Corn and soybean grain yield, phosphorus removal, and soil-test responses to long-term phosphorus fertilization strategies

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Introduction

The prevailing phosphorus (P) management system in Iowa and the Midwest is based on soil P testing, response-based fertilizer application for low-testing soils, and removal-based fertilizer application to maintain desirable soil-test P (STP) values. Several issues are important for an effective implementation of this philosophy. These include use of appropriate soil-test methods and field calibrations to determine optimum STP levels and fertilization rates, knowledge of fertilization and cropping impacts on STP over time, reliable estimates of P removal with harvest, and use of efficient fertilizer placement methods. In Iowa, continued research during the last two decades has provided yield response calibrations for the Bray-1, Olsen (or bicarbonate), Mehlich-3 colorimetric, and Mehlich-3 ICP (inductively-coupled plasma) soil test methods. Scarcer research has focused on gaining understanding of the effects of long-term fertilization strategies for corn-soybean rotations on yield, P removal with harvest, and STP trends over time. This research is important to improve the effectiveness of P management on crop production and to maintain acceptable water quality in the state of Iowa. This information will allow producers and nutrient management planners to make prudent management choices to both profit from crop production and be mindful of environmental impacts.

Other long-term Iowa studies have shown that eight to nine years of corn and soybean production without fertilizer addition of P are required before statistically significant yield responses begin to be observed in soil testing high to very high (30-40 ppm, Bray-1 P). Phosphorus removal was not measured in these trials, but they showed that rates of 27 to 35 lb P_2O_5/acre/year maintained an optimum soil-test level (16 to 20 ppm). The STP level, P application rate, soil type, and yield level (by affecting P removal) influence the amount of P required to maintain or increase STP. Studies in Minnesota showed that rates between 39 and 53 lb P_2O_5/acre maintained STP. Estimating grain P removal requires knowledge of grain P concentrations and good yield estimates. The Iowa studies mentioned above where net P additions or removal was not measured indicated that 35 to 57 lb P_2O_5/acre/year increased Bray-1 STP in the top 6 inches of soil by 1 ppm/year. Minnesota studies on soils relatively similar indicated that 41 to 71 P_2O_5/acre/year were required to increase TP by 1 ppm/year. Coupling of grain P removal and fertilizer applications to calculate a net P addition or removal along with its relationship to STP change would be a valuable tool for predicting the time or P removal required to lower the STP of a given site by a certain amount. Therefore, the goals of the study summarized here were to evaluate how the P placement method and P application rate for corn-soybean rotations affect long-term yield, P removal, and STP trends.

Summary of methods

The study was conducted over 12 years at five locations representative of major Iowa soil and crop production areas. The trials were located in the Northeast (NERF), North central (NIRF), Northwest (NWRF), Southeast (SERF), and Southwest (SWRF) research farms. Twelve treatments consisted of different placements and rates of P for corn-soybean rotations managed with no-tillage. Both crops were grown each year on adjacent areas of the field using similar design and treatments. To reduce costs, only grain samples from the most meaningful treatments common to all experiments were selected for analysis. We summarize yields and grain P removal for five treatments that consisted of a check receiving no granulated P fertilizer and annual rates of 28 or 56 lb P_2O_5/acre broadcast (coded as B1 and B2) or banded with planter attachments 2 inches besides 2 inches below the seeds (coded as S1 and S2). Although soil was always sampled to depths of 0-3 and 3-6 inches, we summarize results for the 6-inch depth from plots receiving no P and plots receiving broadcast P at 56 lb P_2O_5/acre/year.

Summary of results

Phosphorus rate and placement effects

Grain yield

The crop response to P fertilization varied greatly across the five locations and 12 years of the study mainly as a result of differences in STP and yield levels. The initial STP values and other soil properties are shown in Table 1. Sites initially testing high or very high in STP (NERF and SERF) showed infrequent and small yield responses to P application rate and placement method. At NERF, there was a crop response to P fertilizer only in one year and only for corn, when the high P rate broadcast or banded increased yield over the control. At SERF, P fertilization increased corn yield in two years and soybean yield in one year. At both sites there were no clear differences between the P rates applied. The P placement methods differed only one year at SERF, when corn yield was slightly higher for the banded method. At the site initially testing very low in STP (NWRF) there were very consistent responses to P application across all years of the study and the higher P rate often increased yield further over the low rate. However, the P placement methods differed only in two years for corn, when banded P was slightly better in one year and broadcast P was slightly better in the other year. The two sites initially testing low in STP (NIRF and SWRF) showed increasing responses to P fertilization toward the end of the study, as STP in the control plots decreased into the low and very low STP interpretation classes. The P application rates differed in a few years at NIRF, and there were no differences between the P placement methods at these two sites. Therefore, results confirmed previous Iowa results in that crop response to P is likely in low-testing soils, unlikely in high-testing soils, that the P placement method usually does not affect corn and soybean response to P in Iowa, and that several years of cropping without P additions are needed before crop response is observed in high-testing soils.

Grain phosphorus concentration

All five sites frequently showed statistically significant effects of P fertilization on grain P concentration (GPC) of corn and soybean, although effects were more common in soybean than in corn. There was no effect of the P placement method on GPC at any site. The GPC response to P and the P application rate was larger and more frequent in the three low-testing sites. The relationship between STP (in the 0-6 inch depth) and GPC of corn or soybean GPC showed an initial rapid increase at low STP and then a gentle increase that flattened to some degree (Fig. 1). Although the P concentration in soybean grain was higher than corn, both crops responded similarly to STP increases. This trend was similar to relationships between grain yield and STP that are not shown in this article. A steeper curve and better relationship of soybean grain P concentration with STP than for corn probably results from generally lower STP (and greater response) for the soybean sites than for corn sites and higher P concentration in soybean grain. The STP levels at which GPC appears to reach a sufficient level (not determined given the response shapes) are near the optimal STP levels for grain yield of corn and soybean (16 to 20 ppm). The range of STP precluded any reasonable estimate of luxury P uptake in soybean grain. The results for corn suggest a limited luxury P uptake into grain because the P concentration in corn grain increased with increasing STP levels beyond the optimum range for yield (16 to 20 ppm), but not beyond about 30 ppm STP.

Grain phosphorus removal

Grain P removal was calculated from grain yield and P concentrations, and the treatment effects on removal are not shown or discussed in detail because the responses combined the effects on these two measurements. There was a strong linear correlation between grain P removal and yield in both soybean and corn (Fig. 2) that explained a large proportion of the variation in P removal (73 to 75%). Grain P removal and GPC were linearly related in both soybean and corn as well (not shown) but the relationship was poorer and explained a smaller proportion of the P removal variation (40 to 50%). This large impact of yield on P removal was due to stronger effects of yield level variation than GPC variation in determining grain P removal. The GPC concentration and grain yield were not related for both crops (Fig. 3). The mean GPC observed for corn and soybean in this study (which is indicated in the graphs) were slightly lower than the values assumed in Iowa for P management guidelines, which are 0.375 and 0.8 lb P_2O_5/bu of corn and soybean, respectively (see extension publication Pm-1688). However, the assumed average values were within the observed range of concentrations.

The relationships described lead to the conclusion that good estimates of grain yield are much more important for determining grain P removal than the GPC, and that an average GPC value can be applied to yield estimates to calculate P removal. However, the results showed a large variation in GPC, which suggests a need for better understandings of factors that affect GPC across fields and years in order to improve removal estimates.

Long-term trends of grain yield and phosphorus removal

We summarize trends over time of grain yield, GPC, and grain P removal as the averages for sites with frequent grain yield response and for non-responsive sites. For soybean the responsive sites were NIRF, NWRF, SERF, and SWRF and the non-responsive site was NERF. For corn the responsive sites were NIRF and NWRF and the non-responsive sites were NERF, SERF, and SWRF. Trends for the soybean responsive sites (Fig. 4) showed increasing response to P fertilization with time in grain yield, GPC, and grain P removal compared with the control (P0) treatment. The trends show little or no difference between P placement methods and a clear increase over time in responses of GPC and grain P removal to P application and rates. The non-responsive sites showed no grain yield or grain P removal differences between treatments and even though GPC was highly variable at first, it began to show a response to P in recent years. As the STP level of the control plots declined over time there was less P to be taken up into the grain, but not yet enough of a decline in STP to affect grain yield, which provides some evidence for luxury P uptake in soybean. Trends for corn (Fig. 5) showed approximately similar results to soybean. The differences in GPC and grain P removal between the fertilized treatments and the control increased with time in the yield responsive sites. There were little or no differences in the sites without consistent yield response (and high initial STP) until recent years, when both GPC and grain P removal began showing a small response to P. These trends confirm some luxury P uptake in corn grain. This relationship also appears when comparing GPC and STP because both GPC and P removal showed a response to P when grain yield was not clearly affected.

Important conclusions from long-term trends of grain yield, P removal, and GPC are that there were no differences between P placement methods, that all three measurements responded to P application when STP was insufficient for grain yield production, that there are only small responses of GPC and P removal in high-testing soils in the absence of yield responses, and that increasing responses with time are the result of declining STP in the control plots.

Long-term trends of soil-test phosphorus and phosphorus removal

Soil-test P of fertilized or non-fertilized plots showed increasing or decreasing linear trends over time (there were no statistically significant curvilinear trends) and results are shown in Fig. 6. Table 2 shows the slopes of the increasing trend lines for the 56-lb annual P rate and the slopes of the decreasing trend lines for the non-fertilized plots. These slopes indicate the average rate of STP change by year. A P rate of 56 lb P_2O_5/acre/year increased STP in all sites. The slope of the increasing STP trend was smallest at NERF (1.3 ppm/year increase), highest at NWRF (3.7 ppm/year), and intermediate at other sites. This result suggests a rapid STP increase with P fertilization when initial STP is low and a more gradual increase if it is higher. A reasonable explanation is the impact of yield level and grain P removal (the latter is primarily affected by yield). Since yield and P removal levels at NWRF were the lowest among the sites in part due to low STP (Figs. 4 and 5) more of the added P was available to increase STP. This may not be the only factor because chemical and mineralogical differences among the soils might also explain the results. However, measured soil properties indicated inconsistent and small differences in pH, organic matter, clay, and extractable cations that did clearly explain the different trends.

Calculations from equations in Table 2 for the average STP trend over time across all sites for plots receiving 56 lb P_2O_5/acre/year indicated that 24 lb P_2O_5/year would have increased STP 1 ppm/year. However, the range was 15 (for NERF) to 43 (for NWRF) lb P_2O_5/year when each site was analyzed separately. When the NERF site is excluded (where STP for this P rate was very variable over time and could have affected the buildup estimate) the range across sites was 15 to 26 lb P_2O_5/year. Large differences in initial STP (7 to 33 ppm), STP variability, and P removal (due to yield level) may explain differences in the P needed to increase STP by 1 ppm.

Soil-test P of non-fertilized plots decreased over time at all sites (Fig. 6 and Table 2). Although all relationships were linear, there are obvious plateau trends in recent years at all sites, which were more obvious and more extended over time at the low-testing sites. Previous research over nearly 30 years and involving higher initial STP values at other Iowa sites summarized by Dodd and Mallarino in 2005 also showed clear plateau STP values after many years without P fertilization. The slopes of decreasing trends were steeper at the non-responsive NERF and SERF sites, where initial STP, grain yield, and P removal levels were highest (Figs. 4 and 5).

Average long-term trends for P removal and STP across non-fertilized plots of all sites shown in Fig. 7 clearly show a good relationship between P removal and STP decreasing trends. On average removal of 37 lb P lb P_2O_5/acre/year resulted in an average STP decrease of 0.78 ppm/year, which translates to removal of 47 lb P lb P_2O_5/acre/year to decrease STP 1 ppm/year. An equation (not shown) relating net P addition or removal and STP across fertilized and non-fertilized plots across all sites had a good fit for the drawdown portion but not for the buildup portion due to high variability in the data and relatively small P application rates. This equation showed that a net addition of 15 lb P_2O_5/acre increased STP 1 ppm, which was a value only slightly lower than the average value reported for the Midwest or the Great Plains (16 to 18 lb P_2O_5/acre). Better predictions could be made with a longer study and with higher P application rates that would override effects introduced by P removal and STP variability. The data in Figs. 4, 5, and 7 show that there was a good relationship between P removal and STP change in the long term but not in the short term, probably because of poorly understood P cycling in residues and both temporal and spatial STP variability. This is why producers should consider long-term trends and relationships when making decisions about STP maintenance.

Conclusions

Phosphorus fertilization increased grain yield in low-testing soils but not in high-testing soils. The P placement method did not affect grain yield, grain P concentration, and P removal, even when crops were managed with no-tillage. These results coincide with information from other Iowa sites managed with tillage. The P fertilization and STP effects on grain P concentration were large and frequent in soils testing low or optimum for grain production but small and infrequent in high-testing soils, and the grain P concentration was unrelated to the yield level across sites. The average grain P concentrations suggested in Iowa for STP maintenance (0.375 and 0.8 lb P_2O_5/bu of corn or soybean) were higher than averages in this study but were within the observed range. These grain P concentrations slightly overestimated P removal when yield level was estimated correctly. The yield level variation was much more important than the grain P concentration variation when determining P removal. Grain P removal was well related to declining STP over the long term but not in the short term. On average across all sites, P removal at 47 lb P_2O_5/acre/year without P fertilization corresponded to an average STP decrease of 1 ppm/year, and application of 24 lb P_2O_5/acre/year was required to increase STP by 1 ppm/year. However, these amounts varied greatly across sites being affected by STP and grain yield levels. Grain yield level variation across sites and over time was much more important than variation in grain P concentration for estimating P removal with harvest and P fertilizer rates to maintain STP over time.

Table 1. Locations, soil types and selected soil-test values.

Site	Location	Soil Series	Organic Matter, %	pH
NERF	Nashua	Kenyon	3.9	7.1
NIRF	Kanawha	Webster	5.0	7.0
NWRF	Calumet	Galva	4.5	6.3
SERF	Crawfordsville	Mahaska	4.5	6.1
SWRF	Atlantic	Marshall	3.9	5.9

Soil-Test P Values and Interpretation Classes

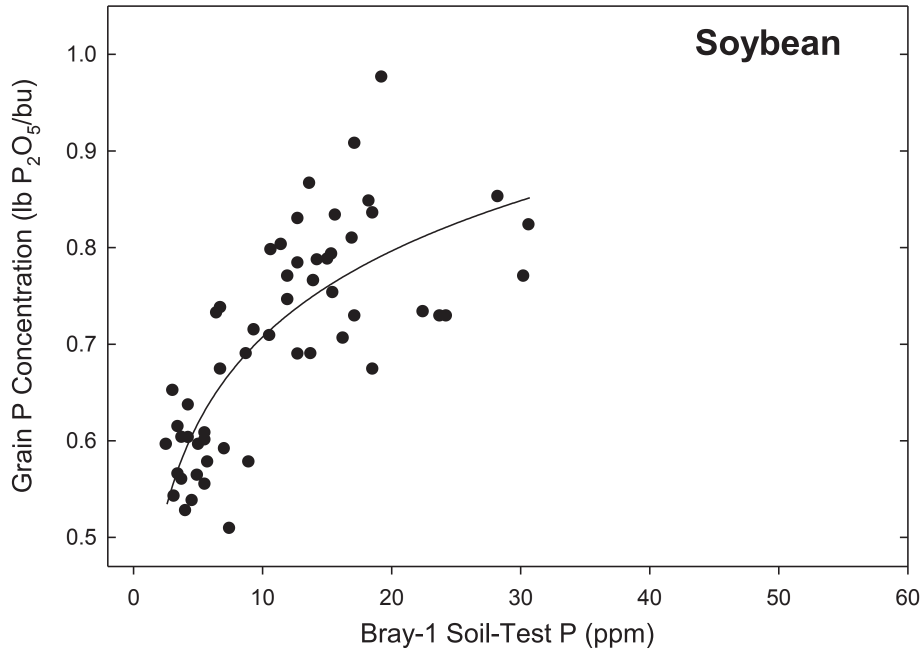
Site	0-3 in.	3-6 in	0-6 in.	Class[1]
	-------------------------- ppm	-------------------------		
NERF	38	28	33	Very high
NIRF	11	9	10	Low
NWRF	9	5	7	Very low
SERF	26	19	23	High
SWRF	22	7	15	Low

[1] The five STP classes are very low ≤ 8, low 8 to 15, optimum 16 to 20, high 21 to 30, and very high 30 ppm (Bray-1).

Table 2. Equation for soil-test P trends over time.

Annual P Rate	Site	Slope[1]	Intercept	R^2	Significance
lb P_2O_5/acre		ppm/year	ppm		P > F
0	NERF	-1.71	30.6	0.79	0.01
	NIRF	-0.43	8.1	0.53	0.01
	NWRF	-0.35	6.4	0.49	0.01
	SERF	-0.87	17.7	0.78	0.01
	SWRF	-0.55	17.3	0.43	0.02
	Mean	-0.78	17.0	0.82	0.01
56	NERF	1.31	31.4	0.29	0.07
	NIRF	2.21	9.3	0.64	0.01
	NWRF	3.72	4.5	0.81	0.01
	SERF	2.2	23.6	0.82	0.01
	SWRF	2.56	23.9	0.87	0.02
	Mean	2.37	19.6	0.9	0.01

[1] ppm Bray-1 soil-test P increase per year, where time was measured in years (1 to 12).



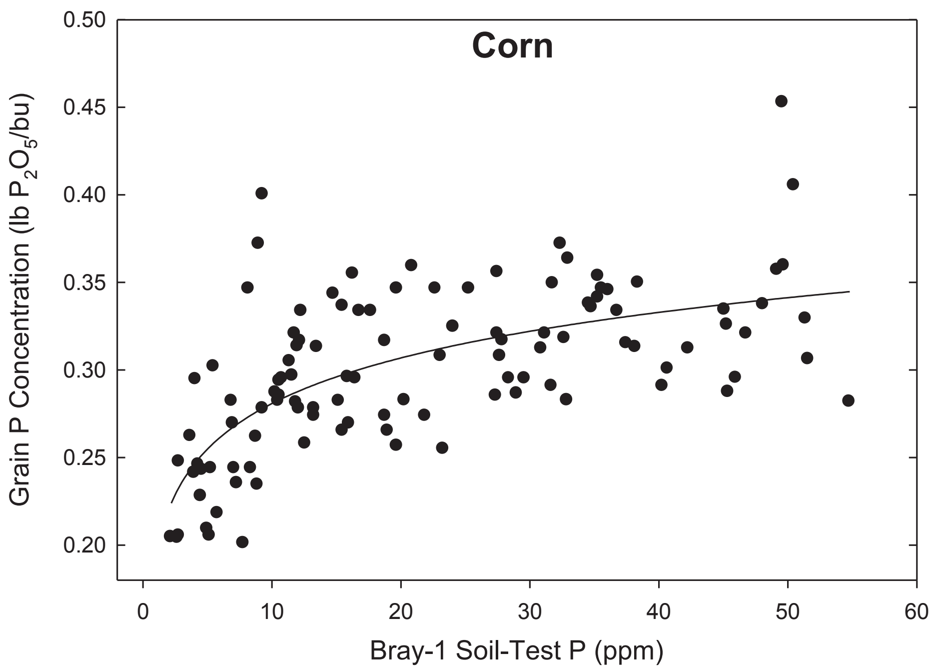


Figure 1. Relationship between grain P concentration and soil-test P for corn and soybean for non-fertilized plots across five sites and 12 years.

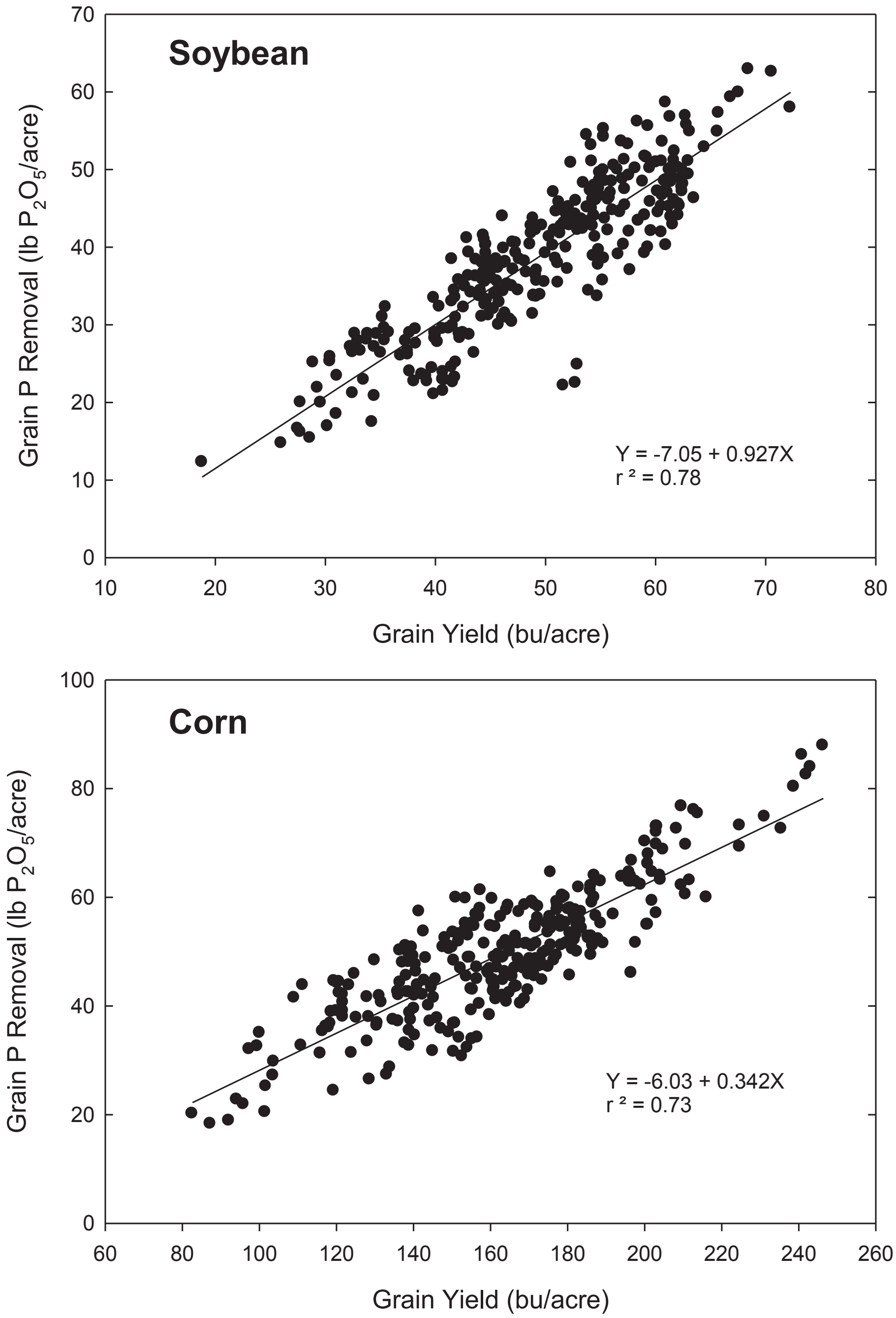


Figure 2. Relationship between grain P removal and grain yield for corn and soybean across five sites and 12 years.

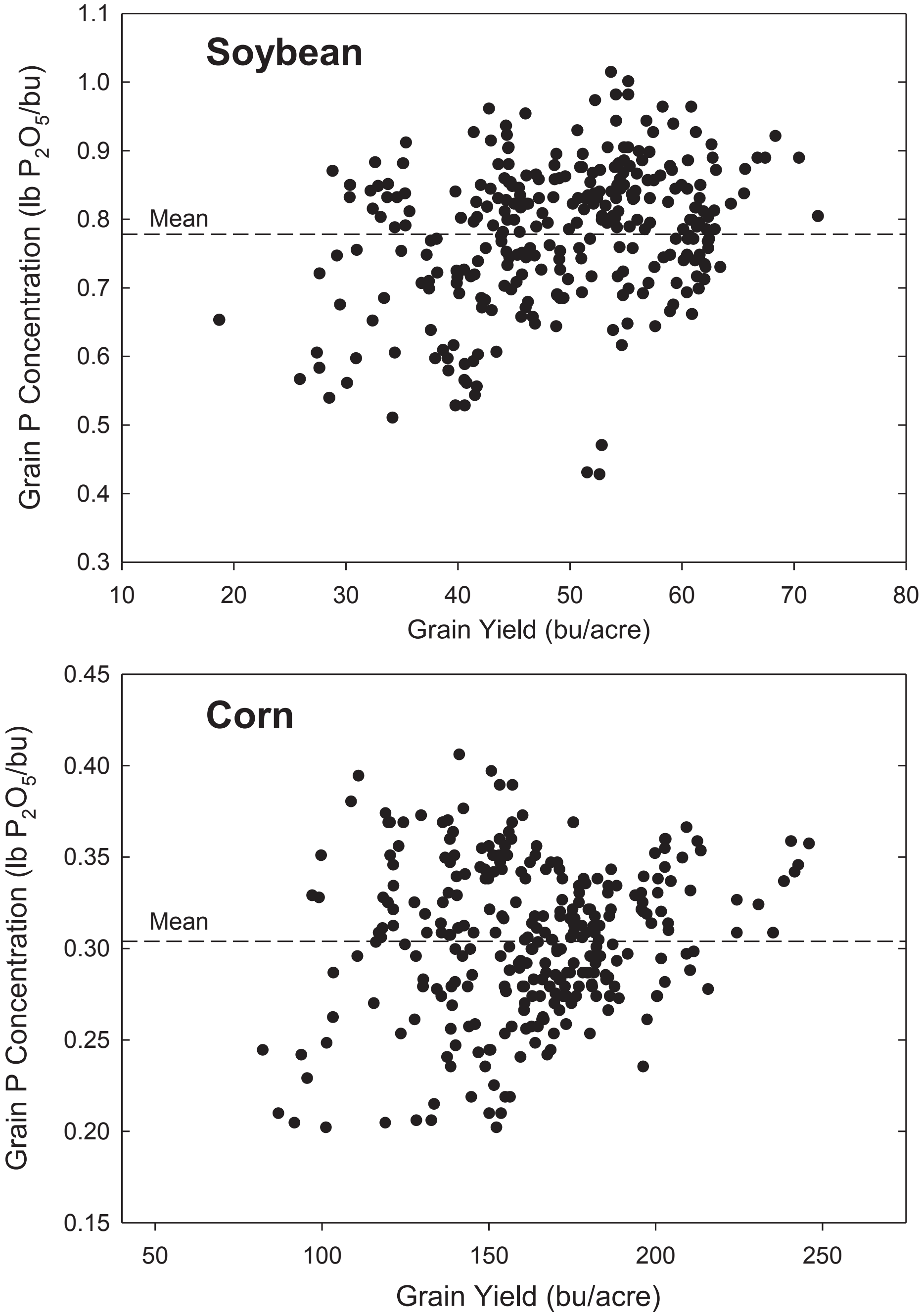


Figure 3. Relationships between grain P concentration and yield for corn and soybean across five sites and 12 years.

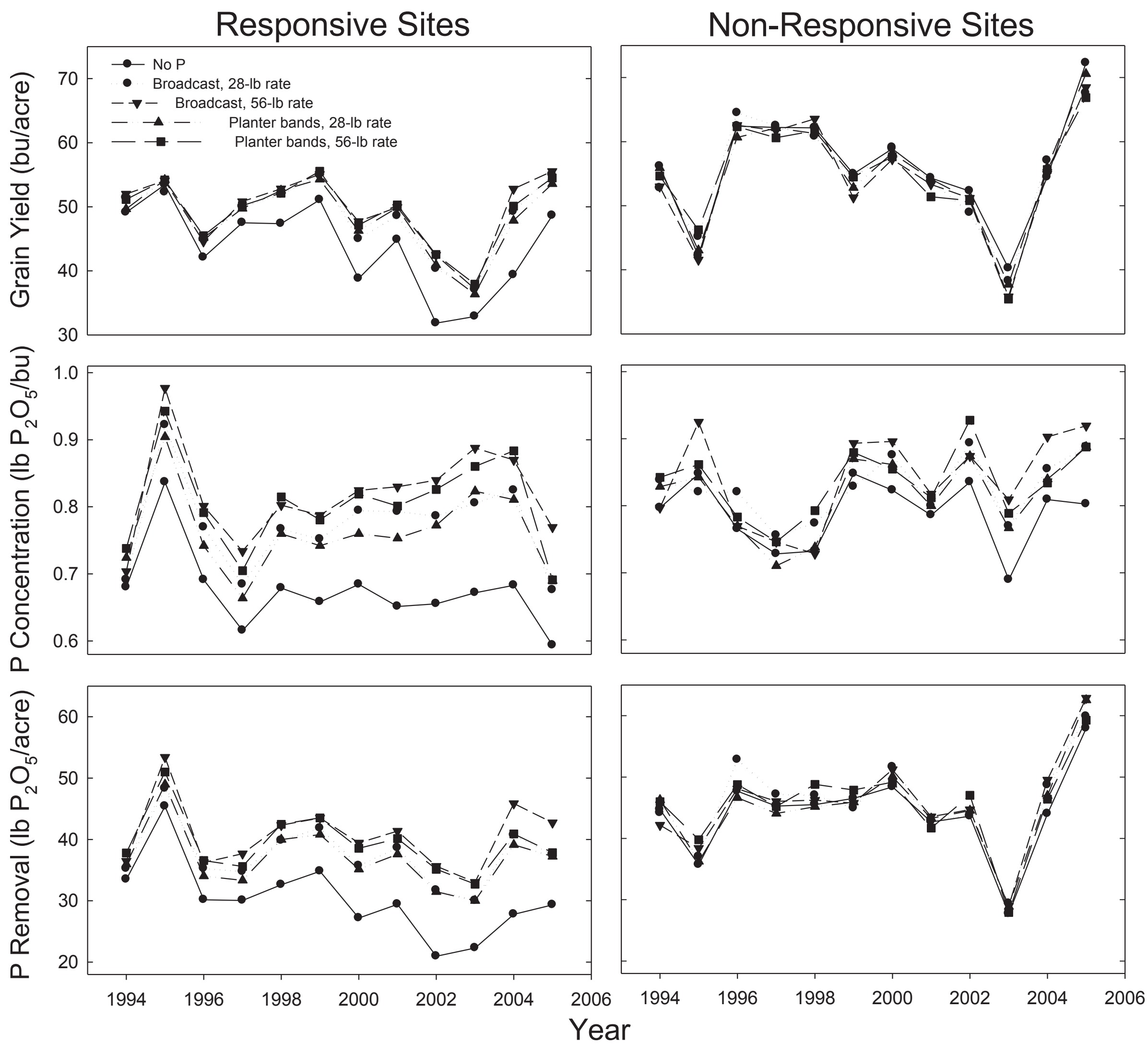


Figure 4. Soybean trends over time for grain yield, grain P concentration, and grain P removal (averages for yield responsive and non-responsive sites).

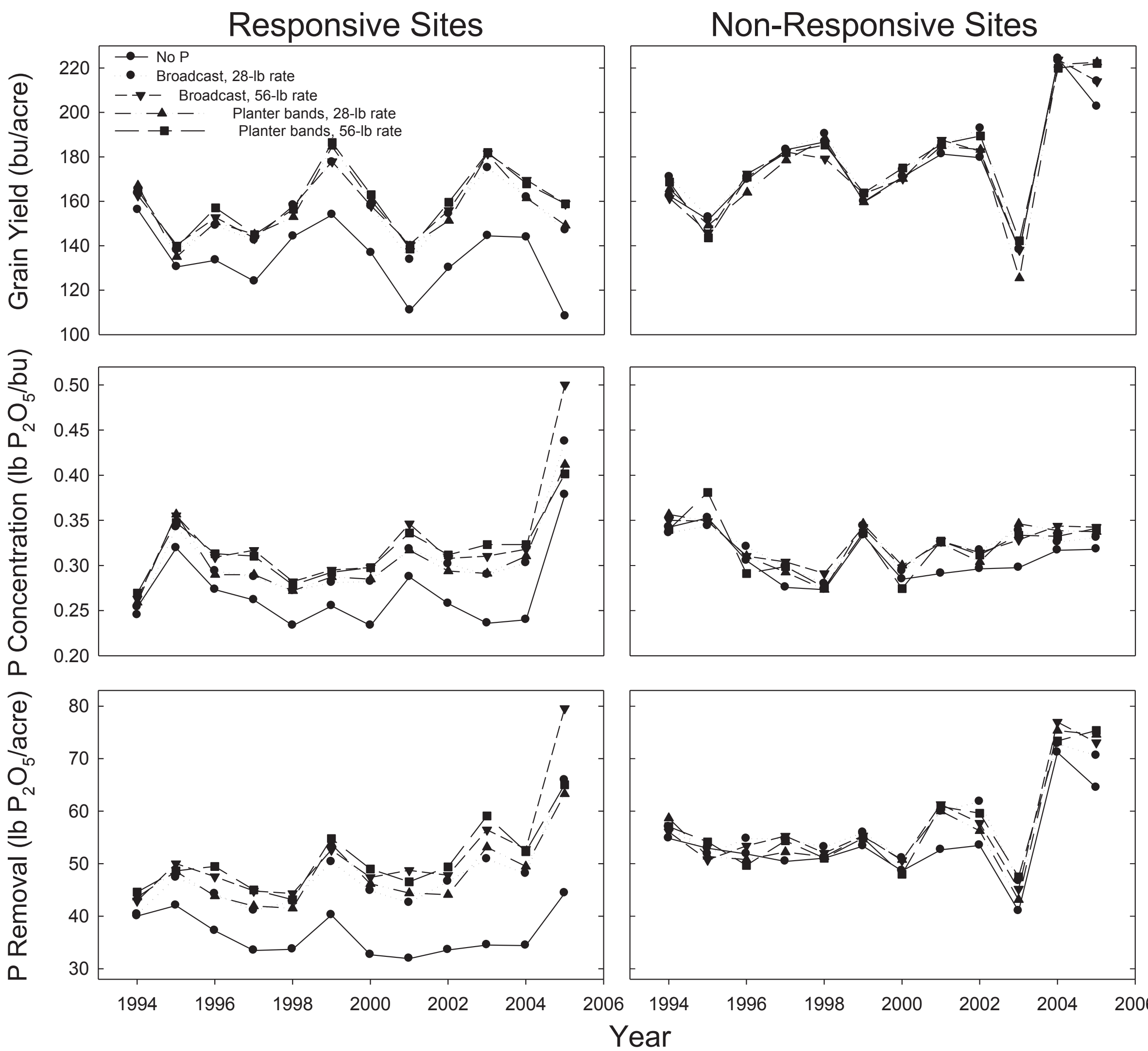


Figure 5. Corn trends over time for grain yield, grain P concentration, and grain P removal (averages for yield responsive and non-responsive sites).

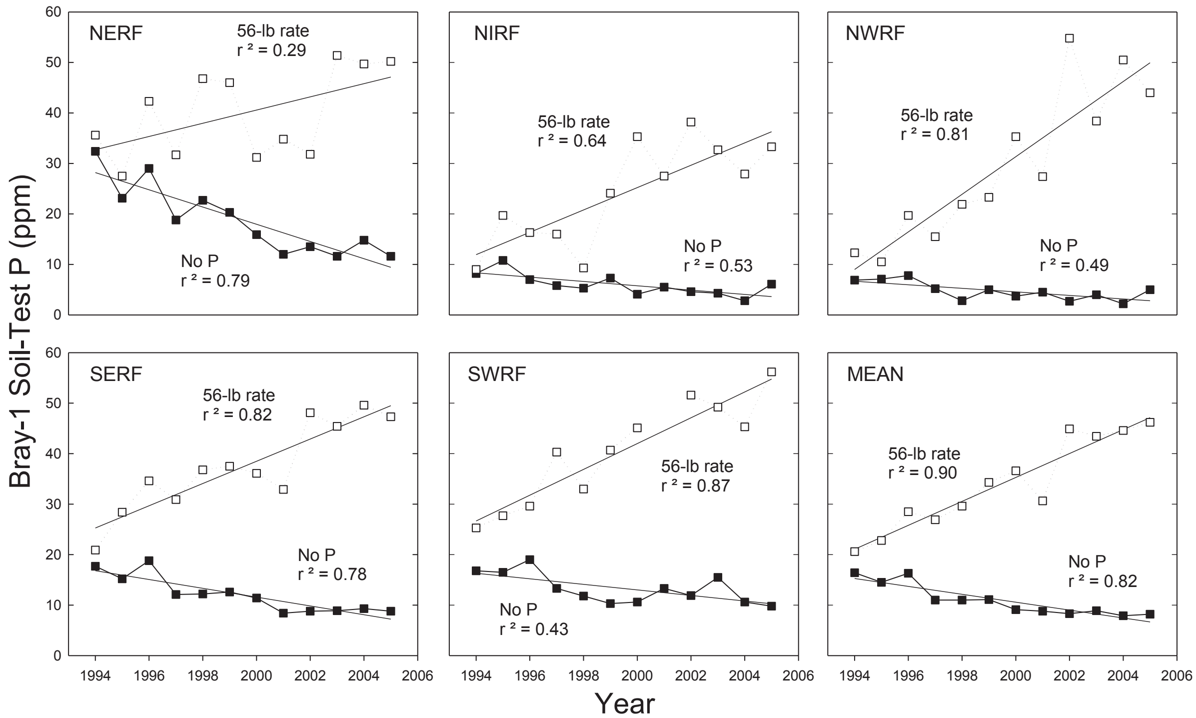


Figure 6. Soil-test P trends over time for plots of corn-soybean rotations receiving no P or 56 lb P_2O_5/acre/year for five sites and the average across sites.

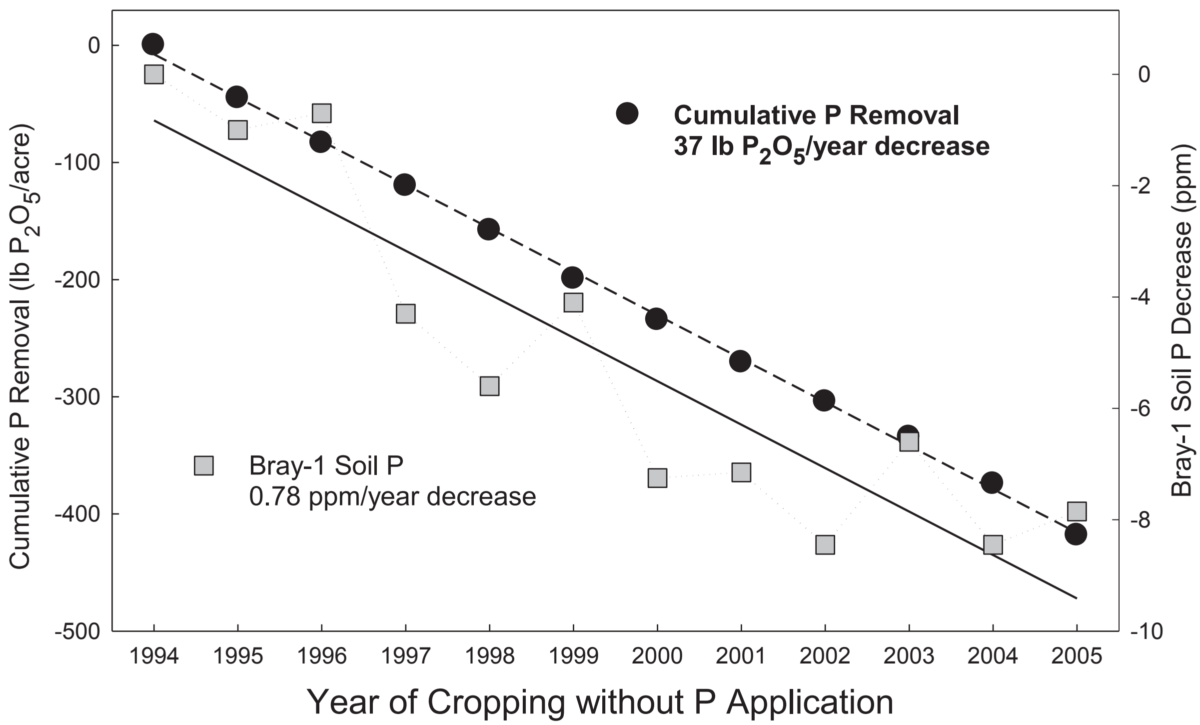


Figure 7. Average relationship between grain P removal and soil-test P over time across five sites and 12 years for plots that did not receive P fertilizer.