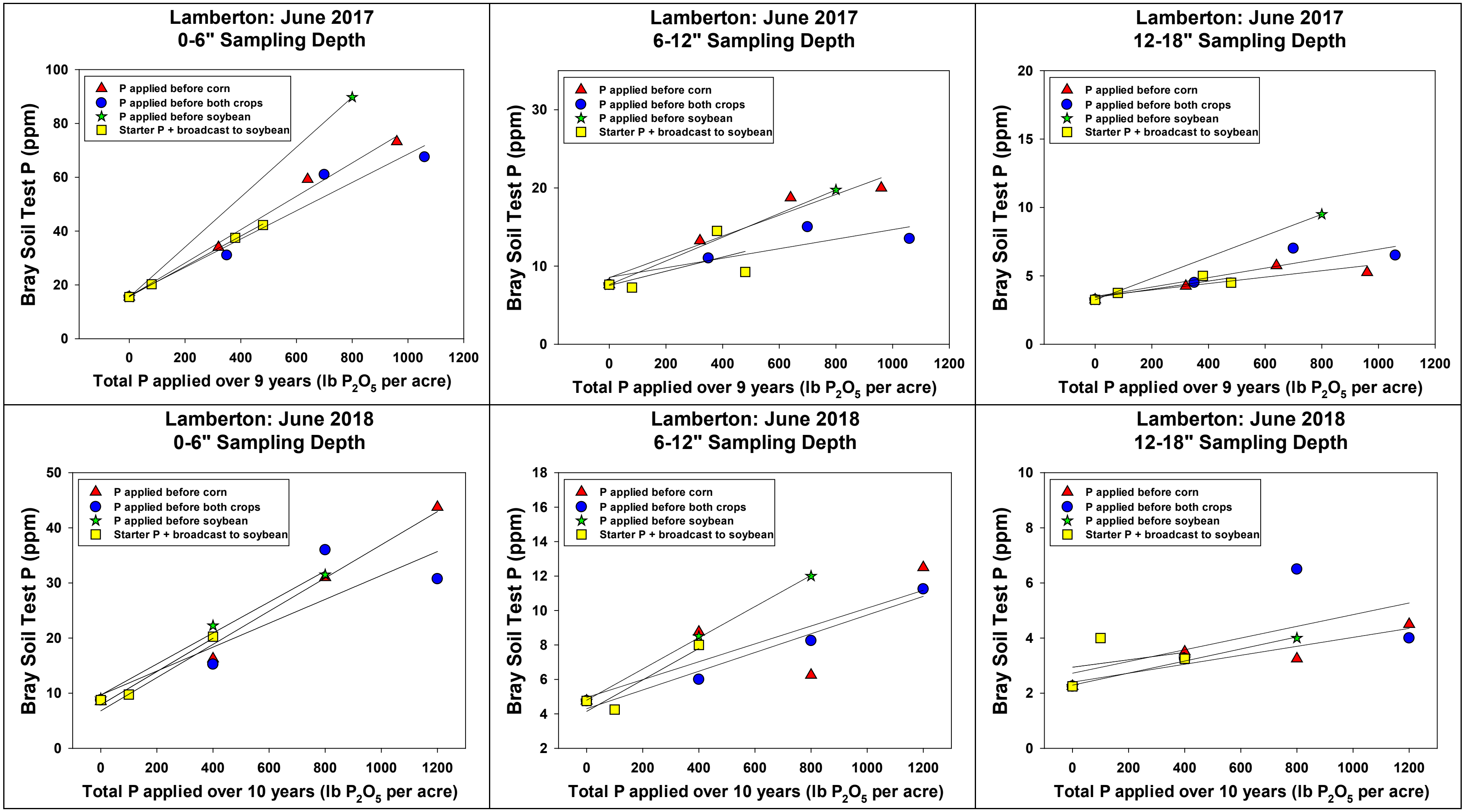

Figure 6. Summary of soil test values based on P fertilizer timing as affected by total rate of P applied over nine (2017 data) or ten (2018 data) cropping years at three sampling depths from the P study at Lamberton. Regression lines are presented when the analysis indicated significant difference between treatments for a specific sampling depth.

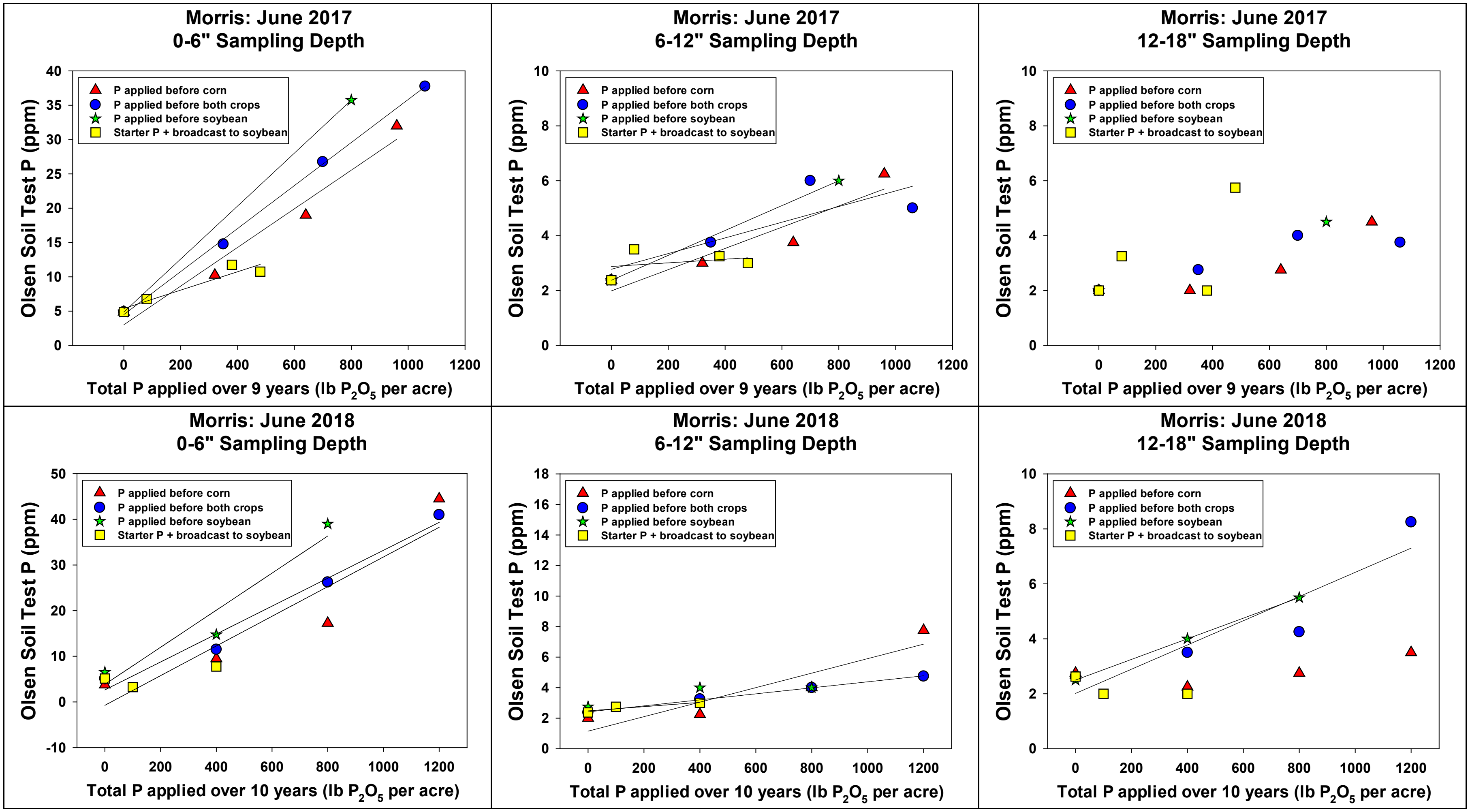

Figure 7. Summary of soil test values based on P fertilizer timing as affected by total rate of P applied over nine (2017 data) or ten (2018 data) cropping years at three sampling depths from the P study at Morris. Regression lines are presented when the analysis indicated significant difference between treatments for a specific sampling depth.

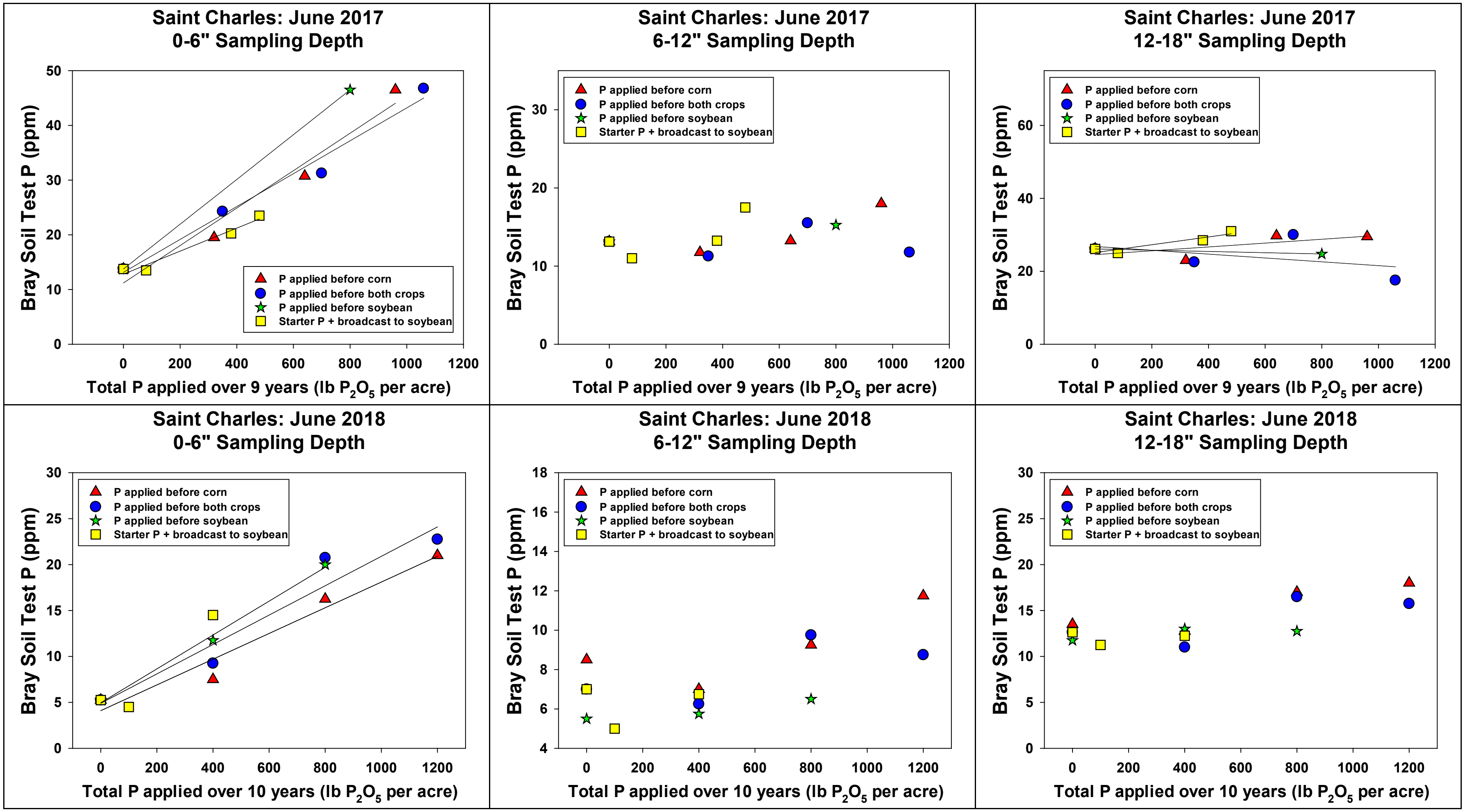

Figure 8. Summary of soil test values based on P fertilizer timing as affected by total rate of P applied over nine (2017 data) or ten (2018 data) cropping years at three sampling depths from the P study at Saint Charles. Regression lines are presented when the analysis indicated significant difference between treatments for a specific sampling depth.