In furrow starter and broadcast phosphorus and potassium fertilization for corn

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In furrow starter and broadcast phosphorus and potassium fertilization for corn

by

Daniel Eric Kaiser

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Soil Science (Soil Fertility)

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Antonio Mallarino, Major Professor
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Ames, Iowa
2003
This is to certify that the master's thesis of

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has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy
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CHAPTER 1. GENERAL INTRODUCTION

INTRODUCTION

Starter fertilization is defined as the placement of small quantities of nutrients in a concentrated zone in close proximity to the point of seed placement at the time of planting (Penas and Hergert, 1990). Choosing to use starter fertilizer is one of the many management strategies available to farmers for growing corn (Zea mays L.). Today’s technologies have given farmers many options for applying starter fertilizer. One of the most popular methods is applying starter 5 cm beside and below the point of seed placement. In recent years, in-furrow starter application has become popular because of it’s simplicity. However, this method has raised some questions regarding impacts on seed germination. As with any system, farmers research the potential benefits and drawbacks before they make a management decision.

Over the past few years farmers have become increasingly aware of some of the negative impacts farming can have on the environment. According to recent surveys Iowa leads the nation in total use of conservation tillage practices (tillage that leaves > 30% residue cover). Total hectares managed with conservation tillage in 2002 equaled 5,184,000 (56% of the total statewide crop land), which has increased 275% since 1990. Although no-till systems do not predominate in Iowa, use has increased by 1,000% since 1990 to a total of 2,065,500 ha in 2002 (CTIC, 2002). However, slow early corn growth that can be associated with no-till management has limited further adoption of this system and has generated questions about the potential benefits of starter fertilization to alleviate this problem.

An independent survey asked current starter fertilizer users why they felt that starter
worked in their row crop operation (Nachurs-Alpine Solutions, 2000). The most common responses were that starter fertilizer gives corn a faster start, increases yields, supplies nutrients to corn roots, and works best for their tillage operations. The main reasons why today’s farmers do not use starter fertilizer center around economics and time. The extra equipment needed to band fertilizer can add substantial cost to a planter, especially for the large planters. Most planters are set up to apply liquid starter, although granulated fertilizer is still used. The extra time needed to fill fertilizer tanks or hoppers may also be a deterrent to starter use.

In certain instances, band application of phosphorus (P) and potassium (K) fertilizer may be beneficial. Phosphorus and K are considered immobile nutrients. Soil P and K move to the roots from relatively short distances. In order for plants to have adequate P and K nutrition additional roots need to be grown to exploit new areas of soil. Aluminum (Al), calcium (Ca), magnesium (Mg), and iron (Fe) are highly reactive with P and they form certain chemical compounds if soil conditions are appropriate. For example, the plant availability of water-soluble P forms may be quickly and significantly reduced by Ca and Mg compounds if soil pH is high and by Al and Fe compounds if pH is very low. Band placement of P can be beneficial in limiting the amount of P reacting with cations under these conditions. If the potential for K retention by certain clay minerals in nonexchangeable forms is high, the band placement may be beneficial for K as well. Banding starter fertilizer near the seed provides a concentrated zone of nutrients that young plants can easily access. Starter fertilization can be particularly advantageous for farmers using no-till management in corn because nutrients can be applied below the soil surface during the planting operations without
additional soil disturbance or traffic.

Over the years there has been a steady increase in soil-test P and K levels in Iowa. However, many fields are being fertilized in spite of high soil-test levels because some farmers do not want to risk P or K deficiency. Large applications of P and K fertilizers for crops in high-testing soils reduces cropping profitability. This practice may also have negative environmental consequences. Increases in the amount of P in surface waters because of excess P loss from agricultural fields has received public attention in recent years. Placing fertilizer below the surface lessens the risk of P loss due to soil erosion and surface runoff. Small sub-surface fertilizer applications, such as starter fertilization, are attractive alternatives to broadcast fertilization if the loss of soil P is a concern. However, research is needed to investigate how starter fertilization can complement (or substitute for) larger broadcast fertilization rates for optimizing fertilizer usage and crop production.

One primary objective of this research initiated in the spring of 2000 in Iowa farmers' fields was to evaluate corn yield response to small amounts of P and K in a liquid starter fertilizer applied to the seed furrow and to determine if this practice could replace larger broadcast fertilization rates. Another objective was to study how corn early growth responses to starter fertilization relate to grain yield responses.

**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 In Furrow Starter and Broadcast Phosphorus and Potassium Fertilization for Corn. The paper includes sections for an
abstract, introduction, materials and methods, results and discussion, conclusions, references, and tables. The paper is proceeded by a general introduction with its own reference list and is followed by a general conclusion section.

REFERENCES CITED


CHAPTER 2. IN FURROW STARTER AND BROADCAST PHOSPHORUS AND POTASSIUM FERTILIZATION FOR CORN

A paper to be submitted to Agronomy Journal

Daniel E. Kaiser, Antonio P. Mallarino, and Manuel Bermudez

ABSTRACT

Broadcast fertilization is the most common P and K fertilization method for corn \textit{(Zea mays L.)} in Iowa and the Corn Belt. However, slow early plant growth typically observed with reduced tillage has made farmers consider the use of starter fertilization. The objectives of this study were (1) to assess corn grain yield, early growth, and early P and K uptake responses to in-furrow liquid starter fertilization and (2) to study the benefits of applying small amounts of in-furrow starter in addition to higher broadcast P and K fertilization rates commonly used by Iowa farmers. Thirteen small-plot trials were established in farmers’ fields across Iowa. Initial soil-test P (STP) and K (STK) values varied between sites. Trials compared PK starter fertilization (at rates ranging from 5 to 7 kg P ha$^{-1}$ and 10 to 14 kg K ha$^{-1}$ across sites), broadcast PK fertilization applied for a 2-year corn-soybean [\textit{Glycine Max} (L.) Merr.] rotation (49 kg P ha$^{-1}$ and 112 kg K ha$^{-1}$), and a combination of both treatments. Nitrogen was applied at rates larger than those recommended to insure the nutrient would be non-limiting. Yield, early corn growth, and PK concentration and uptake were measured. Fertilization increased yield at five sites, usually in soil testing low in STP, and the fertilized treatments did not differ ($P \geq 0.05$). Fertilization usually increased early growth and nutrient uptake. The small starter rates increased early growth and nutrient uptake more than the
larger broadcast rates in 40% of the responsive sites. Starter fertilizer is as effective as much larger broadcast fertilization rates in the short-term (one crop), but longer-term use may result in lower yields and may not maintain adequate soil-test levels. A combination of in-furrow starter fertilization with lower and/or infrequent broadcast fertilization could be a cost-effective fertilization strategy for corn.

Abbreviations: STK, soil-test K; STP, soil-test P.

INTRODUCTION

There has been a steady shift away from conventional tillage intensive operations for corn (Zea mays L.) production to conservation tillage, including no-till management, in Iowa and the Corn Belt (CTIC, 2002). This shift has lead to increased interest in starter fertilization (the placement of small quantities of nutrients in a concentrated zone near the point of seed placement at the time of planting [Penas and Hergert, 1990]) to alleviate potential slow early corn growth associated with no-till systems. Several reasons could explain slow early crop growth with no-till management. Soil temperatures are cooler and soils are wetter under no-till as compared with moldboard and chisel-plow tillage systems mainly because of increased residue cover (Kaspar et al., 1990; Wolkowski, 2000). No-till corn plants often exhibit slower root growth and development than corn in tilled soils (Barber, 1971). Several studies have shown reduced early shoot growth of corn and reduced early P and K uptake under no-till management (McKay et al., 1987; Mallarino et al., 1998; Wolkowski, 2000). Furthermore, Vetsch and Randall (2002) observed an increase in early corn growth when row cleaners were used on a planter to clear residue on the soil surface.
over the seed row, and Mallarino et al. (1999) observed increased early growth when corn was planted after zone (or strip) tillage compared with strict no-till even when the planter had row cleaners.

Reduced tillage also results in shallower mixing of nutrients when fertilizers are broadcast. Under these conditions the concentration of immobile nutrients such as P and K near the soil surface are greatly increased compared to more intensively tilled soils or no-tilled soils in which subsurface fertilizer application methods are used (Mackay et al., 1987; Fanzluebbers and Hons, 1996; Mallarino et al., 1998). Phosphorus and K retention by soil constituents is reduced in surface layers of no-till soils (Karathanasis and Wells, 1990; Guertal et al., 1991). However, because the soil surface frequently becomes dry during late spring and summer, plant nutrient uptake from the shallower soil depths sometimes is limited (Mallarino et al., 1999). Thus, decreased early season plant growth and significant P and K stratification in the soil could limit grain yield production when P and K are surface broadcasted under no-till management. Band fertilization, such as starter application, places fertilizer below the soil surface and increases the concentration of immobile nutrients in a small soil volume (Barber and Kovar, 1985). This placement method may increase P and K use efficiency by crops, especially at low application rates, by reducing P and K retention by soils constituents, applying the nutrients below the soil surface in a more accessible region, and increasing nutrient availability to young plants when the band is placed in close proximity to the seed (Randall and Hoeft, 1988).

Starter fertilization often increases early corn plant weight and height compared with similar or even higher broadcast fertilization rates (Reeves et al., 1986; Touchton, 1988;
Hoeft et al., 1995; Mascagni and Boquet, 1996; Gordon et al., 1997; Mallarino et al., 1999; Bermudez and Mallarino, 2002; Vetsch and Randall, 2002). Because starter fertilizers usually include more than one macronutrient (N, P, and K or N and P), reasons for increased early growth are not straightforward. A review by Randal and Hoeft (1988) indicated that P in the starter, and sometimes N, is responsible for increased early corn growth and yield. Mallarino et al. (1999) worked with separate granulated P and K starter applications at several Iowa locations over several years, and found that P always increased early growth of no-till corn compared with broadcast fertilization and that starter K seldom did. Starter K effects on early plant growth are less consistent than for N and P, although its use often increases early plant K concentration compared with other placements (Mallarino et al., 1999; Vyn et al., 2002). However, including K in a starter is riskier because of increased potential salt injury to seedlings. Studies that examined various nutrient ratios in starter mixtures for corn (Fixen, 1985; Touchton and Karim, 1986; Ritchie et al., 1995; Kovar, 2003) indicated that no best nutrient ratio exists across all conditions, and that starter should include at least N and P. Early corn growth responses to starter P tend to be larger in soils with low STP, but often are observed in high-testing soils (Touchton and Karim, 1986; Rehm et al., 1988; Wolkowski, 2000; Bermudez and Mallarino, 2002). However, corn early growth and yield responses to NP starter mixtures in soils testing high in STP often have been attributed to N in the mixture (Scharf, 1999; Bermudez and Mallarino, 2002).

Many studies have shown that starter fertilization can increase yields compared to a no-starter control (Mengel et al., 1988; Randall and Hoeft, 1988; Scharf, 1999; Wolkowski, 2000; Bermudez and Mallarino, 2002). However, yield responses to starter fertilization have
been smaller and more inconsistent than early growth responses. Reeves et al. (1986) found corn early growth responses to starter in both tilled and no-till systems; however, early season plant growth was indicative of plant yields only in years of insufficient rainfall. Research in Iowa (Mallarino et al., 1999) observed increases in early corn growth in no-till fields due to P fertilizer, which occurred at all locations in all years. However, seldom was there an effect from K fertilizer, and yield response to starter P and K only occurred in soils testing below optimum in STP or STK. Later research (Bermudez and Mallarino, 2002) found significant early corn growth response to NPK or NP liquid starters in most no-till fields within the study and in most areas within fields across different soil series, STP, STK, pH, or organic matter levels. However, grain yield responses were small, unfrequent, and poorly correlated with early corn growth. Research involving K in starter fertilizer (Vetsch and Randall, 2002) found a consistent and sizeable yield increase due to starter; however, early growth responses did not always occur or were smaller in degree.

Starter fertilization may interact with other factors in determining yield responses. Rhoads and Wright (1998) found that corn hybrids responded differently to a NP starter fertilizer and they postulated that a hybrid having a high rate of root growth as well as N and P uptake would be expected to show little or no response to starter fertilizer. Research in Kansas (Gordon et al., 1997) observed that only some corn hybrids responded to a NP starter fertilizer when STP was higher than optimum levels for yield production. However, work in Iowa observed no significant interaction between a NPK starter fertilizer mixture and corn hybrid (Buah et al., 1999). Studies in Wisconsin (Bundy and Andraski, 1991) found the probability of observing corn yield response to various starter fertilizer mixtures increased at
later planting dates for any given hybrid relative maturity.

The most frequently used method of starter fertilizer application has been applying it approximately 5 cm beside and below the point of seed placement; however, in recent years in-furrow application has become more common in the Corn Belt. The increase in farm size, planter size, and costs of attachments needed to apply starter fertilizer beside and below the seed may encourage farmers to shift to other application alternatives. In-furrow starter application, also known as pop-up fertilization, mainly of liquid products is an attractive alternative because of its simplicity. A potential drawback is that seedling damage may occur if high rates of high analysis fertilizers containing N and K are applied in-furrow (Tiesdale et al., 1993). In Iowa, a maximum of 12 kg ha\(^{-1}\) of N plus K\(_2\)O is recommended for in-furrow application to corn in fine-textured soils, and one-half that rate in sandy soils (Sawyer et al., 2002). Lower rates or mixtures with low-salt index (Waters, 1972) N and K compounds should be used to alleviate salt injury to seedlings (Gerwing et al., 1996). Low-salt index fertilizers (fertilizers which usually do not include nitrate and KCl) are commercially available to farmers, although they typically cost more than high-salt alternatives.

Research comparing starter application methods such as beside and below the seed, in-furrow, or as surface-applied bands is scarce. A study conducted under greenhouse conditions that compared placing starter 3.8 cm beside and below the seed versus in-furrow found that corn plants grew faster in the first four weeks when in-furrow starter was used, and the superiority of in-furrow application was still observed seven weeks after application (Miller et al., 1971). Bates (1971) found similar results in field experiments comparing starter applied 3.8 cm beside and below the seed to in-furrow placement. Wolkowski and
Kelling (1985) compared low starter rates applied in the furrow to high rates applied beside and below the seeds. This study found that corn yields tended to be less for an in-furrow starter program if used during consecutive years. One limitation of in-furrow starter application compared to application beside and below the seeds is that nutrient rates have to be rather low, even with low salt-index products. Thus, its use should necessarily be complemented by other fertilization methods to be able to increase STP or STK levels when they are deficient or to maintain desirable levels (Wolkowski and Kelling, 1985; Bates, 1971).

Our experience in the western Corn Belt indicates that a single broadcast application of P and K fertilizers according to estimated crop nutrient removal of a 2-year corn-soybean [Glycine Max (L.) Merr.] rotation is commonly used, even for no-till soils. Thus, a question more relevant than if there is response to starter fertilization for corn compared with equivalent broadcast rates, is if small in-furrow starter fertilization should be used as a substitute or complement to this broadcast fertilization practice. Farmers usually see the positive effect of starter in increasing corn early growth, but reliable documentation of yield increases is difficult. Thus, research is also needed to document early growth and grain yield responses to commonly used starter and broadcast fertilization.

To answer these questions field experiments utilizing in-furrow starter and broadcast applications of PK fertilizer mixtures for corn were conducted across Iowa. Specific objectives of this study were (1) to assess corn grain yield, early growth, and early P and K uptake responses to in-furrow liquid starter applications and (2) to study the benefits of applying small amounts of in-furrow starter in addition to higher broadcast P and K
fertilization rates commonly used by Iowa farmers.

MATERIALS AND METHODS

The experiments for this study were established at nine locations in Iowa farmers’ fields from 2000 until 2002. Sites were selected to represent some of the major soil associations across Iowa and different STP and STK levels. Each county where one or more plots were located and soil information for each site are listed in Table 1. The fields have been managed with a 2-year corn-soybean rotation for many years. Small-plot trials encompassing 0.144 to 0.288 ha (depending on the width of the planter used) were located on areas with one soil series at least 25 m from field borders to minimize border effects. Management practices, except fertilization, were those used by the farmers. Sites 1, 2, and 5 were managed with no-tillage. The remaining sites were tilled by one or two passes with a field cultivator in the spring prior to planting corn, except for Site 8. Field cultivators had shanks containing sweeps that tilled the ground to a depth of about 10 cm and had an attached spike-tooth harrow to level and firm the soil. At Site 8 a disk harrow was used to till the soybean residue in the fall (October), and a field cultivator was used prior to planting in the spring. Hybrids and planting dates varied between trials (Table 2). Plant populations, based on plant counts from each plot at harvest, varied from 61,000 to 73,000 plants ha\(^{-1}\), and were within Iowa State University recommendations.

Corn was planted with equipment owned by the farmers. Plot length at all sites was 15 m. At each trial plot width varied with the planter size and row spacing. At Sites 1, 3, 4, 6, 7, and 8 the row spacing was 76 cm, there were 6 rows per plot, and the plot width was
4.56 m. At Sites 2 and 9 the row spacing was 97 cm, there were 8 rows per plot, and the plot width was 7.76 m. At Site 5 the row spacing was 97 cm, there were 4 rows per plot, and the plot width was 3.88 m.

Treatments applied for corn consisted of a control, starter fertilizer, broadcast P and K fertilizer mixture, and broadcast P and K plus starter. No fertilizer (N, P, or K) was applied to the following soybean crop except for two treatments which are not presented or discussed in this article. Treatments and four replications were grouped in a randomized complete-block design. The starter used in all trials was a commercially available low-salt 3-8-15 (N-P-K) mixture, which is manufactured by reacting H₃PO₄ with aqueous ammonia and KOH and by adding urea. Planters were equipped with fertilizer pumps that applied a liquid fertilizer solution in the seed furrow. Mechanically driven pumps were used at Sites 1, 3, 4, 6, and 7, power take-off driven pumps were used at Sites 2 and 5, and an electric pump was used at Site 8. Application rates varied from 66 to 92 kg ha⁻¹ of product across sites. Thus, rates of N, P, and K applied varied from 2 to 3 kg ha⁻¹ N, 5 to 7 kg ha⁻¹ P, and 10 to 14 kg ha⁻¹ K. The broadcast P and K (granulated triple superphosphate and KCl) rate, except for the P rate applied at Site 3, was the average P and K removed in grain for a 2-year corn-soybean rotation in Iowa (Sawyer et al, 2002), and consisted of 49 kg P ha⁻¹ and 112 kg K ha⁻¹. These were chosen because they are commonly used by farmers of the western Corn Belt for a 2-year corn-soybean rotation, even in high-testing soils. At Site 3, where STP was lowest, broadcast P was applied at 66 kg P ha⁻¹. The broadcast plus starter treatment consisted of a combination of the broadcast and starter fertilization. Farmers applied N before planting across all plots at a rate of 120 to 150 kg N ha⁻¹. An additional rate of 67 kg N ha⁻¹ was
broadcast by hand to all plants immediately after planting.

A second corn-soybean rotational cycle was initiated in the spring of 2002 at sites where treatments were first applied for corn in 2000 (Sites 1 through 4). The fertilizer treatments were reapplied to these same plots. Data from 2000 and 2001 crops will be referred to as the first rotational cycle. Data from 2002 crops will be referred to as the second rotational cycle, and the sites will be referred to as 1b, 2b, 3b, and 4b to correspond to Sites 1 through 4.

Soil samples for the first cycle were collected at random from each replication at all sites before applying the treatments, were analyzed separately, and the results were averaged to represent the initial soil test values for each experimental area. For the 2002 sites (second cycle), samples were collected from all plots in October 2001 after harvesting the previous soybean crop and before soils froze. Each sample was a composite of 10 to 12 cores collected at a 0 to 15 cm depth. All samples were analyzed for P with the Bray-P<sub>1</sub>, Olsen, and Mehlich-3 methods, for K with the ammonium acetate method, and for pH (1:1 soil-water) following standard soil testing procedures recommended by for the North Central Region (Brown, 1998). First cycle soil samples were also analyzed for organic matter by a combustion method (Brown, 1998) using a LECO model CHN-2000 analyzer (Saint Joseph, MI). The current STP and STK interpretations for corn grain production are used in this paper to classify STP and STK ranges (Sawyer et al, 2002). Boundary values for five STP classes for the Bray-P<sub>1</sub> or Mehlich-3 tests with a colorimetric determination of extracted P are ≤ 8 mg kg<sup>-1</sup> for Very Low, 9 to 15 mg kg<sup>-1</sup> for Low, 16 to 20 mg kg<sup>-1</sup> for Optimum, 21 to 30 mg kg<sup>-1</sup> for High, and ≥ 31 mg kg<sup>-1</sup> for Very High. Boundary values for the Olsen P test are
≤5 mg kg\(^{-1}\) for Very Low, 6 to 10 mg kg\(^{-1}\) for Low, 11 to 14 mg kg\(^{-1}\) for Optimum, 15 to 20 mg kg\(^{-1}\) for High, and ≥21 mg kg\(^{-1}\) for Very High. The boundary values for five STK classifications are ≤90 mg kg\(^{-1}\) for Very Low, 91 to 130 mg kg\(^{-1}\) for Low, 131 to 170 mg kg\(^{-1}\) for Optimum, 171 to 200 mg kg\(^{-1}\) for High, and ≥201 mg kg\(^{-1}\) for Very High.

A composite sample consisting of 10 whole plants was collected from each plot, dried at 60 °C in a forced-air oven, weighed, and ground to pass through a 2 mm screen. The aboveground portion of plants was sampled when the height of corn to the center of the whorl measured approximately 15 to 25 cm, which corresponds to the V5 or V6 growth stage (Ritchie et al., 1986). Early growth per plant was determined by dividing the oven dried weight by 10. Plant samples were digested in 70% concentrated H\(_2\)NO\(_3\) and 30% H\(_2\)O\(_2\) in accordance with the procedure outlined by Huang and Schulte (1985). Total P and K in the digests were determined by inductively-coupled plasma (ICP) emission spectroscopy. Plant P and K uptake was calculated from plant P or K concentrations and oven dried weights. Corn ears were hand harvested from a length of 7.6 m in adjacent rows from the center of each plot (from where whole plants had not been sampled). Ears were shelled with a stationary corn sheller, grain was weighed, and a subsample was collected for moisture determination. Grain yield was adjusted to 155 mg kg\(^{-1}\) H\(_2\)O.

Statistical analysis of yield, early corn growth, P and K concentration, and P and K uptake were conducted for each site using the SAS general linear models (GLM) procedure (SAS Institute, 2000) for a randomized complete-block design with fixed treatment and block effects. A protected least significant difference (LSD) procedure was used by calculating LSD values only when main treatment effects were statistically significant (\(P \leq 0.05\)). At
site 1b there was a positive and linear ($P \leq 0.05$) relationship between grain yield and plant population across all treatments and replications (probably because of problems caused by the planter). Thus, reported grain yield data for this site are least square means from a covariance analysis (SAS Institute, 2000) with plant population. Plant population variations within a site were small at all other locations and relationships between population and yield were not significant.

RESULTS AND DISCUSSION

Seasonal Temperature and Precipitation

Early season precipitation and temperature information can be useful to help interpret corn responses to starter fertilization. Table 3 summarizes selected climatic information for the counties where each trial was located. Data were obtained from the nearest National Weather Service station, which were within 2 to 20 km of the sites. The table lists temperature data only for May and June because most trials were planted in May (Table 2) and most plant samples were taken in June. July temperatures were near average and practically the same for all trials, therefore data is not included. Precipitation from May to July is presented because this period covers the important period from corn emergence to silking. The 50-year averaged climatic data included does not differ for most areas in the state. In Iowa, minimum and maximum air temperature for May and June average are 9 and 22 °C for May respectively, and are 15 and 27 °C for June. Monthly average precipitation totals are 11 cm in May, 12 cm in June, and 11 cm in July. Average soil temperatures in the
top 10 cm of soil (standard measurements under a grass cover) have not been taken for as long as other measurements, and long-term averages are not available.

Minimum and maximum temperatures for the 2000 early growing season were typical, except for a slightly warmer than normal May. Most regions received average precipitation early in the growing season. However, both Bremer (Sites 3 and 4) and Iowa (Site 1) Counties received higher than average precipitation during June, and July precipitation was slightly below average. Carroll County (Site 2), located in the western part of the state, received about one-half the average precipitation in May, but received average amounts during June and July. Overall, the climatic conditions in 2000 did not result in lower than average corn yield levels (yield data are not shown in this section, but can be observed in tables that show yield responses).

In 2001, May temperatures were warmer than average across the state, followed by average in June. Precipitation in May was near average for most sites, but in June and July was lower than average for several counties. Counties most affected by low precipitation were Bremer (Sites 6 and 7), Calhoun (Site 8), and Carroll (Site 5). Yield levels were near average for Bremer County but were below average for Calhoun and Carroll Counties. Weather patterns were different for other parts of the state. Precipitation for Cedar County (Site 9) was near average in June and was below average in July. However, low rainfall in July did not seem to limit yield levels in this area; in fact, yield levels tended to be higher than average and higher than for other counties.

Temperatures in 2002 were slightly lower than in the previous years across all sites (about 3 °C less across the state). Precipitation was lower than average during May and June
in all counties. In July, precipitation was higher than average in Bremer (Sites 3b and 4b) and Iowa (Site 1b) Counties, and lower than average in Carroll County (Site 2b). Yield levels reflected these precipitation patterns, in particular the much lower than average yield levels at sites in Carroll County and higher than average levels at sites in Bremer and Iowa Counties.

**Soil-Test P and K Values**

**First cycle sites.**

Initial STP values for the trials ranged from Very Low to Very High according to Iowa State interpretation classes for the Bray-P$_1$ test (Table 1). Trials testing the lowest in P were Sites 3 and 6, which was not surprising because these fields received no broadcast P fertilizer for the past 30 years. At Sites 8 and 9 STP levels were Low. Soils at the remaining sites tested Optimum or higher. The high pH value for Site 1 could indicate that the Bray-P$_1$ test may have underestimated plant-available P. Previous research showed that this test often underestimates plant-available P when soils have pH > 7.3 (Mallarino, 1997) and that the Olsen test provides better availability estimates. However, the Bray-P$_1$ test classified the site as Very High while the Olsen test classified it as High. Use of these two tests resulted in a different STP classification at Sites 2, 5, and 9. However, the differences in classification were caused by only 1 mg kg$^{-1}$, which is within normal error limits. Hereon the Bray-P$_1$ test classes will be used because differences were minor, and because the Bray-P$_1$ test is more frequently used in Iowa and the Corn Belt.

Soil-test K levels also were variable across trials according to the Iowa State University interpretation classes. One site tested Very Low (Site 3), three sites tested Low
(Sites 4, 6, and 9), three sites tested Optimum (Sites 1, 7, and 8), and two tested Very High (Sites 2 and 5).

Second cycle sites.

Knowledge of soil-test levels before applying treatments for the second cycle of trials in 2002 is important to correctly interpret crop responses. The STP levels measured in Fall 2001 for Sites 1b, 2b, 3b, and 4b (Table 4) reflect residual effects of treatments applied for the previous corn crop and the effect of two cropping seasons (corn and soybean). Soil-test P of Sites 1b and 4b, which initially tested Very High, did not differ across treatments ($P < 0.05$). This result is reasonable because the broadcast rates applied the expected 2-year P removal in grain and the influence of the low starter P rate on STP probably could not be detected with such a high initial STP levels. Significant STP differences between treatments for Sites 2b and 3b indicate that plots receiving broadcast fertilization had higher STP levels than the control, whereas plots that received starter alone did not. In spring 2000, Site 2 tested borderline between Optimum and High in STP and Site 3 tested Very Low. Comparison of STP values in Table 1 and Table 4 indicates that broadcast fertilization approximately maintained STP values at both sites (values were only 2 to 3 mg P kg$^{-1}$ higher in fall 2001). However, starter fertilization did not maintain STP at Site 2b (values were 6 mg P kg$^{-1}$ lower in fall 2001) and did not change the very low initial value at Site 3b. Lower STP values were expected in fall 2001 for the starter only treatment because of the low P rate applied, which was about one-eighth the broadcast rate (and expected P removal in grain by
the two crops of the rotation). Soil pH levels did not change for the second cycle and Olsen P test values showed similar trends to the Bray-P<sub>1</sub> test, so data are not shown.

Soil-test K levels in fall 2001 (Table 5) of the four treatments did not differ in Sites 1b, 2b, and 3b. At Site 4b, STK levels were highest for plots that received the broadcast treatment, were intermediate for plots receiving starter alone, and were lowest for the control. Comparison of initial STK values in 2000 (Table 1) and in fall 2001 (Table 5) indicates that STK decreased for all treatments in Sites 1b, 2b, and 4b, including those receiving the broadcast treatment. It is possible that the removal rate in harvested products exceeded the K rate applied. Nutrient concentrations in grain were not measured, but yields for the fertilized treatments were higher than average at these sites. At Site 3b, where yields were about average, STK across treatments did not differ in the Fall of 2001, but values for plots receiving the broadcast or broadcast plus starter treatments increased about 10 mg K kg<sup>−1</sup> compared with values for the control and starter treatments. These results suggest that use of starter alone or lower than removal K fertilization rates will result in decreased STK levels.

**Corn Grain Yield**

**First cycle yields.**

Corn yield was significantly ($P \leq 0.05$) increased by fertilization in four (Sites 1, 3, 6, and 8) of the first cycle trials (Table 6). The three fertilized treatments did not differ at these sites. These results, from a statistical standpoint, indicate that small amounts of P and K applied as a starter can produce similar yields to larger P and K broadcast rates, and there is no yield advantage to using starter fertilizer in conjunction with broadcast fertilization.
However, in three sites (Sites 3, 6, and 8) the data shows a higher yield for the two treatments receiving broadcast fertilization. Although this increased response could not be confirmed with the probability level chosen, the trend is reasonable because these sites were among those with lowest STP and STK values.

The methods used make it difficult to determine whether the addition of P or K, or both, resulted in the increased yield at the four responsive sites. Soil-test P values below Optimum (Table 1) can explain the response in Sites 3, 6, and 8. Soil-test K was below Optimum for Sites 3 and 6 and Optimum for Site 8. In Site 8, it is likely that the yield response was most likely due to the addition of fertilizer P, however, there may have been some effect from fertilizer K as well. At Site 1, STP values were High but STK was Optimum, so it is possible that K fertilizer was responsible for increasing yields. According to current interpretations, the probability of response to fertilizer P or K is >25% for soils testing Very Low or Low and < 25% for soils testing Optimum, and <5% for soils testing High (Sawyer et al., 2002). The yield responses observed at these sites agree with previous STP calibrations (Mallarino, 1997). The lack of differences between P placement agrees with earlier work by Bordoli and Mallarino (1998), who used comparable P rates for granulated fertilizer applied broadcast or with the planter 5 cm beside and below the seeds.

Data in Table 6 show that corn yield was not increased by any fertilization treatment at Site 7, which tested Low in STP and Optimum in STK. Soil-test values for the soil samples collected from each replication before planting corn (not shown) indicate that both STP and STK levels varied from Very Low to Very High across the experimental area. Thus, it is likely that this variability influenced the results observed at this site. In all other non-
responsive sites, STP was either Optimum (Site 5), High (Site 9), or Very High (Sites 2 and 4). Initial STK was Low (Sites 4 and 9), Optimum (Site 7), or High (Sites 2 and 5). Sites 2 and 5 were managed with no-till and the remaining were managed with tillage.

**Second cycle yields.**

Yield data for the second cycle trials (Table 6) showed a significant ($P < 0.05$) response to fertilization only at Site 3b. There were significant differences between treatments at this site. Comparisons between plots that received fertilization show that broadcast fertilization increased yield and starter alone did not. Yields of the broadcast and broadcast plus starter treatments did not differ, indicating no advantage for applying both starter and broadcast fertilization. Results for the previous corn crop (Site 3, Table 6) showed that all fertilized treatments increased yield statistically similarly compared with the control. In fall 2001, all plots at this site tested below Optimum in both STP and STK and there was a small difference in STP but no difference in STK (Tables 4 and 5), which indicates little or no residual effects of treatments applied for the first cycle corn. Thus, differences in response for the second cycle likely were the result of the new treatment application. This may indicate that in the short term, for one crop, starter alone may be adequate to produce comparable yield to larger broadcast rates. However, small amounts of starter most likely will not be able to maintain or increase STP and STK levels as larger broadcast rates can and differences will develop over time.

In the nonresponsive sites of the second cycle, STP of the control plots was Low in Site 2b and Optimum or higher in Sites 1b and 4b. Soil-test K of the control plots was Low
in Sites 1b and 4b, and Very High in Site 2b. Although no responsive trends were observed at Sites 1b and 4b, Site 2b showed a major yield difference between the fertilized treatments and the control (400 to 1,000 kg ha\(^{-1}\)), which achieved statistical significance at the \(P \leq 0.07\) level. Thus, the results for the second cycle are similar to those for the first cycle in that yield responses seem to occur frequently when STP levels are below Optimum but are less predictable when STK is below Optimum.

**Early Corn Growth**

**First cycle sites.**

The treatment effects on early corn growth for the first cycle trials that were sampled are shown in Table 7. One or more fertilization treatments increased early corn growth significantly \((P \leq 0.05)\) in all sites except at Site 5, but a nonsignificant increasing trend also was observed at this site. Plots receiving starter increased early growth at Sites 1 and 2 but the broadcast alone treatment did not. These two sites were managed with no-till, STP was Very High, and STK was Optimum at Site 1 and Very High at Site 2. At Site 5 there was a non-significant responsive trend (at the 0.05 probability level), and plant growth for the starter alone treatment also was larger than for the broadcast treatment alone (which was similar to early growth in the control). Reasons for smaller and less significant early growth response at this site are not obvious. The field was managed with no-till, STP was Optimum, STK was Very High, rainfall amounts in May were the largest across all trials, and air temperatures were near values for other sites (Table 3).
Corn early growth differences between fertilized treatments were inconsistent for Sites 6 through 9, all of which were managed with tillage. The fertilized treatments did not differ at Site 6, which was Very Low in STP and Low in STK. The STP and STK values at Sites 7 and 8 were within the same interpretation classes, with STP Low and STK Optimum, but differences between treatments were dissimilar for the two sites. Only plots receiving broadcast fertilization increased plant growth at Site 7 and the starter alone increased growth more than the broadcast fertilization at Site 8. At Site 9, plots receiving starter increased growth more than the broadcast treatment. At this site, STP was Very High and STK was Optimum.

Second cycle sites.

Results for the second cycle trials shown in Table 7 indicate that one or more fertilization treatments significantly \( P \leq 0.05 \) increased early growth at Sites 1b, 3b, and 4b. At Sites 1b and 4b there were no differences between the fertilized treatments. Site 1b was managed with no-till, and soil-test values for the control and starter plots were Optimum for STP and Low for STK (Tables 4 and 5). At Site 3b, application of either broadcast or starter alone increased early growth more than the control, and application of both increased growth further. This site was managed with tillage, and initial STP and STK were Very Low or Low across all treatments. Site 4b was managed with tillage, and for all treatments STP was Very High and STK was Low. We cannot explain with certainty the lack of treatment effects on early growth at Site 2b. The starter had increased growth for the first cycle corn (Table 7), and the plots of second cycle that had received the control and starter treatments tested Low
or Optimum in STP (Table 4) and STK was Very High (Table 5). The lack of early growth response is puzzling because of the earlier planting date in 2002 (Table 2).

**Summary Discussion of Grain Yield and Early Growth Responses**

Corn early growth response to fertilization occurred more frequently and to a higher degree than grain yield responses. All sites where grain yield responded to fertilization also showed an early growth response, but an early growth response not always translated into a yield response. Early growth responses to fertilization were observed in nine of 11 sites sampled but yield responses were observed only at four of those sites (plants were not sampled at two sites, and there was a yield response at one of them). Moreover, comparisons of treatment means for early growth and yield at the sites where responses to both were observed showed that only at Site 6 the treatment differences were similar for both measurements (no difference between fertilized treatments). The fertilized treatments differed in increasing early growth at seven of the nine responsive sites, but the grain yield response for the fertilized treatments never differed. For example, in two no-till sites the starter increased growth more than the broadcast fertilization alone but this difference was not reflected in grain yield. Also, when broadcast plus starter fertilization increased early growth further than either fertilizer applied alone (which was usually the case when both STP and STK were below Optimum) grain yields were similar across all fertilized treatments. Previous research in Iowa with granulated starter P or K fertilizers applied 5 cm beside and below the seeds (Bordoli and Mallarino, 1998; Mallarino et. al., 1999) or liquid NPK or NP starter mixtures that varied across sites and were applied in the furrow or beside and below
the seeds (Bermudez and Mallarino, 2002) reported large and consistent early growth responses in no-till corn at most sites, but proportionally smaller and unfrequent grain yield responses.

The sites with a significant early growth response to fertilization had STP ranging from Very Low to Very High, STK ranging from Low to Very High, and were managed with tillage or no-tillage. Three of the four corresponding yield responsive sites tested below Optimum in STP and Optimum or High in STK, and one tested borderline between High and Very High in STP and Optimum in STK. Previous Iowa research with granulated starter P or K fertilizers applied separately for no-till corn (Bordoli and Mallarino, 1998; Mallarino et. al., 1999) showed that both early growth and grain yield responses to starter K were less frequent than responses to starter P, although the frequency of low- and high-testing sites was approximately similar according to current Iowa soil-test interpretations. Also, results of previous on-farm research with liquid starter fertilizers (Bermudez and Mallarino, 2002) indicated that growth or yield responses were due to the N or P in the starter mixtures (not K). However, some of the growth or grain yield responses observed in this study may be attributed to the K in the mixtures. For example, this could be the case for early growth responses at Sites 9 and 4b because STP was High or Very High and STK was Low. This could also be the case for grain yield response at Site 1 because STP was borderline between High and Very High and STK was Optimum. However, at other yield responsive sites STP was Very Low or Low and STK ranged from Very Low to Optimum so responses were most likely due to the P in the mixtures. We do not believe the small amount of N applied with the starter caused early growth or yield responses because much larger N rates (larger than
recommended for corn after soybeans) were applied before and immediately after planting at all sites.

The air or soil temperature information available for this study did not show clear evidence of an impact on growth that could explain differences in responses across sites. Corn planting was done within a 2-week period for most sites (except two sites), and neither planting dates nor hybrid characteristics (not shown) help explain differences in response across sites. Above average early season rainfall seemed to explain larger response to starter at some sites compared to other sites or to broadcast fertilization. However, some of the largest growth increases from starter fertilizer compared with broadcast fertilization were observed in sites with the largest rainfall amounts in May, which was when most sites were planted.

**Plant Phosphorus Concentration and Uptake**

**First cycle sites.**

Fertilization significantly ($P < 0.05$) influenced early corn P concentration in three first cycle sites (Table 8) but responses were inconsistent across sites and treatments. At Sites 6 and 9, only the broadcast or the broadcast plus starter treatments increased plant P concentration over the control. This response is most likely explained by larger amounts of P being applied with the broadcast treatment. At Site 8, fertilization decreased plant P concentration, and the decrease was more pronounced for plots receiving starter. This response may be explained by very large fertilization effects on early growth and known plant growth - nutrient uptake interactions as a result of fertilization in low-testing soils, which
were discussed in detail by Steenbjerg (1951). A severe P deficiency probably resulted in a large early growth response to P compared with other sites that was not compensated with a similar response in P uptake. Observation of early growth response in Table 7 and uptake response in Table 8 support this interpretation of results. The difference in plant growth and P concentration response between the sites may also be attributed to differences in rainfall patterns. Rainfall during May at Site 8 was above average and higher than at Sites 6 and 9. Soils may have been wetter at Site 8 thereby limiting root growth and inducing a temporary severe P deficiency that emphasized the dilution of plant P concentration by a large plant growth response to starter.

Early plant P uptake of first cycle corn was significantly increased by fertilization at Sites 6 through 9 and was not affected at other sites (Table 8). Phosphorus uptake responses reflected more closely P effects on early growth than on plant P concentration. For example, as was discussed before, all fertilizer treatments increased early growth and P uptake at Site 8, where fertilization decreased plant P concentration, and at Site 7, where fertilization did not affect plant P concentration. At Sites 6 and 7, plots receiving broadcast fertilization increased P uptake further than application of starter alone. In contrast, at Sites 8 and 9 starter treatments increased early growth further than the broadcast alone treatment. The STP values cannot explain these differences entirely, because STP was Very Low or Low in Sites 6, 7, and 8 and borderline between Optimum and High in Site 9. Rainfall in May at Site 8 was greater than average and higher than Sites 6, 7, 9 (Table 3), while air and soil temperatures were not very different across sites. Thus, plant P uptake at Site 8 may have been limited by poor root growth due to excessively wet soils and could have increased the
response to starter. The difference between Sites 5 and 6 versus Site 9 is unclear. However, the earlier planting date of Site 9 (Table 2) may have caused a response to starter due to cooler soil temperatures.

Second cycle sites.

Early plant P concentration was significantly \((P < 0.05)\) increased only at one site (Site 2b) of the second cycle trials (Table 8), and the fertilized treatments did not differ. The control plots at this site tested Low in STP while plots of other treatments tested Optimum or above, and this site was planted the earliest (Table 2). However, the increased P concentration did not translate to significantly higher P uptake probably because fertilization did not affect early growth either (Table 8). Fertilization increased plant P uptake only at Site 3b, where the response increased with increasing amounts of fertilizer applied. Initial STP was Very Low or Low across all treatments. Neither plant P concentration nor P uptake were significantly increased at Sites 1b and 4b, where control plots tested either borderline between Optimum and High (Site 1b) or Very High (Site 4b).

Plant Potassium Concentration and Uptake

First cycle sites.

Fertilization influenced early plant K concentration more frequently than P concentration. One or more fertilizer treatments increased K concentration \((P < 0.05)\) in five of the seven first cycle sites from where samples were collected (Table 9), but differences between treatments were inconsistent across sites. Application of starter fertilizer alone
increased K concentration further than the broadcast fertilizer alone only at Sites 1 and 9. Site 1 was managed with no-till and STK levels were Optimum (Table 5) while Site 9 was managed with tillage and STK was Low. Application of broadcast fertilizer alone increased K concentration further than the starter alone only at Site 6, which was managed with tillage and STK was Low. The broadcast plus starter fertilization treatment was the only treatment that increased K concentration compared with the control at Site 5 and was better than either treatment applied alone at Site 8. Site 5 was managed with no-till and STK was High, while Site 8 was managed with tillage and STK was Optimum. Concerning the two non-responsive sites, Site 2 was managed with no-till and tested Very High in STK whereas Site 7 was managed with tillage and tested Optimum in STK. Consideration of tillage, soil-test values, or climatic conditions were not useful in providing clear explanations for the inconsistency of fertilization treatment differences across sites.

Fertilization increased \((P < 0.05)\) early plant K uptake at six of the first cycle sites (Table 10), which were sites where fertilization also increased early growth (Table 8). Plant K uptake did not respond to fertilization only at Site 5, where fertilization increased K concentration but did not increase early growth (at a 0.05 probability level). This site was managed with no-till (similarly to Sites 1 and 2) and tested High in STK (intermediate between STK of Sites 1 and 2). The reason for the lack of early growth response to any fertilization treatment at this site is not clear (as was discussed above). Application of starter alone increased K uptake further than broadcast fertilization alone at Sites 1 and 2. These sites were managed with no-till and tested Optimum or Very High in STK. The broadcast alone treatment increased K uptake more than the starter alone at Site 6 and 7, a result that
seems to be a combination of results for K concentration and early growth. Both sites were managed with tillage, and STK was Low at Site 6 and Optimum at Site 7. The broadcast plus starter fertilization produced the largest K uptake increases in Sites 8 and 9. These sites were managed with tillage, and STK was Optimum in Site 8 and Low in Site 9. Responses at these two sites did not match responses of either K concentration or early growth, and the result seemed to be that of a combination of those responses.

**Second cycle sites.**

Early plant K concentration was significantly ($P < 0.05$) increased in three of the four second cycle sites (Table 9). At Sites 1b and 3b, plots receiving broadcast fertilization increased K concentration further than starter alone. At Site 4b, the broadcast fertilization alone also produced higher plant K concentration than the starter alone, but the broadcast plus starter treatment produced the highest K concentration. All plots of these three sites tested Low in STK. There was no significant fertilization effect on K concentrations at Site 2b, which tested Very High in STK, was managed with no-till, and was planted the earliest. Early plant K uptake was also significantly increased in same three sites (Table 9). Similar to results for other sites, the differences between the fertilized treatments seemed the result of a combination of treatment effects on K concentration and early growth. Plant K uptake did not differ across the fertilized treatments at Site 1b, increased with the fertilizer rate applied at Site 3b, and was highest for the broadcast plus starter treatment compared with either treatment applied alone.
Summary Discussion of Plant Phosphorus and Potassium Content Responses

Interpretations of early plant nutrient concentrations and uptake responses is very difficult because treatments involved P and K mixtures, patterns of STP and STK variation across sites differed greatly, and responses of early plant growth, nutrient concentration, and nutrient uptake are intimately related. Results indicate that large and frequent fertilizer effects on early plant growth explained responses of early P and K uptake. Dilution of P in the increased plant dry matter determined small and unfrequent fertilizer effects on plant P concentration. This effect was not as marked for plant K concentration. In fact, our results showing increased K concentration in many sites agrees with earlier reports of large luxury accumulation of K compared with P in corn early growth (Mallarino et al., 1999).

Only in a few instances fertilization effects on both early growth and P concentration determined a proportionally larger P uptake response. This difference was twice as much or larger in Sites 5 and 2b, which were managed with no-till and had STP Low or Optimum. These results indicate that increased P availability usually effected early growth more than P uptake relative to plant size. Because the fertilization treatments included a PK mixture, these results for plant P concentration could also indicate that K had an important role in increasing early growth.

Fertilization increased plant K concentration at twice the number of sites in which P concentration was increased, and K uptake response was observed at all sites in which early growth response was observed (nine sites) regardless of the STK value. These observations do not necessarily mean that K in the fertilizer mixture increased early growth more than P did. Parallel Iowa research with NP starter fertilizer for tilled and no-till corn (Bermudez and
Mallarino, 2002) showed increases in early plant K concentration and uptake at all sites even though the fertilizer did not include K and there were unfrequent P concentration responses. Thus, it is possible that K increased early growth in our study but it is also possible that increased K uptake was the result of P effects in increasing plant growth. We cannot confirm one or the other possibility with the methods used.

**SUMMARY AND CONCLUSIONS**

Corn yield responses to PK fertilization (starter or broadcast) were observed in five of 13 sites. In four responsive sites, STP was below the current Optimum level for corn and STK ranged from Very Low to Optimum. In the other responsive site, which was managed with no-till, STP was borderline between the High and Very High classes and STK was Optimum. Responses were not observed in three sites where either nutrient was below Optimum levels. In all first cycle responsive sites, the small amount of a PK starter applied in the furrow produced corn yields statistically comparable to those produced with the much larger PK broadcast application. When either STP or STK were within the Very Low interpretation classes, the broadcast fertilizer rates usually produced higher yields than starter, but the difference never achieved the 0.05 probability level. Moreover, when soil-test levels were Very Low for a first corn crop, the starter rate was too small to provide adequate P and K nutrition for the corn of a second rotation cycle (after a soybean crop that was not fertilized).

Early growth responses occurred more frequently than grain yield responses in nine of 11 sites in which plants were sampled at the V5 to V6 growth stage. Early plant growth
responses were observed across all STP or STK interpretation classes. At two no-till sites and two tilled sites, the starter increased corn early growth more than the much larger broadcast rate regardless of soil-test levels. Broadcast fertilization increased early growth more than starter alone in one site, which was tilled and tested Low in STP and Optimum in STK. The combination of starter and broadcast fertilization never increased early growth more than either fertilizer applied alone.

Fertilization increased early plant K concentration and uptake more frequently than P concentration and uptake. The nutrient uptake responses usually corresponded to early growth responses. The small starter rate increased P uptake more than the larger broadcast rate at two of five sites in which P uptake was increased by fertilization. The starter increased K uptake more than the broadcast fertilizer only at three of nine sites in which K uptake was increased.

Overall, the results showed that in-furrow PK starter fertilization in the short term (one crop) can produce corn yield responses statistically comparable to much larger broadcast PK rates. Starter or broadcast fertilization usually increased early corn growth and nutrient uptake. The starter alone proved more effective in increasing early growth in approximately one-half of the responsive sites, and this effect was similar for no-till or tilled soils. Large and frequent early growth responses to starter or broadcast fertilization did not translate in large and frequent grain yield responses. There was no yield benefit from starter fertilization when PK rates commonly used for a 2-year corn-soybean rotation were applied before corn to no-till or tilled soils. However, in the short term, in-furrow PK starter rates approximately eight times smaller produced statistically comparable grain yield. The results indicate that a
combination of in-furrow starter fertilization with lower and/or unfrequent broadcast fertilization could be a cost-effective fertilization strategy for corn.

REFERENCES CITED


Table 1. Field locations, soil series, and selected initial soil-test values.  

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† Soil-test values for second rotational cycle trials are not shown in this table.
‡ K, ammonium-acetate extracted K, OM, organic matter.
Table 2. Year, location, planting date, corn hybrid, and tillage information for all sites.

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† Site numbers followed by the letter b indicate corn of a second rotational cycle.
‡ A, Asgrow; C, Crows; DK, Dekalb; G, Garst; P, Pioneer; and R, Renze; RO, Otillie.
§ fc, soybean residue field cultivated in spring; dc, disked in the fall and field cultivated in the spring; nt, no-till.
Table 3. Monthly temperature averages and precipitation totals for the counties where the sites were established.†

<table>
<thead>
<tr>
<th>County</th>
<th>Year</th>
<th>Site</th>
<th>May</th>
<th>June</th>
<th>May</th>
<th>June</th>
<th>May</th>
<th>June</th>
<th>May</th>
<th>June</th>
<th>July</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bremer</td>
<td>2000</td>
<td>3, 4</td>
<td>12</td>
<td>15</td>
<td>24</td>
<td>27</td>
<td>17</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>6, 7</td>
<td>10</td>
<td>14</td>
<td>21</td>
<td>25</td>
<td>16</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>3b,4b</td>
<td>7</td>
<td>16</td>
<td>20</td>
<td>28</td>
<td>13</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calhoun</td>
<td>2001</td>
<td>8</td>
<td>9</td>
<td>14</td>
<td>21</td>
<td>26</td>
<td>16</td>
<td>21</td>
<td>29.0</td>
<td>9.9</td>
<td>7.4</td>
</tr>
<tr>
<td>Carroll</td>
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<td>10</td>
<td>14</td>
<td>24</td>
<td>27</td>
<td>18</td>
<td>22</td>
<td>7.1</td>
<td>9.3</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>5</td>
<td>10</td>
<td>14</td>
<td>22</td>
<td>27</td>
<td>17</td>
<td>21</td>
<td>18.5</td>
<td>14.4</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>2b</td>
<td>7</td>
<td>17</td>
<td>21</td>
<td>30</td>
<td>15</td>
<td>25</td>
<td>9.9</td>
<td>7.9</td>
<td>6.7</td>
</tr>
<tr>
<td>Cedar</td>
<td>2001</td>
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<td>10</td>
<td>14</td>
<td>23</td>
<td>24</td>
<td>18</td>
<td>21</td>
<td>15.5</td>
<td>9.6</td>
<td>8.1</td>
</tr>
<tr>
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<td>2000</td>
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<td>11</td>
<td>14</td>
<td>23</td>
<td>25</td>
<td>18</td>
<td>22</td>
<td>12.8</td>
<td>14.8</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>1b</td>
<td>7</td>
<td>16</td>
<td>21</td>
<td>28</td>
<td>14</td>
<td>23</td>
<td>10.1</td>
<td>6.9</td>
<td>11.2</td>
</tr>
</tbody>
</table>

† Monthly temperature averages and precipitation totals as reported by the nearest National Weather Service weather station.
Table 4. Initial Bray-P1 soil-test P values for second cycle sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Control</th>
<th>Starter</th>
<th>Broadcast</th>
<th>Broadcast + starter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg P kg⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1b</td>
<td>19</td>
<td>17</td>
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<td>27</td>
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<td>2b</td>
<td>13a</td>
<td>17a</td>
<td>25b</td>
<td>23b</td>
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<tr>
<td>3b</td>
<td>5a</td>
<td>6a</td>
<td>8b</td>
<td>9b</td>
</tr>
<tr>
<td>4b</td>
<td>53</td>
<td>55</td>
<td>59</td>
<td>61</td>
</tr>
</tbody>
</table>

† Letters following numbers represent significant differences (LSD, $P \leq 0.05$) between treatments when there was a significant main treatment effect.
Table 5. Initial soil-test K values for second cycle sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Control</th>
<th>Starter</th>
<th>Broadcast</th>
<th>Broadcast + Starter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1b</td>
<td>107</td>
<td>106</td>
<td>114</td>
<td>118</td>
</tr>
<tr>
<td>2b</td>
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<td>218</td>
<td>217</td>
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<tr>
<td>3b</td>
<td>90</td>
<td>93</td>
<td>97</td>
<td>102</td>
</tr>
<tr>
<td>4b</td>
<td>97a</td>
<td>107ab</td>
<td>120bc</td>
<td>124c</td>
</tr>
</tbody>
</table>

† Letters following numbers represent significant differences (LSD, $P \leq 0.05$) between treatments when there was a significant main treatment effect.
Table 6. Treatment effects on corn grain yield.

<table>
<thead>
<tr>
<th>Site</th>
<th>Control</th>
<th>Starter</th>
<th>Broadcast</th>
<th>Broadcast + starter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>kg ha⁻¹</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>10628a</td>
<td>11594b</td>
<td>11395b</td>
<td>11309b</td>
</tr>
<tr>
<td>2</td>
<td>8047</td>
<td>8468</td>
<td>8425</td>
<td>8081</td>
</tr>
<tr>
<td>3</td>
<td>8389a</td>
<td>9488b</td>
<td>9720b</td>
<td>9933b</td>
</tr>
<tr>
<td>4</td>
<td>10231</td>
<td>10344</td>
<td>10588</td>
<td>10414</td>
</tr>
<tr>
<td>5</td>
<td>6981</td>
<td>7754</td>
<td>7389</td>
<td>7845</td>
</tr>
<tr>
<td>6</td>
<td>9462a</td>
<td>10025b</td>
<td>10512b</td>
<td>10260b</td>
</tr>
<tr>
<td>7</td>
<td>10589</td>
<td>10866</td>
<td>10880</td>
<td>11444</td>
</tr>
<tr>
<td>8</td>
<td>6512a</td>
<td>7006b</td>
<td>7571b</td>
<td>7443b</td>
</tr>
<tr>
<td>9</td>
<td>11479</td>
<td>11876</td>
<td>11934</td>
<td>12090</td>
</tr>
<tr>
<td>1b</td>
<td>10658</td>
<td>10951</td>
<td>10286</td>
<td>11158</td>
</tr>
<tr>
<td>2b</td>
<td>9334</td>
<td>9718</td>
<td>10428</td>
<td>9997</td>
</tr>
<tr>
<td>3b</td>
<td>11836a</td>
<td>12183a</td>
<td>13658b</td>
<td>13300b</td>
</tr>
<tr>
<td>4b</td>
<td>13155</td>
<td>13180</td>
<td>13349</td>
<td>13737</td>
</tr>
</tbody>
</table>

† Letters following numbers represent significant differences (LSD, P ≤ 0.05) between treatments when there was a significant main treatment effect.
Table 7. Treatment effects on early corn growth (dry weight) at the V5 to V6 growth stage.

<table>
<thead>
<tr>
<th>Site</th>
<th>Control</th>
<th>Starter</th>
<th>Broadcast</th>
<th>Broadcast + starter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.50a</td>
<td>3.08b</td>
<td>2.72a</td>
<td>2.98b</td>
</tr>
<tr>
<td>2</td>
<td>3.99a</td>
<td>4.76b</td>
<td>3.95a</td>
<td>4.61b</td>
</tr>
<tr>
<td>5</td>
<td>6.03</td>
<td>6.58</td>
<td>6.12</td>
<td>6.43</td>
</tr>
<tr>
<td>6</td>
<td>1.40a</td>
<td>1.71b</td>
<td>1.86b</td>
<td>1.94b</td>
</tr>
<tr>
<td>7</td>
<td>3.28a</td>
<td>3.85ab</td>
<td>4.53c</td>
<td>4.38bc</td>
</tr>
<tr>
<td>8</td>
<td>2.54a</td>
<td>4.64c</td>
<td>3.34b</td>
<td>4.62c</td>
</tr>
<tr>
<td>9</td>
<td>1.50a</td>
<td>1.92b</td>
<td>1.74ab</td>
<td>1.99b</td>
</tr>
<tr>
<td>1b</td>
<td>1.57a</td>
<td>2.84b</td>
<td>2.33b</td>
<td>2.62b</td>
</tr>
<tr>
<td>2b</td>
<td>1.34</td>
<td>1.32</td>
<td>1.26</td>
<td>1.51</td>
</tr>
<tr>
<td>3b</td>
<td>2.29a</td>
<td>3.40b</td>
<td>3.44b</td>
<td>4.53c</td>
</tr>
<tr>
<td>4b</td>
<td>2.81a</td>
<td>3.68b</td>
<td>3.66b</td>
<td>3.89b</td>
</tr>
</tbody>
</table>

† Letters following numbers represent significant differences (LSD, \( P \leq 0.05 \)) between treatments when there was a significant main treatment effect.

‡ Sites 3 and 4 were not sampled.
Table 8. Treatment effects on early corn P concentration and uptake (V5 to V6 growth stage).

<table>
<thead>
<tr>
<th>Site</th>
<th>Control</th>
<th>Starter</th>
<th>Broadcast</th>
<th>+ Starter</th>
<th>Control</th>
<th>Starter</th>
<th>Broadcast</th>
<th>+ starter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mg g⁻¹</td>
<td></td>
<td>mg plant⁻¹</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.46</td>
<td>0.45</td>
<td>0.45</td>
<td>0.43</td>
<td>12.24</td>
<td>13.40</td>
<td>12.10</td>
<td>12.78</td>
</tr>
<tr>
<td>2</td>
<td>0.31</td>
<td>0.32</td>
<td>0.36</td>
<td>0.33</td>
<td>13.10</td>
<td>14.45</td>
<td>13.67</td>
<td>15.21</td>
</tr>
<tr>
<td>5</td>
<td>0.53</td>
<td>0.54</td>
<td>0.57</td>
<td>0.58</td>
<td>31.90</td>
<td>35.28</td>
<td>34.82</td>
<td>37.03</td>
</tr>
<tr>
<td>6</td>
<td>0.50a</td>
<td>0.48a</td>
<td>0.57b</td>
<td>0.55b</td>
<td>6.93a</td>
<td>8.63b</td>
<td>10.40c</td>
<td>10.53c</td>
</tr>
<tr>
<td>7</td>
<td>0.55</td>
<td>0.53</td>
<td>0.56</td>
<td>0.53</td>
<td>18.10a</td>
<td>20.55ab</td>
<td>24.43b</td>
<td>23.08ab</td>
</tr>
<tr>
<td>8</td>
<td>0.47a</td>
<td>0.42b</td>
<td>0.45c</td>
<td>0.42b</td>
<td>11.84a</td>
<td>19.16c</td>
<td>15.23b</td>
<td>19.30c</td>
</tr>
<tr>
<td>9</td>
<td>0.52a</td>
<td>0.53a</td>
<td>0.53a</td>
<td>0.58b</td>
<td>7.78a</td>
<td>10.81c</td>
<td>9.38b</td>
<td>11.48c</td>
</tr>
<tr>
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<td>0.47</td>
<td>0.48</td>
<td>0.48</td>
<td>8.76</td>
<td>12.06</td>
<td>10.50</td>
<td>12.30</td>
</tr>
<tr>
<td>2b</td>
<td>0.39a</td>
<td>0.42b</td>
<td>0.42b</td>
<td>0.43b</td>
<td>5.26</td>
<td>5.60</td>
<td>5.51</td>
<td>6.51</td>
</tr>
<tr>
<td>3b</td>
<td>0.44</td>
<td>0.43</td>
<td>0.48</td>
<td>0.44</td>
<td>9.92a</td>
<td>14.05b</td>
<td>17.57c</td>
<td>21.26d</td>
</tr>
<tr>
<td>4b</td>
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<td>0.40</td>
<td>0.44</td>
<td>0.45</td>
<td>12.48</td>
<td>13.12</td>
<td>15.82</td>
<td>16.61</td>
</tr>
</tbody>
</table>

† Letters following numbers represent significant differences (LSD, $P \leq 0.05$) between treatments when there was a significant main treatment effect.

‡ Sites 3 and 4 were not sampled.
Table 9. Treatment effects on early corn K concentration and uptake (V5 to V6 growth stage).

<table>
<thead>
<tr>
<th>Site</th>
<th>Control</th>
<th>Starter</th>
<th>Broadcast</th>
<th>Broadcast + starter</th>
<th>Control</th>
<th>Starter</th>
<th>Broadcast</th>
<th>Broadcast + starter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>mg g⁻¹</td>
<td></td>
<td></td>
<td></td>
<td>mg plant⁻¹</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.38a</td>
<td>3.44b</td>
<td>2.86a</td>
<td>3.70b</td>
<td>59.59a</td>
<td>103.98b</td>
<td>77.95a</td>
<td>119.42b</td>
</tr>
<tr>
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<td>3.60</td>
<td>3.81</td>
<td>3.63</td>
<td>3.86</td>
<td>145.32a</td>
<td>197.97b</td>
<td>168.85a</td>
<td>178.51b</td>
</tr>
<tr>
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<td>2.71a</td>
<td>3.01ab</td>
<td>3.20ab</td>
<td>3.31b</td>
<td>165.65</td>
<td>198.50</td>
<td>193.11</td>
<td>211.48</td>
</tr>
<tr>
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<td>3.48a</td>
<td>4.00b</td>
<td>4.12b</td>
<td>46.25a</td>
<td>57.66b</td>
<td>72.64c</td>
<td>75.90c</td>
</tr>
<tr>
<td>7</td>
<td>3.30</td>
<td>3.56</td>
<td>3.71</td>
<td>3.68</td>
<td>95.64a</td>
<td>138.98b</td>
<td>158.39b</td>
<td>161.08b</td>
</tr>
<tr>
<td>8</td>
<td>1.84a</td>
<td>2.58b</td>
<td>2.49b</td>
<td>2.96c</td>
<td>45.97a</td>
<td>111.05c</td>
<td>83.78b</td>
<td>135.95d</td>
</tr>
<tr>
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<td>2.97b</td>
<td>2.65c</td>
<td>3.35d</td>
<td>33.75a</td>
<td>58.69b</td>
<td>46.62b</td>
<td>66.68c</td>
</tr>
<tr>
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<td>1.89a</td>
<td>2.46ab</td>
<td>2.76bc</td>
<td>3.17c</td>
<td>28.77a</td>
<td>67.20b</td>
<td>64.52b</td>
<td>71.61b</td>
</tr>
<tr>
<td>2b</td>
<td>3.31</td>
<td>3.56</td>
<td>3.61</td>
<td>3.71</td>
<td>44.15</td>
<td>47.35</td>
<td>45.20</td>
<td>55.64</td>
</tr>
<tr>
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<td>1.83a</td>
<td>2.14a</td>
<td>2.97b</td>
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<td>41.33a</td>
<td>69.21a</td>
<td>103.77b</td>
<td>136.90c</td>
</tr>
<tr>
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<td>2.80a</td>
<td>3.46b</td>
<td>4.28c</td>
<td>4.57d</td>
<td>86.29a</td>
<td>136.62b</td>
<td>141.06b</td>
<td>184.13c</td>
</tr>
</tbody>
</table>

† Letters following numbers represent significant differences (LSD, P ≤ 0.05) between treatments when there was a significant main treatment effect.
‡ Sites 3 and 4 were not sampled.
CHAPTER 3. GENERAL CONCLUSIONS

The objectives of this study were to evaluate corn yield response to small amounts of P and K in a liquid starter fertilizer applied to the seed furrow and to determine if this practice could replace larger broadcast fertilization rates, as well as to study how early growth responses to starter fertilization relate to grain yield responses. The study involved 13 small plot trials located in nine farmers' fields over a 3-year period. Treatments applied were a control, a liquid PK in-furrow starter, PK broadcast fertilizer, and a PK broadcast plus PK in-furrow starter.

The results showed that corn yield responses to PK fertilization were observed in five of thirteen sites. In four responsive sites, STP was below the current Optimum level for corn and STK ranged from Very Low to Optimum. In the other responsive site, STP was borderline between the High and Very High classes and STK was Optimum. Responses were not observed in three sites where either nutrient was below Optimum levels. In all responsive sites, a small amount of a PK starter applied in the furrow produced corn yields statistically similar to those produced with much larger PK broadcast rates. However, in some low-testing soils, the starter rate was too small to provide adequate P and K for the corn of a second rotation cycle (after a soybean crop that was not fertilized).
Early growth responses occurred more frequently than grain yield responses and were observed across all STP or STK interpretation classes. At two no-till sites and two tilled sites, starter increased corn early growth more than the much larger broadcast rate regardless of soil-test levels. Broadcast fertilization increased early growth further than the starter only in one site, which was tilled and tested Low in STK and Optimum in STK. The combination of starter and broadcast fertilization never increased early growth more than either fertilizer applied alone.

Fertilization increased early plant K concentration and uptake more frequently than P concentration and uptake, and the nutrient uptake responses usually corresponded to early growth responses. Although the large broadcast rate usually increased nutrient uptake more than the small starter rate, the starter rate increased nutrient uptake more than the broadcast rate at approximately 40% of the responsive sites.

Overall, the results showed that in-furrow PK starter fertilization in the short term (one crop) can produce corn yield responses statistically similar to much larger broadcast PK rates. Large and frequent early growth responses to starter or broadcast fertilization did not translate in large and frequent grain yield responses. There was no yield benefit from starter fertilization when PK rates commonly used for the corn-soybean rotation were applied to no-till or tilled soils. However, in the short term, in-furrow PK starter rates approximately eight times smaller produced comparable grain yield. The results indicate that a combination of in-
furrow starter fertilization with lower and/or unfrequent broadcast fertilization could be a cost-effective fertilization strategy for corn. Although broadcast P and K fertilization is not recommended for high-testing soils, many risk weary farmers still fertilize their fields. The results of this study indicate the application of a small amount of starter in the seed furrow is an environmentally better way of applying fertilizer to high-testing soils if no application is a concern to farmers.