Long-term corn and soybean response to phosphorus fertilization in Iowa

by

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CHAPTER 1: GENERAL INTRODUCTION

INTRODUCTION

Corn and soybean are grown extensively throughout the Midwestern United States and many other regions as the major crops for agricultural production. Achieving the highest crop yields possible while considering costs of inputs increases the profitability of crop production. Management of soil nutrients that are required by these crops has been well documented as a method of increasing yield and profitability of corn and soybean production.

Phosphorus (P) long ago has been identified as an essential nutrient and one of the three main macronutrients together with nitrogen (N) and potassium (K). Phosphorus was naturally deficient in Iowa soils and most regions of the Midwest. Growers have known for many years that increasing soil-test P levels could increase their corn and soybean yields and profits. For decades, growers have been intensively applying P fertilizer to their fields. Because large applications in excess of crop removal have been applied during decades, present soil-test P levels of many fields are higher than needed for maximizing corn and soybean yield. There is a soil-test P level at which additional P fertilization does not increase corn and soybean yields.

Identifying what soil-test P levels are required for maximum corn and soybean yields is key for improved P management. Once these levels are identified, it then becomes important to understand how soil-test P changes over time under intensive cropping and to identify the P application rates that maintain those levels. Those growers who have aggressively increased their soil-test P levels over recent years can benefit from understanding how the soil-test P will decrease over time to a level that has been determined to be optimum for corn and soybean production. At the same time, some fields have soil-test P levels that are below optimum levels needed to support crop production at the maximum potential for those soils. Although these cases are few, there is a need to identify effective ways to apply P fertilizers to increase soil-test P to optimum levels.

The challenges that researchers face then are (1) identifying optimum soil P tests for crops, (2) understanding at what rate soil-test P increases-decreases over time based on the initial soil-test P level and the amount of fertilizer that is being applied to the soil, and (3) how corn and soybean yield is affected by P fertilization and STP based on three Iowa long-term experiments. Not only do these factors vary across different soils, but corn and soybean yields may respond differently to soil-test P and P fertilization.

This study was conducted with the objective of answering those questions. It was based on long-term P experiments established in middle or late 1970s at three different locations in Iowa. Corn and soybean were grown in rotation, and various P fertilization treatments were applied until 2002. Grain yield and soil-test P values, among other soil tests, were measured to achieve the objectives.

THESIS ORGANIZATION

This thesis is presented as one paper suitable for publication in scientific journals of the American Society of Agronomy. The title of the paper is "Long-term

Corn and Soybean Response to Phosphorus Fertilization in Iowa." The paper is divided in sections that include abstract, introduction with literature review, methods, results and discussion, conclusions, references, tables, and figures. The paper is preceded by a general introduction and is followed by a general summary.

CHAPTER 2: LONG-TERM CORN AND SOYBEAN RESPONSE TO PHOSPHORUS FERTILIZATION IN IOWA

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ABSTRACT

Efficient P fertilization practices are of great concern to Corn Belt farmers because of the agronomic and environmental implications of increasing soil-test P (STP) trends. This study evaluated (1) long-term STP trends for various initial STP levels and annual P application rates, (2) yields of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] as affected by P fertilization and STP. Yield and STP data were collected from three experiments established in Iowa during the 1970s on Webster (fine-loamy, mixed, mesic Typic Endoaquolls) - Nicollet (fine-loamy, mixed, mesic Aquic Hapludolls) soils, Webster - Canisteo (fine-loamy, mixed, calcareous, mesic Typic Endoaqualls) soils, and Kenyon (fine-loamy, mixed, mesic Typic Hapludolls) soils. Crops were grown in rotation each year until 2002. Three initial contrasting STP levels ranging from 17 to 75 mg kg^{-1} (Bray-P1) were created at two sites, and annual treatments of 0, 11, 22, and 33 kg P ha^{-1} were superimposed. At a third site, annual rates of 0, 22, and 45 kg P ha^{-1} were applied annually. Annual P rates required to maintain 16-20 mg kg^{-1} STP were similar at Webster-Nicollet-Canisteo soils (13-17 kg P ha^{-1}), however, >30 kg P ha^{-1} was required to maintain STP levels four times higher. At the Kenyon soil, a similar Phosphorus rate maintained a higher STP level (28 mg kg^{-1}). Critical STP concentrations identified with linear-plateau and quadratic-plateau models across sites were 18-23 mg kg^{-1} for corn and 11-18 mg kg^{-1} for soybean. Results indicate that 10-15 years of cropping without P fertilization were required on high testing soils before yield response to P was observed.

Abbreviations: AGRON, Agronomy and Agricultural Engineering Research Farm; NERF, Northeast Iowa Research Farm; NIRF, Northern Iowa Research Farm; STP, soil-test P.

INTRODUCTION

Phosphorus is an essential nutrient for corn and soybean production. Management decisions concerning P fertilization can have large effects on crop yield and grower profitability. Many Corn Belt growers have been applying P fertilizer during the last 50 years with the knowledge that corn and soybean yields increase when soil-test P (STP) is deficient. This result of P fertilization has been demonstrated by extensive research (Olsen et al., 1962; deMooy et al., 1973; Cope, 1981; Thom, 1985; Rehm, 1986; Obreza and Rhoads, 1988; Webb et al., 1992). In an effort to increase profitability, however, many growers have over-applied P resulting in very high STP levels. Soil-test values summaries for samples submitted to Iowa soil testing laboratories show that the fraction of soils testing higher than optimum according to current interpretations increased from approximately one-fourth of the samples in the 1960's to more than one-half of the samples in recent years (Killorn et al., 1990; Potash and Phosphate Institute, 2001). Increasing STP levels above optimum values through P applications results in little or no economic benefit to crop growers (Cope, 1981; McCallister et al., 1987; Mallarino et al., 1991; Webb et al., 1992; Cox, 1996; Mallarino, 1997).

Understanding the increase and decrease rates of STP for long-term corn-soybean production with various P fertilization strategies can aid growers in managing nutrients more efficiently. Knowing how STP declines when P rates less than crop removal are applied or how it increases when rates greater than crop removal are applied will aid in managing P fertilizer for optimum STP levels. Because STP levels in many Corn Belt soils test higher than optimum for crops, this knowledge can be used to determine how long a corn or soybean field will need to be in production without fertilization before STP decreases to levels that should be maintained. Research in Minnesota showed that STP levels could be maintained at 18 to 20 mg kg^{-1} (Bray-1 test) with 19 to 24 kg P ha^{-1} $year^{-1}$ for fields managed with a corn-soybean rotation (Randall et al., 1997). In Iowa, 16 kg P ha^{-1} $year^{-1}$ was required to maintain an initial STP value of 18 mg P kg^{-1} (Bray-1 test) for the same rotation (Webb et al., 1992).

Research has also shown that high-testing soils require more P fertilizer annually to maintain the original STP levels (McCallister et al., 1991; McCollum, 1991; Mallarino et al., 1992; Webb et al., 1992). In Iowa, for example, 33 kg P ha^{-1} year^{-1} was required to maintain an initial STP level of 75 mg kg^{-1} (Bray-1 test) while, in contrast, 16 kg P ha^{-1} year^{-1} was required to maintain an initial STP value of 17 mg P kg^{-1} (Webb et al., 1992). Research on soils along the Atlantic seaboard (McCollum, 1991) has also displayed large differences in the rate required to maintain different STP values. In this study, annual P additions at average crop removal rates to soils testing 108 mg kg^{-1} STP (Mehlich-1 test) decreased the annual STP decline rate by 25% compared with no P application. Similar annual removal rates had a much greater effect when STP was 61 mg kg^{-1}, decreasing the annual STP decline rate by 51% compared with no P fertilization for this initial level. When the initial STP value was near the critical level for those soils (24 mg kg^{-1}), the crop-removal based annual P applications almost maintained STP values. The larger P requirements for maintaining higher STP values have been explained mainly by increased P removal, either through increases in yield or P concentration of harvested products (or a combination of both). However, different reactions of applied P in the soil that affect plant-availability of P also can partly explain these differences in P maintenance needs. McCollum (1991) suggested that conversion to non extractable forms via chemical reactions with soil constituents is a far greater contributor to the net STP decline than biological removal at STP values higher than the critical levels for crop production.

Critical soil-test concentrations of P indicate values above which fertilization no longer results in yield responses or economic benefits (Dahnke and Olson, 1980). Previous research has determined critical concentrations of STP for corn and soybean (Cox, 1992; Mallarino and Blackmer, 1992; Webb et al., 1992; Mallarino, 1997; Randall et al., 1997). In Iowa, corn and soybean yield responses have seldom been observed when STP (Bray-1 test) was above 16-20 mg kg^{-1} (Mallarino et al. 1991; Mallarino and Blackmer, 1992; Webb et al., 1992; Mallarino, 1997). In soils of eastern regions of the USA, McCollum (1991) observed that corn yield was maximized when Mehlich-1 STP was near 24 mg kg^{-1}. Research done by Beegle and Oravec (1990) identified Bray-Kurtz P1 and Mehlich-3 critical STP values of 19 and 20 mg kg^{-1} for corn, respectively, and (Cox, 1996) identified a critical STP range for soybean of 18 to 33 mg kg^{-1} and 23 to 41 mg kg^{-1} (Mehlich-3 test) for corn.

There is a need for confirming critical STP ranges for corn and soybean for current production conditions and to better quantify possible differences between critical levels for these crops. STP field calibrations have not been re-evaluated since 1991 for soybean and 1997 for corn in Iowa. Furthermore, results of research on P placement for no-till and ridge-till soybean (Borges and Mallarino, 2000, 2003) suggested lower STP needs for soybean, but the results were not strong enough to establish different calibrations. Long-term experiments can provide useful information of STP trends over time as affected by cropping and P fertilization as well as STP calibrations. The objectives of this research were to (1) study long-term STP trends over time for different initial STP levels and annual P application rates, (2) study corn and soybean yield as affected by P fertilization and STP based on three Iowa long-term experiments, and (3) determine optimum STP levels for corn and soybean production.

MATERIALS AND METHODS

Long-term field experiments were established at the Northern Iowa Research Farm (NIRF) near Kanawha from 1976 to 2002, the Agronomy and Agricultural Engineering Research Center (AGRON) near Boone from 1975 to 2002, and the Northeast Iowa Research Farm (NERF) near Nashua from 1979 to 2002. Partial results from the early years of the experiment at NERF were summarized in 1991 (Mallarino et al., 1991) and from the experiment at NIRF in 1992 (Webb et al., 1992). Data from the experiment at AGRON were never published before.

Soils were a complex of mainly Webster and Canisteo series with Webster predominating at NIRF, a complex of Webster and Nicollet series in approximately equal proportions at AGRON, and Kenyon series at NERF. Crops at the three experiments were corn and soybean grown in rotation. The experimental area at each site was divided into two halves, corn and soybean were grown each year by switching field half each year, and identical experimental designs were established at each field half. The corn hybrids, soybean cultivars, herbicides, planting dates, and plant populations used were among those recommended for the regions over time and will not be shown. Cornstalks were chisel-plowed in the fall, and then disked or field-cultivated the following spring before planting. Soybean residues were disked or field-cultivated in the spring. The row width was 76 cm for both crops in all experiments.

Experiments at AGRON and NIRF were based on a randomized complete-block split-plot design, with three replications at AGRON and four replications at NIRF. Treatments applied to large plots were initial contrasting STP levels and treatments applied to subplots were annual P applications. All treatments were applied to both field halves for both crops. Initial P fertilization (triple superphosphate) was applied in 1974 at AGRON and 1975 at NIRF to 12 by 24 m plots at 0, 145, and 291 kg P ha^{-1} to create three contrasting initial STP levels (IP1, IP2, and IP3). Subplots used for the annual P treatments were 8 rows wide and 12 meters in length at both locations. The following year, annual P treatments of 0, 11, 22, and 33 kg P ha^{-1} (AP0, AP1, AP2, and AP3) were superimposed over each of the initial treatments. These annual treatments were applied each year in the fall (in October or November) after crop harvest and before tillage. At NIRF, no P was applied in fall 1996 (for the 1997 crops) and only the highest annual treatment (AP3) was applied to all initial treatments since fall 1997. At AGRON, only the highest annual rate (AP3) was applied to the IP3 initial treatment from fall 1997 to 2001. Nitrogen fertilizer (urea) was applied to corn at 168-201 kg N ha^{-1} immediately before spring tillage operations. Potassium was applied at rates that maintained the soils in the high soil-test K class. At AGRON, ground limestone was applied to all plots in January 1990 at a rate of 6.7 Mg ha^{-1} of effective calcium carbonate equivalent.

At NERF, the experiment was established in 1979. Treatments were factorial combinations of annual P and K applications for both crops arranged as a randomized complete-block design with three replications. Nutrient rates were 0, 22, and 44 kg P ha^{-1} (P0, P1, and P2) and 0, 67, and 134 kg K ha^{-1}, which were applied in the fall after harvest and before tillage. The plots were 6 rows wide and 15 m long. Nitrogen fertilizer (anhydrous ammonia) was spring-applied to corn at 168-201 kg N ha^{-1}. Initial pH was 5.8, and ground limestone was applied to all plots at a rate of 7.8 Mg ha^{-1} in the fall of 1981 for a target of pH 6.5. Only average results for P from plots that received the two high K rates are presented and discussed in this article. Analysis of variance (not shown) indicated that there was no significant ($P \leq 0.05$) yield response to K until the last 10 years of the study, and there was no P by K interaction in any year.

Soil samples were collected each year after harvest and before applying the annual P treatments. The plots sampled varied over time. At AGRON subplots under corn and soybean residue were sampled every year, at NIRF all subplots were sampled during the first 12 years of the study, and at NERF all samples were collected during the first 2 years. Analysis of STP for these early years indicated no statistical difference between samples collected from half of the field (corn or soybean residue). Thus, to reduce costs, only plots under soybean residue were sampled from 1989 to 1995 at NIRF and from 1981 to 1986 at NERF. Subplots receiving no annual P fertilization of both field halves began to be sampled again since fall 1996 at NIRF and fall 1997 at NERF. Comparisons of STP results from the recent soil samples confirmed the lack of statistical differences for STP from the two field halves observed in the early years. Each composite sample consisted of 10 cores taken from within each subplot, and cores were 1.9 cm in diameter and were taken to a depth of 15 cm. Extractable P and soil pH was determined each year at the Iowa State University Soil and Plant Analysis Laboratory. Soil pH was determined with a soil:water ratio of 1:2 (v/v) and extractable P was determined with the Bray-1 method. Soil testing procedures were among those recommended for the North Central Region by the North Central Soil and Plant Analysis Committee

(NCR-13). Procedures used over time were similar, except that tests were done on field-moist samples until 1990 (North Dakota Agricultural Experiment Station, 1980) and on oven-dried samples at 35 to 40 °C since then (Brown, 1998). Unpublished work at the Iowa State University Soil and Plant Analysis Laboratory (J.R. Webb and A.P. Mallarino, 1991, personal communication) showed no statistical difference between moist and dry sample analyses for P by the Bray-1 test.

Analyses of variance (ANOVA) were conducted using the General Linear Models (GLM) of SAS (SAS Inst., 2000) for fixed block and treatment effects. Orthogonal contrasts were used to compare treatment means for the annual P treatments (within the initial P treatments at AGRON and NIRF). Regression analyses for study of trends of STP over time and relationships between yield response and STP were conducted using the GLM and Nonlinear Models (NLIN) procedures of SAS (SAS Institute, 1988). Corn and soybean yield differences and regression trends were considered statistically significant at $P \leq 0.05$.

Trends of STP over time for each site and treatment combination were analyzed based on a linear model and an exponential model asymptotic to a maximum or a minimum. The exponential model used was the Mitscherlich equation as expressed by Nelson and Anderson (1977), and is presented only if the residual sums of squares were significantly smaller ($P \leq 0.05$) than for the linear model. The models were fit to STP means across replications and field halves (crops) from each site, each initial P treatment (at AGRON and NIRF), and annual P treatment. At AGRON and NIRF, only STP data collected until fall 1996 were used for these calculations because no annual P treatment was applied at NIRF for the 1997 crop and the low annual treatments were discontinued later on at both sites. Also, data from the first year at AGRON was not used for the modeling of STP trends over time because the initial single P applications were very high and a sharp STP decrease during the first year would have an unreasonable effect on model fits.

For identification of critical STP concentrations, linear-plateau (Waugh et al., 1973), quadratic-plateau (SAS Institute, 2000), and the Mitscherlich (also as expressed by Nelson and Anderson, 1977) models were fit to relationships between relative yield responses and STP values. Relative yields for a crop, site, and year were defined as the mean yield across replications of plots receiving no P for that year expressed as a percentage of the maximum yield with annual P fertilization. At NIRF and AGRON, the maximum fertilized yield used was the mean for the AP3 treatment (33 kg P ha^{-1}) across all replications for each initial treatment. At NERF, the maximum fertilized yield used was the mean for the P2 treatment (44 kg P ha^{-1}). The STP values used for these calculations were those from plots that had received no annual P application over time (AP0) and those from the plots for which the annual P treatments were discontinued in recent years. Soil-test P data for corn were available for all years of the experiments and were used for the calculations. Soil-test P data for soybean were not always available (because subplots with corn residue were not sampled some years), but data from the adjacent field halves were used because (as was mentioned before) when samples were collected from both field halves there was no significant STP difference between the two field halves at any site. Critical STP concentrations are directly determined when linear-plateau and quadratic-plateau models are fit, and are the STP values at which the two portions of each model join. Because the Mitscherlich model predicts an asymptote to a maximum, critical levels were calculated for 95 and 99% of the maximum predicted yield (Mallarino and Blackmer, 1992).

RESULTS AND DISCUSSION

Trends of Soil-Test Phosphorus Over Time

The three initial P treatments applied at AGRON and NIRF resulted in three contrasting initial STP levels at each site. At AGRON, STP values immediately before applying the first annual treatments (fall 1974) for the IP1, IP2, and IP3 treatments were 22, 49, and 96 mg P kg^{-1}. By the following year, average STP values for the AP0 annual treatment had dropped to 18, 37, and 71 mg kg^{-1} for the IP1, IP2, and IP3 treatments, respectively. At NIRF, average STP values immediately before applying the first annual treatments were 17, 43, and 75 mg P kg^{-1} for the IP1, IP2, and IP3 treatments, respectively. By the following year, average STP values for the AP0 annual treatment had dropped only to 14, 33, and 67 mg P kg^{-1} for the IP1, IP2, and IP3 treatments, respectively. These results indicated that at AGRON, and for unknown reasons, the P applied for the two high initial treatments had not reacted sufficiently with the soil by fall 1974 and likely explained the very sharp STP decrease during the first year. Thus, for this site, STP values for fall 1975 will be considered initial values for study of maintenance P rates and STP trends over time.

The soil series at AGRON and NIRF have rather similar properties except for slightly better internal drainage for the Nicollet soil present in some areas at AGRON and higher pH at small areas of Canisteo at NIRF. The soil pH (15 cm depth) at AGRON ranged from 6.2 to 7.0 over time and across plots within the site. However, at NIRF average pH ranged from 6.6 to 7.5 during a similar period and in some individual plots tested as high as pH 8.1 in some years. The alkaline pH values indicate the presence of calcium carbonate, which can result in lower availability of applied P and lower STP. Although no economic benefit may be obtained by maintaining the two highest initial STP levels (Mallarino et. al., 1991), many fields in the Corn Belt test as high and information from these plots can be used to determine long-term effects of cropping high-testing soils with or without additional P application.

As farmers develop nutrient management plans, being able to predict potential STP changes over time for different fertilization strategies would assist in nutrient planning. Study of continuous trends of soil-test P over time provides useful information to determine the impacts of cropping and P fertilization on soil P levels. Study of these trends is useful to determine rates of soil-test P increase or decrease and also to determine the annual P fertilization rate that maintain desirable soil-test P levels for various cropping and soil conditions. The regression models fit for each initial and annual P treatment are shown in Table 1, and the observed STP trends are shown in Figs. 1 to 3 for the three sites together with the best fit model. When a STP trend over time is determined to be curvilinear, a mean STP change across all years will not truly represent the STP increase-decrease rate as the rate of change varies over time. At AGRON and NIRF, trends for plots that received no annual P application, regardless of initial STP, were determined to be curvilinear over the length of the experiments. Most other decreasing or increasing trends were linear, except for the IP1 - AP3 treatment combination at NIRF. Differences in R^2 between models often were very small, however, and the linear coefficient of linear models will be used to approximate average STP change over time.

Analysis of STP trends over time without annual P application for the lowest initial STP level (the IP1 - AP0 combination) at AGRON and NIRF and for no P application (P0) at NERF are particularly useful because initial STP was near optimum values for corn and soybean (16 to 20 mg kg^{-1}). The linear models shown in Table 1 indicate an annual decline rate for these treatments of 0.4 mg kg^{-1} for both AGRON and NIRF. However, this value does not reflect how the lack of annual P applications in these soils resulted in a more rapid decline during the first few years (Figs. 1 and 2, and Table 1). Calculations based on the curvilinear model show that STP levels declined to the Low (and responsive) STP interpretation class (9 to 15 mg kg^{-1}) after only 2 years of cropping. The trends show a more rapid decreasing trend during approximately the first 10 years compared with recent years. Within this early period, STP decreased on average 1.0 and 1.4 mg kg^{-1} year^{-1} at NIRF and AGRON, respectively. During the last years, STP stayed almost constant and showed a total decline of only about 1 mg kg^{-1} at both sites. At NERF, where initial STP was 28 mg kg^{-1}, lack of annual P fertilization resulted in a linear STP decrease over time. The estimated rate of STP decline was 0.67 mg kg^{-1} year^{-1}. This rate of decrease is less steep than the rate of decrease for the first 10-year period at the AGRON and NIRF sites. Thus, in Webster and Nicollet soils (AGRON and NIRF sites) testing near Optimum in STP, discontinuing P applications would result in a

STP decrease to values within the upper part of Very Low class (0 to 8 mg kg^{-1}) in approximately 10 years and would remain approximately constant thereafter. In Kenyon soils, the data suggest a more gradual, linear, and slightly less steep rate during a longer period of time.

Because no annual P rate exactly maintained initial STP levels, the maintenance rate for the three initial STP levels at AGRON and NIRF and for the NERF site were estimated by interpolation of linear coefficients of trends that most closely maintain STP. At AGRON, annual P rates that would have maintained STP were 13 kg P ha^{-1} for 18 mg kg^{-1} STP (IP1), 22 kg P ha^{-1} for 37 mg kg^{-1} (IP2), and 30 kg P ha^{-1} for 71 mg kg^{-1} (IP3). At NIRF, the P rates would have been 17 kg P ha^{-1} for 17 mg kg^{-1} STP (IP1), 26 kg P ha^{-1} for 43 mg kg^{-1} STP (IP2), and 34 kg P ha^{-1} for 75 mg kg^{-1} STP (IP3). At NERF, the initial STP level of 28 mg kg^{-1} would have been maintained with an annual P rate of 13 kg ha^{-1}.

The maintenance P rates for the AGRON and NIRF sites were very similar and were only 4 kg P ha^{-1} less at AGRON than at NIRF for all the initial treatments. However, there was a larger difference between results for these sites and results at NERF. Although the initial STP at NERF was higher than the lowest initial STP at AGRON and NIRF, an approximately similar annual P rate was required to maintain the higher STP value (13, 17, and 13 kg P ha^{-1} at AGRON, NIRF, and NERF, respectively). Effects of different soil properties on reactions of applied P likely explain the lower maintenance needs for a higher STP value at NERF. The Kenyon soil has a slightly coarser texture and is better drained than soils at AGRON and NIRF (USDA-NRCS, 2001). At NERF, average soil pH was 5.8 in 1979 but was limed in 1981 and values have ranged from 6.1 to 7.0 since 1982. This range was similar to the pH range at AGRON, but was lower than at NIRF (pH 6.6 to 7.5). The other possible reason for different maintenance needs, yield levels and P removal, is not likely. Mean corn yield levels over time for those initial STP treatments were similar at AGRON and NERF (within 100 kg ha^{-1}) and approximately 200 kg ha^{-1} greater than at NIRF. Mean soybean yields were greater at NERF, intermediate at AGRON, and lowest at NIRF (a difference of 250 to 300 kg ha^{-1} between each site). The P maintenance values observed for the NIRF site are near values reported by Webb et al. (1992) for the first 14 years of this experiment (no data have been published from the AGRON site). Results for NERF were similar to values reported by Mallarino et al. (1991) for the first 10 years of this experiment.

When initial STP was near Optimum values (IP1 initial treatment at AGRON and NIRF and at NERF), the two highest annual P rates at the AGRON and NIRF sites and the high annual rate at NERF greatly increased STP (Figs. 1, 2, and 3). The STP increases were smaller for other treatment combinations at AGRON and at NIRF and for the P1 rate at NERF. The increasing trends usually were linear. Although curvilinear trends increasing asymptotically to a maximum fit better than linear trends in one instance, the difference in R^2 between the models was very small. At NIRF, the highest annual rate increased STP curvilinearly and the model describes a continuously decreasing rate of STP increase. Calculations based on the model indicate that the average increasing rate was 2.0 mg kg^{-1} year^{-1} during the first 10 years and 0.6 mg kg^{-1} year^{-1} during the last years. The linear model estimated a 1.2 mg kg^{-1} year^{-1} increasing trend. At AGRON, the STP trend for similar treatments was linear and increased 1.5 mg kg^{-1} $year^{-1}$. At NERF, with an initial STP of 28 mg kg^{-1}, the increasing trend due to the highest annual P rate was also linear and increased 2.5 mg kg^{-1} $year^{-1}$. The higher increasing rate at NERF compared with rates at AGRON and NIRF is consistent with the lower maintenance rate requirements discussed before for this site. Thus, results indicate that build-up of STP above Optimum levels is more rapid for Kenyon soils than for Webster, Nicolett, and Canisteo soils.

The methods used and knowledge of P reactions in soils do not allow for a supported explanation of the curvilinear trends asymptotic to a maximum for the IP1-AP3 combination at NIRF. Curvilinear increasing trends were not observed at AGRON or NERF for other annual rates that increased STP. Linear increasing trends have been observed in other long-term experiments in the USA (Cope, 1981; McCollum, 1991; McCallister et al., 1991). As will be shown later on, yield levels increased over time in these studies (probably because of better hybrids) but the trend was similar across sites and treatments so increased P removal is an unlikely reason. High STP variability at the highest levels (which can be recognized in the figures) could explain the results. An asymptotic increase of STP to a maximum is possible under conditions in which P loss from the soil through removal by crops and surface erosion of highly enriched soils increase with increasing STP level.

Observation of STP trends in Figs. 1 and 2 for the two highest initial STP levels (IP2 and IP3) at AGRON and NIRF confirm previous results in that maintenance rates increase significantly with increasing initial STP levels. Research for other regions have also shown that higher initial STP levels require greater maintenance P rates (McCollum, 1991; McCallister et al., 1991). The methods used do not allow for supported explanations of higher maintenance needs at higher STP levels. However, higher P removal with grain harvest is a possible explanation because previous Iowa research showed increased P concentration in corn grain at high STP levels and high P fertilization rates even when yield was not increased (Mallarino, 1996).

Previous work had shown a great deal of variation in the amount of annually applied P required to build-up STP above Optimum levels for field conditions under cropping. The importance of this issue recently increased dramatically because of concerns about water quality impairment and states requirements for nutrient management planning. In Minnesota, Randall et al. (1997) reported that an annual application of 26 kg P ha^{-1} was needed to raise STP 1 mg kg^{-1} on Webster soils where continuous corn was grown for 7 years followed by 11 years of a corn-soybean rotation. In Indiana, Barber (1979) reported that on a Raub silt-loam soil managed with a corn-soybean-wheat (*Triticum aestivum* L.) rotation a net annual application of 17 kg P ha^{-1} greater than crop removal was required to raise STP 1 mg kg^{-1}. Data from our study based on the highest annual P treatment and Optimum initial STP, indicates that 31 and 26 kg P ha^{-1} was needed to raise STP by 1 mg kg^{-1} at NIRF and AGRON, respectively. Data from NERF based on the highest annual treatment indicate that 28 kg P ha^{-1} would raise STP 1 mg kg^{-1}. These results are higher than values reported for the early years of the NIRF and NERF sites (Mallarino et al., 1991; Webb at al., 1992). Differences in amounts of P required to increase STP across sites can be attributed to soil properties and also yield levels affecting P removal in harvested products. However, part of the variation in reported numbers reflects different ways of accounting for P removal in harvested products. The annual P required to increase 1 mg kg^{-1} STP reported for this study would decrease markedly if annual P removal in grain were subtracted from the applied P to calculate a "net" rate of increase. This cannot be done accurately because P concentration in grain was not measured. However, approximate values can be calculated by subtracting the estimated annual P rate needed to maintain a STP value near Optimum levels from the rate determined to raise STP 1 mg kg^{-1} based on the highest annual P rate used (which applied P in excess of removal and any P retention by the soil in not available forms). This calculation indicates that an annual net P application (greater than removal) of 14 kg P ha^{-1} would raise STP 1 mg kg^{-1} for Webster-Nicollet-Canisteo soils and 15 kg P ha^{-1} (greater than removal) would raise STP 1 mg kg^{-1} for Kenyon soils when soils are managed with a corn-soybean rotation.

Effect of Annual Phosphorus Applications on Grain Yield

The effect of annual applications of P ranging from 11 to 33 kg P ha^{-1} at AGRON and NIRF (AP1, AP2, and AP3 treatments) and 22 or 45 kg P ha^{-1} at NERF (P1 and P2 treatments) on corn and soybean yields varied greatly across initial treatments and over time. The initial STP values ranged from values currently considered within the Optimum interpretation class to values almost four times higher. Probably because of these STP levels, crop responses were seldom observed during the first few years of the experiments. The number of years it took the crops to start responding to P increased as the initial STP value increased. Also, the number of responsive years decreased as the initial STP value increased.

At AGRON, corn yields (Table 2) were significantly ($P \leq 0.05$) greater with annual P applications than the controls in 15 of the 28 years for the IP1 treatment, 11 years for the IP2 initial treatment, and only 4 years for the IP3 treatment. The four responsive years for the IP3 treatment were observed during the last 12 years of the experiment. Analyses of responses for the different annual P treatments indicate that the annual P rate needed to maximize yield varied across the initial STP treatments. Rates higher than 11 kg P ha^{-1} (AP1) increased yield further in 2 years for IP1, 2 years for IP2, and 1 year for IP3. The highest annual rate (AP3) significantly increased yield over the AP2 rate in one year for the IP1 initial treatment and 1 year for the IP3 initial treatment. It was 10 years before corn was responsive to P fertilization for the IP1 initial treatment, 12 years for IP2, and 15 years for IP3. This result reinforces the previous discussion on rate of STP decline based on the initial STP level.

Soybean yields at AGRON (Table 3) were increased by annual P fertilization in 10 of 28 years for the IP1 initial treatment, 8 years for IP2, and 4 years for IP3. The responsive years for IP3 occurred during the last 10 years of the experiment. Analyses of responses for the different annual P treatments indicate that rates higher than 11 kg P ha^{-1} (AP1) increased yield further in 2 years for IP1, 1 year for IP2, and 1 year for IP3. The AP3 treatment never produced significantly greater soybean yield than the AP2 treatment. When initial STP was near Optimum (IP1), 8 years were required to observe soybean response to P fertilization for the first time.

However, responses were not consistent until nearly 13 years after the experiment began. For the IP2 initial treatment, 10 years were required to begin observing occasional yield responses. For the IP3 treatment, 19 years of cropping were required before yield responses were observed. This again supports the previous discussion of STP trends over time, indicating the time it takes for high initial STP levels to decline into responsive soil-test interpretation categories.

At NIRF, corn yield responses (Table 4) were very similar to AGRON. Yield responses due to annual P fertilization were significantly ($P \leq 0.05$) greater than the controls in 23 of 27 years for the IP1 initial treatment, 12 years for IP2, and 6 years for IP3. The only year since 1979 that did not display increased yield from annual P fertilization over the control for IP1 was 1993. Corn yields in 1993 were the lowest in the 27 years of the experiment due to excessive rainfall during the growing season. It was 4 years after the beginning of the experiment before corn yields were responsive to annual P fertilization for IP1, 10 years for IP2, and 17 years for IP3. This result coincides with the previous discussion on STP trends over time for different initial STP levels. With soils initially testing high in STP (IP2 and IP3), it takes longer for the STP levels to decline to a level at which corn will respond to annual P fertilization. Analyses of individual years for this site indicate increased yield response from the two high annual rates (AP3 and AP2) over AP1 in 4 years for the IP1 initial treatment, 2 years for IP2, and never for IP3. Only in the last year of the experiment the AP3 treatment increased yield over the AP2 treatment, and this occurred in soil with the lower initial STP value (IP1).

Soybean yield responses to annual P applications at NIRF (Table 5) were very similar to results for corn. Yield responses due to annual P fertilization were observed in 24 of 27 years for the IP1 initial treatments, 12 years for IP2, and 6 years for IP3 (during the last 10 years). Individual analyses by year indicate that additional significant yield responses to the two highest annual P rates were observed in 9 of the last 16 years for IP1, 4 of the last 5 years for IP2, and never for IP3. The AP3 treatment significantly increased yield over the AP2 treatment in only 1 year (for the IP1 initial treatment). The number of crop years required for annual P fertilization to increase soybean yield significantly over that controls varied across the initial STP treatments. Responses were not observed until after 4 years for the IP1 initial treatment, 11 years for IP2, and 17 years for IP3.

At NERF, where the initial STP level was in the High interpretation class initially, crop yield responses to annual P applications developed only in recent years. This was the result of a slow and gradual decline in STP of the control plots, as was discussed before. When annual P rates are not equal to or greater than crop removal, STP will decline into levels below optimum for corn and soybean production. Results for corn (Table 6) showed that significant yield response to annual P fertilization occurred only in 3 of the 24 years of the experiment, and only to the lower rate (P1). These responses were isolated instances and occurred only in 1990, 1999, and 2001. Soybean was more responsive to annual P fertilization than the corn was at NERF (Table 6). Significant yield increases were observed 8 years, and only to the low rate (P1). Six of the responsive years were during the last 8 years of the study. The more frequent soybean response to P compared with corn at this site was not observed at the AGRON and NIRF sites. This difference cannot be explained with certainty. However, consistently higher soybean yield at NERF could partly explain the difference. Mean corn yield levels for the most similar initial STP levels were similar at AGRON and NERF (within 140 kg ha^{-1}) and approximately 300 kg ha^{-1} greater than at NIRF. However, mean annual soybean yields were 300 to 500 kg ha^{-1} greater at NERF compared to the other sites.

Results for STP and yield response trends over time clearly indicate the producers are applying more P than needed in many Iowa fields and that this practice is reducing economic benefits from crop production. Soil-test summaries indicate that more than 50% of Iowa corn and soybean fields test above the Optimum STP interpretation class (16 to 20 mg kg^{-1}). The results of this study indicate for soils testing 43 to 57 mg kg^{-1} STP, corn and soybean required 10 to 15 years of cropping with no annual P additions before STP levels declined to critical values in the Low or Very Low interpretation classes where yields were significantly increased by P fertilization. For soils testing 75-96 mg kg-1, 17 to 20 years of cropping was required.

Soil-Test Phosphorus Critical Concentrations for Corn and Soybean

Figures 4 through 6 show the relationship between STP and relative yield response for corn and soybeans at the three locations. These data indicate that STP values are good indicators of the magnitude and probability of crop response to P application. These relationships are also useful to determine critical STP concentrations for the crops. The Mitscherlich, linear-plateau, and quadratic-plateau models were used to analyze the relationship between STP and relative yield response of corn and soybean. The models and R^2 values are represented in Table 7 and the critical STP concentrations for each model, location, and crop are presented in Table 8. There were large differences in the critical STP values determined by the various models. This result is well known. Mallarino and Blackmer (1992) discussed its implications for fertilizer recommendations and the profitability of fertilization before. These authors showed that the most profitable critical STP concentrations for use in production agriculture usually were near those determined with the linear-plateau model. However, considerations of long-term profitability and the maintenance philosophy in the US determine that optimum critical ranges used encompass concentrations determined by the linear-plateau and quadratic-plateau models (Mallarino, 1997; Sawyer et al., 2002) Thus, although all critical concentrations are shown in Table 8, the range of critical concentrations determined with the linear-plateau and quadratic-plateau will be used to compare results for the different locations and crops in this study.

At AGRON, critical STP concentrations (Table 8) were very similar for corn and soybeans. Corn was not likely to respond to P at STP values greater than 13 to 18 mg kg^{-1}, and soybean was not likely to respond when STP was greater than 11 to 15 mg kg^{-1}. At NIRF, the determined critical concentrations were higher than for AGRON, and the critical range defined with the two models was 19 to 28 mg kg^{-1} for corn and 17 to 23 mg kg^{-1} for soybean. At NERF, the relationship between STP and relative crop yield was not as significant as it was at the other two locations. This can be attributed to the high initial STP at this site, and the resulting small and infrequent crop responses. It is difficult or impossible to determine critical STP values without having a wide distribution of responses. Data for corn indicate unlikely response at STP levels above 12 to 31 mg kg^{-1}. This critical STP range is wider and greater than at AGRON and NIRF because of the reasons explained, its statistical significance was low, and its agronomic reliability should be questioned. In soybean, regression analysis did not estimate a reasonable critical STP level. Although analysis of variance showed more frequent responses for soybean than for corn (Table 6), there was higher variability in relation to STP values and no model produced a reasonable fit.

These relationships between STP and yield and the determined critical concentrations confirm some previous results from Iowa, but do not confirm others. Variations in the critical STP levels for corn and soybeans between the three different soils are evident from this study. Critical concentrations for the NERF site will not be considered because they are unreliable. However, there were differences between AGRON and NIRF. For corn, critical STP ranges were 13-18 mg kg^{-1} on Webster-Nicollet soils (AGRON) and 19-28 for Webster-Canisteo soils (NIRF). For soybean, the critical STP ranges were 11-15 mg kg^{-1} for Webster-Nicolett soils (AGRON) and 17-23 mg kg^{-1} for Webster-Canisteo soils (NIRF). The differences between soils are not large and the ranges partly overlap. Also, the ranges partly overlap with the currently used Optimum interpretation class of 16 to 20 mg kg^{-1} (Sawyer et al., 2002). However, the slightly higher critical concentration range for Webster-Canisteo soil complex at NIRF is consistent with the higher, sometimes alkaline, soil pH.

The critical concentration ranges for soybean at AGRON and NIRF were clearly lower than for corn. Regression analyses with the segmented models were also performed on both crops across all soils (Table 9 and Fig. 7). Across all soils, the range in critical STP concentrations between the linear-plateau and quadratic-plateau models was 18-23 mg kg^{-1} for corn and 11-18 mg kg^{-1} for soybean. The critical concentration range for corn approximately coincides with several previous Iowa studies (Mallarino and Blackmer, 1992; Webb et al., 1992; Mallarino, 1997) and with the current Optimum class for corn (Sawyer et al., 2002). However, the critical concentration range for soybean determined in this study is lower than current Iowa interpretations and also lower than those found in the early years of the NIRF experiment (Webb et al., 1992). Current Iowa recommendations indicate that the Optimum STP interpretation class is 16-20 mg kg^{-1} for both crops. Currently used Optimum STP levels seem appropriate for corn because our results would indicate only a slightly higher critical range and previous research for corn included many more sites (Mallrino and Blackmer, 1992; Mallarino, 1997). However, the currently used Optimum class seems slightly higher than required by soybeans. Further indications of slightly lower STP needs for soybean were provided by previous work done with ridge-till and no-till soybeans (Borges and Mallarino, 2000, 2003).

SUMMARY AND CONCLUSIONS

Results of these experiments spanning nearly 30 crop years showed that long-term trends in STP are greatly affected by the initial STP value and annual additions of P fertilizer to the soil. Soil-test P trends for soils at high initial STP levels decreased more rapidly during the first few years after P applications ceased, then transitioned to a very small, gradual decline over time. Soils initially near the Optimum soil-test interpretation class (16 to 20 mg kg^{-1}) showed a more gradual decline in STP when no P was applied. Another important result was that soils with high initial STP concentrations required higher annual additions of P to maintain the original STP compared with soils testing Optimum. Annual P rates required to maintain initial STP near Optimum values were 13 to 17 kg P ha^{-1} year^{-1}. However, up to 33 kg P ha^{-1} year^{-1} were required when STP values were up to four times higher the optimum values.

Crop yields from plots with high initial STP levels required many years of cropping before there was a response to annual P fertilization. For soils testing 43 to 57 mg kg^{-1} STP, corn and soybean required 10 to 15 years of cropping with no annual P additions before STP levels declined to critical values where yields were significantly increased by P fertilization. For soils testing 75-96 mg kg^{-1}, 17 to 20 years of cropping was required. This result reaffirms that STP is a good indicator of potential corn and soybean yield response to annual additions of P. Corn and soybean yield indicated a significant response to annual P fertilization one-half to two-thirds of the time across the three locations when STP was at Optimum levels or less. However, there was seldom a yield response to annual rates higher than 11 kg P ha^{-1} unless STP of control plots had decreased to less than Optimum levels.

Critical STP concentrations are key to deciding whether or not a soil requires additional P fertilization for corn and soybean production. Across all three locations, soybean yields were no longer responsive when the STP levels were greater than

11-18 mg kg^{-1}, and corn yields were no longer responsive when STP was greater than 18-23 mg kg^{-1}. The STP concentration range identified for corn overlaps the current Optimum interpretation range from the higher side. Although the difference is small, the data suggests that if STP is maintained at the low part of the currently recommended range corn yields may not reach their maximum potential in these soils. The critical range identified for soybean overlaps the current Optimum range from the low side. Thus, these data suggest that the current range may result in P applications for soybean in some fields when additional P is not needed.

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Table 1. Models for relationships between soil-test P and time for various initial and annual P treatments at three sites.[†]

Annual	Initial treatment 1				Initial treatment 2				Initial treatment 3			
P rate	Model[‡]	Equation	*P>F*	R^2	Model	Equation	*P>F*	R^2	Model	Equation	*P>F*	R^2
						AGRON						
0	Mit[§]	$7.9 + 18.1e^{-0.29x}$	0.01	0.86	Mit	$7.4 + 38^{e-0.15x}$	0.01	0.96	Mit	$13.4 + 71.9e^{-0.15x}$	0.01	0.97
	Lin	$14.4 - 0.4x$	0.01	0.64	Lin	$31.6 - 1.2x$	0.01	0.85	Lin	$54.4 - 2.3x$	0.01	0.86
11	Lin	$16.5 - 0.1x$	0.09	0.23	Lin	$35 - 0.92x$	0.01	0.85	Mit	$24.5+ 62.54e^{-0.18x}$	0.01	0.93
									Lin	$58.9 - 1.9x$	0.01	0.80
22	Lin	$17.1 + 0.65x$	0.01	0.74	Lin	$37.4 - 0.05x$	0.93	0.01	Mit	$50.6 + 40.6e^{-0.4x}$	0.01	0.49
									Lin	$61.1 - 0.65x$	0.02	0.35
33	Lin	$16.6 + 1.5x$	0.01	0.82	Lin	$39.3 + 1.2x$	0.01	0.68	Lin	$59.9 + 0.3x$	0.07	0.07
						NIRF						
0	Mit	$6.1 + 14.9e^{-0.29x}$	0.01	0.78	Mit	$5 + 43.3e^{-0.15x}$	0.01	0.94	Mit	$9 + 78.5e^{-0.16x}$	0.01	0.97
	Lin	$12.6 - 0.4x$	0.01	0.52	Lin	$34.6 - 1.6x$	0.01	0.81	Lin	$60.7 - 2.8x$	0.01	0.83
11	Lin	$14.1 - 0.17x$	0.14	0.20	Mit	$13 + 32.7e^{-0.11x}$	0.01	0.76	Mit	$16 + 55.3e^{-0.09x}$	0.01	0.94
					Lin	$37 - 1.1x$	0.01	0.69	Lin	$60.3 - 1.9x$	0.01	0.89
22	Lin	$17.8 + 0.29x$	0.04	0.32	Lin	$39.8 - 0.38x$	0.13	0.21	Lin	$58.8 - 0.79x$	0.01	0.53
33	Mit	$47.8 - 33.2e^{-0.12x}$	0.01	0.75	Lin	$40.5 + 0.7x$	0.01	0.64	Lin	$63 - 0.07x$	0.89	0.01
	Lin	$24.3 + 1.2x$	0.01	0.69								
						NERF (no initial treatment)						
0	Lin	$25.7 -0.7x$	0.01	0.72								
22	Lin	$31.9 + 0.5x$	0.02	0.40								
45	Lin	$38.2 + 2.5$	0.01	0.84								

[†] AGRON, Agronomy and Agricultureal Engineering Research Center; NIRF, Northern Iowa Research Farm; NERF, Northeast Iowa Research Farm

[‡] Both the Mitscherlich and linear models are shown when the residual sums of squares for the Mitscherlich model were significantly ($P \leq 0.05$) smaller than for the linear model.

[§] Mits, Mitscherlich; Lin, linear.

Table 2. Corn yield for various initial and annual P fertilizer treatments at AGRON (yield for 1977, 1989, and 1990 were not available).

	Initial treatments, annual P rates (kg ha^{-1}), and yield														
	Initial treatment 1					Initial treatment 2					Initial treatment 3				
Year	0	11	22	33	Mean	0	11	22	33	Mean	0	11	22	33	Mean
	kg ha^{-1}														
1975	10846	9940	10052	10583	10355	10412	9545	10226	9292	9869	9848	10239	10219	9491	9949
1976	7213	7991	7500	7149	7463	8362	7311	7803	7099	7644	6884	7016	6241	7061	6801
1978	10380	10371	10277	10631	10415	10714	10695	10375	10384	10542	10547	10589	10750	10535	10605
1979	10635	10631	10658	10792	10679	10616	10886	11022	10982	10877	11058	11037	11204	11097	11099
1980	8571	9920	9648	9323	9365	10258	10622	10197	9049	10032	9396	9075	7489	8910	8718
1981	9333	7651	7412	7879	8069	8761	8037	8150	7245	8048	8754	7398	8027	7295	7869
1982	9386	9661	9418	10062	9632	9669	9734	9368	9503	9568	9666	10024	9703	9832	9806
1983	9127	8773	8643	9615	9039	8856	8787	9886	9745	9319	9772	9853	9362	9535	9631
1984	5671 †	7741	7423	6729	6891	7496	8069	7630	6911	7526	6906	7475	7325	7916	7406
1985	7646	7655	8445	8637	8096	7904	7893	9147	8890	8459	8476	8405	8257	8190	8332
1986	11208 †	11787	12086	12352	11858	11534 †	11957	12335	12442	12067	12097	12090	11846	11940	11993
1987	7485 †	9020	9440 ‡	10381 §	9081	8873 †	9149	9843	9601	9367	9526	9845	9768	9749	9722
1988	6363 †	7832	8284	8460	7735	8110	8675	8259	8238	8321	7649	7688	7592	8556	7871
1991	10299 †	11371	11472	12371	11378	9906 †	11269	12090 ‡	12155	11355	10822 †	12726	11942 ‡	10953 §	11611
1992	10479 †	12761	11990	11875	11776	11543 †	12864	12908	12916	12558	11821 †	12759	12902	12718	12550
1993	7738 †	8251	7809	8579	8094	7348 †	8428	7985	8340	8025	7935	8042	8432	8184	8148
1994	11050 †	12732	12703	13393	12469	11896	12435	12734	12686	12438	12789	13253	13284	13253	13145
1995	8363 †	10218	10159	10393	9783	8244 †	9871	10245	10481	9710	8930 †	10462	10487	10427	10076
1996	10080 †	11848	11879	11629	11359	10583 †	11783	11771	11679	11454	11369	11507	12272	12009	11789
1997	6677 †	8278	10092	9799	8711	7224 †	8554	9881	9745	8851	7312 †	10224	9927	9776	9310
1998	10008 †	11251	10922	11987	11042	10872 †	11691	11350	11463	11344	11581	12117	11919	12326	11986
1999	10066	10561	11242	10523	10598	10147	11316	11378	10918	10939	10764	11305	11372	11789	11308
2000	8842 †	9480	9659	10302	9571	8633 †	9505	10100	10024	9565	9936	9974	10163	10663	10184
2001	4599 †	4809	8179 ‡	8179	8179	4500 †	5549	8172 ‡	8464	6671	6335	6623	8426	7563	7237
2002	6287 †	8582	7626	9610	8026	7500	8261	8853	9194	8452	8926	9773	8578	8992	9067
Mean	8734	9565	9721	10038	9514	9199	9715	10068	9898	9720	9564	9980	9899	9950	9848

† Significant ($P \le 0.05$) yield difference between the control and the fertilized treatments.

‡ Significant ($P \le 0.05$) yield difference between the 11- and 22-kg rates.

§ Significant ($P \le 0.05$) yield difference between the 22- and 33-kg rates.

Table 3. Soybean yield for various initial and annual P fertilizer treatments at AGRON (yield for 1977 were not available).

	Initial treatments, annual P rates (kg ha^{-1}), and yield														
	Initial treatment 1					Initial treatment 2					Initial treatment 3				
Year	0	11	22	33	Mean	0	11	22	33	Mean	0	11	22	33	Mean
	kg ha^{-1}														
1975	2668	2904	2698	2530	2700	2968	2806	2887	2788	2862	2513	2729	2426	3012	2670
1976	2034	1743	1917	2046	1935	2044	1851	1955	1886	1934	1981	1976	2007	1917	1971
1978	3179	3112	3084	3283	3165	3358	3273	3218	3046	3224	3128	3287	3101	3246	3191
1979	2688	2866	2858	2732	2786	2649	2799	2980	2542	2742	2685	2664	2762	2892	2751
1980	3086	2960	3070	3295	3103	3214	3012	3206	3208	3160	3136	3328	3287	3082	3208
1981	2439	2554	2868	2380	2560	2384	2557	2640	2352	2483	2405	2454	2384	2746	2497
1982	2940 †	3131	3160	3249	3120	3145	3235	3233	3232	3211	3204	3376	3256	3120	3239
1983	3211	3450	3424	3219	3326	3270	3619	3301	3310	3375	3304	3015	3179	3540	3259
1984	2314	2291	2221	2625	2363	2458 †	2399	2165 ‡	2162	2296	2314	2461	2478	2244	2374
1985	2085	2412	2750	2293	2385	1937	2289	2468	2370	2266	2262	2417	2188	2728	2399
1986	2623	2806	2529	2871	2707	2873	2867	2405	2701	2712	2625	2685	2876	2878	2766
1987	2717 †	3265	3360	3243	3146	2932 †	3411	3458	3239	3260	3144	3055	3057	3187	3111
1988	2220	1877	2094	2264	2114	2130	2101	2338	2040	2152	2246	2186	2150	2067	2162
1989	3044 †	3312	3424	3270	3263	3131	3248	3395	3248	3255	3301	3212	3144	3404	3265
1990	2869 †	3395	3062	3256	3146	3064	3236	3355	3230	3221	3223	3333	3140	3198	3223
1991	2804 †	3218	3176	3422	3155	2824 †	3133	3312	3149	3105	3082	3095	3100	3328	3151
1992	2694	2934	3012	3167	2952	2499 †	2909	3012	3176	2899	2858	3037	3064	3030	2997
1993	2585	2717	2549	2813	2666	2435 †	2891	2618	2840	2696	2495 †	2564	2620	2795	2619
1994	3174 †	3610	3655	3700	3535	2900	3742	3619	3655	3479	3454	3691	3541	3541	3557
1995	3295 †	3682	3673	3778	3607	3377	3557	3622	3480	3509	3682	3684	3595	3639	3650
1996	2927 †	3375	3745	3675	3431	2708 †	3586	3928	3877	3525	3183 †	3781	3763	3816	3636
1997	2171	2417	2839	2549	2494	2575	2733	2593	2698	2650	2584	3093	2566	2645	2722
1998	2940 †	3079	3484 ‡	3606	3277	2763 †	3233	3565	3621	3296	3137 †	3673	3488 ‡	3412	3428
1999	4186	4430	4278	4748	4410	4227	4240	4338	4242	4262	4608	4633	4673	4525	4610
2000	2423	2463	2925	2787	2649	2323	2355	2819	2473	2492	2540	2980	3028	3021	2892
2001	2025	2234	2364	2395	2255	2091	2300	2204	2295	2223	2356	2295	2408	2418	2370
2002	1770 †	2073	2816 ‡	2637	2324	1853 †	2315	2605	2864	2409	2277	2480	2655	2627	2510
Mean	2713	2896	2978	3034	2905	2741	2939	2993	2933	2902	2869	2983	2957	3024	2958

† Significant ($P \le 0.05$) yield difference between the control and the fertilized treatments.

‡ Significant ($P \le 0.05$) yield difference between the 11- and 22-kg rates.

§ Significant ($P \le 0.05$) yield difference between the 22- and 33-kg rates.

Table 4. Average corn yield by annual and initial P fertilizer treatments at NIRF.

	Initial treatments, annual P rates (kg ha^{-1}), and yield														
	Initial treatment 1					Initial treatment 2					Initial treatment 3				
Year	0	11	22	33	Mean	0	11	22	33	Mean	0	11	22	33	Mean
	kg ha^{-1}														
1976	8651	8784	8527	8579	8635	8709	9105	8889	8342	8761	7848	8113	8403	8047	8103
1977	8411	8449	8383	8329	8393	8485	8522	8616	8759	8596	8309	8505	8344	8497	8414
1978	9461	9615	9739	9969	9696	9858	9736	9193	9480	9567	9621	9273	9280	9369	9386
1979	10087 †	10405	10432	10803	10432	11081	10758	11101	10866	10952	10811	10933	10830	10883	10865
1980	9903 †	10454	10358	10705	10355	10656	10706	10433	10458	10563	10631	10549	10658	10120	10489
1981	10231 †	11195	11556	11360	11086	11600	11747	11380	11862	11647	11155	11441	11277	11349	11305
1982	9137 †	10551	11162	11382	10558	11222	11630	11419	11515	11447	11387	11388	11280	11282	11334
1983	7541 †	9527	9430	9778	9069	9237	9587	9697	9850	9593	9916	9675	9993	9485	9767
1984	6970 †	8806	9828 ‡	10004	8902	9519	9617	9502	9856	9624	9742	9797	10088	9877	9876
1985	9069 †	10973	11678 ‡	11805	10881	10974 †	11297	11667	11835	11443	11728	11404	11322	11631	11521
1986	7304 †	9639	10165	9960	9267	9875	10170	10690	10322	10264	10052	9990	10479	10310	10208
1987	8127 †	10106	10358	10690	9820	9581 †	10534	10355	10601	10268	10320	10435	10371	10399	10381
1988	3777 †	5647	6716	6276	5604	4677 †	5851	6255	6263	5761	6070	5669	5407	5492	5660
1989	7737 †	10114	10860	10860	9893	8949 †	9855	10490	11087	10095	10435	11015	10891	10501	10710
1990	7702 †	8866	9609	9976	9038	8983	9709	10126	9670	9622	8960	10255	9610	9488	9578
1991	8082 †	9624	10347	10289	9586	8554 †	9828	10142	10183	9677	9555	9878	9811	9607	9713
1992	7579 †	11669	12249	12465	10990	10129 †	12020	12454	12000	11651	11106 †	12221	12580	12333	12060
1993	5148	5163	5313	5907	5383	5600	6124	6337	6191	6063	4626 †	5344	5791	5316	5270
1994	9140 †	10805	11722	11501	10792	10622	11851	11346	11031	11212	10766	11481	11299	11361	11227
1995	8941 †	10201	10342	10330	9954	8518 †	10110	10462	10570	9915	9527 †	10426	10553	10120	10156
1996	7161 †	9745	10846	10899	9663	9225 †	10951	11394	10860	10607	9237 †	10879	11065	10656	10459
1997	7102 †	9430	9739	9557	8957	7155 †	9143	9629	9756	8921	8712	9350	8949	9190	9050
1998	7041 †	8673	9976 ‡	10703	9098	9344	10128	10523	10294	10072	9181 †	10408	10664	10247	10125
1999	8511 †	9698	9519	11097 §	9706	7901 †	9947	9761	10057	9417	9897	10344	10140	9623	10001
2000	6824 †	8828	9543	10460	8914	9098	9715	10563	10209	9896	9055	9579	10095	10295	9756
2001	6821 †	7956	7588	10165 §	8133	5964 †	7003	9196 ‡	9648	7953	9030	8022	9107	9196	8839
2002	6911 †	7939	8994 ‡	12746 §	9147	9606 †	9952	12042 ‡	13727	11332	9051 †	10427	11639	12614	10933
Mean	7903	9365	9814	10244	9332	9078	9837	10136	10196	9812	9509	9882	9997	9900	9822

† Significant ($P \leq 0.05$) yield difference between the control and the fertilized treatments.

‡ Significant ($P \leq 0.05$) yield difference between the 11- and 22-kg rates.

§ Significant ($P \leq 0.05$) yield difference between the 22- and 33-kg rates.

Table 5. Average soybean yield by annual and initial P fertilizer treatments at NIRF.

	Initial treatments, annual P rates (kg ha^{-1}), and yield														
	Initial treatment 1					Initial treatment 2					Initial treatment 3				
Year	0	11	22	33	Mean	0	11	22	33	Mean	0	11	22	33	Mean
								kg ha^{-1}							
1976	2586	2660	2560	2567	2593	2671	2735	2468	2343	2554	2598	2499	2528	2529	2538
1977	2380	2384	2349	2534	2412	2485	2487	2556	2530	2514	2338	2403	2403	2467	2403
1978	2928	2912	2963	3004	2952	2896	3063	2856	2884	2925	2945	2932	2824	2715	2854
1979	2719 †	2787	2947	2872	2831	2924	2950	2826	2888	2897	2937	2860	2791	2888	2869
1980	2645 †	2829	2923	2816	2803	2934	2865	2891	2814	2876	2700	2661	2694	2651	2677
1981	2522 †	2715	2866	2804	2727	2759	2895	2668	2741	2766	2891	2778	2707	2762	2785
1982	2551 †	2882	2837	2921	2798	2720	2984	2949	2720	2843	2742	2864	2878	2828	2828
1983	2396 †	2949	2907	2993	2811	2979	3050	2942	2945	2979	2864	2751	2758	2726	2775
1984	2161 †	2724	2622	2669	2544	2554	2640	2791	2815	2700	2558	2692	2686	2664	2650
1985	1691 †	2055	2055	1977	1945	1977	2159	2029	2133	2075	2055	2055	2133	2159	2101
1986	2243 †	2764	2810	2605	2606	2383 †	2906	2987	2790	2767	2691	2729	2537	2563	2630
1987	2154 †	2552	2852 ‡	3083	2660	2838	3179	3156	2882	3014	2859	3008	2942	2968	2944
1988	1870 †	2446	2321	2300	2234	2206	2479	2288	2431	2351	2525	2335	2300	2316	2369
1989	1871 †	2002	2373 ‡	2568	2204	2206	2520	2543	2291	2390	2007	2153	2268	2333	2190
1990	2582 †	3363	3190	3176	3078	3225	3428	3435	3218	3327	3534	3235	3546	3393	3427
1991	2110 †	2552	2768	2768	2549	2446 †	2795	2790	2661	2673	2494	2681	2708	2730	2653
1992	1886 †	2859	2960	2938	2661	2091 †	2958	3220	3086	2839	2689 †	3069	3082	2977	2954
1993	967 †	1322	1532	1570	1348	1476	1682	1613	1528	1575	1292	1652	1652	1523	1530
1994	2752 †	3533	3481	3533	3325	2819 †	3856	3635	3563	3468	3373	3630	3599	3415	3504
1995	2999 †	3236	3642 ‡	3740	3404	3148 †	3501	3688	3371	3427	3096 †	3429	3584	3439	3387
1996	2492 †	3096	3183	3014	2946	2418 †	3189	3327	3153	3022	2860 †	3132	3101	3109	3051
1997	1569 †	2137	2872 ‡	3182	2440	2267 †	2716	3088	2711	2695	2206 †	2727	2921	2905	2690
1998	2434 †	2988	3327 ‡	3389	3035	2418 †	3050	3461 ‡	3415	3086	3127	3384	3286	3389	3296
1999	2470 †	2675	3168 ‡	3656	2992	2978 †	3276	3656	3461	3343	2896 †	3132	3584	3517	3282
2000	2495 †	2798	3353 ‡	3430	3019	2485 †	3009	3625 ‡	3738	3214	3127	3486	3566	3502	3420
2001	2167 †	2583	2845 ‡	3492 §	2771	2860 †	3009	3379 ‡	3584	3208	2845 †	3173	3420	3440	3219
2002	2639 †	2886	3341 ‡	3528	3098	2470 †	2727	3173 ‡	3579	2987	3014	3163	3338	3574	3272
Mean	2307	2692	2854	2931	2696	2579	2893	2964	2899	2834	2713	2838	2883	2870	2826

† Significant ($P \leq 0.05$) yield difference between the control and the fertilized treatments.

‡ Significant ($P\leq 0.05$) yield difference between the 11- and 22-kg rates.

§ Significant ($P\leq 0.05$) yield difference between the 22- and 33-kg rates.

Table 6. Corn and soybean yields for three annual P application rates at NERF.

	Annual P rate (kg ha^{-1}) and yield					
	Corn yield			Soybean yield		
Year	0	22	45	0	22	45
	kg ha^{-1}					
1979	8897	9328	9380	3108	3057	3097
1980	9505	9586	9228	3245	3245	3202
1981	11503	11856	11421	2414	2570	2530
1982	8205	7967	8134	3087†	3158	3245
1983	6184	5835	6343	2782	2740	2876
1984	8005	8150	8098	2432	2337	2491
1985	8754	9005	8619	2358†	2484	2539
1986	11972	11919	11751	3531	3562	3560
1987	10990	10432	11345	2851	2884	3051
1988	6100	6307	6237	1889	1943	1977
1989	7419	7603	7457	2554	2650	2576
1990	11479†	11894	12543	4308	4348	4302
1991	10144	10203	10321	2156	2138	2174
1992	9674	9728	9790	3592	3465	3618
1993	5398	5607	5849	2149	2229	2314
1994	8703	8574	8611	3758	3875	3911
1995	5427	5827	5906	2062†	2225	2407
1996	10798	10920	11070	3430†	3793	3781
1997	11529	12137	11905	3573	3755	3764
1998	9816	10464	10262	4127†	4451	4345
1999	11634†	12152	12357	3293†	3467	3516
2000	10601	11543	11570	3708	3944	3962
2001	9732†	10771	10736	3405†	3638	3762
2002	11792	12426	12782	3765†	3943	4036
Mean	9344	9593	9655	3066	3163	3210

† Significant ($P \leq 0.05$) difference between the control and the two fertilized treatments .

‡ Significant ($P \leq 0.05$) yield increase up to the 45 kg P ha^{-1} rate .

Table 7. Models for relationships between relative yield response and soil-test P for corn and soybean at three sites.

Site	Crop	Model †	Equation	*P* > *F*	R^2
AGRON	Corn	MIT	$100.8 - 88.9e^{-0.232x}$	0.01	0.53
		QP	$52.3 + 5.3x - 0.147x^2$	0.01	0.52
		LP	$62.8 + 2.7x$	0.01	0.50
	Soybean	MIT	$99.8 - 73.9e^{-0.265x}$	0.01	0.39
		QP	$58.4 + 5.4x - 0.179x^2$	0.01	0.39
		LP	$67.1 + 2.8x$	0.01	0.39
NIRF	Corn	MIT	$102.1 - 45.6e^{-0.098x}$	0.01	0.54
		QP	$62.6 + 2.6x - 0.046x^2$	0.01	0.54
		LP	$67.6 + 1.6x$	0.01	0.54
	Soybean	MIT	$102.3 - 61.2e^{-0.133x}$	0.01	0.79
		QP	$54.8 + 3.8x - 0.081x^2$	0.01	0.79
		LP	$62.2 + 2.2x$	0.01	0.77
NERF	Corn	MIT	$106.1 - 27.9e^{-0.058x}$	0.01	0.31
		QP	$78.8 + 1.38x - 0.02x^2$	0.01	0.31
		LP	$77.0 + 1.6x$	0.08	0.07
	Soybean	MIT	$129.6 - 41.9e^{-0.009x}$	0.03	0.10
		QP	$88 + 0.37x - 0.0007x^2$	0.03	0.10
		LP	$44.3 + 5.3x$	0.16	0.05

† MIT, Mitscherlich; QP, Quadratic-Plateau; LP, Linear-Plateau

Table 8. Models for relationships between relative yield response and soil-test P for corn and soybean across three sites.

Location	Crop[†]	Model [‡]	*P* > *F*	R^2	CL99[§]	CL95[§]
AGRON	Corn	MIT	0.01	0.53	19.3	12.3
		QP	0.01	0.52	18.0	
		LP	0.01	0.50	13.4	
	Soybean	MIT	0.01	0.39	16.2	10.1
		QP	0.01	0.39	15.1	
		LP	0.01	0.39	11.1	
NIRF	Corn	MIT	0.01	0.54	38.7	22.3
		QP	0.01	0.54	28.6	
		LP	0.01	0.54	19.6	
	Soybean	MIT	0.01	0.79	30.6	18.5
		QP	0.01	0.79	23.7	
		LP	0.01	0.77	17.0	
NERF	Corn	MIT	0.01	0.31	55.6	28.2
		QP	0.01	0.31	31.3	
		LP	0.08	0.07	12.0	

† Data for soybean at NERF are not shown because no model was signigicant ($P \leq 0.05$)

‡ MIT, Mitscherlich; QP, Quadratic-plateau; LP, Linear-Plateau.

§ CL99 and CL95, critical levels at 99% and 95% of the Mitscherlich asymptotic maximum.

Table 9. Critical soil-test P concentrations for corn and soybean as determined with three statistical models.

Crop	Model [†]	Equation	$P > F$	R^2	CL99[‡]	CL95[‡]
Corn	MIT	$101.35 - 52.9e^{-0.138x}$	0.01	0.52	28.5	16.9
	QP	$60.5 + 3.4x - 0.074x^2$	0.01	0.52	23.0	
	LP	$69.1 + 1.7x$	0.01	0.50	18.0	
Soybean	MIT	$99.5 - 59e^{-0.188x}$	0.01	0.54	21.7	13.1
	QP	$59.7 + 4.1x - 0.11x^2$	0.01	0.53	18.7	
	LP	$59.3 + 3.3x$	0.01	0.52	11.2	

[†] MIT, Mitschelich; QP, Quadratic-plateau; LP, Linear-Plateau.

[‡] CL99 and CL95, critical levels at 99% and 95% of the Mitscherlich asymptotic maximum.

Figure 1. Soil-test P values as a function of initial cropping years for three initial P treatments and four annual P application rates at AGRON.

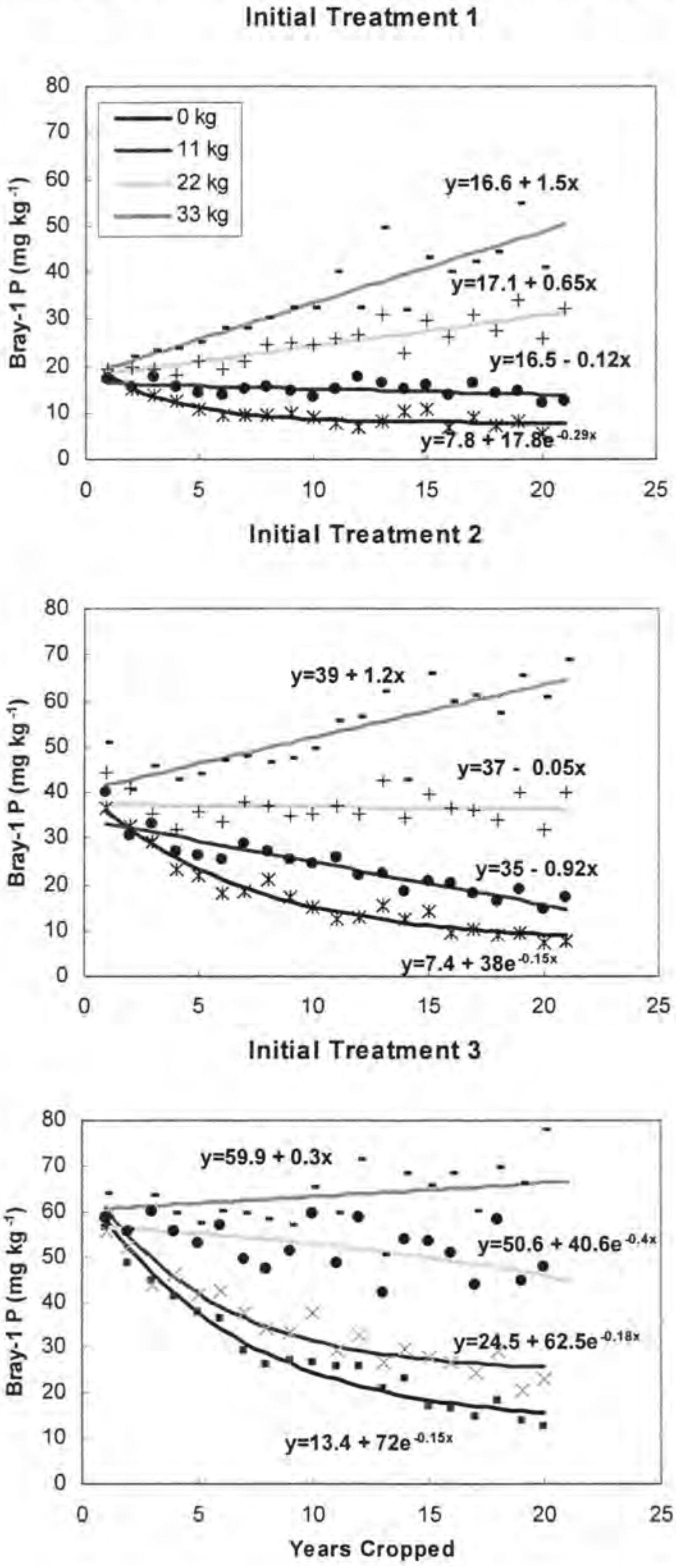
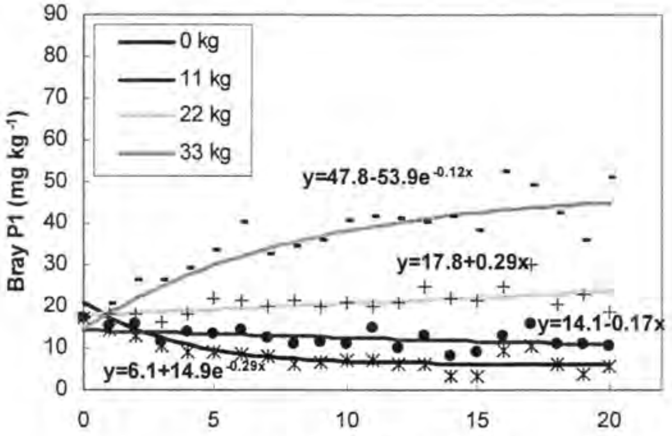
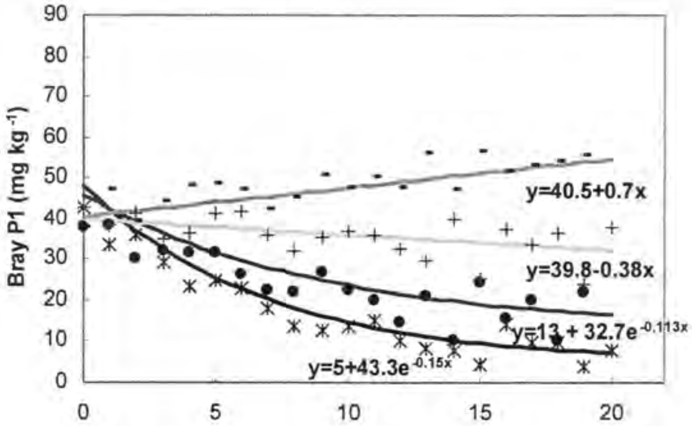


Figure 2. Soil-test P values as a function of initial cropping years for three initial P treatments and four annual P application rates at NIRF.

Initial Treatment 1



Initial Treatment 2



Initial Treatment 3

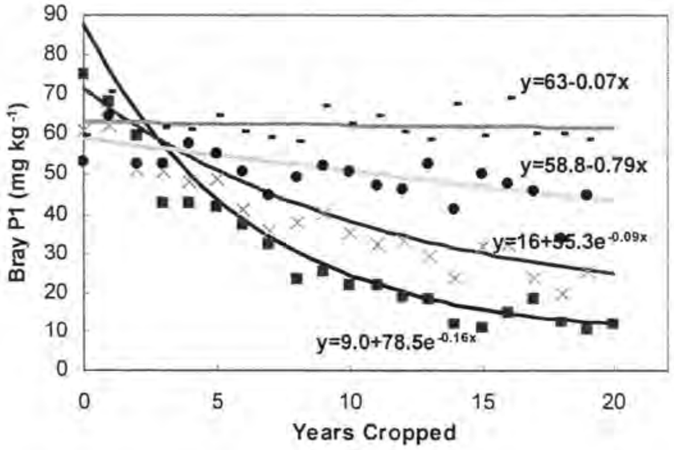


Figure 3. Soil-test P values as a function of cropping years for three annual P application rates at NERF.

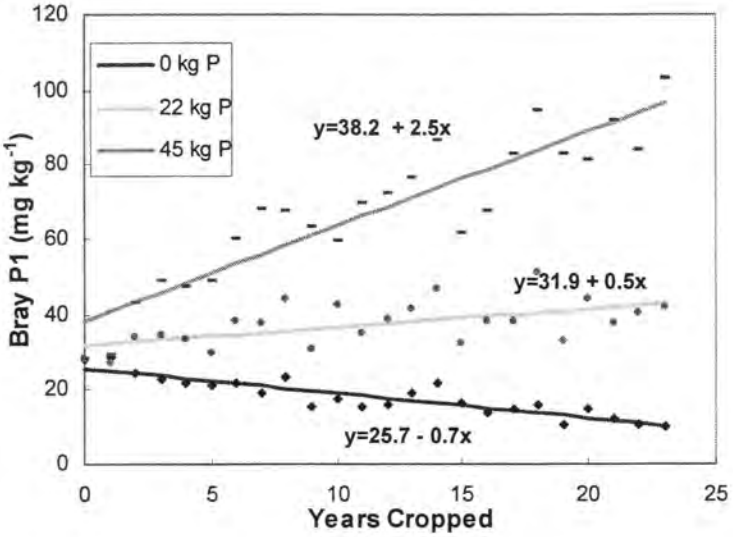


Figure 4. Relationship between soil-test P and relative yields of corn and soybean at AGRON.

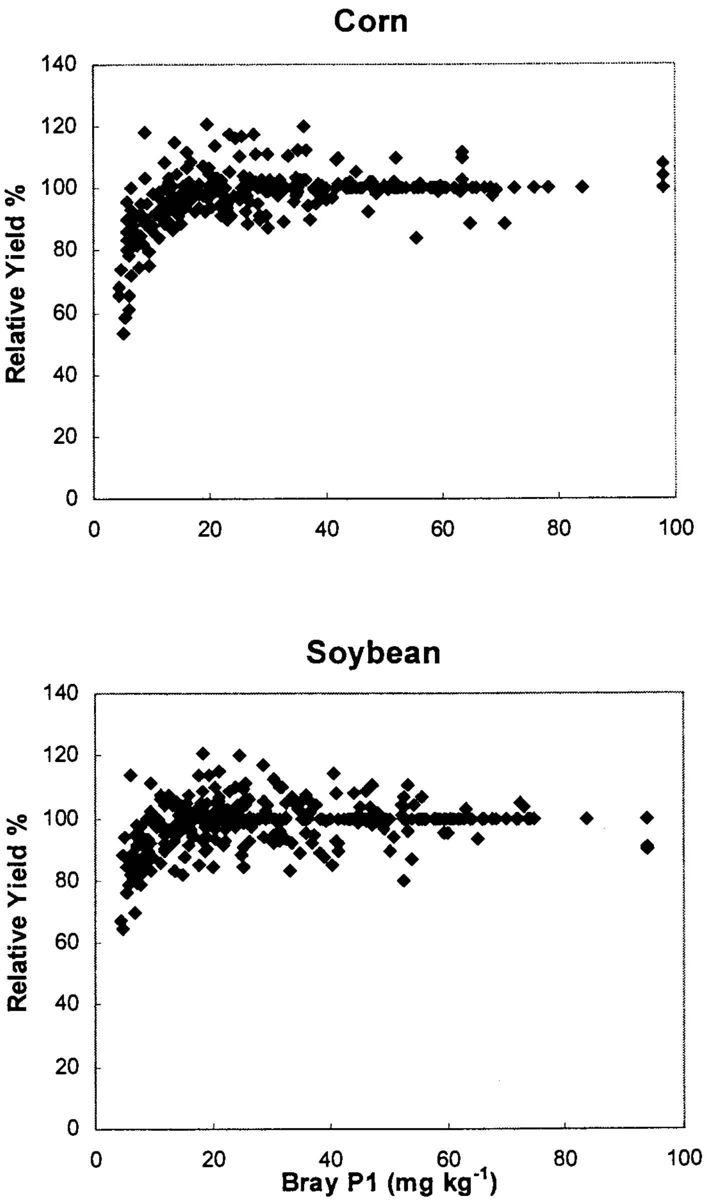


Figure 5. Relationship between soil-test P and relative yields of corn and soybean at NIRF.

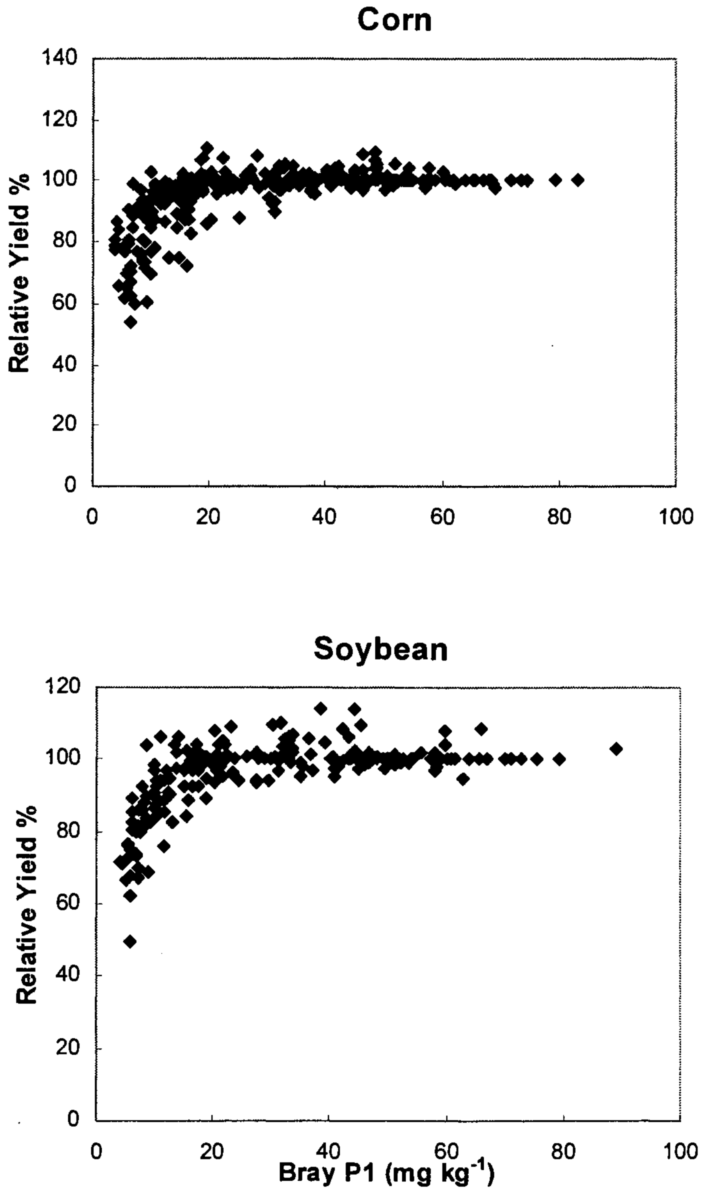


Figure 6. Relationship between soil-test P and relative yields of corn and soybean at NERF.

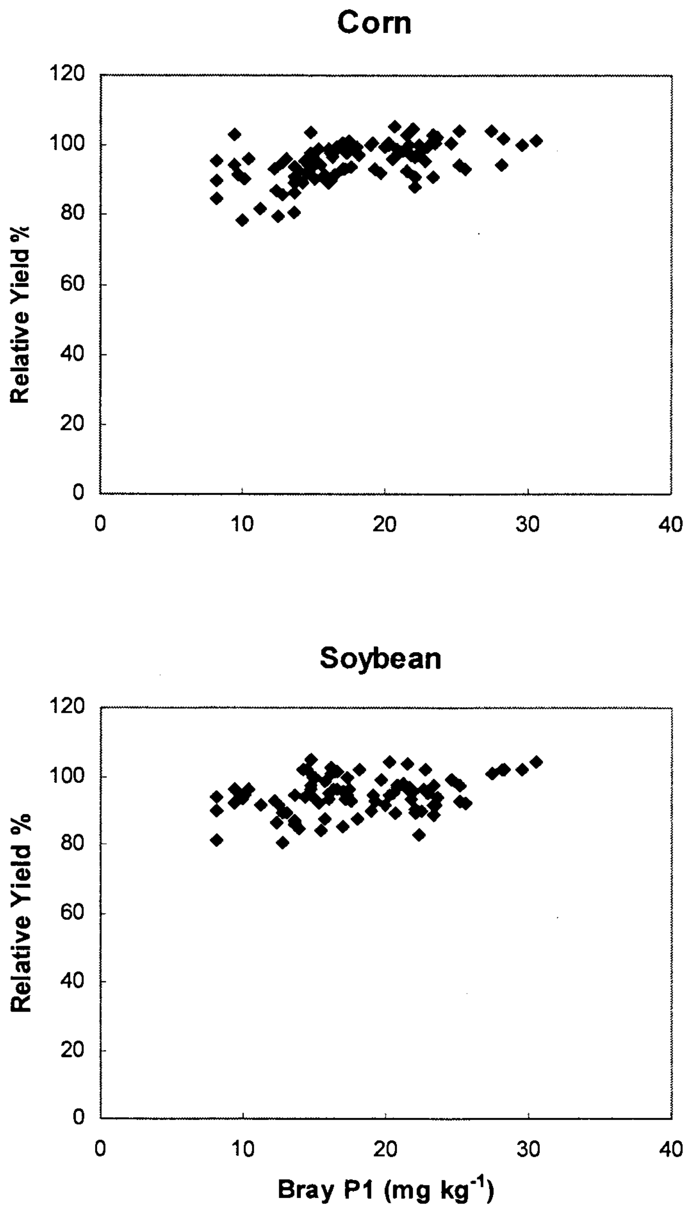
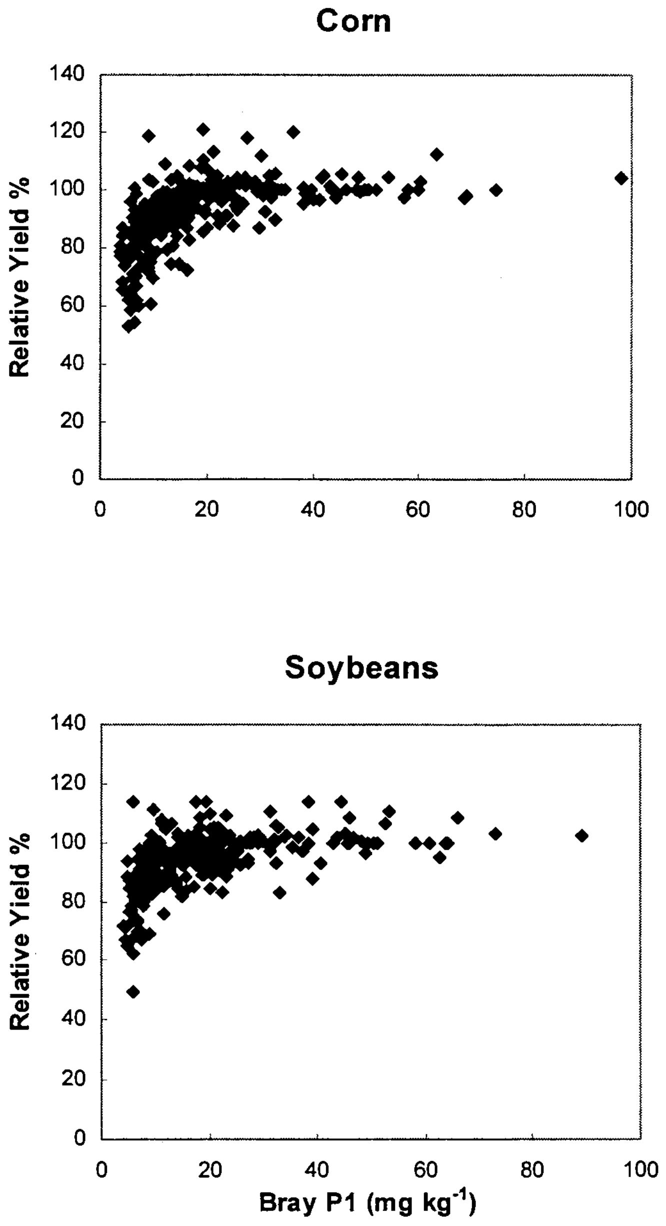


Figure 7. Relationship between soil-test P and relative yields of corn and soybeans at all three locations (AGRON, NIRF, AND NERF).



CHAPTER 3: GENERAL CONCLUSIONS

The main objectives of this study were (1) to analyze long-term STP trends to determine at what rate STP increases-decreases over time based on the initial STP level and the amount of P fertilizer that was applied to the soil, (2) analyze how annual additions of P fertilizer at various rates affect corn and soybean yield responses, and (3) establish critical P concentrations that are required for production of corn and soybean. To achieve these objectives, STP and yield data from three long-term P experiments that were started in the middle to late 1970's were analyzed. Treatments were contrasting initial STP values and different annual additions of P fertilizer at two locations, and different annual additions of P fertilizer at the third location.

The results showed that long-term trends in STP were greatly affected by the initial STP value and annual additions of P fertilizer to the soil. STP of soils at high initial STP levels decreased more rapidly during the first few years after P applications cease, then transitioned to a very small gradual decline over time. Soils initially near levels currently considered optimum for corn and soybean showed a more gradual decline in STP when no P was applied. Another important result was that soils with high initial STP concentrations required higher annual additions of P to maintain the original STP compared with soils testing at optimum levels.

Crop yields from plots with high initial STP levels required 10 to 15 years of cropping before there was a response to annual P fertilization. This result reaffirms that soil testing for P is a good indicator of potential corn and soybean yield response to annual additions of P. Corn and soybean yields indicated a significant response to annual P fertilization one-half to two-thirds of the time across the three locations when soil P was near optimum levels or less. Critical STP concentrations determined in this study were near, but not exactly similar to the current Optimum range for these crops. Although the differences were small, the data suggest that the currently used range is slightly lower than it should be for corn and that its use may not result in optimum yields in some fields. The critical range identified for soybean partly overlapped the current range from the low side and, thus, it's use may result in P fertilization for soybean in some fields when additional P is not needed.