Yield and early growth responses to starter fertilizer in no-till corn

by

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GENERAL INTRODUCTION

Many farmers, agricultural scientists, and extension specialists have concern over severe problems associated with fertilization practices commonly used in conventional agriculture. For example, the use of excess N fertilizer or animal manure can result in ground water contamination. Phosphate in runoff water can enter neighboring lakes or streams and degrade water quality. Soil erosion associated with conventional tillage and the lack of crop rotation can also degrade the soils significantly. Many farmers need to change farming practices in order to improve the sustainability of crop production. No-till systems became popular among scientists because they have the potential to alleviate these problems. Particular advantages of no-tillage over conventional tillage are the increase of residue cover, the reduction of soil erosion, and the increase of crop water use efficiency. However, a pivotal disadvantage of no-tillage for spring planted crops is that it creates soil conditions that are cooler and wetter at planting time. Until the 1990's, there was an increase in the number of Iowa farmers adopting no-till systems. Presently this tendency has slowed or has reversed. The main reason for Iowa farmers to switch back from no-till to some kind of tillage management is the concern for low crop yields. Iowa research has showed slightly lower yields for no-till corn compared with corn managed with chisel-disk tillage.

From a soil fertility perspective, high residue cover can restrict early plant and root growth and development. Colder and wetter soils can reduce early nutrient uptake and early growth for major agricultural crops. Early season plant growth is often poorer than with conventional tillage systems, and this is often thought as part of the cause of some grain yield reduction. Starter fertilization is a common fertilizer practice used in some areas of the U.S. to improve nutrient uptake and early crop growth even in soils high in available nutrients. However, several questions have arisen about the use of this placement option with major concerns relating to the application method, the nutrient ratio, and the amount to use. From an environmental perspective, starter fertilization can help reduce the amount of fertilizer added (P and K) especially in soils with high fertility levels.

With the advent of precision agriculture technologies, such as differentially corrected global positioning systems (DGPS), yield monitors, geographic information systems (GIS), and grid sampling, more producers are able to generate yield maps capable of describing the yield variability over the landscape. GIS software can then be used to process this yield data for independent analyses of the different areas or be used in statistical procedures that account for spatial correlation.

This study reports the methodology used and the results of strip trials conducted in several farmer fields. The objectives were (1) to study crop yield and early growth responses to starter fertilization in no-till corn and (2) to evaluate the responses of starter fertilization over the landscape using precision agriculture technologies.

Thesis Organization

The thesis is presented as one paper suitable for publication in scientific journals of the American Society of Agronomy. The title of the paper is ”Yield and early growth responses to starter fertilization in no-till corn”. The paper is divided in sections that include an abstract, introduction, materials and methods, results and discussion, conclusions, reference list, and tables. The paper is preceded by a general introduction and followed by general conclusions.

YIELD AND EARLY GROWTH RESPONSES TO STARTER FERTILIZER IN NO-TILL CORN

A paper to be submitted to the Journal of the America Society of Agronomy

Manuel Bermudez and Antonio Mallarino

Abstract

Reduced yield of no-till corn (*Zea mays* L.) as compared to conventional tillage in humid regions is partly attributed to slower early growth. Starter fertilization often is recommended to increase early growth and grain yield. The objectives of this study were to evaluate yield and early growth responses to starter fertilization in no-till corn and to assess the variation in growth and grain yield responses over the landscape using precision agriculture technologies. Eight trials were conducted from 1995 through 1998 in farmers' fields which had received 8 to 14 years of no-till management. Treatments were liquid NPK starter and no starter. Rates and nutrient ratios varied among the fields. A strip trial methodology was used for all trials. Yield monitors, intensive soil sampling, differential global positioning systems with real-time differential correction (DGPS), and geographical information systems (GIS) were used to study yield and early growth (dry weight at the V5 to V6 developmental stages) responses. The response data were analyzed using conventional analysis of variance (ANOVA) and by accounting for spatial correlation of yields with nearest-neighbor analyses (NNA) in conjunction with ANOVA. Accounting for spatial correlation improved the evaluation of treatment effects. The methodology had no effect on the estimated treatment means but reduced the standard errors of the estimation. In-the-furrow starter fertilization increased yield in most fields. The responses were larger (approximately 200 to 600 kg ha^{-1}), when soil-test P (STP) was below optimum levels for corn and were not related with other soil tests, landscape position, or soil survey mapping units. Small responses observed in high-testing soils to applications in the furrow likely were produced by the small amount of N in the starter (9 kg N ha^{-1} or less) because no preplant N was applied at any field except at Site 8. Nitrogen probably was responsible for the large response at the only site where the starter was applied at a higher rate and beside and below the seeds. The early growth responses to starter fertilization were large and occurred in most fields, were larger when soil test P was low, and also were significant when soil test P was very high. Across all sites, starter fertilization increased early growth by 29% and grain yield by 3.7%. The grain yield response was positively, but poorly, correlated with early growth response within and across sites. Overall, the study showed little economic justification for applying starter fertilizer in the furrow when available soil P is above optimum levels for corn grain production.

Introduction

Reduced tillage is a common agricultural practice used by farmers in Iowa. Reduced tillage minimizes soil erosion and increases crop water use efficiency by providing residue cover and soil conditions that are cooler and wetter than for conventional tillage systems (Blevins et al., 1971; Thomas et al., 1973; Jones et al., 1969). These conditions can reduce early nutrient uptake and early growth for spring seeded crops. Reduced yield of no-till corn as compared to conventional tillage in humid regions is partly attributed to slower early growth (Gordon et al., 1995). Similar conditions can increase both nutrient uptake and growth during summer periods with low rainfall or high moisture losses through evaporation or transpiration.

Several studies found that reduced soil temperatures affected root growth and nutrient uptake (Barber, 1971; Barber, 1978; Al-Darby and Lowery, 1987; Cox et al., 1990; Fortin, 1993). Colder temperatures tended to reduce plant growth and the diffusion of P and K to roots. Studies also have found that no-till and mulch-till reduced early growth of corn in the Northern Corn Belt, compared with conventional tillage, as a result of cooler soil temperatures (Griffith et al., 1973; Mock and Erbach, 1977; Al-Darby and Lowery, 1986; Carter and Barnet, 1987; Imholte and Carter, 1987; Swan et al., 1987; Kaspar et al., 1990; Fortin and Pierce, 1991). Reduced early growth could limit grain yield. Sometimes, however, delayed early growth and development under conservation tillage does not reduce grain yield because corn often attains physiological maturity before a killing freeze in the fall (Swan et al., 1987; Cox et al., 1990). In extreme cold years, no-till systems can produce uneven emergence or crop development in comparison to conventional tillage systems. Fortin (1993) found that residue removal along rows produced development rates similar to conventional tillage. He also found that crop yield was unaffected by residue removal despite considerable changes in soil temperature and water content and in crop development rate and height during vegetative stages.

Starter fertilization is a common fertilizer practice in some areas of the U.S.A. Starter fertilization usually refers to small fertilizer amounts applied at planting time in bands near the seeds (Penas and Hergert, 1990). The fertilizer is applied either in a band beside and below the seeds or with the seed (normally called in-the-furrow or pop-up). Starter fertilization often is recommended to increase early growth and grain yield. In Iowa, for example, a complete NPK starter mixture is often recommended for corn when soil conditions are expected to be cooler and wetter than normal as such conditions tend to delay seed germination and emergence and early vegetative growth (Voss, 1985). Research suggests that the magnitudes of increased growth and yield due to starter fertilization increase when the starter is applied to soils with low soil-test P (Rehm et al., 1988; Welch et al., 1966), cool soils (Randall and Hoeft, 1988), or in reduced tillage (Howard and Tyler, 1987).

In the Midwest region of the U.S.A., starter fertilization often increases early growth to a larger extent than grain yield (Randall et al., 1988; Bullock et al., 1993). Mengel et al. (1992) found that starter fertilization increased corn yield in only one site under conventional tillage but in eight sites under no-till in Indiana, although no detailed information was provided in this publication about soil-test levels and preplant fertilization. Several authors have attributed the response to starter fertilizer to the P in the mixture (Randall et al., 1985; Randal and Hoeft, 1988; Black, 1993). These suggestions are consistent with the usually high P requirements for early plant growth and development (Black, 1993). In some situations, however, responses to N also occur (Ritchie et al., 1995). Most response studies with starter for no-till corn have been conducted with NPK mixtures, however, and little can be said of the importance of each nutrient in the crop response. Rehm et al. (1988) found significant responses to P and K starter fertilization during a cool and wet spring season despite high soil test values. Mengel et al. (1988) in southern Indiana soils observed that the use of seed applied N and

P starter fertilizer enhanced early growth and increased corn yields in both plow and no-till systems at low rates of P and K preplant fertilization. At higher preplant rates, starter fertilization enhanced early vegetative growth but had no significant effect on grain yield. The starter fertilizer increased grain yields in spite of very high soil test P levels but the starter yield response was confined to plots receiving the low preplant fertilizer rates. Therefore soil-test values, preplant fertilization, soil temperature, soil moisture, and tillage practice affect the response of corn to starter fertilization.

The placement of the starter either in bands beside and below the seeds or in the furrow (in contact with the seed) could generate different crop responses. These two placements seldom have been compared for corn in the same experimental settings. Extensive research with other crops such as cotton (*Gossypium hirsutum* L.) may not apply to corn. Mascagni and Boquet (1998) showed the potential injury of direct contact between fertilizer and corn seed. They also found that application of in-furrow starter N and P fertilizer at low rates increased corn yield, decreased harvest grain moisture, and advanced the silking date. The use of in-the-furrow (or “pop-up”) starter placement is prefered by many corn producers, because it is more practical and less costly.

With the advent of precision farming technologies such as yield monitors, DGPS, and GIS in the Corn Belt, researchers and producers can generate yield maps capable of identifying and estimating the yield variability over the landscape. The within-field variability of soil nutrients has been well recognized. At the field scale, the main factors producing variability are soil type, topography, previous crop and soil management practices (Mallarino and Wittry, 1997). This variability is likely to cause field areas to differ in responses to added fertilizer. Current research has focused on predicting the relationships of yield variability with soil parameters and over the landscape utilizing different statistical methods (Clarke et al., 1996; Mallarino et al., 1996; Sudduth et al, 1996; Schneider et al., 1997; Thylen, 1997). The ability to accurately record geographical coordinates and data for specific locations within a field could greatly improve field-scale, on-farm research (Oyarzabal et al., 1996; Reetz, 1996). On-farm research on the basis of strip plots is an accepted methodology for complementing traditional small-plot research, for generating local recommendations, and for demonstrating management practices (Rzewnicki et al., 1988; Shapiro et al., 1989). Treatments are applied to narrow and long strips (usually of the length of the fields), and the grain is harvested with common combines and weighed using large capacity balances. Precision agriculture technologies were successfully adapted to these types of field trials (Oyarzabal et al., 1996; Mallarino and Wittry, 1997).

Research is needed to study the relationships between corn early growth and grain yield responses to small amounts of NPK starter fertilization applied in the furrow with the seeds across varied no-till production conditions. Furthermore, no research has assessed the within-field variation of starter responses over the landscape. This study reports the methodology used and the results of strip trials on several farmers’ fields. The objectives were to evaluate yield and early growth responses to starter fertilization in no-till corn and to assess the variation in growth and grain yield responses over the landscape using precision agriculture technologies.

Materials and Methods

Eight strip-trials were conducted from 1995 through 1998 to study corn yield and early growth responses to starter fertilizer in Iowa farmers' fields that had 8 to 14 years of no-till management. Table 1 shows summarized field information for the research sites and for the starter treatment applied at each field. Management practices were those used by each farmer and, thus, corn hybrids, seeding rates, planting dates, herbicide management, and planting equipment varied among fields. Concerning P and K fertilizer management other than the starter treatments, Sites 1, 2, 4, 5, and 7 received broadcast P and K fertilization in November of the previous year, which is the most common practice in Iowa. Previous Iowa research showed that subsurface preplant P fertilization often increased early growth and P content of corn but did not increase grain yield (Mallarino et al., 1999). Site 3 had received no P or K fertilization since fall 1994 and Site 8 had received no P and K since November 1996. Site 6 received preplant broadcast P and K fertilization three weeks before planting the corn. These rates of application were uniform within a field, and varied between fields from 35 to 50 kg P ha^{-1} and 90 to 120 kg K ha^{-1}. The rates were decided by the farmers on the basis of approximately 80% of the estimated P and K removed in corn and soybean grain in a two-year period. Nitrogen fertilizer (28% urea-ammonium nitrate solution in Sites 1, 2, 4, 6 and 7 and anhydrous ammonia in other sites) also was applied across the fields at rates deemed adequate by each farmer (110 to 145 kg N ha^{-1}). In all sites except Site 8, all the uniform N rates were applied at the V5 to V6 developmental stages. Thus, in these sites, the N in the starter was the only N applied at or before planting. At Site 8, a rate of 114 kg N ha^{-1} as anhydrous ammonia was injected the previous fall.

A strip-trial methodology was used for all trials. Approximately 6 to 10 ha at each field located far from field borders were selected for the experiments. The width of each experimental area was divided across future corn rows into blocks that ranged from 24 to 48 m in width. These blocks corresponded to replications of the experimental design. Each block was further subdivided into two strips along the future corn rows to fit two treatments. There were one or more passes of the planter applying the same treatment on each strip. The strips were the experimental units that received the different treatments. The length of the strips varied from 270 to 600 m among fields, without considering approximately 40 m of border on each end, but was uniform within each field. Measurements were made with a measuring tape or wheel, and georeferences were recorded with a hand-held global positioning receiver with real-time differential correction.

The starter fertilizer was applied at planting time with the planter. A sixteen-row planter set for 76-cm row spacing was used for Sites 1 to 6 and 8. An eight-row planter set for a 96-cm row spacing was used for Site 7. Treatments in Sites 1 to 7 were liquid NPK starter in the furrow and no starter. Treatments in Site 8 were liquid NPK starter applied 5 cm beside and below the seeds and no starter. The number of replications varied across fields. There were eight replications in Site 1, five in Site 2, three in Sites 4 and 8, and four in the remaining sites. Liquid starter fertilizer rates and grade varied for each field (Table 1).

Soil samples were collected near planting time following a systematic grid-point sampling scheme in which grid lines were spaced 60 to 90 m apart in the direction across the future corn rows and 24 to 36 m in the direction along crop rows. The width across rows coincided with the width of a replication. Composite samples (10 to 12 cores from a 15-cm depth) were collected from an area approximately 20 m^2 in size located at the center of each cell. Soil samples were analyzed for P (Bray-P_1 method), K (ammonium acetate method), organic matter (Walkey-Black method), and pH (1:1 soil-water) following standard soil testing procedures recommended for the North Central Region (Brown, 1998). Table 2 shows descriptive statistics for selected soil test values. Iowa State University soil test interpretation classes for P and K in corn grain production will be used at times to classify soil test ranges in this report (Voss et al., 1996). Classes and values for soil test P are Very Low (0 to 8 mg kg^{-1}), Low (9 to 15 mg kg^{-1}), Optimum (16 to 20 mg kg^{-1}), High (21 to 30 mg kg^{-1}), and Very High (> 31 mg kg^{-1}). Classes and values for soil test K are Very Low (0 to 60 mg kg^{-1}), Low (61 to 90 mg kg^{-1}), Optimum (91 to 130 mg kg^{-1}), High (131 to 170 mg kg^{-1}), and Very High (> 171 mg kg^{-1}). Whole corn plants were sampled when corn height to the center of the whorl averaged 15 to 25 cm across treatments and field areas (V5 to V6 developmental stages usually). Ten plants were cut at ground level from the center of each of the two treatment strips within each replication and each soil sampling cell along the crop rows. Thus, two plant samples (one that received starter and one without starter) correspond to one soil sample for all fields. Plant samples were dried at 60 ^{0}C and weighed.

Grain yields were measured and recorded every second using combines equipped with yield monitors and real-time DGPS receivers. The yield monitors used were impact flow-rate sensors (Ag Leader 2000, Ag Leader Technology, Ames, IA; Green Star, John Deere Inc., or Micro Trak). Differential corrections were obtained through the U.S. Coast Guard AM signal. The spatial accuracy was checked by georeferencing several positions in the field with a hand-held DGPS receiver. Yield data were unaffected by field borders due to the experimental plots being located at least 40 m from any border. While harvesting, each combine trip (a 4.5-m swath) was identified with a unique number that was recorded with the georeferenced yield data. The raw yield data recorded by the yield monitors were carefully analyzed for common errors. Such errors included incorrect geographic coordinates due to total or partial loss of good differential correction, the effects of waterways or grass strips, and incorrect settings in the time lag for the grain path through the combine (from the combine head to the yield monitor). The data were imported into spreadsheets and then exported to ArcView (ESRI, 1998) for GIS management and later to the SAS statistical package (SAS Institute, 1996) for statistical analyses. The maps in Figure 1 and 2 are ArcView layouts that show an example (for Site 3) of the strip trial methodology used and the type of maps generated. Figure 1 shows soil survey series and various soil test values. Figure 2 shows treatments, yield points, means of grain yield and early growth by strip, and grain yield differences by strip and soil sample cell.

The yield responses were analyzed by three procedures. Two procedures analyzed treatment effects on yield assuming a randomized complete block design (RCBD) without (Procedure 1) or with (Procedure 2) accounting for the spatial correlation of yield. The third procedure assessed treatment effects across the landscape within each field in relation to soil measurements made. In Procedure 1, the data input were yield means for the strips (i. e., the experimental units receiving the treatments) and the conventional ANOVA for a RCBD was used. Procedure 2 accounted the spatial correlation of yields by using nearest neighbor analysis (NNA) in conjunction with the RCBD. Previous research has shown that accounting for spatial correlation with NNA or other techniques can reduce the experimental error and makes the analysis more sensitive in discerning treatment differences. Previous studies have shown the advantages of using NNA to adjust spatially correlated data in different ways (Hinz, 1987; Bhatti et al., 1991; Hinz and Lagus, 1991; Stroup et al., 1994, and Mallarino et al., 1998). The NNA was used to calculate values of a covariate which is included in a second step into the RCBD following a procedure used before (Hinz and Lagus, 1991, Mallarino et al., 1998). One covariate value is calculated to correspond to each number input for the RCBD analysis. The first step in the calculation is to obtain yield residuals for each site by removing treatment and block effects with a conventional ANOVA. Afterwards, the covariate values are calculated by subtracting each yield residual from the mean value of its residual neighbors. Four neighbors (one from each N, S, E, and W direction) were used for this study, because preliminary work in our research group (D. Dousa, P. Hinz, and A. P. Mallarino, personal communication) found that for this type of study, using four neighbors usually was more efficient in reducing experimental error than using six to 14 neighbors. The yield input data for this procedure were means of all yield monitor points recorded at 1 s intervals for small areas delineated by the width of the combine head (4.5 m) and the length of the soil sampling cell (24 to 36 m among fields) along the crop rows. The individual data recorded every 1 s interval by the yield monitors were not directly considered because of the known lack of accuracy of yield monitors over distances shorter than 30 to 40 m (Lark et al., 1997; Colvin et al., 1995).

The third procedure assessed treatment effects separately for different parts of the experimental areas with different soil test values following a procedure described by Oyarzabal et al. (1996). The yield input data were means for areas defined by the width of each strip (20 m) and the separation distance of the soil sampling grid lines (24 to 36 m) in the direction along crop rows. The soil-test input data were the values for areas defined by the width of each replication (40 m) and the separation distance of the sampling grid lines in the direction along crop rows (24 to 36 m). Each yield value was classified according to the soil-test value interpretation class. Values were not considered for this analysis when there were less than 3 cells for a similar soil-test class within a field. In this case, the data for those cells were merged with a neighboring class. The ANOVA included estimates of soil-test class and interaction treatments by soil-test class effects. The soil-test classes are considered as repeated measures within the experimental units. A significant interaction between soil-test class by treatment (i. e., starter) suggests that treatment effects differed for areas of the field with different soil-test levels. When the interaction was significant, an additional ANOVA estimated the significance of treatment effects for each soil-test class. Treatment effects on plant dry weight were analyzed with the three procedures in the same manner as described using the yield data.

Simple correlation and regression analysis (CORR and GLM procedure of SAS) were used to study relationships between relative yield increases due to starter fertilization and soil test values for areas defined by each strip and soil sampling cell. Relative yield increases were used in an attempt to minimize differences in absolute yields between fields and areas within a field. The relative increases were calculated from treatment means (without starter and with starter for the area defined by a soil sampling cell) by subtracting the yield without starter from the yield with starter, dividing by the yield without starter, and multiplying by 100.

Results and Discussion

The trials encompassed widely different growing conditions, which were typical of corn production areas in Iowa. Results of soil tests and some weather measurements are of particular importance to interpret results of starter fertilization. Analyses of soil samples collected by intensive grid sampling showed large nutrient variability within and across fields. Table 2 shows descriptive statistics for selected soil variables. For STP, most trials encompassed at least four interpretation categories used by Iowa State University. With the exception of one trial, which tested very low in some areas, STP ranged mostly from low to very high. For soil-test K (STK), no trial showed soil samples in the very low or low ranges, which suggests that the fields had non-limiting levels of K according to current interpretations for corn. Table 3 shows mean monthly rainfall and air temperature for the months of April, May, and June. Data for these months are shown because of their potential impact on early growth and on the effect of starter fertilization on crop growth. There was high variation in precipitation across sites, and variation in air temperature was less pronounced. The data for some sites are especially noteworthy. Precipitation and air temperatures during April and May were markedly lower for Site 3, which was located in north central Iowa. Sites 1, 2, and 7 had the highest rainfall during

April and May, but in June Site 7 also had high rainfall (this site had the highest rainfall during the 3-month period) whereas Sites 1 and 2 had the lowest rainfall among all sites.

Table 4 shows yield means for the two treatments and the eight trials. The table also shows statistical analyses performed with two methods, which include the standard errors and levels of significance for fertilizer effects. Results of performing the conventional RCBD showed that starter fertilization increased corn yields in three trials when a 5% probability was used (Sites 1, 3, and 7) and at two additional trials when a 10% probability levels was used (Sites 2 and 8). In these sites, yield increases were largest at Sites 3, 7, and 8 (276 to 627 kg ha^{-1}). Yield increases were smaller at Sites 1 and 2 (126 to 194 kg ha^{-1}). It is important to note, however, that the magnitudes of the latter small yield differences were similar to those observed in all other sites classified as nonresponsive by the RCBD (Sites 4, 5, and 6). It is possible that higher variation or experimental error was responsible for the lack of statistical significance in these other sites.

Use of the statistical procedure that improves the conventional RCBD by adjusting for spatial correlation of yields led to a different statistical interpretation of the response at some sites (Table 4). It must be remembered that this analysis was not applied to Sites 4 and 6 because yield monitor points were lost and only yield means along the entire length of the strips were recorded. The least square means obtained by adjusting the conventional RCBD for spatial correlation with the NNA were very similar to the observed, unadjusted treatment means. Adjusting for spatial correlation reduced standard errors and increased the levels of significance of treatment effects in most trials, however. Thus, the main advantage of adjusting for spatial correlation with NNA was to reduce experimental error as opposed to adjusting the yield means. This result was also observed by Mallarino et al. (1998) using other fertilization treatments. The increased design efficiency by adjusting for spatial correlation leads to a different interpretation of the results in some trials but not in others. At a 5% probability level, the statistics for both procedures showed significant responses at Sites 1, 3, and 7. The RCBD-NNA increased the statistical significance at the responsive Sites 2 and 8, and changed from non significant to significant the small response at Site 5. Thus, the RCBD-NNA procedure showed that fertilization did influence yields statistically in Site 5, although the yield response was small (80 kg ha^{-1}). The difference in the contribution of the NNA between fields could be explained by two reasons. One is that the spatial correlation of yield was less in some trials. The second reason could be that the NNA technique used does not always account for the spatial correlation appropriately.

Study of yield responses, independently of the statistical significance, showed large responses at Sites 3 and 8, intermediate at Site 7, and small at other sites. Sites 3 and 7 had STP levels in most areas of the field that were in the responsive range for corn. The larger response at Site 3 than at Site 7 could be attributed to the lower STP at Site 3 (the mean was in the Very Low category) than at Site 7 (the mean was in the Low category). However, other measured variables differed between these two sites. Perhaps the most important is that spring rainfall and air temperature for Site 3 were the lowest among all sites (Table 2). Site 7, in contrast, had the highest spring rainfall among all sites and air temperatures were among the highest observed, too. The large response at Site 8 cannot be obviously explained by STP (the mean was in the High category), rainfall, temperature, or other measurements. It must be noted that at this site the starter was applied beside and below the seeds at a high rate (163 kg ha^{-1}), whereas in the rest of the trials it was applied in the furrow at a lower rate (65 kg ha^{-1}). Many other factors could have influenced the response to starter, which cannot be fully discussed or understood with the methods used in this study. One important factor could have been N availability. As a matter of fact, N could explain the small overall response to starter even in soils with high STP. Previous research has shown that responses to NPK starter usually are due to P, sometimes can be explained by the N in the starter (especially when it is applied beside and below the seeds), and seldom can be explained by K (Randall and Hoeft, 1988; Ritchie et al., 1995). No site received preplant N fertilization except Site 8, but even in this case it was applied 5 months before planting (in November of the previous year). Incidentally, the high N rate applied beside and below the seed at Site 8 (16.3 kg N ha^{-1}) is likely to explain the high response in Site 8 because soil P was in the high category. The smaller responses at other sites with soil P deemed optimum or higher for corn could be explained by the small amount of N (3.9 to 6.5 kg N ha^{-1}) applied in the furrow.

Table 5 shows the influence of the starter fertilization on early growth of corn for the six trials where plants were sampled at the V4 to V5 developmental stage (plant samples were not collected for trials conducted in 1995). Similarly to procedures used for grain yield, the plant weight data were analyzed using two distinct statistical methods. Comparisons of observed treatment means and means adjusted for spatial correlation show little difference. Although there were some differences in actual values, the rankings of the treatments were similar for the two procedures. Observation of the treatment means reveals that starter fertilization increased plant dry weight at all sites, although responses were not always statistically significant. These results were expected because other studies found that starter fertilization often enhances early growth independently of soil tests or weather conditions (Mengel et al., 1988; Randall and Hoeft., 1988; Bullock et al., 1993). The largest plant weight differences were found in Sites 3 and 7 where the STP classes were Very Low and Low, respectively. Both methods of analysis showed dry weight responses to starter fertilization in Sites 3, 6, and 7. At Site 3, however, the starter effect achieved statistical significance at the $P< 0.5$ level only with the RCBD-NNA procedure. Differences between methods were much less for early growth than for yield. The smallest differences were found at Sites 5 and 8. However, a large response in plant weight at Site 6 (a site with Very High STP) support previous evidence that starter fertilization normally increases early growth regardless of the STP level. An important result of this study is that the application of starter in the furrow at the rates used did not adversely affect seed emergence or corn stands at any site (plant population data not shown). None of the fertilizers applied in the furrow provided more than 9 kg ha^{-1}of N plus K, which probably produced no excessive concentration of soluble salts near the seeds.

Use of statistical procedures designed to study differences in grain yield or early growth responses to starter fertilization for areas with different values of several measured variables showed meaningful results only for STP. Table 6 shows grain yield means and response statistics obtained for field areas with different STP levels. The results suggest that within-field variation in STP does influence the effect of starter fertilization and that the likelihood of response increases in soils with STP below Optimum. Statistically significant responses were not observed in all low P testing soils, however, and sometimes were observed in high P testing soils. For example, responses were significant for all STP classes at Site 1. On the other hand, responses never were statistically significant at Site 5, although the more powerful RCBD-NNA analysis detected an overall small response (Table 4). One possible reason for these discrepancies is that soil tests are not perfect estimates of soil P availability (due to the extraction or sampling error). Another possible reason is that the response could be due to nutrients other than P in the starter, most likely N in these studies because STK was above optimum in all fields and no N other than that in the starter was applied at or before planting with the exception of Site 8.

Table 7 shows early growth means and response statistics obtained for areas of Sites 3 to 8 with different STP (early growth was not measured in Sites 1 and 2). The results show no consistent differences in early growth response across the STP categories. These results suggest that early growth was responding to other nutrients than P in the starter or that increased P availability near the seeds always tended to increase early growth independently of the STP level. Although the methods used in this study do not allow for a supported conclusion, previous research with NPK starter (Welch et al., 1966; Randall and Hoeft, 1988, Rehm et al., 1988) and with granulated P starter applied beside and below the seeds in Iowa (Mallarino et al., 1999) suggests that the latter explanation is more likely.

Analyses of variance or regression analyses of grain yield and early growth responses for different ranges of STK, soil pH, soil organic matter, elevation, or for different soil types showed that responses were not related to values of any of those measurements and data are not shown. Responses could have been higher for field areas with soil lower in organic matter (possibly with low N availability) or with wetter and poorly drained soils (possibly colder and with low nutrient availability in spring). Although much speculation is possible concerning reasons for these results, the methods used in this study allow only for few relevant comments. A lack of relationship between starter response and STK can be explained by STK levels that were optimum or higher according to current Iowa State University interpretations for corn, and to the fact that the starter used in Sites 3, 7, and 8 had no K. The lack of relationships between response and soil or landscape characteristics related to soil conditions during seedling emergence and early growth stages could be explained by various reasons. One reason, perhaps the most obvious and likely, is that many factors interact. For example, soils of higher landscape positions usually had lower soil organic matter but soil temperature likely (measurements were not collected) was higher because soils were better drained.

Grain moisture was recorded with the yield monitor and analyzed to check any possible difference in corn moisture at harvest time. Starter fertilization did not influence grain moisture significantly, and data are not shown. Corn grain tended to produce drier grain, but the difference across all sites was only 0.5 % moisture.

Study of both grain yield (Table 4) and early growth (Table 5) responses to starter fertilization across all sites showed a small (3.9%) mean increase in grain yield and a much larger (29%) increase in early growth. Correlation and regression analyses within and across sites in which early growth was measured showed a poor relationship between responses in early growth and grain yield. The analyses were performed for sites where early growth was measured and where records of yield monitor data points within a strip allowed for estimates of yield responses for different parts of the field. Thus, data are presented for Sites 1 and 2 where early growth was not measured, and for Sites 4 and 6 where only strip yield averages are available. The responses in early growth and grain yield were linearly correlated ($P < 0.05$) in Sites 3 (r = 0.40), 5 (r = 0.21), 7 (r = 0.24) and 8 (r = 0.28). Figure 3 shows the correlation across all these sites. Relative yield and early growth increases (to minimize differences in absolute yield or early growth among sites) were positively but poorly correlated (r = 0.50), even when four obvious outliers were not considered or plotted. These results support the idea that starter fertilization increases early growth more and more frequently than grain yield, and that a response in early growth is not always reflected in grain yield. Obviously, growth conditions during the rest of the season also influence yield and may render irrelevant any starter effect in increasing early growth.

Conclusions

The results showed that accounting for spatial correlation of yield in conjunction with conventional analysis of variance improved the evaluation of treatment effects by strip trials harvested with yield monitors and global positioning systems. This methodology had no effect on the estimated treatment means but significantly reduced the standard errors of the estimation.

In-the-furrow starter fertilization increased yields in several fields, although responses were large enough to offset the costs of application only in three fields. Responses across or within fields were larger (approximately 200 to 600 kg ha^{-1}) when STP was below optimum levels for corn, and were not related with other soil tests, landscape position, or soil survey mapping units. Small responses to starter applied in the furrow in high-testing soils likely were produced by the small amount of N in the starter because no preplant N was applied at any field except at Site 8. Nitrogen probably was responsible for the large response at the only site where the starter was applied at a higher rate and beside and below the seeds.

The early growth responses to starter fertilization were large and occurred in most fields, which was in contrast to grain yield responses. Early growth responses were larger when soil test P was low but also was significant when soil P was very high. Across all sites, starter fertilization increased early growth by 29% and grain yield only 3.7%. The grain yield response was positively but poorly correlated with early growth response within and across sites.

Overall, the study showed little economic justification for applying starter fertilizer in the furrow when available soil P is above optimum levels for corn grain production.

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Table 1. Information on location, hybrid, planting date, population, type of starter, and amount used.

Site	County	Year	Hybrid	Planting Date	Population	Starter Mixture †	Starter Rate Product	N	P	K
					--Seed/ha--		--kg/ha--	-------kg/ha--------		
1	Benton	1995	CIBA-4494	05/02	71600	7-21-7	65	4.5	5.9	1.9
2	Linn	1995	CIBA-4494	05/06	72100	6-24-24	65	3.9	6.8	6.5
3	Grundy	1997	DK-566	04/29	74100	10-34-0	65	6.5	9.6	0
4	Benton	1997	DK-586	05/03	71600	7-21-7	65	4.5	5.9	1.9
5	Grundy	1998	A-601	05/11	76100	7-18-5	65	4.5	5.2	1.3
6	Benton	1998	DK-586	04/29	71600	6-18-6	65	3.9	5.2	1.6
7	Carroll	1998	DK-580RR	04/25	62500	10-34-0	91	9.1	13.5	0
8	Linn	1998	GH-H2390	05/14	76100	10-34-0	163	16.3	24.2	0

† Comercial name (N, P_2O_5, K_2O).

Table 2. Descriptive statistics for selected soil tests for eight strip trials.

Site	Soil test	Mean	Minimum	Maximum	SD
1	P (mg/kg)	30	7	62	12
	K (mg/kg)	136	84	239	32
	NO_3 (mg/kg)	11	5	20	3
	pH	6.5	5.8	7.2	0.3
	Org. Matter (g/kg)	44	30	78	6
2	P (mg/kg)	35	13	85	14
	K (mg/kg)	153	73	272	31
	NO_3 (mg/kg)	2	1	6	1
	pH	6.8	6.1	7.4	0.3
	Org. Matter (g/kg)	46	15	82	14
3	P (mg/kg)	7	3	23	4
	K (mg/kg)	138	93	190	25
	NO_3 (mg/kg)	-	-	-	-
	pH	6.5	5.8	7.3	0.3
	Org. Matter (g/kg)	44	35	58	5
4	P (mg/kg)	29	8	127	19
	K (mg/kg)	212	113	564	106
	NO_3 (mg/kg)	-	-	-	-
	pH	6.0	5.0	7.0	0.5
	Org. Matter (g/kg)	38	29	50	5
5	P (mg/kg)	23	10	96	10
	K (mg/kg)	143	76	215	24
	NO_3 (mg/kg)	9	6	14	2
	pH	6.3	5.7	7.0	0.3
	Org. Matter (g/kg)	35	5	50	7
6	P (mg/kg)	47	21	99	16
	K (mg/kg)	157	95	258	35
	NO3 (mg/kg)	19	11	20	4
	pH	6.1	5.5	6.9	0.4
	Org.Matter (g/kg)	47	36	61	6

Continues in next page.

Table 2. (continued)

Site	Soil test	Mean	Minimum	Maximum	SD
7	P (mg/kg)	15	10	23	4
	K (mg/kg)	189	131	247	25
	NO_3 (mg/kg)	-	-	-	-
	pH	6.3	6.0	6.8	0.2
	Org. Matter (g/kg)	38	25	44	4
8	P (mg/kg)	37	14	79	14
	K (mg/kg)	137	89	226	32
	NO_3 (mg/kg)	35	9	123	32
	pH	5.5	5.0	6.0	0.3
	Org. Matter (g/kg)	35	20	44	5

Table 3. Information on location, rain, and air temperature for April, May, and June.

			April		May		June	
Site	County	Year	Rain	Temperature	Rain	Temperature	Rain	Temperature
			mm	C	mm	C	mm	C
1	Benton	1995	150	8.4	157	15.1	66	22.3
2	Linn	1995	147	8.6	188	14.9	96	21.7
3	Grundy	1997	33	6.1	99	11.4	124	21.3
4	Benton	1997	63.5	8.1	137	13.2	124	21.5
5	Grundy	1998	76	9.3	137	18.1	240	19.4
6	Benton	1998	81	10.8	119	19.4	210	20.4
7	Carroll	1998	135	9.4	135	18.2	205	19.2
8	Linn	1998	81	10.8	119	19.4	210	20.4

Table 4. Effect of starter fertilization on corn grain yields as evaluated by two methods of analysis for eight strip trials.

Site	Treatment and statistics[‡]	Method of Analysis[†] RCBD	NNA
		------------------ kg/ha	----------------
1	Starter	7299	7312
	No starter	7105	7124
	SE	37.0	14.3
	P>F	0.009	0.001
2	Starter	11683	11673
	No starter	11557	11564
	SE	38.7	11.1
	P>F	0.105	0.006
3	Starter	8246	8265
	No starter	7619	7607
	SE	93.4	19.4
	P>F	0.018	0.001
4	Starter	9582	-
	No starter	9350	-
	SE	66.5	-
	P>F	0.131	-
5	Starter	9701	9735
	No starter	9621	9587
	SE	93.2	26.2
	P>F	0.565	0.003
6	Starter	9294	-
	No starter	9005	-
	SE	99.7	-
	P>F	0.136	-

Continues in next page.

Table 4. (continued)

Site	Treatment and statistics[‡]	Method of Analysis[†]	
		RCBD	NNA
		------------------ kg/ha	----------------
7	Starter	9601	9557
	No starter	9325	9369
	SE	82.0	73.3
	P>F	0.053	0.048
8	Starter	10542	10542
	No starter	10077	10071
	SE	141.0	54.5
	P>F	0.082	0.005

† RCBD = observed means and statistics for the randomized complete block design, NNA = Least square means and statistics from RCBD analysis combined with nearest neighbor analysis.

‡ SE = standard error of a mean.

Table 5. Effect of starter fertilization and the analyses method on corn dry weight for six strip trials.

Site	Treatment and statistics[‡]	Method of Analysis[†]	
		RCBD	NNA
		-------------- g/pl --------------	
3	Starter	2.48	2.50
	No starter	1.57	1.55
	SE	0.20	0.15
	P>F	0.052	0.023
4	Starter	2.65	2.62
	No starter	1.90	1.91
	SE	0.47	0.33
	P>F	0.375	0.281
5	Starter	1.99	1.99
	No starter	1.88	1.88
	SE	0.11	0.11
	P>F	0.554	0.540
6	Starter	2.44	2.45
	No starter	1.86	1.85
	SE	0.14	0.12
	P>F	0.043	0.039
7	Starter	3.23	3.24
	No starter	2.28	2.27
	SE	0.08	0.08
	P>F	0.003	0.003
8	Starter	2.83	2.83
	No starter	2.55	2.54
	SE	0.09	0.09
	P>F	0.167	0.166

[†] RCBD = observed means and statistics for the randomized complete block design, NNA= Least square means and statistics from RCBD analyses combined with nearest-neighbor analyses.

[‡] SE = standard error of a mean.

Table 6. Mean grain yield as affected by starter fertilization for areas of six fields having different soil-test P values.

		Soil-test P class														
		Very Low			Low			Optimum			High			Very High		
Trial	Trt†	Yield	*P*>F	A‡	Yield	*P*>F	A	Yield	*P*>F	A	Yield	*P*>F	A	Yield	*P*>F	A
		kg/ha		%	kg/ha		%	kg/ha		%	kg/ha		%	kg/ha		%
1	S	-	-	-	7461	0.08	13	7455	0.10	9	7313	0.01	32	7285	0.06	46
	NS	-			7206			7181			7095			7076		
2	S	-	-	-	-	-	-	11288	0.84	11	11645	0.02	28	11840	0.11	61
	NS	-	-					11356			11338			11664		
3	S	8090	0.02	24	8667	0.03	53	8993	0.14	23	-	-	-	-	-	-
	NS	7419			8115			8641			-			-		
5	S	-	-	-	9557	0.60	11	9388	0.69	32	9783	0.39	39	10272	0.21	18
	NS	-			9338			9338			9639			10165		
7	S	-	-	-	10234	0.09	60	8648	0.30	40	-	-	-	-	-	-
	NS	-			9858			8522			-			-		
8	S	-	-	-	-	-	-	-	-	-	10190	0.06	34	10711	0.26	66
	NS	-			-						9664			10284		
Mean§	S	8090	0.02	5	8980	0.01	21	9154	0.30	19	9580	0.04	22	9799	0.12	33
	NS	7419			8629			9008			9357			9635		

† Trt = Treatment; S= Starter, NS= No Starter

‡ A= Percentage area for each soil test class. Percentage area for the mean was calculated based on the total number of cells.

§ Mean calculated excluding Site 8, where the starter was applied 5cm beside and below the seed.

Table 7. Means on early growth as affected by starter fertilization for areas of six fields having different soil-test P values.

		Soil-test P class														
		Very Low			Low			Optimum			High			Very High		
Trial	Trt†	E.G.¶	*P*>F	A‡	E.G.	*P*>F	A	E.G.	*P*>F	A	E.G.	*P*>F	A	E.G.	*P*>F	A
		g/pl		%	g/pl		%	g/pl		%	g/pl		%	g/pl		%
3	S	2.41	0.03	24	2.79	0.07	53	2.64	0.98	23	-	-	-	-	-	-
	NS	1.43			1.68			2.62			-			-		
4	S	-	-	-	4.16	0.31	33	2.25	0.87	21	2.36	0.04	30	2.16	0.74	16
	NS	-	-		3.21			2.02			2.01			2.05		
5	S	-	-	-	1.73	0.44	11	1.86	0.60	32	2.12	0.16	39	2.07	0.97	18
	NS	-			1.93			1.79			1.85			2.07		
6	S	-	-	-	-	-	-	-	-	-	-	-	-	2.43	0.05	100
	NS	-			-			-			-			1.83		
7	S	-	-	-	3.21	0.02	60	3.26	0.14	40	-	-	-	-	-	-
	NS	-			2.20			2.39			-			-		
8	S	-	-	-	-	-	-	-	-	-	2.79	0.19	34	2.84	0.53	66
	NS	-			-						2.22			2.71		
Mean§	S	2.41	0.03	7	2.97	0.16	33	2.50	0.32	23	2.42	0.11	17	2.37	0.50	20
	NS	1.43			2.25			2.20			2.02			2.16		

† Trt = Treatment; S= Starter, NS= No Starter

‡ A= Percentage area for each soil test class. Percentage area for the mean was calculated based on the total number of cells.

§ Mean calculated excluding Site 8, where the starter was applied 5cm beside and below the seed.

¶ E.G.= Early Growth.

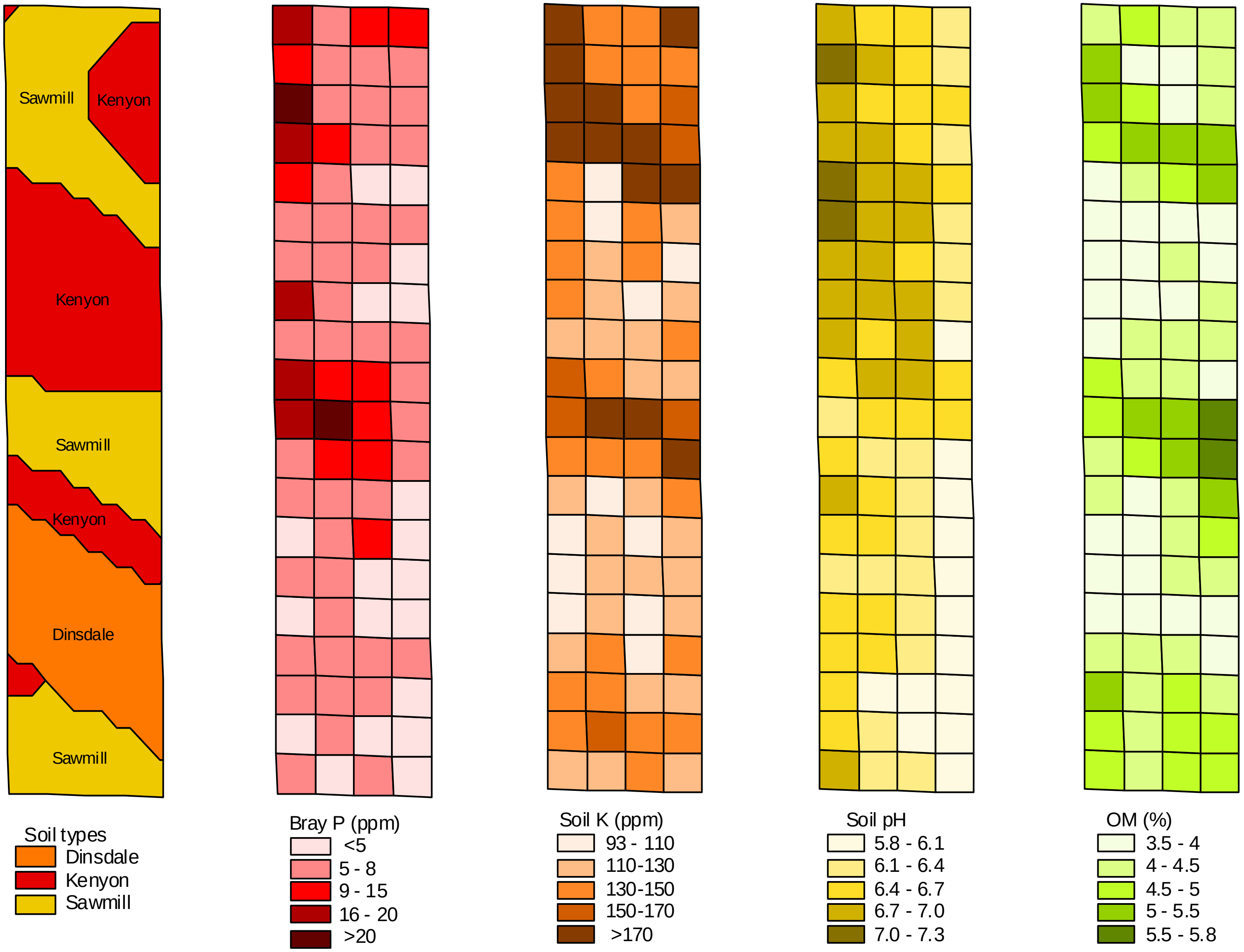

Figure 1. Soil types and grid sampling for different soil test values in Site 3.

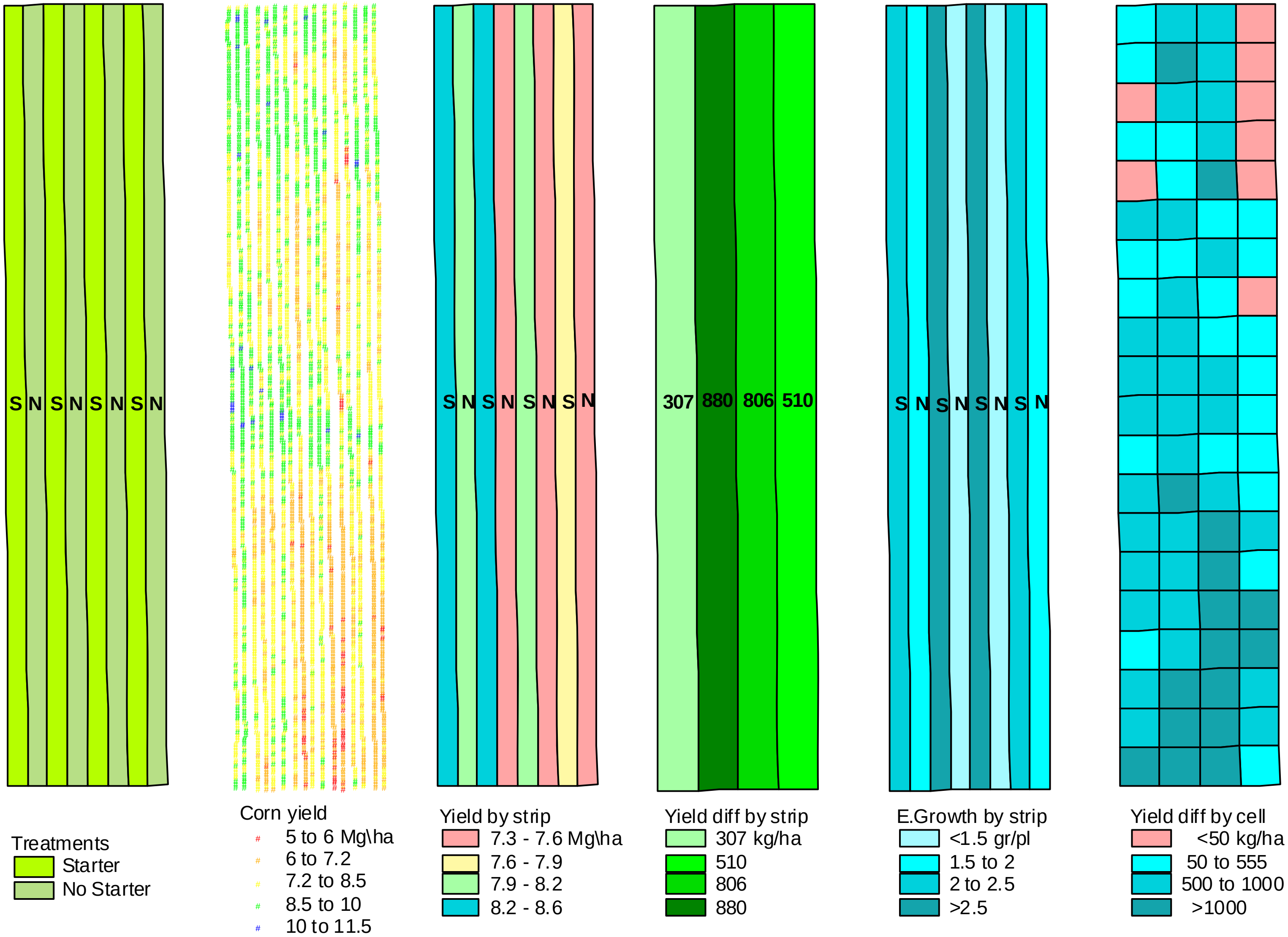

Figure 2. Treatments, yield map, average yield and early growth by strip, and yield difference by strip and soil sample cell in Site 3.

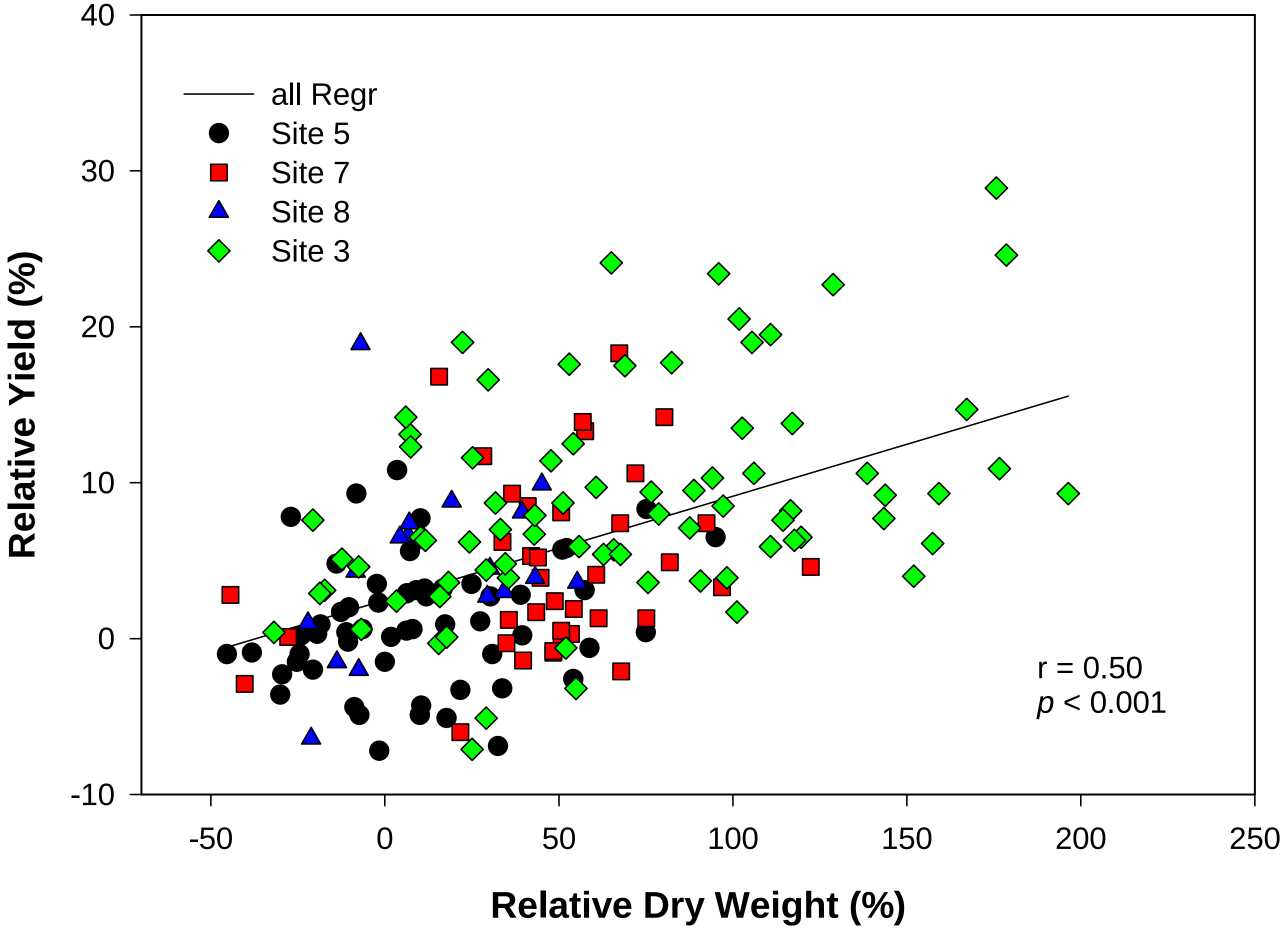

Figure 3. Correlation between relative yield and relative dry weight across all sites.

GENERAL CONCLUSIONS

The overall objective of this study was to assess the effect of starter fertilization in cornfields. Specific objectives were to evaluate yield and early growth responses to starter fertilization in no-till corn and to assess the variation in growth and grain yield responses over the landscape using precision agriculture technologies. Eight cornfields managed with no-tillage were sampled and studied from 1995 through 1998. A strip trial methodology was used for all fields. An intensive grid soil sampling was conducted in all fields and whole samples (V5 to V6 developmental stages) were collected from most fields. Grain yields were measured and recorded using combines equipped with yield monitors and global positioning systems. Analyses of grain yield and early growth responses were performed using conventional analysis of variance and by accounting for spatial correlation of yield with a nearest neighbor analysis in conjunction with analysis of variance.

The results showed that accounting for spatial correlation of yield in conjunction with conventional analysis of variance improved the evaluation of treatment effects by strip trials harvested with yield monitors and global positioning systems. This methodology had no effect on the estimated treatment means but significantly reduced the standard errors of the estimation.

In-the-furrow starter fertilization increased yields in several fields, although responses were large enough to offset the costs of application only in three fields. Responses were larger (approximately 200 to 600 kg ha^{-1}) when soil P levels were below optimum levels for corn, and were not related with other soil tests, landscape position, or soil survey mapping units. Responses for areas with different soil tests within fields also showed that soil P was the only measured variable that was related to within-field variation in the response. Small responses to starter applied in the furrow in high-testing soils likely were produced by the small amount of N in the starter (9 kg N ha^{-1} or less) because no preplant N was applied at any field except at Site 8. Nitrogen probably was responsible for the large response at the only site where the starter was applied at a higher rate and beside and below the seeds.

The early growth responses to starter fertilization were large and occurred in most fields, which was in contrast to grain yield responses. Early growth responses were larger when soil test P was low but also were significant when soil P was very high. Across all sites, starter fertilization increased early growth by 29% and grain yield only 3.7%. The grain yield response was positively, but poorly, correlated with early growth response within and across sites.

Overall, the study showed little economic justification for applying starter fertilizer in the furrow when available soil P is above optimum levels for corn grain production. The results showed, however, that very small amounts of fertilizer can produce significant yield increases in soils testing low in P. Thus, from an economic perspective starter fertilization may be a viable alternative in combination with reduced bulk applications of broadcast P fertilizer. The results also showed a benefit of starter fertilization from an environmental perspective. The starter significantly increased early growth and early canopy cover across most conditions. Increased early canopy cover can reduce P and soil losses to water supplies at a time of high rainfall intensity. In addition, it is generally believed that the farmers' belief of lower grain yield with no-till compared to conventional tillage is actually a perception rooted in obviously slower early growth with no-till. Thus, the starter fertilization effect in increasing early growth of no-till corn across most conditions can help to promote no-till systems that minimize soil erosion.

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