CORN RESPONSES TO DEEP PLACEMENT OF PHOSPHORUS AND POTASSIUM IN HIGH YIELD PRODUCTION SYSTEMS

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I dedicate this thesis to my father, James Doyle Schmidt,

and to my grandfathers, Doyle Edmund Schmidt and Ivan Earl Buckmaster.

The lives of these three farmers instilled in me a love for agriculture,

and more importantly, a love for God.

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ABSTRACT

Kline, Ann Marie. M.S., Purdue University, August 2005. Corn Responses to Deep Placement of Phosphorus and Potassium in High Yield Production Systems. Major Professor: Dr. Tony J. Vyn.

The pursuit of higher corn yields has caused concern of yield limitations resulting from soil vertical stratification of available P and exchangeable K, especially as conservation tillage and higher plant densities become more prevalent. In the Midwest, P and K are typically broadcast over the soil surface, but interest in strip tillage systems combined with deep-banding nutrients is growing. Deeper placement is encouraged on the basis that essential nutrients are placed in more favorable zones for root uptake. Equipment advances now permit banded nutrient applications to depths of 30-cm. However, research investigating the efficacy of P and K applications to these deeper depths is lacking. In this research endeavor, nutrient placement depths of 15 and (or) 30-cm were compared to broadcast or no application of P and K fertilizers using two corn hybrids at two plant densities. In a separate experiment, corn root and shoot responses to 15-cm banded applications of P and (or) K were evaluated. Both rain-fed experiments were established on dark prairie soils with medium-testing P and K concentrations and high yield potential. Occasionally significant and positive corn growth responses to the 30-cm placement depth of P and K were observed. However, overall, results do not indicate that deeper placement of P and K should be used in place of broadcasting. The

30-cm placement resulted in increased early vigor, but did not increase LAI or stay-green later in the season. Corn yields were not different among banded or broadcast treatments. Furthermore, corn responses to broadcasting versus deep-banded applications of P and K did not interact with hybrid or plant population. Root response parameters (volume, area and weight), as well as shoot weights, from early growth sampling revealed that broadcast treatments were as good, or better, than 15-cm banded P plus K treatments. Apparent chlorophyll concentrations in ear leaves were higher for the broadcast treatment on post-silking dates when significant differences occurred. However, these apparent benefits for broadcasting did not result in grain yield advantages. Preliminary results suggest that there is no benefit in ultra-deep banding of P and K fertilizers in these environments.

LITERATURE REVIEW

Although optimum nutrient management has long been acknowledged as being critical for producing high yielding corn, there are multiple factors that cause fertility decision-making to be a complex process. For instance, application rates, the source of the nutrient and the associated availability to the crop, the timing of application, and where the nutrient is placed with respect to the crop are all important considerations in good nutrient management decisions. These considerations interact with many other factors such as tillage system, soil type, hybrid, plant population, and, of course, the environment. All these factors play a unique role, making the nutrient management process extremely complex.

Nutrient Placement

The placement of nutrients, specifically phosphorus (P) and potassium (K), has been of interest as conservation-tillage corn producers seek to refine management practices that will boost their yields. Conservation tillage has gained favor as more attention is placed on erosion control and maintaining or improving soil structure. In addition, conservation tillage requires less time in the fields and saves fuel and other expenses.

No-till production of many crops typically result in nutrient stratification in soils due to the continual surface application of nutrients without incorporation, and because uptake by the crop takes nutrients from the soil (Howard et al., 1999; Mackay et al., 1987; Crozier et al., 1999; Robbins and Voss, 1991). The popularity of no-till and lack of soil mixing and the subsequent nutrient stratification may be a cause for concern with respect to fertility management.

Reduced tillage may also require higher initial soil test levels to achieve yield levels similar to conventional tillage because residue-protected soils at planting are comparatively cooler and more poorly aerated, which may lower nutrient availability (Nelson et al., 1992; Chassot & Richner, 2002). The soil in a no-till system will also be wetter at planting because of the extra residue. These soil conditions may cause slower germination and early season growth (Hoeft et al., 2001; Chassot & Richner, 2002). Decreased temperature and increased bulk density, which are common in no-till systems, can cause reduced early growth in corn (Chassot & Richner, 2002). Strip tillage with a deeper placement of P and K is hypothesized as a way to reduce nutrient stratification in the soil profile, allowing more effective nutrient uptake.

Early Season Responses to Nutrient Placement

In Iowa, deep (15-cm) placement of P fertilizer increased early corn growth over broadcast placement in some fields, but it didn't result in higher yields (Mallarino et al., 1999). Other Iowa research also reported some increases in early growth with a deep P placement (Borges & Mallarino, 2001). Uptake of P was higher at 10 sites out of 15 sites (only one site significant) when the nutrient was deep-banded (Borges & Mallarino, 2001), but fertilizer placement had no effect on early P concentration in other studies (Mengel et al., 1988; Rehm, 1986). For an irrigated northeast Nebraska study, however, Rehm (1986) reported that deep banding of P significantly decreased early growth of corn at some sites, although at most sites deep P banding had no effect

Most studies report that deeper K placement often encourages early growth of corn at low to medium soil-test levels. Placement of K seldom influenced early growth of corn at soil test levels that were optimum or higher, but did increase K uptake when applied by a planter band or 13-18 cm deep-banded (which resulted in slightly higher yields) (Mallarino et al., 1999). This is similar to another study where early growth was increased by deep (15-20 cm) band K (also resulting in higher yields) as opposed to broadcast applications of K (Borges & Mallarino, 2001). Likewise, Vyn et al. (2002) reported that in a zone tillage system, deep-banding K increased early season corn mass relative to broadcast or broadcast plus shallow (starter) treatments. In addition, in the mulch tillage system, deep banding K was similar to the shallow placement, but resulted in increased early growth over the broadcast application (Vyn et al., 2002). Broadcast surface-strip placement of P & K increased early growth when compared to broadcast or deep (20 cm) banding in an earlier study (Mengel et al., 1988).

Potassium uptake by corn usually increases with a deep K band application. Applying K in strips (surface or 20 cm deep) significantly increased the K concentration of young plants and the earleaf over the broadcast in one investigation (Mengel et al., 1988) and in another, deep band K improved K uptake in 11 out of 15 sites (Borges & Mallarino, 2001). Vyn & Janovicek (2001) found that deep placement of K resulted in higher early season K concentrations as compared to a shallow or broadcast placement in both no-till and mulch tillage systems. However, a different study showed earleaf K concentrations to be higher at some sites when fertilizer was broadcast and incorporated, as compared to a no-till broadcast or deep-banded zone tillage systems.

More than one study concluded that judging the effects of deep banding by looking at early growth is misleading, especially in soils that are not deficient in available P and exchangeable K (Mallarino et al., 1999; Borges & Mallarino, 2001).

Mid-season Responses to Nutrient Placement

Mid-season corn responses to P and K placement methods have been variable. At 2 weeks before silking, P uptake was higher for broadcast (fertilizer was incorporated) versus 15-cm deep band application (Rehm, 1986). When a surface-strip placement was used for application, K concentration in the earleaf was higher than when fertilizer was broadcast or deep-banded to a 20 cm depth (Mengel et al., 1988). Both Vyn et al. (2002) and Ebelhar & Varsa (1999) found no differences between their K application treatments (banded versus broadcast) for earleaf K concentrations in Ontario and Illinois studies, respectively. In another Ontario study, K placement (deep, shallow or broadcast) had no effect on corn plant biomass at silking (Vyn et al., 2002).

In some cases, broadcasting appears to be preferable to banded applications. For instance, midseason responses indicated that a conventional (broadcast K then incorporation) system produced a higher biomass than zone till (15-cm deep K placement) or no-till (broadcast K) systems (Vyn & Janovicek, 2001).

Yield Responses to Nutrient Placement

Although many studies have concentrated on potential crop yield responses to deep P and/or K placement due to the relatively immobile nature of these nutrients in soils, results have been inconsistent. Several studies have reported yield benefits to deeper, banded nutrient placement in crops such as corn (Bordoli & Mallarino, 1998; Borges & Mallarino 2001; Mackay et al., 1987; Vyn & Janovicek, 2001), soybeans (Hudak et al. 1989), and grain sorghum (Sweeney, 1997). Yet many other studies have concluded that broadcast is as effective as banding in corn (Bordoli & Mallarino, 1998; Borges & Mallarino, 2000; Borges & Mallarino, 2001; Ebelhar & Varsa 1999; Mallarino et al., 1999; Mengel et al., 1988; Rehm, 1986; Vyn et al., 2002) and soybeans (Buah et al., 2000; Ebelhar & Varsa 1999). In some of these studies, yield benefits were seen with a deep-banded K placement, but not with a deep-banded P placement.

Soybean results have been inconsistent about whether deep placement is beneficial. Hudak et al. (1989) found that placing K in narrower bands (both surface and deep placement) tended to increase soybean yields. This is different from soybean results found in Iowa by Buah et al. (2000). They reported no benefit to banded applications of P and K as compared to broadcast. Likewise, Yin and Vyn (2002) saw no benefit of deep-banded K over broadcast K in soybeans and Borges and Mallarino (2003) saw only small and infrequent responses to P placement. A review of placement methods by Randall & Hoeft (1988) concluded that, for soybeans, using a broadcast application resulted in yields that were as good as, or better than, banded applications, especially for fields with low P and K soil test values.

Research on deeper banding of P and K in corn has also been variable. Phosphorus placement method seldom influenced corn grain yield in an Iowa study for any tillage system, even with low testing soils (Bordoli & Mallarino, 1998). One study showed that broadcast P (when compared to a shallow N plus P band) increased yields in both no-till and disk-till systems (Howard et al., 2002). Deep banding K (at 15-cm) increased corn yields slightly (approximately 0.2 Mg ha^{-1}) at several sites over the broadcast or planter-band placements (Bordoli & Mallarino, 1998). The yield increase was observed even in soils that tested high for exchangeable K concentration; therefore, low soil-test K status below the soil surface layer was not the sole reason for the response. The reports concluded that dry weather conditions early in the season were likely somewhat responsible for the response to deep placement. This agrees with work done by Borges & Mallarino (2001) who observed a yield advantage to deep (15-20 cm) band K over broadcast, but saw little response to deep-banded P.

Ebelhar & Varsa (1999) observed no K placement effects on corn yield between surface banding and broadcast, but none of their treatments were deep-banded. Vyn et al. (1999) reported that there were significant yield benefits to deep (15-cm) banding K, particularly in zone-tillage systems, but not in a mulch tillage system. Deep banding K (15-cm) in a zone tillage system also increased corn yields when compared to broadcast placement in conventional tillage and no-till situations (Vyn & Janovicek, 2001). However, in continuous no-till corn with optimal soil moisture, surface broadcasting was found to be as good as deep banding K despite soil exchangeable K stratification, and in some situations deep banding appeared to be detrimental relative to broadcast application (Vyn et al., 2002).

Most research indicates that at high soil test levels (>30 lb P/acre and >250 lb K/acre), crop yield responses to P and K placement are rare (Randall et al., 2001; Randall & Hoeft, 1988). Research by Vyn & Janovicek (2001) also show that K fertilization only produced higher yields on fields with exchangeable K concentrations of less than 120 mg per kg.

Weather conditions may be a factor in the variable responses to P and K placement methods. Both surface strip and deep banding (15-20 cm) of K have increased yields over broadcast, especially in dry years; these responses are also seen where the soil test levels are low or in conservation tillage systems (Randall & Hoeft, 1988). Studies have shown that temperature and moisture conditions affect K uptake. Potassium influx, root length increase, and shoot K concentration were twice as high or more when the temperature went from 15 C to 29 C (Ching & Barber, 1979). In addition, root growth rate and shoot K uptake increase when soil moisture was initially increased (Mackay & Barber, 1985). Potassium uptake is greatly dependent on soil moisture (Sardi & Fulop, 1994; Seiffert et al., 1995) and available K levels (Sardi & Fulop, 1994). Soil moisture has a stronger influence on dry matter production and K accumulation than the exchangeable K concentrations in the soil (Sardi & Fulop, 1994).

Corn responses to P and K fertilizer applications are typically greatest in dry conditions (Nelson et al., 1992). Robbins and Voss (1991) suggested that during extended periods of dry weather, surface P and K might become positionally unavailable.

In addition to the previously discussed factors like weather, tillage system, and initial soil-test concentrations, it is also possible that corn response to P and K fertilizer placements are influenced even more by other crop management factors. Two of these are hybrid and plant population.

Corn Responses to Plant Population

Higher plant populations can result in higher yields (Nelson et al., 1992; Paszkiewicz & Butzen, 2003), and closing the yield gap between actual and potential yields will require increased plant densities (Arkebauer et al., 2004; Walters et al., 2004). Increased yields have been partially due to genetic improvement of corn hybrids to withstand greater stresses, therefore allowing higher planting populations (Paszkiewicz & Butzen, 2003).

When planting corn at higher densities, there are additional factors to consider. Higher populations result in greater demands for nutrients (Arkebauer et al., 2004). Understanding crop nutrient needs is essential to producing high yielding corn, especially with high planting populations.

Higher plant populations increase leaf area indices (Tetio-Kagho & Gardner, 1988; Borras et al., 2003) and crop growth rates up to a threshold plant density (Tetio-Kagho & Gardner, 1988). These higher densities also alter the light distribution within the canopy (Tetio-Kagho & Gardner, 1988). Higher plant populations increased the leaf senescence rate and decreased the source-to-sink ratio in an Argentine study (Borras et al., 2003).

Increased populations decreased kernel set per ear (Sangoi et al., 2002; Borras et al., 2003; Tetio-Kagho & Gardner, 1988). However, the kernel yield per land area increased up to a maximum yield as densities increased up to 10 plants per meter (Tetio-

Kagho & Gardner, 1988). In a separate study, higher yields were associated with high populations where populations ranged from 3 to 12 plants per square meter (Borras et al., 2003).

Increased plant population increased barrenness for all hybrids studied (Sangoi et al., 2002). Test weight, kernel density and kernel weight decreased with higher plant density (Vyn & Tollenaar, 1998). This disagrees with data by Borras et al. (2003) where kernel weight increased as population increased. In a separate study, kernel weight was unaffected by plant population (Tetio-Kagho & Gardner, 1988). Plant population effects on overall yield are likely to be more dependent on kernel number per unit area than on relative kernel weights.

Dry matter yields showed similar trends as kernel yields. Vegetative dry matter per plant decreased at high densities, but increased when analyzed per land area up to 10 plants per meter (Tetio-Kagho & Gardner, 1988).

In higher populations, there may be an advantage to a deeper placement of nutrients in the soil. The higher biomass per unit area will require more nutrients to maintain similar tissue nutrient concentrations. These nutrients may be more available with deep-banded placement as the corn roots begin to compete for plant-available P and K. If corn plants at high population densities maintain superior access to critical nutrients, the same plants may be able to keep higher leaf P and K concentrations later in the growing season and during grain fill. This would result in an increased possibility of grain yield responses to deep placement.

Corn Responses to Hybrid Selection

Hybrid selection is of utmost importance when seeking high yields. Genotypic diversity makes each hybrid unique when discussing any aspect of corn growth and development. Genetic improvement has largely been the reason for increasing yields, but hybrids may differ widely in their response to environmental stresses as well as nutrient inputs. Potential yield responses to fertility placement may be very much affected by hybrid interactions. For example, one study showed that two hybrids from the same decade produced similar yields in conditions with adequate water; but, in dry conditions, one hybrid produced 27% higher yields than the other (O'Neill et al., 2004). These same hybrids also produced similar yields when nitrogen (N) levels were adequate, but one hybrid yielded 42% more when N was limiting (O'Neill et al., 2004).

Hybrid yield and harvest index responses have been observed to vary in response to nutrient availability (Echarte & Andrade, 2003). A study of different hybrids showed that they differed widely in their response to starter N (Rhoads and Wright, 1998). Modern hybrids tend to have greater harvest index stability, which is related to the lower shoot biomass thresholds for yield at low resource availability, and greater reproductive flexibility at high resource availability. This could help explain the greater tolerance for high plant densities with newer hybrids (Echarte & Andrade, 2003). Rehm (1995) and Vyn et al. (1999) reported that K uptake and grain yield were affected by hybrid; therefore choosing optimum K rates may depend on hybrid.

Root and canopy structure are obviously different when comparing many hybrids. Costa et al. (2002) observed that root lengths and surface areas were higher with hybrids bearing a leafy trait as compared to a conventional hybrid. Mean root diameters did not differ by hybrid in the same study.

Root Characteristics of Corn

Characteristics such as surface area, length, diameter, and mass have often been used to describe root systems. Although roots are arguably the most essential component of crop growth and development, there is not as much data as might be expected in this area because acquiring root data can be a tedious, expensive, and time-consuming task. Root responses to fertilizer placement are complex and are often a function of year, soil type and depth (Qin et al., 2005). In addition, soil conditions that result from conservation tillage may have adverse effects on root parameters such as root length, radius, and distribution in the soil (Chassot & Richner, 2002). In dense soils common in no-till systems, a lower root/shoot ratio can put a greater stress on the root to provide sufficient nutrients to the shoot. This could be why the early growth of corn was slower in the no-till system (Chassot & Richner, 2002).

Barber (1971) observed deeper root systems under conventional tillage; no-till treatments had fewer roots, and the roots tended to be larger in diameter. In this study, corn residue appeared to decrease root growth. Tillage, in general, tended to loosen the soil and increase aeration, producing more fine roots in the tilled areas. Initial nutrient levels also play a role in root morphology. One study reported that root surface area increased at higher levels of phosphorus (Mackay & Barber, 1984).

Root systems are extremely important to the uptake rate and uptake efficiency of P and K fertilizers. Barber (1984) presents a model that uses not only soil parameters (initial nutrient concentration, buffer power, diffusion coefficient), but also root parameters (length, radius, rate of elongation, and distance between root axes) to determine nutrient uptake.

Another factor that affects root growth and nutrient uptake is temperature. In one study, uptake of phosphorus increased 2.2-fold as soil temperatures rose from 18°C to 25°C (Mackay & Barber, 1984). They also reported that there was a 2.7-fold increase in total root length and a 3-fold increase in root surface area with the higher soil temperature. In addition, the rate of root growth increased 5-fold when soil temperatures increased from 18°C to 25°C (Mackay & Barber, 1984).

Total root length in modern corn hybrids is comparable. Root length within a specific diameter range was similar for all genotypes studied according to work done by Costa et al. (2002). Schenk and Barber (1980) found that the root distribution of genotypes differed between the topsoil and subsoil, as well as in root surface (per unit of shoot). They also concluded that root nutrient absorption characteristics for P and K uptake are heritable; the kinetic parameters that affect P and K uptake were different by genotype. However, root radius did not differ by genotype, or even with plant age (Schenk and Barbe,r 1980).

Roots less than 0.5 mm represent the majority of measured roots in corn (96-98 percent of all measured roots) (Costa et al., 2002). Therefore, though the smallest diameter roots are not large, they are likely responsible for the uptake of the majority of nutrients. These finer roots will effectively explore a given soil zone more intensively, and hopefully take advantage of nutrients placed deeper into the soil profile.

Summary

The deeper placement of P and K for corn production has been studied with varying results. This indicates that an across the board recommendation for fertilizer placement is not likely; there are many factors to consider when determining the best approach for nutrient management. Tillage system, soil test levels, rainfall and weather patterns all contribute to the growing environment of corn.

The studies discussed in the following chapters were initiated to evaluate the effectiveness of deeper placement of phosphorus and potassium. All of the studies reviewed previously were using a 20 cm or less band placement of phosphorus and or potassium. In our experiments, we added a deeper band (30-cm) in addition to the 15-cm banded and broadcast placements, as well as a combination 15 + 30-cm band.

A determination of the effectiveness of deep-banded P and K, in the context of considering corn hybrid selection and plant population, was considered a valuable research investigation to pursue. Hybrid and population are two important management considerations for crop producers and those choices will likely influence the relative effectiveness of deeper P and K placement. The objectives of the studies reported here are to determine if a deeper placement of P and K is beneficial, while observing the interactions of hybrid and planting population with fertilizer placement on the physiological development and chemical composition properties of corn.

CHAPTER ONE. HIGH YIELD CORN RESPONSES TO BANDING DEPTH OF PHOSPHORUS AND POTASSIUM FERTILIZERS

Abstract

The pursuit of higher corn yields has resulted in concerns of yield limitations resulting from vertical soil stratification of P and K, especially as conservation tillage and higher plant densities become more prevalent. In the Midwest, P and K are typically broadcast over the soil surface, but there is interest in strip tillage systems combined with deep-banding nutrients. Deeper placement is encouraged on the basis that essential nutrients are placed in a more favorable zone for root uptake for non-irrigated production systems.

Equipment advances now permit banded nutrient applications to depths of 30-cm. However, research to investigate the effectiveness of P and K applications to these deeper depths has been lacking. Experiments were initiated in 2001 to observe the impacts of deep placement on corn growth and yield on dark prairie soil with approximately medium concentrations of available P and exchangeable K. Two corn hybrids (Pioneer 34B24 and Pioneer 24M95) were planted at two populations (79,000 and 104,000 plants per hectare) in combination with five different placements of P and K including a control (no

added fertilizer), broadcast on the soil surface, shallow band (15 cm), deep band (30 cm), and a deep plus shallow band (15+30 cm).

Occasionally significant and positive corn growth responses to the 30-cm placement depth of P and K were observed. Early shoot weights were higher when P and K fertilizers were deep-banded as compared to a broadcast or shallow-banded placement. The early vigor observed in the deep-banded treatment did not translate into higher leaf area indices. The shallow-banded treatment resulted in significantly higher LAI than the 30 cm band. However, overall, results do not indicate that the deeper placement of P and K is preferable to broadcasting. Chlorophyll readings during grain fill indicated that the broadcast placement had better "stay-green" ability than the 30 cm deep-banded treatment. Corn yields were not affected by fertility treatments in 2001; in 2002 both the deep-band and combined shallow plus deep band treatments resulted in significantly higher yields than the control, but not relative to broadcasting. Corn responses to fertility placement treatments did not interact with hybrid or population densities. The results observed in this study demonstrate that corn response to P and K fertilizer placement is not straightforward. Deep in-row placement of P and K was not superior to broadcast placement even at very high plant densities. Corn responses to deeper placement of P and K fertilizers were observed in some of the parameters measured, but the combined data from two years of study do not show obvious trends.

Introduction

Fertilizer rates and placement of nutrients are important factors to consider when crop producers seek to produce maximum yielding corn. Because of the relative immobility of P and K in the soil, it seems that a deeper placement of these nutrients might be beneficial to corn growth in conservation tillage situations. The method of P and K placement has typically been broadcasting over the top of the soil. Broadcast application methods plus the annual root and shoot uptake have resulted in significant nutrient stratification when soils are not routinely inverted with conventional tillage systems (Howard et al., 1999; Mackay et al., 1987; Crozier et al., 1999; Robbins and Voss, 1991).

Several studies have reported yield benefits to deeper, banded nutrient placement in corn (Bordoli & Mallarino, 1998; Borges & Mallarino 2001; Mackay et al., 1987; Vyn & Janovicek, 2001). Yet many other studies have concluded that broadcast is as effective as banding in corn (Bordoli & Mallarino, 1998; Borges & Mallarino, 2000; Borges & Mallarino, 2001; Ebelhar & Varsa 1999; Mallarino et al., 1999; Mengel et al., 1988; Rehm, 1986; Vyn et al., 2002). In some of these studies, yield benefits were seen with a deep-banded K placement, but not with a deep-banded P placement.

It is not certain why some environments show an advantage to deep placement while others do not. Corn responses to P and K fertilizer applications are typically greatest in dry conditions (Nelson et al., 1992). Robbins and Voss (1991) concluded that during extended periods of dry weather, surface P and K became positionally unavailable.

Weather certainly plays a role in the effects of deep placement, but is not alone in its influence on nutrient uptake.

Early season results on deep placement of P and or K fertilizers vary widely. Some show increased early growth with deeper P placement (Mallarino et al., 1999; Borges & Mallarino, 2001) while others observed significantly decreased or no effect on early growth (Rehm, 1986).

With regard to K, some studies have reported that early growth was increased by deep band K as opposed to broadcast applications of K (Borges & Mallarino, 2001; Vyn et al., 2002). Mallarino et al. (1999) and Borges & Mallarino (2001) both concluded that judging the effects of deep banding by looking at early growth alone is misleading, especially in soils that are not deficient in available P and exchangeable K.

Mid-season corn responses to P and K placement methods have also been variable. At 2 weeks before silking, Rehm (1986) found that P uptake was higher for broadcast versus 15-cm deep band application. However, in other studies, broadcast and deep-banded treatments were not different for K uptake (Mengel et al., 1988; Vyn et al., 2002; Ebelhar & Varsa, 1999).

Yield responses to placement on P and K have resulted in various conclusions. P placement method seldom influenced corn grain yield in a multiple-location Iowa study for any tillage system, even with low testing soils (Bordoli & Mallarino, 1998). Deep banding K (at 15-cm) increased corn yields significantly at several sites over the broadcast or planter-band placements (Bordoli & Mallarino, 1998). The yield increase was observed even in soils that tested high (>30 mg kg^{-1}) for exchangeable K concentration; therefore, low soil-test K status was not the sole reason for the response.

The reports concluded that weather conditions were likely somewhat responsible for the response to deep placement. This agrees with work done by Borges & Mallarino (2001) who observed a yield advantage to deep (15-20 cm) band K when compared to broadcast, but saw little response to deep-banded P.

Vyn et al. (1999) reported that there were significant yield benefits to deep (15-cm) banding K, particularly in zone-tillage systems. Deep banding K (15-cm) in a zone tillage system also increased corn yields over broadcast placement in conventional tillage and no-till situations (Vyn & Janovicek, 2001). However, in continuous no-till corn with optimal soil moisture, surface broadcasting was found to be as good as deep banding K despite soil exchangeable K stratification, and in some situations deep banding appeared to lower yields relative to broadcast application (Vyn et al., 2002).

Most research indicates that at high soil test levels, crop yield responses to P and K placement are rare (Randall et al., 2001; Randall & Hoeft, 1988). Research by Vyn & Janovicek (2001) also show that K fertilization only produced higher corn yields on fields with exchangeable K concentrations of less than 120 mg per kg.

Designation of “high” soil test level is fairly vague; soil test interpretations vary widely among individual states and interpreters. A&L Great Lakes Laboratories, the Fort Wayne, IN, company used to analyze our soil samples, uses the following scale for P: 0-8 is very low, 9-15 is low, 16-20 is optimum, 21-30 is high and 31+ is very high. Their scale for K is: 0-60 is very low, 61-90 is low, 91-130 is optimum, 131-170 is high, and 171+ is very high. These ranges are probably very similar to other company and university interpretations in the Eastern Corn Belt. However, we speculate that these interpretations were decided on many years ago and may not be appropriate for some of the current high yield situations.

When determining P and K rates, typically recommendations come from university or other published literature. We studied the Tri-State Fertilizer Recommendations for Corn, Soybeans, Wheat, & Alfalfa (Vitosh et al., 1996). With this publication, yield potential is used to determine the recommended P and K rates. However, yields only go up to 180 bu/acre for corn. In the present era of crop production, yields of 200+ bu/acre are not uncommon in many areas of the Corn Belt. Determining the proper P and K rates to apply for this kind of yield potential is not accommodated in current literature. Interpretations of soil test values and the resulting fertilizer recommendations may be outdated for producers in high yielding environments

Fertilizer placement, of course, is one of many factors studied to attain higher yields. Increased yields have been partially due to corn hybrids that have been genetically improved to withstand greater stresses, therefore allowing higher planting populations (Paszkiewicz & Butzen, 2003). Higher plant populations increase leaf area indices (Tetio-Kagho & Gardner, 1988; Borras et al., 2003) and crop growth rates up to a threshold plant density (Tetio-Kagho & Gardner, 1988). These higher densities also alter the light distribution within the canopy (Tetio-Kagho & Gardner, 1988). In an Argentine study, higher plant populations increased the leaf senescence rate and decreased the source-to-sink ratio (Borras et al., 2003). Higher populations typically result in greater demands for nutrients (Arkebauer et al., 2004). Understanding crop nutrient needs is essential to producing high yielding corn, especially with high planting populations.

In higher populations, there may be an advantage to a deeper placement of nutrients in the soil. These nutrients may be more available as the corn roots begin to compete for P and K. Therefore, the corn plants may be able to keep higher leaf P and K concentrations later in the growing season and during grain fill. This would result in an increased possibility of grain yield responses to deep placement.

Genetic improvement has largely been the reason for increasing yields, but hybrids may differ widely in their response to environmental stresses as well as nutrient inputs. Hybrid yield responses to environmental stresses varied in response to nutrient availability (Echarte & Andrade, 2003). Rehm (1995) and Vyn et al. (1999) reported that K uptake and grain yield were affected by hybrid; therefore choosing optimum K rates would depend on hybrid selection.

It is likely that crop management might also affect the level of response to the placement of these nutrients. Optimum plant populations differ by hybrid (Echarte & Andrade, 2003) and as plant densities increase, there is a greater demand for nutrients (Arkebauer et al., 2004). The placement of these extra nutrients may be a factor in how available they are to plants at progressively higher populations.

Research was initiated in 2001 to investigate the effects of deep banding phosphorus and potassium in high yielding corn management systems. The effectiveness of deep banding (versus traditional broadcast placement) may help farmers understand how placement of these nutrients will affect corn growth and development in environments where high yields are intentionally pursued via practices such as very high plant populations.

Although previous research has looked at banded fertilizers (with varying results), the depths of these bands are typically less than 20 cm. Root systems penetrate much deeper than 20 cm, so this study incorporates a deeper 30-cm placement in the treatments to ascertain if this would allow higher uptake. Since hybrids differ in their root morphology, it is likely that there may be variations in how they respond to deep fertilizer placement. In addition, the interactions of fertilizer placement with hybrid and plant population may be key to understanding the value of deep banding P and K fertilizers.

Materials & Methods

Site Description

The study was initiated in 2001 at the Purdue Animal Sciences and Education Center (ASREC) located near West Lafayette, Indiana (40° 28’ N Lat., 86° 59’ W Lon.). The soil is characterized as a mix of Toronto-Millbrook complex (fine, silty, mesic Udollic Ochraqualf) and Drummer soils (fine, silty, mesic Typic Haploquoll). The Toronto-Millbrook complex is a somewhat poorly drained, deep soil with 0 to 2 percent slopes and a silt loam texture. The Drummer soil is a very deep, nearly level, poorly drained soil with a silty clay loam texture.

Field History

The approximately 5-hectare site was in a corn-soybean rotation, with soybeans planted in 2000. Fall moldboard plowing and spring secondary tillage were completed prior to planting in 2001. In 2001, corn was planted on one half of the site and soybeans on the other. In 2002, these were switched.

Experimental Design and Treatments

The experiment was designed in a split-split-plot arrangement, as a randomized complete block. There were four replications in 2001 and five replications in 2002. Plot areas were 19.8 x 9.1 m (65' x 30'). Two hybrids were randomly assigned to the whole plots, with the two populations being the split plot. The hybrids were selected because they came from different genetic backgrounds. The low population of 79,000 plants per hectare was chosen to represent a normal density that crop producers would use. The higher population of 104,000 plants per hectare was chosen to reflect the densities that some high yield producers use. Within these, five fertility treatments were randomly assigned. The plot design and treatments are described in more detail below.

Main Treatments (2 Hybrids):

1. Pioneer 34B24: 110 CRM, Bt
2. Pioneer 34M95: 110 CRM, Bt

Sub-Treatments (2 Populations)

1. 79,000 plants ha^{-1} (32,000 plants per acre)
2. 104,000 plants ha^{-1} (42,000 plants per acre)

Sub-Sub-Treatments (5 Fertility Treatments):

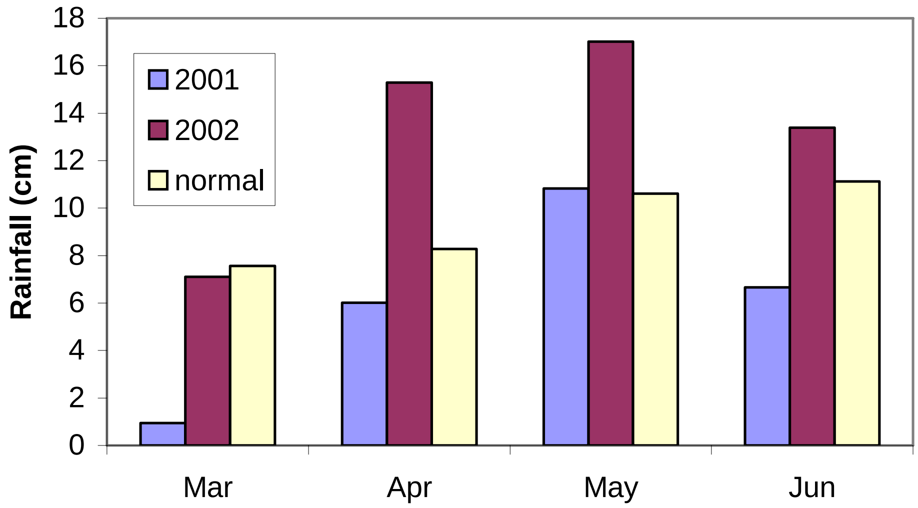
1. Control: no added P or K other than starter
2. Broadcast P and K: applied on the surface and lightly incorporated
3. 15 cm (6-inch) Band P and K
4. 30 cm (12-inch) Band P and K
5. 15+30 cm (6+12-inch) Band P and K: rate split between the two depths

The rates of P and K for all treatments, excluding the control, were 99 kg ha^{-1} (88 pounds per acre) P_2O_5 and 129 kg ha^{-1} K_2O (115 pounds per acre). Phosphorous fertilizer was applied as 0-46-0 and K was applied as muriate of potash (0-0-60) in the spring before planting. All banded treatments were applied at the appropriate depth(s) with a Gandy system attached to a DMI Nutriplacr 2500 equipped with mole knives and berming disks. All five sub-treatments were strip-tilled with the DMI tool to a consistent depth even if no fertilizer was banded (i.e. sub-sub treatments 1 and 2) to remove any confounding of tillage practices with fertilizer treatments.

Crop Management

Corn was planted in 76.2 cm (30-inch) rows directly over the strip-tilled fertilizer bands (if applicable). All treatments, including the control, had a uniform starter fertilizer application of 9-18-9 plus zinc. In 2001, the starter rate was 20 gallons per acre; in 2002, it was reduced to 12 gallons per acre). This was partially due to fertilizer burn symptoms noticed early in the 2001 growing season. In 2001, the plots were planted on May 3rd; in 2002, they were not planted until June 11 (Pioneer hybrid 34B24) and June 17 (Pioneer hybrid 34M95) due to higher than average spring rainfalls (Figure 1).

Figure 1. Monthly Precipitation Averages in Lafayette, Indiana *



* from Purdue University Applied Meteorology Group

Nitrogen was applied as a split application in both years at rates that were considered to be high enough that N availability would not be limiting corn yield potential. Excluding the starter, a total of 337 kg ha^{-1} (300 pounds N per acre) was applied in 2001. In 2002, the rate was decreased to a total of 280 kg ha^{-1} (250 pounds N per acre) because late planting was expected to lower the overall yield potential (and, therefore, the need for the very high N rate applied in 2001). For 2001, the N was split into three UAN applications (28-0-0); in 2002, two UAN applications (28-0-0) were side-dressed during the growing season.

During the growing season, weed and insect control actions were taken as necessary. In May 2001, Harness Extra (acetachlor and atrazine) and Atrazine 4L were applied at 4.38 and 1.46 liters ha^{-1} (3.75 and 1.25 pints per acre), respectively. In mid-June of that year, 53 g ha^{-1} (0.76 ounces per acre) Beacon (primisulfuron-methyl) was applied. Due to Japanese Beetle and Western Corn Rootworm presence during silking, Warrior (λ-cyhalothrin) was aerially applied at 270 g ha^{-1} (3.8 ounces per acre) in June and again in July.

In 2002, Dual II Magnum (S-metolachlor) and Atrazine 4L were used in June at 2.3 and 2.9 liters ha^{-1} (2 and 2.5 pints per acre). Later in June, Beacon (primisulfuron-methyl) was applied at 53 g ha^{-1} (0.76 ounces per acre). Due to a persistent annual grass problem, the plots were row-crop cultivated in early July.

Soil Measurements

Soil samples were taken before any treatments were applied. All plots were sampled by bulking 10 soil cores per plot. These were sub-divided into three depth-intervals: 0-10, 10-20 and 20-40 cm (0-4, 4-8, and 8-16 inches). These were sent to an independent laboratory and analyzed for organic matter, available phosphorus (using Mehlich 3), exchangeable potassium, magnesium, soil pH, buffer pH, cation exchange capacity (CEC), and percent base saturation for K, Mg, Ca, and H. Summaries of these results are shown in Tables 1 and 2. No vertical stratification of P and K in the upper 20 cm was evident in 2001 because of the recent moldboard plowing.

Table 1. Mean Soil Test Results for Experimental Site Prior to Treatments Applied in 2001*

Depth cm	OM %	P ppm	K ppm	Mg ppm	CEC meq/100g
0-10	3.4	15.4	94	474	14.1
10-20	3.5	15.3	107	462	14.9
20-40	3.0	6.8	84	478	15.3

* Extractions: Loss on Ignition (LOI) used for OM, Mehlich 3 used for P detemination

Table 2. Mean Soil Test Results for Experimental Site Prior to Treatments Applied in 2002*

Depth cm	OM %	P1 ppm	K ppm	Mg ppm	CEC meq/100g
0-10	3.9	25	143	573	16.6
10-20	3.8	15	101	571	16.5
20-40	3.2	7	79	578	16.5

* Extractions: Loss on Ignition (LOI) used for OM, Mehlich 3 used for P detemination

Plant Measurements

Shoot samples at the V4 growth stage were analyzed for P and K concentrations. Samples were taken by cutting the plant at the soil surface, drying the tissue, and grinding for analysis. In 2001, a modified wet ash digestion (Wolf 1982) was used for K determination. Sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) were combined with the ground plant material and digested on a heating block. These were analyzed with a Varian 400 atomic absorption spectrophotometer. Digestion for P analysis was done using a combination of potassium sulfate and copper sulfate (K_2SO_4 & $CuSO_4$) as well as sulfuric acid (H_2SO_4). These samples were analyzed using a Lachat FIA 8000.

In 2002, the V4 samples were taken, but during the process of drying, some samples became moldy, requiring some samples to be discarded. Therefore, V4 shoot samples were weighed and analyzed only for 2001.

In 2001, plant height was measured at the V6 stage by measuring from the soil surface to the tallest leaf when extended.

Leaf area indices (LAI) were determined at the V6 and R1 growth stages (all growth stages taken using Leaf Collar Method) by taking 10 whole plant samples per plot (five consecutive plants in two areas of the plot). Plants were cut off at the soil surface. The leaves were then separated at the collar and analyzed for leaf area with a LI-COR Model 3100 area meter (LI-COR Biosciences, Lincoln, Nebraska). This gave us the amount of leaf area per plant. We calculated the actual leaf area index (LAI) by using known plant populations per acre and the leaf areas per plant. The total leaf area was converted to leaf area per unit soil area and is reported as the leaf area index (LAI). The leaf area measurements were taken from areas within plots with the expected plant population for the treatment. This ensured that the soil area we used to calculate the LAI was correct.

Ear leaves at the R1 growth stage were analyzed for P and K concentrations. The leaves were cut at the leaf collar, dried, and ground for analysis. The method for P and K analysis was the same as the shoot samples at the V4 growth stage in 2001. In 2002, due to time constraints, samples were sent to an independent laboratory where they were analyzed for N, P, K, Ca, Mg, S, B, Fe, Mn, Cu, Zn, and Al.

To observe the leaf senescence rates for the treatments, chlorophyll meter readings were taken on a bi-weekly basis during the grain fill period. These were taken on the ear leaf, approximately halfway between the tip and the leaf sheath with a Minolta SPAD 502 chlorophyll meter (Minolta Co., Osaka, Japan).

Corn grain yield was evaluated by hand harvesting two 8.0 m (26 feet) lengths of row per plot after physiological maturity. Final plant populations were counted in each of these areas. In the first year, grain moisture was determined with a Dickey John GAC 2000 (Dickey John Corp., Auburn, Illinois). In 2002, the GAC was inoperative; therefore grain moisture was determined using a Farmex MT3 (Farmex Electronics Corp., Streetsboro, Ohio) moisture meter. The yields were adjusted to 15.5 % moisture content in both years. Grain was analyzed by an independent laboratory for N, P, K, Mg, S, B, Fe, Mn, Cu, Zn, Al.

Statistical Analysis

The included statistical analyses were accomplished using Statistical Analysis Software (SAS) version 8.2 (SAS Institute, Inc., Cary, North Carolina). Simple univariate statistics (means, standard deviations, minimums and maximums) were computed for each parameter. To determine the need for transformations, a Box-Cox analysis was performed.

Because the planting dates for each year were very different, years could only be pooled for certain variables. The data are shown with years separate and also with pooled years when statistically appropriate. The split-split block error terms were all pooled into one error term. Pooling decisions ($P < 0.25$) were based on a majority rules basis.

Fisher protected LSD values ($P < 0.05$) were used for the mean separation tests except where noted. In 2002, hybrids could not be directly compared due to a difference in planting dates.

Results & Discussion

Leaf Area Index

Leaf area measurements quantitatively define one aspect of plant canopy structure. The leaf area index (LAI) indicates the plant leaf area per unit of ground area; it is fundamental to processes such as photosynthesis, evapotranspiration, and respiration because it determines relative light interception and relative surface area for gas exchange.

In any given environment, the resulting LAI of corn is primarily affected by hybrid and population decisions. In addition, the placement of fertilizer relative to the row may affect uptake of available P and exchangeable K when the soil-test levels are low (< 60 mg $K1^{-1}$) (Vyn et al., 2002) or when dry conditions occur (Bordoli & Mallarino, 1998). If a plant is deficient in nutrients, especially P, leaf growth rates may decrease. The number of leaves and the surface area of leaves may also decline with fertility limitations (Marschner, 1988).

In the present experiment, there were no LAI differences among fertility treatments at the V6 stage of plant growth in either year (Table 3). The lack of significant differences may partially be explained by sampling variability (e.g. small sample size) and the consistent use of starter fertilizer. Since all plots, controls included, received an initial starter of both P and K, the nutrients from this band may have been sufficient to more than adequately meet the nutrient requirements for corn growth at the V6 stage.

Table 3. Effects of Hybrid, Population and P plus K Treatments on LAI at V6 and R1 Growth Stages †

	V6 Leaf Area Index		R1 Leaf Area Index	
	2001	2002	2001	2002
Pioneer 34B24	0.77 a	0.45	5.24 a	4.66
Pioneer 34M95	0.54 b	0.43	4.41 b	4.39
79,000 plants ha^{-1}	0.61 b	0.39 b	4.37 b	4.12 b
104,000 plants ha^{-1}	0.71 a	0.48 a	5.28 a	4.94 a
Control	0.68	0.41	4.77 ab	4.38
Broadcast	0.63	0.48	4.88 ab	4.53
15-cm Band	0.67	0.44	5.15 a	4.52
30-cm Band	0.68	0.43	4.59 b	4.57
15 + 30-cm Bands	0.62	0.44	4.74 ab	4.63
Treatment ‡	Significance Level		Significance Level	
Hyb	**		**	
Pop	**	**	**	**
Fert	ns	ns	*	ns
Hyb x Pop	ns		*	
Hyb x Fert	ns		ns	
Pop x Fert	ns	ns	ns	ns
Hyb x Pop x Fert	ns		ns	

* significant at 0.05 probability level
** significant at 0.01 probability level
† Data followed by the same letter within year (column) are not significantly different according to a Fisher protected LSD ($P = 0.05$)
‡ Hyb = hybrid, Pop = population, and Fert = fertility treatment

At the V6 growth stage, Pioneer 34B24 had a significantly greater leaf area than Pioneer 34M95 in 2001 ($P < 0.01$). Hybrids could not be compared directly in 2002 due to different planting dates. As anticipated, population effects were consistently significant ($P < 0.01$) with the higher populations resulting in greater leaf area per unit soil area (Table 3). This was expected due to the increased number of plants per unit area. Leaf area per plant was higher for the low population, but leaf area values on a per unit soil area basis favored the high population. It was also not surprising to see a hybrid effect, since the hybrids chosen came from very different parents and different genetic pools. Hybrid 34B24 had a significantly higher leaf area than Pioneer 34M95 for both growth stages ($P < 0.01$).

At the R1 growth stage, fertilizer treatment differences were observed in 2001 (Table 3). The 15-cm banded treatment had a significantly higher LAI than the 30-cm banded treatment in 2001. All other fertilizer treatments were not significantly different. As seen in Table 4, hybrids responded differently to plant density treatments. Both hybrids had more LAI at the higher plant population, but the proportional increase in LAI with plant population was more dramatic in Pioneer 34B24. However, no significant fertilizer treatment interactions were observed for LAI with either hybrid or plant population.

Table 4. Hybrid by Population Interaction with respect to LAI at R1 Growth Stage in 2001*

Hybrid	79,000 (pl/ha)	104,000 (pl/ha)
	- - - - - - LAI	- - - - - -
34B24	4.68 a B	5.81 a A
34M95	4.07 b B	4.74 b A

*data followed by the same letter are not significantly different within a row (capital letters) or a column (lower case) according to a Fisher protected LSD ($P = 0.05$)

Early Shoot Weight and Plant Height

Shoot weight and height measurements allow comparison of plant growth and vigor among treatments. In 2001, shoot weights were taken at the V4 growth stage.

Therefore, only one year of data exists for these parameters. Heights were also only taken during the first season.

Highest shoot weights at the V4 growth stage were found where P & K was banded at 30-cm (Table 5); this treatment also had the lowest LAI at R1 (Table 3). The 30-cm Band P & K treatment resulted in a significantly higher shoot weight than both the 15-cm and broadcast fertilizer treatments. Lowest shoot weights were seen in the 15-cm treatment, which had the highest LAI at the R1 stage. The apparent early season shoot weight advantage versus leaf area disadvantage at R1 for the banded treatments at the 30-cm depth may suggest that, for this year at least, corn response to placement depth differed by development stage. Perhaps the 15-cm placement was initially detrimental to corn growth rates because of the relatively high rates of K in the initial rooting area below seed depth, but beneficial as plants completed vegetative growth. Some burning of corn leaf margins was observed at V4 in 15-cm banded treatments in 2001 (no data collected).

Table 5. Effects of Hybrid, Population, and P plus K Placement Treatments on Shoot Weights and Heights in 2001 †

	V4 Shoot Weight (g)	V6 Height (cm)
Pioneer 34B24	9.38 a	40.8 a
Pioneer 34M95	7.31 b	36.5 b
79,000 plants ha^{-1}	8.40	37.8
104,000 plants ha^{-1}	8.29	39.4
Control	8.87 ab	38.4
Broadcast	8.00 bc	38.7
15-cm Band	7.42 c	37.6
30-cm Band	9.17 a	39.2
15+30-cm Bands	8.26 abc	39.2
Treatment‡	Significance Level	
Hyb	**	**
Pop	ns	ns
Fert	**	ns
Hyb x Pop	ns	ns
Hyb x Fert	*	ns
Pop x Fert	ns	ns
Hyb x Pop x Fert	ns	ns

** significant at 0.01 probability level
* significant at the 0.05 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid, Pop = population, and Fert = fertility treatment

Plant height differences among fertility treatments were largely non-significant, but Pioneer hybrid 34B24 was taller at the V6 stage than Pioneer 34M95 (Table 5). Prior research has shown varying results when early growth was compared with alternate P and/or K fertilizer placements. Mallarino (2000) showed that banded P frequently increased early corn growth; he also concluded that starter P increased early growth more frequently than deep-banded P (Mallarino et al., 1999). However, others have seen no effect from P placement on early growth (Rehm 1986). In a study by Mengel et al. (1988), a strip placement of P and K on the soil surface increased early growth when compared to a broadcast placement but deep banding of a similar rate (at a depth of 20 cm) was not as effective as the strip application. Furthermore, some studies noted that differences resulting from P and K fertility treatments in early growth were not well correlated with actual yield differences in corn (Borges & Mallarino, 2001; Mallarino et al., 1999; Mallarino, 2000).

Table 6. Effects of Hybrid and P & K Depth on Shoot Weight (g) at V4 in 2001 *

Hybrid	Fertility Treatment				
	Control	Broadcast	15-cm Band	30-cm Band	15+30-cm Bands
34B24	10.49 a A†	8.76 b	8.34 b A	10.82 a A	8.47 b
34M95	7.25 B	7.24	6.50 B	7.52 B	8.04

* significant at the 0.05 probability level
† Data followed by the same lower case letter within a row are not significantly different from other fertility treatments according to a Fisher protected LSD (*P* = 0.05), and data followed by the same upper case letter within a column are not significantly different between hybrids according to a Fisher protected LSD (*P* = 0.05)

The hybrid by fertility treatment interaction for shoot weight was also significant (Tables 5 and 6). The 15-cm band of P & K resulted in a consistently low shoot weight for both hybrids (Table 6). The amount of P & K in the bands was a point of concern for the young root systems as they grew into these concentrated regions. There were visible symptoms of some leaf burn at the V4 stage of plant development. Nutrient analyses, however, did not show significantly increased levels of whole plant P or K at the V6 growth stage (see Table 7). Another interesting observation is the high shoot weight of the control treatment with Pioneer 34B24; however, the 30-cm band fertility treatments were not significantly lower in shoot weight than the control treatment with either hybrid.

We might speculate that the fertilizer concentration (and particularly K) in the band was too high for high seedling growth rates. At the V4 growth stage, the roots would have been near the 15-cm band. At this stage, the young plants are still dependent to some extent on seed reserves; it is around the V6 growth stage that the nodal root system is supplying all of the required nutrients to sustain plant growth (Nielsen, 2003). However, when nutrient concentrations were analyzed at the V6 stage, there is no indication that the tissue concentration of P and K was any higher for the 15-cm banded treatment than other treatments (Table 7).

Early Shoot and Ear-leaf Nutrients

Whole plant nutrient concentrations were taken at approximately the V6 stage. The nutrient analyses were done primarily to determine whether hybrid, population or P & K placement depths caused significant differences in uptake of P and K. At this early growth stage, population differences were significant for the concentrations of P and K in the shoot, but fertility treatments were not (Table 7). The lack of fertility differences could be because of the application of starter fertilizer as discussed previously; perhaps P and K were not limiting at these corn developmental stages for any of the fertility treatments, even the control. In previous research, deep placement of K increased the early season K concentration in certain tillage systems (Vyn et al., 2002 and Mallarino et al. 1999). Although Mallarino et al. (1999) found increased early season K concentration in banded treatments, they reported that this seldom corresponded to enhanced early growth.

At the V6 growth stage, the lower population resulted in significantly higher plant P ($P < 0.01$), S ($P < 0.05$), and Mg ($P < 0.01$) concentrations than the higher plant population (Table 7). Pioneer 34B24 resulted in higher concentrations of Mg, S, B, Mn and Cu than Pioneer 34M95 (P < 0.0.1 for all except Mn, where $P < 0.05$, data not shown). Year 2002 data was not available.

During the vegetative stages, optimal P levels range from 0.3 to 0.5% (Marshner, 1988). Lower P concentrations at the lower population may have indicated less root competition for available P. It could also represent the effects of different root and shoot partitioning in response to population. Potassium is needed in higher quantities and is typically present at a 2 to 5% range in healthy plants (Marshner, 1988). Concentrations in this study easily fell within these boundaries.

Table 7. Effects of Hybrid, Population and P & K Placement on Concentrations of P, K, Mg, and S in the Whole Plant at the V6 Growth Stage in 2001.

	V6 Shoot P	V6 Shoot K	V6 Shoot Mg	V6 Shoot S
	- - - - - - - - - - - - - -	-%-	- - - - - - - - - - - - - -	
Pioneer 34B24	0.36	3.65	0.45 a	0.35 a
Pioneer 34M95	0.37	3.79	0.41 b	0.33 b
79,000 plants ha^{-1}	0.38 a †	3.72	0.43	0.35 a
104,000 plants ha^{-1}	0.35 b	3.72	0.43	0.34 b
Control	0.36	3.71	0.43	0.33
Broadcast	0.36	3.82	0.42	0.34
15-cm Band	0.37	3.80	0.44	0.35
30-cm Band	0.37	3.68	0.44	0.35
15+30-cm Bands	0.36	3.59	0.43	0.34
Treatment‡		Significance Level		
Hyb	ns	ns	**	**
Pop	**	ns	ns	*
Fert	ns	ns	ns	ns
Hyb x Pop	ns	ns	ns	ns
Hyb x Fert	ns	ns	ns	ns
Pop x Fert	ns	ns	ns	ns
Hyb x Pop x Fert	ns	ns	ns	ns

** significant at 0.01 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid, Pop = population, and Fert = fertility treatment

R1 ear-leaf samples were taken next to the primary ear to investigate possible P and K concentration differences resulting from hybrids, populations, and fertilizer placements. No significant differences were noted for either P or K concentrations in

2001 (Table 8). Samples were sent to an independent laboratory for analysis in 2002 for a complete nutrient analysis of N, P, K, Ca, Mg, S, B, Fe, Mn, Cu, Zn, and Al. No significant differences were apparent in P or K among fertility treatments in 2002 (Table 8). Vyn et al. (2002) also reported that K application method (whether broadcast or deep band at 15-cm depth) affected the ear-leaf K concentrations. Another study indicated a significant increase in ear-leaf K concentration when nutrients were strip banded on the soil surface versus broadcast or deep banding at 8 inches (Mengel et al., 1988).

According to the Tri-State Fertilizer Recommendations extension bulletin (Vitosh et al., 1996), the sufficiency range for earleaf P (sampled at initial silking) is 0.3 to 0.5 percent. The data collected in this study is clearly under the reported sufficiency range; however, our samples were not taken at initiation of silking, but approximately at the R2 growth stage. Just how much this difference in stage of sampling might affect nutrient concentration is not clear.

Sufficiency ranges for ear-leaf K concentrations fall between 1.91 to 2.50 percent at initial silking (Vitosh et al., 1996). Our data for 2001 falls within this range; however, the 2002 concentrations were considerable lower. The reason(s) for this are uncertain.

Table 8. Effects of Hybrid, Population and P & K Placement on Concentrations of P and K in the Earleaf

	Ear-leaf P		Ear-leaf K	
	2001	2002	2001	2002
Pioneer 34B25	0.22	0.27	2.04	1.44
Pioneer 34M95	0.20	0.26	2.30	1.88
79,000 plants ha^{-1}	0.23	0.27	2.13	1.63
104,000 plants ha^{-1}	0.20	0.27	2.22	1.73
Control	0.21	0.26	2.01	1.69
Broadcast	0.21	0.26	2.26	1.59
15-cm Band	0.23	0.26	2.25	1.71
30-cm Band	0.21	0.26	2.17	1.68
15+30-cm Bands	0.21	0.28	2.17	1.78
Treatment‡	Significance Level		Significance Level	
Hyb	ns		ns	
Pop	ns	ns	ns	ns
Fert	ns	ns	ns	ns
Hyb x Pop	ns		ns	
Hyb x Fert	ns		ns	
Pop x Fert	ns	ns	ns	ns
Hyb x Pop x Fert	ns		ns	

‡ Hyb = hybrid, Pop = population, and Fert = fertility treatment

No treatment differences in shoot or ear-leaf P or K concentrations were observed at any growth stage tested. Even the control plots showed no significant difference versus the plots with P and K added. We expected to find placement differences especially relative to the control; however, no differences in either percent P or percent K in the ear-leaf were statistically significant (Table 8).

Previous research has shown ear-leaf K concentration differences resulting from alternate K placements (Vyn et al., 2002). Ebelhar & Varsa (1999), however, reported that broadcasting resulted in lower K concentrations in whole plants early in the season than a surface band of K; however, there was no difference in ear-leaf K concentration. Similarly, Vyn et al. (2002) has noted increases in early season K concentrations with deep (15-cm) bands of K as compared to a shallow placement; although no differences were found among application methods for ear-leaf K concentrations.

Chlorophyll Readings

Chlorophyll readings were taken to determine the effects of hybrid, population and P & K treatments on chlorophyll values and apparent ear-leaf senescence during grain fill. These readings were used to judge the "stay-green" of corn. A hybrid that retains photosynthetic efficiency longer would be expected to achieve greater yields. The hybrids grown in this study were selected because of their different genetic backgrounds

In 2001, measurements were taken from July 17th through September 14th. Hybrid and population differences were observed each time readings were taken. Pioneer 34B24 always had higher chlorophyll readings (data not shown). The relationship of leaf thickness to the chlorophyll meter reading has not been documented. Low plant population also resulted in higher chlorophyll readings in each case (data not shown). This agrees with studies done in Argentina that showed earlier leaf senescence for higher plant densities (Borras et al., 2003). According to the same study, "among the cultural practices analyzed in our work, plant population had the largest effect on senescence progress." The group studied combinations of hybrids, planting populations, row spacings and pollination treatments.

Figure 2 shows the progression of chlorophyll readings throughout the 2001 season. Treatment responses have a similar trend on most dates, but significant treatment differences were only apparent on two of the eight dates. These responses suggest that the broadcast treatment either has a higher stay-green capacity than the other treatments or at least has a different rate of development. Also, the readings for the 30-cm band treatment seem to consistently be lower until the last two dates, when the control and 30-cm band treatments appeared to have similar senescence levels for the ear-leaf. However, due the lack of significant differences, we cannot make any definitive conclusions.

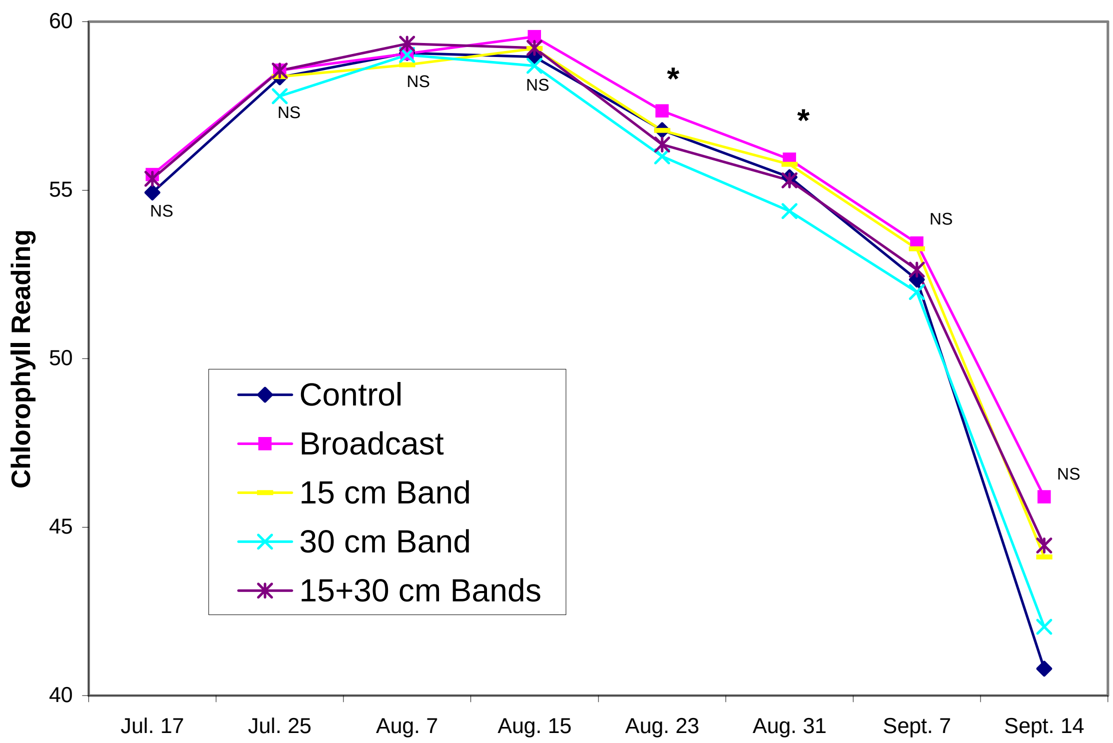


Figure 2. Average Chlorophyll Readings over all Hybrids and Populations in 2001 * †
* significant at the 0.05 probability level
NS denotes no significance at *P* = *0*.05

Treatment differences were significant on August 23rd and August 31st (Figure 2 and 3). On both of these dates, the 30-cm band was consistently lower than the broadcast P & K treatment, and the 30-cm band was significantly lower than the 15-cm band on the second date (Figure 3). The broadcast placement of P & K consistently had the highest chlorophyll readings. At the end of the season, the separation of the treatments is more obvious (Figure 2). Differences were not significant because of the variability of the data; however, it is interesting to note that the control treatment drops off more quickly than the others.

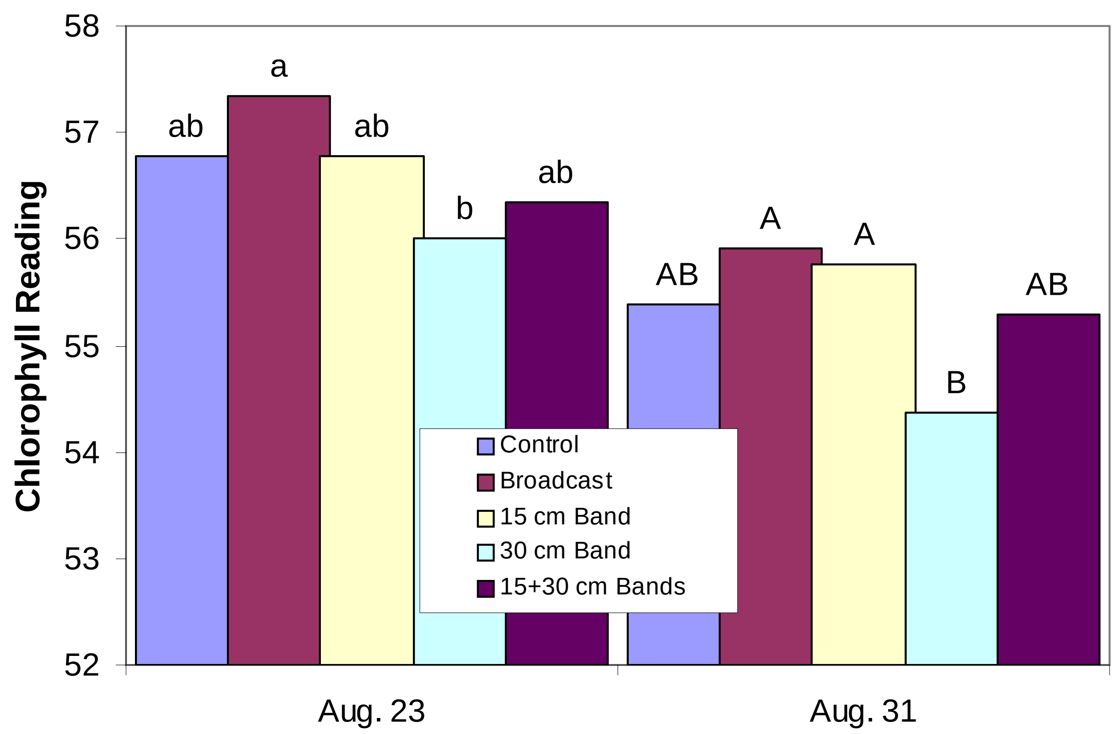


Figure 3. Significant Effects of Fertility Placement on Chlorophyll Readings in 2001 †
† Data followed by the same letter are not significantly different according to a Fisher protected LSD (P = 0.05)

Because of the later planting date in 2002, time was more limited and measurements were not taken until later in the season, from September 11th through October 2nd. Hybrids could not be directly compared. The lower populations again had higher chlorophyll readings except for the last day that readings were taken (data not shown). Significant P & K treatment differences were observed only on October 2 (Figure 4).

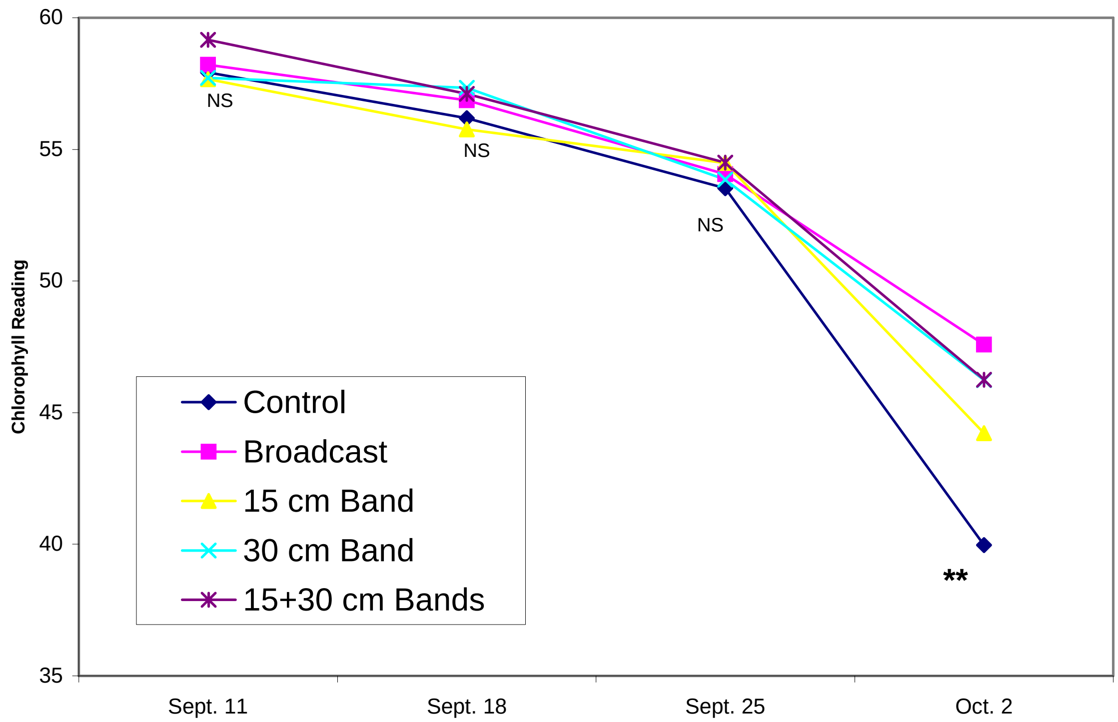


Figure 4. Average Chlorophyll Readings over all Hybrids and Populations in 2002 †
** significant at the 0.01 probability level
NS denotes no significance at $P = 0.05$

For the October 2nd readings, the broadcast treatment again had the highest chlorophyll reading, but it was only significantly higher than the control (Figure 5). For both years, the same pattern is seen at the end of the season where the control drops off more quickly than the other treatments. Other than the starter fertilizer, the control plots had no additions of P or K fertilizers. At the end of the season, lack of nutrient availability may have resulted in the control plot plants' senescing earlier than the treatments with additions of P & K fertilizers before planting.

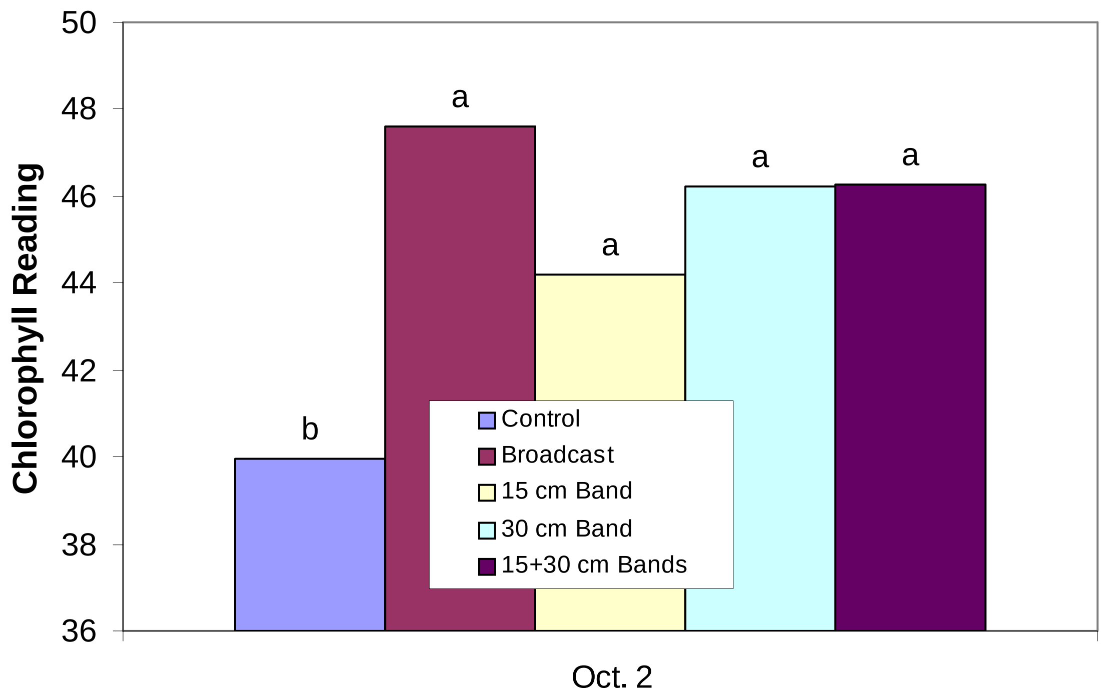


Figure 5. Significant Effects of Fertility Placement on Chlorophyll Readings in 2002 †
† Data followed by the same letter are not significantly different according to a Fishers protected LSD

Grain Yield

In 2001, P & K placement had no significant effect on yield (Table 9). Hybrid and population, however, both had significant ($P < 0.05$) effects on yield. Pioneer 34B24 was higher yielding than Pioneer 34M95. The lower plant population of 79,000 plants ha^{-1} yielded 490-kilograms per hectare more than the higher plant population of 104,000 plants ha^{-1}.

In 2002, both the 30-cm and the 15 + 30-cm P & K banded plots yielded significantly higher than the control (Table 9). Neither the broadcast nor the 15-cm banded treatments yielded more than the control. Yield differences due to population were not significant in 2002. There was, therefore, no yield benefit to planting at the higher population in either year. Furthermore, there were no significant treatment hybrid x fertility, population x fertility, or hybrid by population x fertility interactions for corn yield in either 2001 or 2002 (Table 9).

The fertility placement effect in 2002, but not in 2001, may have been a function of the soil P and K stratification status present before treatment initiation in 2002. In 2001, the soil tests showed rather uniform P and K concentrations through the 20 cm depth (Table 1) because of recent moldboard plowing. The soil test results were more stratified for 2002 (Table 2) because the soil was left undisturbed after soybean harvest in 2001; natural variation between the two sides of the field may also have been a factor. Soil test levels for P and K were similar at the 20-40 cm depth for both years. The later planting date in 2002 may have been an additional factor in the observed fertility placement effects.

Table 9. Hybrid, Population and Fertility Treatment Effects on Grain Yield in 2001 and 2002

	Yield (kg/ha)	
	2001	2002
Pioneer 34B24	13600 a †	12300
Pioneer 34M95	13100 b	12200
79,000 plants ha^{-1}	13600 a	12300
104,000 plants ha^{-1}	13100 b	12200
Control	13200	11900 b
Broadcast	13400	12200 ab
15-cm Band	13300	12300 ab
30-cm Band	13100	12500 a
15 + 30-cm Bands	13500	12400 a
Treatment‡	Significance Level	
Hyb	*	
Pop	*	ns
Fert	ns	*
Hyb x Pop	ns	
Hyb x Fert	ns	
Pop x Fert	ns	ns
Hyb x Pop x Fert	ns	

** significant at 0.01 probability level
* significant at the 0.05 probability level
† Data followed by the same letter within year are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid, Pop = population, and Fert = fertility treatment

Mengel et al. (1988) observed that in southern Indiana, varying pre-plant methods of P placement (including a 20-cm deep band) did not significantly affect corn yields. Likewise, other studies reported no significant corn differences between P and/or K placement methods (Ebelhar & Versal, 1999; Mengel et al., 1988). Other research, however, has detected varying degrees of yield increases to deeper additions of P and/or K fertilizers (Mallarino et al., 1999; Borges & Mallarino, 2001; Mallarino, 2000. Borges

& Mallarino (2001) concluded that deep banding K in ridge-till corn increased efficiency compared to broadcast applications. Some research in Iowa observed no significant yield differences between P placements in corn, but found some small yield advantages to placing K deeper in the soil (Bordoli & Mallarino 1998; Mallarino 2000). Vyn et al. (2002) observed that banding K alone at 15-cm resulted in lower yields than broadcast application in no-till cornfields with low soil-test levels. They also reported that there was no yield benefit to deep banding compared to starter banding (even though the starter rate was 50% lower than the deep-banded rate) in any tillage system. They therefore concluded that surface broadcasting is sufficient even with stratified soils, although starter placement might also be beneficial. However, until the present study, research had not investigated banding depths any deeper than 15-20 cm.

Grain Nutrients

No fertility treatment differences were seen (at the 5% level) among any of the tested nutrients, including percent P and percent K (Tables 10 and 11). The broadcast treatment resulted in significantly greater P and K concentrations than the control at the 10% probability level in 2002.

Table 10. Effect of hybrid, population, and fertility treatments on P concentration in harvested grain

	Grain P (%)	
	2001	2002
Pioneer 34B24	0.37 a †	0.42
Pioneer 34M95	0.33 b	0.38
79,000 plants ha^{-1}	0.36 a	0.40
104,000 plants ha^{-1}	0.34 b	0.40
Control	0.33	0.37
Broadcast	0.34	0.43
15-cm Band	0.37	0.40
30-cm Band	0.35	0.40
15 + 30-cm Bands	0.35	0.40
Treatment‡	Significance Level	
Hyb	**	
Pop	*	ns
Fert	ns	ns
Hyb x Pop	ns	
Hyb x Fert	ns	
Pop x Fert	ns	ns
Hyb x Pop x Fert	ns	

** significant at 0.01 probability level
* significant at the 0.05 probability level
† Data followed by the same letter within year are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid, Pop = population, and Fert = fertility treatment

Table 11. Effect of hybrid, population, and fertility treatments on K concentration in harvested grain

	Grain K (%)	
	2001	2002
Pioneer 34B24	0.45 a †	0.45
Pioneer 34M95	0.41 b	0.41
79,000 plants ha^{-1}	0.44	0.43
104,000 plants ha^{-1}	0.43	0.43
Control	0.42	0.41
Broadcast	0.42	0.46
15-cm Band	0.45	0.43
30-cm Band	0.44	0.44
15 + 30-cm Bands	0.43	0.43
Treatment‡	Significance Level	
Hyb	**	
Pop	ns	ns
Fert	ns	ns
Hyb x Pop	ns	
Hyb x Fert	ns	
Pop x Fert	ns	ns
Hyb x Pop x Fert	ns	

** significant at 0.01 probability level
† Data followed by the same letter within year are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid, Pop = population, and Fert = fertility treatment

In 2001, grain nutrient levels of P and K were higher in Pioneer 34B24 than in Pioneer 34M95 (Tables 10 and 11). In 2002, the hybrid differences followed a similar pattern, but could not be directly compared due to different planting dates.

As with the P and K data, grain nutrient levels of Mg, S, B, and Zn at harvest were higher in Pioneer 34B24 than in Pioneer 34M95 (*P* < 0.01, data not shown). Grain

P concentrations were higher at the low population, which is what we saw for the early whole plant data, although it was not seen in earleaf data.

The placement of P & K was significant only for Mn and Zn concentrations, and these occurred in both years. Manganese levels were always lowest for control treatments. Zinc levels were also low in the control treatments (Table 12). The 15-cm band treatment resulted in the highest Mn and Zn levels in 2001. In 2002, broadcast treatments showed the highest concentration of Mn and Zn. There is no particular explanation for these effects, and – to our knowledge – there are no similar studies reported in the literature. There was a small amount of zinc in the starter fertilizer, but this was put on all fertility treatments, including the control. The small changes in these micronutrient concentrations may not have been enough to be of practical significance for any resulting corn used in livestock rations.

Table 12. Effect of P & K Placement on Mn and Zn levels in grain *†

Treatment	Mn Levels (ppm)		Zn Levels (ppm)	
	2001	2002	2001	2002
Control	6.21 b	6.36 b	26.80 ab	27.28 b
Broadcast	6.29 b	7.52 a	26.00 b	30.98 a
6" Band	7.29 a	6.70 b	29.20 a	27.58 b
12" Band	6.61 ab	7.04 ab	28.28 ab	28.16 b
6+12" Bands	6.33 b	6.91 ab	26.61 ab	28.78 b

* significant at 0.05 probability level
† Data followed by the same letter within year are not significantly different according to a Fisher protected LSD

Summary

The results detailed in this chapter prove that response of corn growth to P and K fertility placement is indeed multi-faceted. Significantly positive or negative corn responses to the placement depth of P and K were seen in some growth and nutrient concentration parameters, but the overall data from the 2-year study does not reveal any obvious trends.

For example, in 2001 we observed an increased shoot weight at the V4 growth stage with the 30-cm depth P and K placement as compared to the broadcast and 15-cm nutrient placement. When looking at only Pioneer 34B24, we saw that both the control and the deep band (30-cm) placement had significantly higher shoot weights than all other fertility treatments. We might expect the early vigor of the 30-cm band treatment to translate into increased leaf area index (LAI) later, but the effect was the opposite. The 15-cm band treatment had a significantly higher LAI at the R1 growth stage as compared to the 30-cm band. These data confirm once again that improved early vigor does not always translate into higher leaf areas later in the season.

The chlorophyll readings also exhibited significant differences with regard to nutrient placement. In 2001, the broadcast treatment had significantly higher chlorophyll readings than did the 30-cm band treatment. In this case, the early advantage in shoot weight for the 30-cm band treatment was not reflected later in the season when the leaves for this treatment senesced faster.

For 2001, the control did not always have the lowest values for any given trait. This was different than would have been predicted. It is possible that the initial soil nutrient concentrations were not low enough (or stratified enough) to show significant differences in the placement of P and K. It is confusing that there were some significant differences in fertility placements, and yet not relative to the control. It is hard to say what placement method is best when looking at the 2001 data because we often did not get any advantage over no fertilizer P or K added (the control) when compared to the treatments with fertilizer. This suggests that neither P nor K was limiting yields. The addition of starter P and K in each treatment may have made any potential treatment differences less evident. Previous research has shown that the use of seed-applied starter (N and P in this case) increased yield even with high soil test levels (Mengel et al., 1988).

For 2002, chlorophyll readings were again highest for the broadcast treatment. As we would expect, the control had the lowest readings. The yield differences seen in 2002, however, did not show the broadcast as being the highest yielding. In this study, superior stay-green did not indicate higher yields. In fact, it was the deep 30-cm band and the combined 15 + 30-cm band treatments that yielded more than the control. The treatments with fertilizer were not significantly different from each other.

We could conclude from the 2002 data that the treatments with P and K fertilizers have an advantage over the control. Looking at the yield data alone, we note that the deep banding had the highest yields, albeit not significantly more than broadcast P and K. It would be advantageous to accumulate more data over more years to see if this trend is significant.

Hybrids often showed differences in nutrient concentration (with whole plants and in grain), leaf area, and yields. The low population resulted in increased grain P concentration, and higher yields in 2001. Higher populations always had higher LAI; this was true for both years and both V6 and R1 growth stages.

However, this increased LAI did not increase yield. This suggests that P and K was not the limiting factor for converting LAI into yield. If starter fertilizer had not been used, it may have been easier to recognize the effects of deep fertilizer placement.

There were not many interactions among hybrid and (or) population treatments with fertilizer placements. Although these initial results suggests that there may be little gain in pursuing further fertilizer P and K placement research by involving multiple hybrids and plant populations, the study also involved just a single location, starter application to every treatment, and less initial soil nutrient stratification than most Indiana farmers encounter.

CHAPTER TWO. CORN ROOT AND SHOOT RESPONSES TO PRE-PLANT BANDING OF P VERSUS K FERTILIZERS

Abstract

In the Midwest, P and K are typically broadcast over the soil surface, but there is increasing interest in strip tillage systems combined with deep banding of nutrients. This is especially the case as conservation tillage becomes more prevalent. Deeper placement is encouraged on the basis that essential nutrients are placed in a more favorable zone for root uptake. However, only limited research information is available on actual root responses to nutrient placement because of the large amount of resources needed to investigate root systems. Evaluation of root system response to the placement of P and K fertilizers either individually, or in combination, may assist the determination of when deep placement of one or both nutrients may be advantageous.

An experiment was initiated in 2001 to look at the corn root and shoot responses to banded P and banded K fertilizer with respect to broadcast and control treatments. The study was grown for two years at different sites. The 2001 site was a low P, medium K testing soil, and the 2002 site was a high P, medium K testing soil.

The two hybrids tested demonstrated significant differences in root systems at the V4-V5 growth stage. Pioneer 34B24 had a higher root area, surface area, diameter, and volume than Pioneer 34M95. The root length, shoot weight and shoot to root ratios of Pioneer 34B24 were also greater than observed with Pioneer 34M95. Hybrid by fertility treatment interactions for both root volume and root area during early growth stages occurred because root volume and area were relatively higher for the broadcast treatment with Pioneer 34M95, but not with Pioneer 34B24.

Root data from both years generally revealed that the broadcast treatment was always as good as, or better than, the banded P plus K placement. Samples taken from the largest diameter category of roots (those greater than 4 mm) showed that the large diameter typically had shorter root lengths, higher volumes and fewer tips. Overall root volume was highest with the broadcast and deep-banded P plus K placement treatments in 2002. Shoot and root weights from 2001 also followed this same trend, with the broadcast having significantly higher weights than all other treatments.

Despite the early season advantages noted with broadcast P plus K, grain yields were never higher with broadcast treatment. In fact, in 2002, the yield from the broadcast treatment was significantly less than that of the band P plus K, the band P alone, and the band K alone treatments. Positive yield responses to banding P alone were even more surprising in 2002 because of the very high soil test P concentrations. Grain nutrient concentrations were not significantly affected by fertility treatments in either year. Although fertility placement treatments affected some root characteristics early in the season, final corn grain yield responses to fertility treatments were either not significant, or were apparently influenced by other unknown factors.

Introduction

Fertilizer rates and placement of nutrients are important factors to consider when crop producers seek to produce maximum yielding corn. Because of the relative immobility of P and K in the soil, it seems that a deeper placement of these nutrients might be beneficial to corn growth in conservation tillage situations. The method of P and K placement has typically been broadcasting over the top of the soil, and that application method plus the annual root and shoot uptake has resulted in significant nutrient stratification when soils are not routinely inverted with conventional tillage systems (Howard et al., 1999; Mackay et al., 1987; Crozier et al., 1999; Robbins and Voss, 1991).

This research was initiated to investigate the effects of deep banding phosphorus and potassium together, and separately, in corn. Evaluating crop growth as it is affected by banded nutrients is essential to understanding crop responses.

Information on root responses to nutrient placement is limited because of the large amount of resources needed to investigate root systems. However, it is a necessary task because root system response to the placement of P and K will determine whether deep placement is advantageous. In addition, the root response to individually banded nutrients might be different than the response of nutrients banded together.

Root and canopy structure are obviously different among hybrids. Costa et al. (2002) observed that root lengths and surface areas were higher with hybrids bearing a leafy trait as compared to a conventional hybrid. Previous research also indicates that hybrid selection influences how the crop responds to added nutrients (Vyn et al., 1999).

It is likely that the crop might also respond to the placement of these nutrients, and to different combinations of nutrients. Root and canopy structure are obviously different when comparing many hybrids.

In Iowa, there have been reports that deep (15-cm) placement of P fertilizer increased early corn growth and P uptake over broadcast placement in some fields (Mallarino et al., 1999; Borges & Mallarino, 2001), but fertilizer placement had no effect on early P concentration in other Corn Belt studies (Mengel et al., 1988; Rehm, 1986).

In one study, deep banding K resulted in increased early growth over the broadcast application (Vyn et al., 2002), but others report broadcast and deep placement (20-cm) had similar early growth patterns (Mengel et al., 1988). Two studies conclude that K uptake by corn usually increases with a deep K band application (Mengel et al., 1988; Borges & Mallarino, 2001). However, more than one study concluded that judging the effects of deep banding by looking at early growth is misleading, especially in soils that are not deficient in available P and exchangeable K (Mallarino et al., 1999; Borges & Mallarino, 2001).

Mid-season corn responses to P and K placement methods have been variable. At 2 weeks before silking, P uptake was higher for broadcast (fertilizer was incorporated) versus 15-cm deep band application (Rehm, 1986). Both Vyn et al. (2002) and Ebelhar & Varsa (1999) found no differences between their K application treatments (banded versus broadcast) for earleaf K concentrations in Ontario and Illinois studies, respectively.

Several studies have reported yield benefits to deeper, banded nutrient placement in corn (Bordoli & Mallarino, 1998; Borges & Mallarino 2001; Mackay et al., 1987; Vyn

& Janovicek, 2001). Yet many other studies have concluded that broadcast is as effective as banding in corn (Bordoli & Mallarino, 1998; Borges & Mallarino, 2000; Borges & Mallarino, 2001; Ebelhar & Varsa 1999; Mallarino et al., 1999; Mengel et al., 1988; Rehm, 1986; Vyn et al., 2002). In some of these studies, yield benefits were seen with a deep-banded K placement, but not with a deep-banded P placement.

Phosphorus placement method seldom influenced corn grain yield in an Iowa study for any tillage system, even with low testing soils (Bordoli & Mallarino, 1998). Deep banding K (at 15-cm) increased corn yields slightly at several sites over the broadcast or planter-band placements (Bordoli & Mallarino, 1998). The yield increase was observed even in soils that tested high for exchangeable K concentration; therefore, low soil-test K status below the soil surface layer was not the sole reason for the response. The reports concluded that weather conditions were likely somewhat responsible for the response to deep placement. This agrees with work done by Borges & Mallarino (2001) who observed a yield advantage to deep (15-20 cm) band K over broadcast, but saw little response to deep-banded P.

Vyn et al. (1999) reported that there were significant yield benefits to deep (15-cm) banding K, particularly in zone-tillage systems, but not in a mulch tillage system. Deep banding K (15-cm) in a zone tillage system also increased corn yields over broadcast placement in conventional tillage and no-till situations (Vyn & Janovicek, 2001). However, in continuous no-till corn with optimal soil moisture, surface broadcasting was found to be as good as deep banding K despite soil exchangeable K stratification, and in some situations deep banding appeared to be detrimental relative to broadcast application (Vyn et al., 2002).

Most research indicates that at high soil test levels, crop yield responses to P and K placement are rare (Randall et al., 2001; Randall & Hoeft, 1988). Research by Vyn & Janovicek (2001) also show that K fertilization only produced higher yields on fields with exchangeable K concentrations of less than 120 mg per kg.

Weather conditions may be a factor in the variable responses to P and K placement methods. Both surface strip and deep banding (15-20 cm) of K have increased yields over broadcast, especially in dry years, where the soil test levels are low, or in conservation tillage systems (Randall & Hoeft, 1988).

Studies have shown that temperature and moisture conditions affect K uptake. Potassium influx, root length increase, and shoot K concentrations were twice as high or more when the temperature went from 15 C to 29 C (Ching & Barber, 1979). In addition, root growth rate and shoot K uptake increase when soil moisture was initially increased (Mackay & Barber, 1985). Potassium uptake is greatly dependent on soil moisture (Sardi & Fulop, 1994; Seiffert et al., 1995) and available K levels (Sardi & Fulop, 1994). Soil moisture has a stronger influence on dry matter production and K accumulation than the exchangeable K concentrations in the soil (Sardi & Fulop, 1994).

Information on root responses to nutrient placement is limited because of the large amount of resources needed to investigate root systems. However, it is a necessary task because root system response to the placement of P and K will determine whether deep placement is advantageous. In addition, the root response to individually banded nutrients might be different than the response of nutrients banded together.

Root and canopy structure are obviously different among hybrids. Costa et al. (2002) observed that root lengths and surface areas were higher with hybrids bearing a leafy trait as compared to a conventional hybrid. Previous research also indicates that hybrid selection influences how the crop responds to added nutrients (Vyn et al., 1999). Perhaps alternate hybrids also respond differentially to the placement of nutrients such as P and K, and to different combinations of nutrients.

Root growth tends to increase when phosphorus is at high levels in the soil, but not in response to high concentrations of potassium (Marschner, 1988). It may, then, be beneficial to place these nutrients together in the band in order to get increased root growth due to the P. More root proliferation would likely increase the root area, thereby allowing a greater uptake of K as well.

An experiment was initiated in 2001 to observe the impacts of banded P and/or K placement on corn development (including roots) and corn yield. Two corn hybrids (Pioneer 34B24 and Pioneer 24M95) were planted in combination with five different treatments of P and/or K including a control (no added fertilizer), broadcast on the soil surface, banded P plus K, banded P alone, and banded K alone. The banded treatments were delivered to a depth of 15 cm.

The objectives of this experiment are to determine the corn root and shoot development and corn yield responses to the banding of phosphorus and potassium, applied both together and separately, and to understand what impact hybrid selection plays in these responses.

Materials & Methods

Site Description

The study was initiated in 2001 at the Purdue Agronomy Center for Research and Education (ACRE) located near West Lafayette, Indiana (40° 28' N Lat., 86° 59' W Lon.). The soil is characterized as a mix of the Toronto-Millbrook complex (fine, silty, mesic Udollic Ochraqualf) and Drummer soils (fine, silty, mesic Typic Haploquoll). The Toronto-Millbrook complex is a somewhat poorly drained, deep soil with 0 to 2 percent slopes and a silt loam texture. Drummer soils are nearly level, very deep, poorly drained soils with a silty clay loam texture. In 2002, the study was moved to a different site at the same research center. The soil at this location is characterized as a Raub-Brenton complex (fine, silty, mesic Aquic Argiudoll). This soil has a 0 to 1 percent slope, and is somewhat poorly drained. It is a deep, silt loam soil.

Field History

The field used in 2001 was in a corn-soybean rotation, with beans planted in 2000. In the early spring of 2001, anhydrous ammonia was injected onto the undisturbed soybean stubble and the soil was then chisel plowed and cultivated prior to planting.

The site used in 2002 was actually two adjacent fields of equal size with slightly different crop histories but approximately similar soil P and K concentrations. One had been in a relay-cropping system (soybeans into wheat) whereas the other had previously been planted to full-season soybeans. These fields were chisel plowed in the fall of 2001, followed by two passes with a field cultivator and a rolling harrow in the spring.

Experimental Design and Treatments

The experiment was designed as a split-plot, randomized complete block. There were five replications in 2001 and six replications in 2002. Two hybrids were randomly assigned to the whole plots, and five fertility treatments were randomly assigned to the split-plots. Hybrids were selected to reflect different genetic parentage. Populations were chosen to represent common plant densities and well above normal populations to reflect what some high yield achievers are planting. In 2001 each split plot was 9.1 m (30’) wide and 22.9 m (75’) long. In 2002, they were again 9.1 m wide, but were only 18.3 m (60’) long. The plot design is described in more detail below.

Main Plots (2 Hybrids):

1. Pioneer 34B24: 110 CRM, Bt
2. Pioneer 34M95: 110 CRM, Bt

Subplots (5 Fertility Treatments):

1. Control: no added P or K other than starter
2. Broadcast P and K: applied on the surface and lightly incorporated
3. Band P and K: applied at a 15 cm (6-inch) depth
4. Band P: applied at a 15 cm (6-inch) depth
5. Band K: applied at a 15 cm (6-inch) depth

The rates of P and K for all treatments, excluding the control, were 99 kg ha^{-1} P_2O_5 (88 pounds) and 129 kg ha^{-1} K_2O (115 pounds). Phosphorous fertilizer was applied as 0-46-0 and K was applied as muriate of potash (0-0-60). All banded treatments were applied in the spring with a Gandy system attached to a DMI Nutriplacr 2500. The latter system included "mole knife" shanks operated to a depth of 20 cm on all plots (whether they received banded fertilizer or not).

Crop Management

Corn was planted in 76.2 cm (30-inch) rows directly over the fertilizer bands. The planting rate was 83,000 plants ha^{-1} in an attempt to achieve a final population of 79,000 plants ha^{-1} (32,000 plants per acre). All treatments, including the control, had a uniform starter fertilizer application of 9-18-9 plus zinc. In 2001, the starter rate was 20 gallons per acre); in 2002, it was reduced to 12 gallons per acre). In 2001, the plots were planted on the 7^{th} of May. In 2002, corn was not planted until June 11 and June 17 due to higher than normal spring rainfalls (see Chapter 2, Figure 1). The two planting dates for 2002 were due to a large storm system that arrived while planting. All of hybrid 34B24 was planted on the June 11^{th} date and the hybrid 34M95 was planted on the June 17^{th} date.

Nitrogen was applied as a split application in both years. Excluding the starter, a total of 310 kg N ha^{-1} (280 pounds per acre) was applied in 2001. Part of this was applied in early spring as anhydrous ammonia, and the rest was side-dressed with urea ammonium nitrate (UAN). In 2002, the rate was decreased to a total of 280 kg N ha^{-1}

(250 pounds per acre) due to the delayed planting and lower yield expectations. This was split into two UAN applications that were side-dressed during the growing season.

During the season, weed and insect control actions were taken as necessary. In May 2001, Harness Extra (acetachlor and atrazine) and Atrazine 4L were applied at 4.38 and 1.46 liters ha^{-1} (3.75 and 1.25 pints per acre), respectively. In mid-June of that year, 53 g ha^{-1} (0.76 ounces per acre) Beacon (primisulfuron-methyl) was applied. Due to Japanese Beetle and Western Corn Rootworm problems, Warrior (λ-cyhalothrin) was aerially applied at 270 g ha^{-1} (3.8 ounces per acre) in June and again in July.

In 2002, Dual II Magnum (S-metolachlor) and Atrazine 4L were used in June at 2.3 and 2.9 liters ha^{-1} (2 and 2.5 pints per acre). Later in June, Beacon (primisulfuron-methyl) was applied at 53 g ha^{-1} (0.76 ounces per acre).

Soil Measurements

Soil samples were taken before any treatments were applied. All plots were sampled by bulking 10 soil cores per plot. These were sub-divided into three depth-intervals: 0-10, 10-20 and 20-40 cm (0-4, 4-8, and 8-16 inches). All samples were sent to an independent testing lab and analyzed for organic matter, available P (using Mehlich 3), exchangeable K, Mg, soil pH, buffer pH, cation exchange capacity (CEC), percent base saturation for K, Mg, Ca, and H. A brief summary of these results is shown in Tables 13 and 14.

Table 13. Summary of Soil Test Results for 2001*

	OM	**P1**	**K**	**Mg**	**CEC**
cm	%	ppm	ppm	ppm	meq/100g
0-10	3.9	15.3	151	576	16.6
10-20	3.6	15.3	71	540	17.8
20-40	3.2	5.3	67	529	17.1

* Extractions: Loss on Ignition (LOI) used for OM, Mehlich 3 used for P

Table 14. Summary of Soil Test Results for 2002*

	OM	**P1**	**K**	**Mg**	**CEC**
cm	%	ppm	ppm	ppm	meq/100g
0-10	4.7	95	139	794	22.3
10-20	4.3	73	115	801	21.7
20-40	3.4	32	89	782	21.0

* Extractions: Loss on Ignition (LOI) used for OM, Mehlich 3 used for P

Plant Measurements

This study focuses on plant root responses to alternative P and K placements. Whole roots and shoots were taken at the V4 growth stage (all growth stages taken using Leaf Collar method). Five complete root systems per plot were dug and the roots washed. The shoots were dried and weighed to determine shoot weights as well as to calculate the shoot to root ratio. They were then ground and analyzed for P and K content.

In 2001, a modified wet ash procedure (Wolf 1982) was used for K determination. Sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) were combined with the ground plant material and digested on a heating block. These were analyzed with a Varian 400 atomic absorption spectrophotometer. Digestion for P analysis was done using a combination of potassium sulfate and copper sulfate (K_2SO_4 & $CuSO_4$) as well as sulfuric acid (H_2SO_4). These samples were analyzed using a Lachat FIA 8000. In 2002, due to time constraints, samples were sent to an independent laboratory where they were analyzed for N, P, K, Ca, Mg, S, B, Fe, Mn, Cu, Zn, and Al.

Root systems were washed and then stored in ethanol until morphometric analysis. During this study, the complete root systems of corn at the V4 / V5 stage were excavated and cleaned. They were then stored in ethanol until morphometric analysis. This was done using WIN Rhizo software, an image analysis system (Regent Instruments, Quebec, Canada). Length, volume, surface area, and number of tips were automatically calculated from the scanned image. The root systems were analyzed for many parameters and then divided into 5 diameter classes for further analysis. After analysis, the roots were dried and weighed.

Soil cores of 2.5 cm (1 inch) diameter were taken at the V10 growth stage for partial-system root analyses later in the vegetative development period. Five samples were taken within the row and five separate samples were taken between the rows of corn. Each of these samples was divided into three depths: 0-10, 10-20 and 20-40 cm (0-4, 4-8, and 8-16 inches). They were then washed and analyzed using the same WIN Rhizo software with which the whole roots were analyzed.

In 2001, plant height was measured at the V6 stage by measuring from the soil surface to the tallest leaf when extended.

To observe the leaf senescence rate for the treatments, chlorophyll meter readings were taken on a bi-weekly basis. These were taken on 30 (2001) and 20 (2002) random ear leaves per plot. The readings were taken approximately halfway between the tip and the leaf sheath with a Minolta SPAD 502 chlorophyll meter (Minolta Co., Osaka, Japan).

Corn grain yield was evaluated by hand harvesting two 8 m (26 feet) lengths of row per plot. Final plant populations were also counted in each of these areas. Grain moisture was determined using a Farmex MT3 (Farmex Electronics Corp., Streetsboro, Ohio) moisture meter. The yields were adjusted to 15.5 % moisture content. In 2001, harvest occurred on October 30th. Due to a later planting date, harvest did not occur until November 21st in 2002. Grain sub-samples from each plot was sent to an independent lab and analyzed for N, P, K, Mg, S, B, Fe, Mn, Cu, Zn, Al.

Statistical Analysis

Statistical analyses were completed using Statistical Analysis Software (SAS) version 8.2 (SAS Institute, Inc., Cary, North Carolina). Simple statistics (means, standard deviations, minimums and maximums) were calculated for each parameter. To determine the need for transformations, a Box-Cox analysis was performed.

Fisher protected LSD values ($P < 0.05$) were used for mean separation tests except where noted. In 2002, hybrids could not be compared due to a difference in the planting dates.

Results & Discussion

V4 Whole Root Analysis

Root systems are an integral part of corn developmental responses to management systems. Corn root growth and the corresponding nutrient uptake are influenced by genotype and by nutrient applications (Costa et al., 2002; Seiffert et al., 1995), as well as by soil structure (Barber, 1971). Weather also plays an important role in root development and nutrient uptake (Ching & Barber, 1971; Mackay & Barber, 1985).

In our study, corn hybrid differences were apparent for root area in 2001 (Tables 15-17). No significant differences among fertility or hybrid treatments were found for root length measurements (Table 15). In 2002, hybrid root characteristics could not be statistically compared due to different planting dates. At the V4 growth stage, root area, surface area, diameter, volume, number of tips and number of forks all showed Pioneer hybrid 34B24 to have higher values than 34M95 in 2001 (Tables 15-17). It is interesting that in the accompanying study in 2001, Pioneer 34B24 was also the hybrid with higher leaf area indices than Pioneer 34M95 at both the V-6 and R-1 stages (Table 3).

The lack of differences between root lengths in hybrids is similar to a previous study (Costa et al., 2002). In addition, prior research had shown that hybrids differed in their surface area (Schenk & Barber, 1980), which we saw in this study as well (Table 15). However, Schenk and Barber (1980) did not observe root radius differences and in this study, the genotypes were significantly different for root diameter (Table 16). Schenk and Barber (1980) noted that one hybrid had the most roots in the topsoil, where the P and K levels were highest. In this study, there was no interaction between hybrid and fertilizer placement for any of the root parameters that were measured.

Table 15. Effects of Hybrid and Fertility Treatment on Total Root Length, Area and Surface Area at the V4 to V5 Growth Stage †

	Root Length (cm)		Root Area (cm^2)		Surface Area (cm^2)	
	2001	2002	2001	2002	2001	2002
Pioneer 34B24	324	429	37.0 a	66.3	116 a	208
Pioneer 34M95	296	491	32.6 b	87.2	102 b	274
Control	303	448	33.3	74.4	105	234
Broadcast	312	441	36.3	77.5	114	243
15 cm P&K	311	473	34.7	80.7	109	254
15 cm Band P	309	472	34.5	73.2	108	230
15 cm Band K	314	468	35.3	77.9	111	245
Treatment‡	Significance Level		Significance Level		Significance Level	
Hyb	ns	ns	*	ns	*	ns
Fert	ns	ns	ns	ns	ns	ns
Hyb x Fert	ns	ns	ns	ns	ns	ns

* significant at the 0.05 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid and Fert = fertility treatment

In 2002, a significant increase in root volume at the V5 growth stage was detected when P and K fertilizers were broadcast or placed at a 15 cm depth as compared to having only a banded P application (Table 16). In addition, the control, where no P or K was added, and the banded K-alone treatments were not significantly different from any other treatment. Because the control was also not statistically different from any of the fertilized treatments, this could indicate that the balance of P and K in the band appears to be important for root volume (Table 16) although not as important for root surface area

(Table 15). One factor that should be acknowledged is that the V-stage of the corn was also one growth stage larger for 2002 than 2001.

Soil available P was very high for the 2002 site, and therefore no dramatic response in root proliferation (area or root length density) was expected in response to the addition of more P. For root characteristics measured on a physical basis (Tables 15-17), it appears that neither P nor K fertilizer treatments had much influence at this growth stage.

Table 16. Effects of Hybrid and Fertility Treatment on Root Diameter, Root Length per Volume, and Root Volume at the V4 to V5 Growth Stage †

	Root Diameter (mm)		Root Len/Vol (cm/m^3)		Root Volume (cm^3)	
	2001	2002	2001	2002	2001	2002
Pioneer 34B24	1.15 a	1.62	324	429	3.4 a	8.7
Pioneer 34M95	1.11 b	1.84	296	491	2.9 b	12.9
Control	1.11	1.73	303	448	2.9	10.4 ab
Broadcast	1.17	1.81	312	441	3.4	11.5 a
15 cm P&K	1.12	1.78	311	473	3.1	11.7 a
15 cm Band P	1.12	1.59	309	472	3.1	9.6 b
15 cm Band K	1.13	1.74	314	468	3.2	11.1 ab
Treatment‡	Significance Level		Significance Level		Significance Level	
Hyb	*	-	ns	-	*	-
Fert	ns	ns	ns	ns	ns	*
Hyb x Fert	ns	-	ns	-	ns	-

* significant at the 0.05 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid and Fert = fertility treatment

The numbers of root tips, forks and crossings showed no statistical differences among fertility treatments (Table 17). In 2001, Pioneer 34B24 had a significantly higher number of root forks and tips than Pioneer 34M95.

Table 17. Effects of Hybrid and Fertility Treatment on the Number of Root Tips, Forks, and Crossings at the V4 to V5 Growth Stage †

	Root Tips		Root Forks		Root Crossings	
	2001	2002	2001	2002	2001	2002
Pioneer 34B24	376 a	1193	1361 a	2490	104	148
Pioneer 34M95	316 b	1184	1031 b	3017	80	141
Control	341	1302	1160	2775	90	155
Broadcast	335	993	1202	2535	91	118
15 cm P&K	347	1174	1199	2906	93	148
15 cm Band P	341	1267	1146	2727	90	155
15 cm Band K	365	1207	1273	2824	96	147
Treatment‡	Significance Level		Significance Level		Significance Level	
Hyb	*	-	*	-	ns	-
Fert	ns	ns	ns	ns	ns	ns
Hyb x Fert	ns	-	ns	-	ns	-

* significant at the 0.05 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid and Fert = fertility treatment

Whole Root Analysis Within Diameter Class

The root diameters were divided into 5 categories and analyzed: less than 1 mm, 1 to 2 mm, 2 to3 mm, 3 to 4 mm, and greater than 4 mm. Corn roots within specific diameter classes were compared against each other to identify differences in the total length, area, volume and number of tips per diameter class.

The root masses were somewhat larger in 2002, due to their excavation at a slightly later developmental stage (V5 in 2002 versus V4 in 2001) as well as differences in weather patterns between years. For many of the root characteristics, however, the response patterns were similar.

In both years, root diameter class made a very significant difference ($P < 0.01$) in the length, area, volume and number of tips (Tables 18, 21, 23, and 27). The two hybrids responded differently with respect to root length, area and volume in 2001, but could not be compared in 2002. However, overall fertility treatment differences (without interactions) were not significant in either year.

Previous research has observed that the finest class of roots represents the majority of the measured roots (Costa et al., 2002). This was also the case in this study. As seen in Table 18, well over half of the length of the root system was due to roots of less than 1mm in diameter.

When comparing all hybrids and fertility treatments, the class of roots with a diameter of less than 1 mm diameter had the longest total root length. This pattern was similar for both years over all hybrid and fertilizer treatments (Table 18). Data from 2002 show that the 3 to 4 mm diameter class actually had the lowest total length ($P < 0.01$), whereas 2001 data showed a very linear trend of increasing root diameter coincident with decreasing total length of the root system. This may have been due to the later sampling stage in 2002 when nodal roots began to develop. Table 19 shows the fertility treatment by root diameter interaction. In the 15 cm band P treatment with the largest root diameter class, root length was not significantly higher for the diameter class above 4 mm relative to the 3-4 mm diameter class as it had been for all other fertility treatments.

Table 18. Length (as log transform) of Roots as affected by Hybrid, Fertilizer Treatment, and Diameter Class at Growth Stage V4-V5

	Log Length † ‡	
	2001	2002
Pioneer 34B24	1.52 (65) a	1.73 (86)
Pioneer 34M95	1.44 (59) b	1.84 (98)
Control	1.47 (61)	1.77 (90)
Broadcast	1.50 (62)	1.78 (88)
15 cm P & K	1.48 (62)	1.80 (95)
15 cm Band P	1.48 (62)	1.77 (94)
15 cm Band K	1.48 (63)	1.79 (93)
< 1 mm	2.27 (199) a	2.37 (254) a
1 to 2 mm	1.78 (62) b	1.94 (91) b
2 to 3 mm	1.39 (26) c	1.63 (45) c
3 to 4 mm	1.05 (13) d	1.41 (27) d
> 4 mm	0.92 (10) e	1.57 (43) c
Treatment §	Significance Level	
Hyb	*	-
Fert	ns	ns
Diam	**	**
Hyb x Fert	ns	-
Hyb x Diam	**	-
Fert x Diam	ns	*
Hyb x Fert x Diam	ns	-

* significant at 0.05 probability level
** significant at 0.01 probability level
† Data followed by the same letter are not significantly different within year according to a Fisher's protected LSD
‡ Numbers in parentheses are back-transformed data (given in cm)
§ Hyb = hybrid, Fert = fertilizer treatment, and Diam = diameter

Table 19. Root Length within Diameter Class and Fertility Treatment in 2002 at Growth Stage V5

P & K Treatment	Diameter Class † ‡				
	< 1 mm	1 to 2 mm	2 to 3 mm	3 to 4 mm	> 4 mm
Control	2.35 (249)a A	1.92 (87)a B	1.60 (42)a C	1.40 (27)a D	1.58 (44)a C
Broadcast P & K	2.34 (236)a A	1.92 (88)a B	1.63 (45)a C	1.40 (27)a D	1.59 (45)a C
15 cm P & K	2.37 (257)a A	1.97 (97)a B	1.64 (47)a C	1.42 (28)a D	1.59 (45)a C
15 cm Band P	2.40 (268)a A	1.94 (91)a B	1.62 (45)a C	1.39 (27)a D	1.52 (40)a CD
15 cm Band K	2.38 (258)a A	1.95 (92)a B	1.64 (44)a C	1.42 (28)a D	1.56 (42)a C

† Data followed by the same lower case letter are not significantly different than others within that column. Data followed by the same uppercase letter are not significantly different within that row according to a Fisher's protected LSD

‡ Numbers in parentheses are back-transformed data (given in cm)

Hybrid differences were significant ($P < 0.05$) for root length, area, and volume in 2001 (Table 20). Pioneer 34B24 had longer root lengths, larger areas and higher volumes than Pioneer 34M95. Table 20 shows that it was in the larger diameter classes (> 2 mm) that Pioneer 34B24 surpassed Pioneer 34M95 in length, area and volume. Hybrids could not be compared in 2002 due to a difference in planting date.

Table 20. Effect of Hybrid and Root Diameter Class on Log Length, Area, and Log Volume of Roots in 2001 at Growth Stage V4

	Hybrid	Diameter Class ** † ‡				
		< 1 mm	1 to 2 mm	2 to 3 mm	3 to 4 mm	> 4 mm
Length	34B24	207 A	64 B	28 a C	14 a D	11 a E
	34M95	191 A	60 B	25 b C	12 b D	9 b E
Area	34B24	25.3 B	30.6 A	23.4 a C	16.3 a E	20.8 a D
	34M95	24.6 B	28.6 A	20.3 b C	13.5 b E	15.6 b D
Volume	34B24	158 D	529 C	676 a B	661 a B	1355 a A
	34M95	161 D	518 C	611 b B	571 b C	1013 b A

** significant at 0.01 probability level

† Data followed by the same lower case letter within a column are not significantly different than others within that column. Data followed by the same uppercase letter are not significantly different within that row according to a Fisher's protected LSD

‡ Numbers for length and volume are back-transformed data with length given in cm, area given in cm^2, and volume in mm^3

The effect of diameter class on the root area was very significant ($P < 0.01$) in both years, but the pattern was not consistent (Table 21). In 2001, the 1 to 2 mm diameter class had the largest root area, while in 2002, the > 4 mm diameter class had the largest root area. Presumably this was a function of sampling at a later stage of development, and a reflection of the overall increase in surface area in 2002. This could have been due to the influence of nodal roots that had begun to develop by this later growth stage. Fertility treatments had no significant effect on total root area in either year.

Table 21. Area of roots as affected by Hybrid, Fertilizer Treatment, and Diameter Class at Growth Stage V4-V5

	Area (cm^2) †	
	2001	2002
Pioneer 34B24	23.3 a	41.7
Pioneer 34M95	20.5 b	54.5
Control	21.0	46.8
Broadcast	22.8	48.7
15 cm P & K	21.8	50.8
15 cm Band P	21.7	46.0
15 cm Band K	22.2	48.1
< 1 mm	24.9 b	33.2 b
1 to 2 mm	29.6 a	45.5 b
2 to 3 mm	21.8 c	38.7 b
3 to 4 mm	14.9 e	33.8 b
> 4 mm	18.2 d	89.2 a
Treatment‡	Significance Level	
Hyb	*	-
Fert	ns	ns
Diam	**	**
Hyb x Fert	ns	-
Hyb x Diam	**	-
Fert x Diam	ns	*
Hyb x Fert x Diam	**	-

* significant at 0.05 probability level
** significant at 0.01 probability level
† Data followed by the same letter are not significantly different within a column according to a Fisher's protected LSD (P = 0.05)
‡ Hyb = hybrid, Fert = fertilizer treatment, and Diam = diameter

For Pioneer 34M95 data, the broadcast treatment had a significantly higher root area than all other treatments in the largest diameter class (Table 22). The control had the lowest root area, but it was not statistically lower than any of the banded treatments.

Table 22. Effect of Hybrid, Root Diameter and Fertilizer Treatment on Root Area in 2001 at Growth Stage V4

Hybrid	P&K Treatment	Diameter Class * † ‡				
		< 1 mm	1 to 2 mm	2 to 3 mm	3 to 4 mm	> 4 mm
34B24	Control	25.8 B	30.7 A	23.1 B	16.1 D	19.9 C
	Broadcast P&K	24.6 B	30.4 A	23.6 B	16.1 D	19.1 C
	15 cm P & K	25.8 B	31.7 A	24.4 BC	17.2 D	22.8 C
	15 cm Band P	25.0 B	29.8 A	22.8 B	15.1 D	19.6 C
	15 cm Band K	25.2 B	30.6 A	23 BC	16.8 D	22.3 C
34M95	Control	23.2 B	27.4 A	18.5 C	12.4 D	12.5 b D
	Broadcast P&K	24.5 B	29.2 A	23.1 B	15.4 C	21.9 a B
	15 cm P & K	24.6 B	27.3 A	18.7 C	12.3 D	13.3 b D
	15 cm Band P	24.9 B	29.0 A	21.1 C	14.2 D	15.0 b D
	15 cm Band K	25.5 B	29.9 A	20.2 C	13.2 D	15.1 b D

** significant at 0.01 probability level

† Data followed by the same lower case letter are not significantly different than others within that column. Data followed by the same uppercase letter are not significantly different within that row according to a Fisher's protected LSD

The highest total root volumes were found in the largest diameter class for both years (Table 23). The smallest diameter class had the least amount of volume in the roots. This is the opposite relationship that root length had with the diameter class. Although the largest root diameters had the least total length, their volumes were still the highest. The large diameter of the roots more than made up for their lack of length when calculating volumes. The small diameter roots likely include root hairs and the largest diameter roots likely include nodal roots. In 2001, Pioneer 34B24 had a significantly larger root volume than Pioneer 34M95. No hybrid comparisons were possible in 2002 due to the difference in planting dates.

Table 23. Mean Root Volume (as Log Transform) as affected by Hybrid, Fertilizer Treatment, and Diameter Class at Growth Stage V4-V5

	Log Volume † ‡	
	2001	2002
Pioneer 34B24	2.71 (676) a	2.96 (1745)
Pioneer 34M95	2.65 (575) b	3.11 (2571)
Control	2.67 (586)	3.02 (2071)
Broadcast	2.71 (674)	3.04 (2292)
15 cm P & K	2.68 (621)	3.06 (2336)
15 cm Band P	2.68 (613)	3.00 (1918)
15 cm Band K	2.69 (634)	3.04 (2173)
< 1 mm	2.19 (160) c	2.34 (228) d
1 to 2 mm	2.71 (524) b	2.90 (833) c
2 to 3 mm	2.78 (644) b	3.05 (1205) b
3 to 4 mm	2.74 (616) b	3.13 (1495) b
> 4 mm	3.00 (1184) a	3.75 (7029) a
Treatment §	Significance Level	
Hyb	*	-
Fert	ns	ns
Diam	**	**
Hyb x Fert	ns	-
Hyb x Diam	**	-
Fert x Diam	ns	*
Hyb x Fert x Diam	*	-

* significant at 0.05 probability level
** significant at 0.01 probability level
† Data followed by the same letter are not significantly different within year according to a Fisher's protected LSD
‡ Numbers in parentheses are back-transformed data (given in mm^3)
§ Hyb = hybrid, Fert = fertilizer treatment, and Diam = diameter

Similar to the earlier whole root area data, when hybrids were compared separately in 2001, 34M95 had increased root volume when P and K were broadcast versus banded or no added fertilizer (Table 24). This indicates that hybrid does play an important factor in root morphology, and therefore hybrids may respond differently to the placement of P and K. The treatments with P or K banded alone were statistically similar to the banded P & K together, as well as the control. It was unexpected that the band P and band K alone treatments did just as well as the band of P and K together, especially in 2001, when the soil-test P values were not as high. This may have been due to the uniform starter band applied to all treatments.

Table 24. Effects of Hybrid, Root Diameter and Fertilizer Treatment on Root Volume in 2001 at Growth Stage V4

Hybrid	P & K Treatment	Diameter Class * † ‡				
		< 1 mm	1 to 2 mm	2 to 3 mm	3 to 4 mm	> 4 mm
34B24	Control	161 D	522 C	666 B	654 B	1299 A
	Broadcast P & K	156 D	538 C	700 B	668 B	1278 A
	15 cm P & K	161 D	544 C	700 B	692 B	1498 A
	15 cm Band P	156 D	514 C	657 B	611 BC	1259 A
	15 cm Band K	156 D	528 C	659 B	679 B	1442 A
34M95	Control	155 C	497 B	557 B	527 B	819 b A
	Broadcast P & K	156 D	530 C	686 B	642 BC	1387 a A
	15 cm P & K	163 C	492 B	567 B	520 B	868 b A
	15 cm Band P	165 C	529 B	640 B	607 B	989 b A
	15 cm Band K	168 C	542 B	605 B	559 B	1002 b A

* significant at 0.05 probability level

† Data followed by the same lower case letter are not significantly different than others within that column. Data followed by the same uppercase letter are not significantly different within that row according to a Fisher's protected LSD

‡ Numbers are back-transformed data only (given in mm^3)

Table 25. Effect of Fertilizer Treatment on Root Area (cm^2) by Diameter Class in 2002 at Growth Stage V5

P & K Treatment	Diameter Class * † ‡				
	< 1 mm	1 to 2 mm	2 to 3 mm	3 to 4 mm	> 4 mm
Control	32.0 B	43.0 B	36.4 B	32.9 B	89.6 ab A
Broadcast P & K	31.9 B	44.0 B	38.9 B	33.6 B	95.0 a A
15 cm P & K	34.5 B	48.7 B	41.0 B	35.3 B	94.5 ab A
15 cm Band P	33.7 B	45.0 B	38.3 B	33.2 B	79.8 b A
15 cm Band K	33.7 B	46.8 B	38.9 B	34.3 B	87.0 b A

* significant at 0.05 probability level
† Data followed by the same lower case letter are not significantly different than within that diameter class and data followed by the same uppercase letter are not significantly different within that fertility treatment according to a Fisher's protected LSD
‡ Numbers in parentheses are back-transformed data (given in cm)

In 2002 among the largest diameter class (> 4 mm), the fertilizer treatments with P alone or K alone had the lowest values for root areas and volumes, even relative to the control (Tables 25 and 26). Highest root volumes in this largest diameter class occurred with the broadcast P and K treatment. These results suggest that placing the phosphorus and potassium together will result in a larger root mass than using only one of these two nutrients. However, the largest diameter class of roots is likely the nodal root system, which does not play a large role in nutrient uptake.

In the 2001 data, the P alone and K alone treatments performed as well as the combined banded treatment. It might have been expected to see the benefit of banding both nutrients together in a site where the soil-test values were low. We cannot explain why this occurred in 2002, although we note that the planting date was much later in 2002, and weather factors may have affected the response to combined P and K fertilizers versus either alone. In addition, the diameter class of >4 mm would likely not have a high impact on nutrient uptake, because these roots are likely nodal roots. In the smaller diameter classes where more nutrient uptake would occur (partially due to root hairs) (Barber, 1985), there were no differences among fertility treatments.

It was surprising to see that in 2002 the control, with no added P or K, had just as much root area and root volume as the broadcast and the banded P and K treatments (Tables 25 and 26). However, the original levels of soil-test P in 2002 were extremely high (see Table 14).

Table 26. Effect of Fertilizer Treatment on Log Volume of Roots in 2002 at Growth Stage V5

P & K Treatment	Diameter Class * † ‡				
	< 1 mm	1 to 2 mm	2 to 3 mm	3 to 4 mm	> 4 mm
Control	2.32 (216) D	2.87 (773) C	3.02 (1107) B	3.12 (1422) B	3.75 (6838) ab A
Broadcast P & K	2.33 (225) D	2.89 (816) C	3.06 (1225) B	3.14 (1498) B	3.79 (7695) a A
15 cm P & K	2.36 (244) D	2.94 (906) C	3.08 (1299) B	3.15 (1584) B	3.79 (7647) a A
15 cm Band P	2.33 (222) D	2.88 (793) C	3.02 (1147) B	3.09 (1416) B	3.67 (6012) b A
15 cm Band K	2.35 (235) D	2.92 (876) C	3.06 (1246) B	3.15 (1555) B	3.74 (6954) b A

* significant at 0.05 probability level

† Data followed by the same lower case letter are not significantly different than within that diameter class and data followed by the same uppercase letter are not significantly different within that fertility treatment according to a Fisher's protected LSD

‡ Numbers in parentheses are back-transformed data (given in cm^3)

As anticipated, values for number of tips within a diameter class showed that the smallest diameter roots had the highest number of tips (Table 27). This was also the diameter class with the longest lengths (Table 18). It is important to note that the number of tips measurement can count broken roots as tips; measured numbers may be higher than actual in the undisturbed soil environment.

The P alone band did not increase root growth. Previous research observed that root growth tends to increase when phosphorus is at high levels in the soil (Marschner, 1988). The root characteristics for banded P alone and banded K alone were very similar.

Root cores were also taken for the same treatments at the V10 growth stage in both years. The summarized, but unanalyzed, data can be seen in Appendix A.

Table 27. Number of Tips (as Log transform) as Affected by Root Diameter at Growth Stage V4-V5

	Log Tips † ‡	
	2001	2002
Pioneer 34B24	0.98 (75)	1.29 (239)
Pioneer 34M95	0.95 (63)	1.34 (242)
Control	0.95 (68)	1.32 (260)
Broadcast	0.97 (67)	1.30 (199)
15 cm P & K	0.96 (69)	1.32 (233)
15 cm Band P	0.97 (68)	1.31 (253)
15 cm Band K	0.98 (73)	1.32 (257)
< 1 mm	2.48 (325) a	2.91 (1156) a
1 to 2 mm	1.13 (14) b	1.41 (27) b
2 to 3 mm	0.61 (4) c	0.93 (9) c
3 to 4 mm	0.33 (2) d	0.65 (4) d
> 4 mm	0.27 (1) e	0.68 (5) d
Treatment §	Significance Level	
Hyb	ns	-
Fert	ns	ns
Diam	**	**
Hyb x Fert	ns	-
Hyb x Diam	ns	-
Fert x Diam	ns	ns
Hyb x Fert x Diam	**	-

** significant at 0.01 probability level

† Data followed by the same letter are not significantly different within year according to a Fisher's protected LSD

‡ Numbers in parentheses are back-transformed data

§ Hyb = hybrid, Fert = fertility treatment, and Diam = diameter

The root attributes discussed do not show conclusive evidence that any specific nutrient placement approach was superior. However, the broadcast placement of both P and K was more likely to enhance root area or volume than other treatments. Responses to fertility placement might have been more dramatic if no starter had been used in the study. Previous research has shown that roots placed near P bands tend to increase root growth in that specific area of the soil, while K bands do not promote more extensive root growth (Barber, 1985). In our study, we did not see any differences in root response to P versus K banded alone.

V4 Shoot & Root Data

In both 2001 and 2002, shoot weights at the V4-V5 growth stage were largest when P and K fertilizers were applied using the broadcast method of placement (Table 28). In 2001, this was a significant response relative to all other placement methods. In 2002, the broadcast treatment increased shoot weight significantly only relative to the banded P alone. In addition, Pioneer 34B24 resulted in significantly higher shoot weights when compared to Pioneer 34M95 in 2001. Hybrids could not be compared in 2002.

Table 28. Effect of Hybrid and Fertility Treatment on Shoot Weight at the V4-V5 Growth Stage †

	Shoot Weight (g/plant)	
	2001	2002
Pioneer 34B24	2.3 a	4.3
Pioneer 34M95	1.6 b	3.0
Control	1.9 b	3.7 ab
Broadcast	2.2 a	3.9 a
15 cm P&K	1.8 b	3.6 ab
15 cm Band P	1.9 b	3.4 b
15 cm Band K	1.8 b	3.7 ab
Treatment‡	Significance Level	
Hyb	**	-
Fert	*	*
Hyb x Fert	ns	ns

** significant at the 0.01 probability level
* significant at the 0.05 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid and Fert = fertility treatment

Root weights were taken at the same time as shoot weights. In 2001, the root weight data showed a similar pattern to the shoot weight data (Table 29) in that broadcast placement resulted in a higher root weight than all other treatments. In 2002, however, fertility placement results were not significant despite the fact that shoot weights were also higher that year with the broadcast treatment.

Table 29. Root Weight as Affected by Hybrid and Fertility Treatments at the V4-V5 Growth Stage †

	Root Weight (g/plant)	
	2001	2002
Pioneer 34B24	0.40	1.01
Pioneer 34M95	0.36	1.31
Control	0.37 b	1.13
Broadcast	0.43 a	1.19
15 cm P&K	0.36 b	1.25
15 cm Band P	0.36 b	1.07
15 cm Band K	0.36 b	1.14
Treatment‡	Significance Level	
Hyb	ns	-
Fert	*	ns
Hyb x Fert	ns	ns

* significant at the 0.05 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid and Fert = fertility treatment

Although fertility differences were observed in both shoot weights and root weights, the ratio of shoot to root weights were never significantly affected by fertility treatments (Table 31). Hybrids were different in shoot/root ratio in 2001 (Table 31).

Table 30. Effect of Hybrid and Fertility Treatments on Shoot-to-Root Ratio at the V4-V5 Growth Stage †

	Shoot:Root Ratio	
	2001	2002
Pioneer 34B24	5.7 a	5.2
Pioneer 34M95	4.7 b	2.2
Control	5.5	3.6
Broadcast	5.3	3.9
15 cm P&K	5.0	3.4
15 cm Band P	5.3	4.0
15 cm Band K	4.9	3.7
Treatment‡	Significance Level	
Hyb	*	-
Fert	ns	ns
Hyb x Fert	ns	ns

* significant at the 0.05 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid and Fert = fertility treatment

V4-V5 Nutrient Analysis

Analysis of P and K concentrations were completed at the V4-V5 growth stage in both years. Levels of P in the shoots did not show any significant differences for either hybrid or fertility treatments in either year (Table 31). In 2002, however, K levels were significantly different depending on the fertility treatment. Banded P and K combined and banded K alone resulted in the highest percentage of K in the plant tissue. These treatments showed a statistically significant (P=0.05) advantage over the P alone band and the control, which were the treatments with no additional K.

As previously stated, there is greater expectation of a benefit to added fertilizer when soil test levels are low. However, the 2001 season (with lower soil available P) did not show significant shoot K concentration differences with respect to fertility treatments, while the 2002 season did (very high available P, see Tables 13 and14). Corn shoot nutrient concentration differences in response to fertility treatments may have been masked by the environment or weather patterns influencing crop growth and nutrient uptake. Indeed, soil-test P and K concentrations were above the accepted critical levels in both years.

Table 31. Effects of Hybrid and Fertility Treatment on P and K concentrations in Whole Plants at the V4-V5 Growth Stage †

	P concentration (%)		K concentration (%)	
	2001	2002	2001	2002
Pioneer 34B24	0.31	0.45	2.41	3.37
Pioneer 34M95	0.32	0.44	2.42	3.92
Control	0.31	0.45	2.62	3.19 c
Broadcast	0.33	0.43	2.27	3.66 ab
15 cm P&K	0.32	0.45	2.36	3.92 a
15 cm Band P	0.32	0.45	2.14	3.52 bc
15 cm Band K	0.30	0.45	2.68	3.93 a
Treatment‡	Significance Level			
Hyb	ns	-	ns	-
Fert	ns	ns	ns	*
Hyb x Fert	ns	-	ns	-

* significant at the 0.05 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid and Fert = fertility treatment

Plant Height

Height measurements were taken at the V7 growth stage in 2001 only. The broadcast method of fertilizer placement resulted in taller plants than a band placement (Table 32). The broadcast was also taller than the control, and the P alone and K alone treatments. If plant height is an indicator of vigor, then this data would support the broadcast method of P and K placement to be the best. Pioneer hybrid 34B24 was a significantly taller plant than Pioneer 34M95 at the V7 crop growth stage.

Table 32. Plant height as affected by Hybrid and Fertility Treatment at Growth Stage V7

Height (inches)	
	2001
Pioneer 34B24	44.8 a
Pioneer 34M95	42.0 b
Control	43.2 b
Broadcast	46.1 a
15 cm P&K	43.2 b
15 cm Band P	43.3 b
15 cm Band K	41.0 b
Treatment‡	Significance Level
Hyb	*
Fert	**
Hyb x Fert	ns

** significant at the 0.01 probability level
* significant at the 0.05 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid and Fert = fertility treatment

Chlorophyll Readings

Chlorophyll readings allow a measurement of the “greenness” of plant tissue. In this study, we used it as a way to measure the “stay green” ability of a hybrid later during grain filling. In 2001, hybrid differences were observed on each data collection date (Table 33). Pioneer 34B24 always had the higher chlorophyll reading, making it a greener hybrid than 34M95.

Early in the 2001 season, chlorophyll readings were lowest for banded K only treatments (Table 33). As time passed, both the control and the K only treatments resulted in lowest chlorophyll readings. Although not significant in the final sampling date, the broadcast and banded P and K treatments were the highest. Because of natural senescence, there was much more variation as the season progressed, making significant differences harder to achieve.

It is possible that the soil available P was more limiting to leaf chlorophyll retention than soil exchangeable K in 2001. This would explain why the band P alone treatment was not different than the broadcast or band P plus K treatments. The band K treatment, however, had significantly lower chlorophyll readings for one date in 2001; the latter leaf response to K treatment might have been affected by low soil available P.

Table 33. Effects of Hybrid and Fertility Treatment on Chlorophyll Readings in 2001 †

	8-Aug	7-Sep	25-Sep
Pioneer 34B24	60.6 a	54.9 a	28.0 a
Pioneer 34M95	58.9 b	53.0 b	22.1 b
Control	60.0 a	52.7 c	22.1
Broadcast	59.7 a	54.7 a	26.9
15 cm P&K	60.3 a	54.3 ab	26.5
15 cm Band P	60.6 a	54.8 a	24.3
15 cm Band K	58.3 b	53.2 bc	25.7
Treatment‡	Significance Level		
Hyb	*	*	*
Fert	*	**	ns
Hyb x Fert	ns	ns	ns

** significant at the 0.01 probability level
* significant at the 0.05 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid and Fert = fertility treatment

In 2002, no treatment differences were seen until late September and early October (Table 34). The September 23 data show that the broadcast treatment was greener than either nutrient banded alone, but not significantly different than either the banded P plus K or the control. The October 5 data show the banded P alone had the lowest chlorophyll reading and the banded K alone had a high chlorophyll reading. This does not match the 2001 data, but may reflect an earlier end to grain filling (attainment of physiological maturity) in banded P alone versus the other fertility treatments. Banded K alone and banded P plus K were similar in their apparent chlorophyll content on this last day, a response that seems reasonable given that the soil tests showed exchangeable K was more limiting than available P.

Table 34. Effects of Hybrid and Fertility Treatment on Chlorophyll Readings in 2002 †

	6-Sep	13-Sep	20-Sep	23-Sep	5-Oct
Pioneer 34B24	60.4	59.6	53.9	56.8	42.1
Pioneer 34M95	57.2	56.8	51.8	54.3	40.4
Control	59.1	58.2	52.2	56.2 ab	43.3 a
Broadcast	58.3	57.9	52.9	56.7 a	40.4 ab
15 cm P&K	58.5	57.9	54.0	55.7 ab	42.0 a
15 cm Band P	58.6	58.2	52.7	54.4 b	38.3 b
15 cm Band K	59.5	58.7	52.7	54.7 b	42.0 a
Treatment‡			Significance Level		
Hyb	-	-	-	-	-
Fert	ns	ns	ns	*	*
Hyb x Fert	-	-	-	-	-

** significant at the 0.01 probability level
* significant at the 0.05 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid and Fert = fertility treatment

Grain Yield

No yield responses to either hybrid or fertility treatments were observed in 2001 (Table 35). In 2002, however, there were significant differences among some fertility treatments. The 15 cm P and K, the 15 cm Band P, and the 15 cm Band K treatments yielded significantly more than the broadcast treatment. Studies in Minnesota have noted lower yields when P was deep-banded (5-inch depth, fall application) as compared to a starter band at planting (Randall et al., 2001). Our study involved starter-banded P on all treatments, and yet deep-banded P still yielded more than some other placements (Table 35).

The broadcast treatment had the lowest yield in 2002 (Table 35). This was surprising because there was no prior evidence of a compromised root system or a lower shoot weight for this treatment. When root characteristics were significantly different among treatments, the broadcast treatment often had the largest area or volume. Chlorophyll readings do not indicate that there was a difference in development rate or "stay-green" ability with the broadcast method of fertilizer placement. There was no indication that early shoot P concentrations were any higher for the deep-banded P treatments than for the broadcast treatment (Table 31). It is also odd that the yield advantage with deep banding of P came about in the year with very high initial soil P concentrations to begin with. Indeed, the soil P levels were so high that we wouldn't have expected any yield response to P fertilizer. Therefore, we cannot explain why the broadcast treatment resulted in lower yields than the banded treatments in 2002. However the yield advantage of the banded treatments versus broadcast is significant and indicates that in some situations, deep banding of P and K fertilizers in the intended row zone ahead of planting is beneficial.

Table 35. Effects of Hybrid and Fertility Treatment on Harvested Yield †

	Yield (kg/ha)	
	2001	2002
Pioneer 34B24	13800	11980
Pioneer 34M95	13300	12540
Control	13230	12170 ab
Broadcast	13800	11850 b
15 cm P&K	13550	12230 a
15 cm Band P	14050	12610 a
15 cm Band K	13170	12350 a
Treatment‡	Significance Level	
Hyb	ns	-
Fert	ns	*
Hyb x Fert	ns	-

* significant at the 0.05 probability level
† Data followed by the same letter are not significantly different according to a Fisher protected LSD
‡ Hyb = hybrid and Fert = fertility treatment

Grain moisture contents were not affected by treatments in 2001, but this might have been a function of the relatively late harvest (data not presented). Individual plot grain moisture contents ranged from 15.8 to 20.1 percent in 2001. These must have been due to spatial variability in various areas of the field because when the moistures were averaged over fertilizer treatments, the means ranged from just 18.8 to 19 percent. Deep banding was, therefore, not beneficial in achieving earlier maturity or faster dry-down relative to broadcast application. Most of the benefit from deep banding may have been hidden by the uniform starter application in our study. Harvest moisture data from 2002 is not available.

Grain Nutrients

The harvested grain was analyzed to look for differences in nutrient concentrations (Table 36). No differences were seen in percent P or K present in the grain sample for either hybrid or fertilizer treatments in either year. Overall P concentrations were much higher in 2002 than in 2001, but this may reflect the much higher soil available P status in 2002. Additional nutrient analyses can be seen in Appendix C.

Table 36. Effects of Hybrid and Fertility Treatment on Nutrients in Harvested Grain

	Grain P conc. (%)			Grain K conc. (%)	
	2001	2002		2001	2002
Pioneer 34B24	0.30	0.45	Pioneer 34B24	0.38	0.47
Pioneer 34M95	0.30	0.40	Pioneer 34M95	0.37	0.41
Control	0.27	0.42	Control	0.35	0.44
Broadcast	0.27	0.45	Broadcast	0.34	0.46
15 cm P&K	0.32	0.45	15 cm P&K	0.39	0.46
15 cm Band P	0.33	0.39	15 cm Band P	0.41	0.41
15 cm Band K	0.29	0.44	15 cm Band K	0.38	0.45
Treatment‡	Significance Level		Treatment‡	Significance Level	
Hyb	ns	-	Hyb	ns	-
Fert	ns	ns	Fert	ns	ns
Hyb x Fert	ns	-	Hyb x Fert	ns	-

‡ Hyb = hybrid and Fert = fertility treatment

Summary

Hybrid differences were apparent throughout the two-year study, with Pioneer 34B24 having higher root area, surface area, diameter, and volume than Pioneer 34M95. The root length, shoot weight and shoot-to-root ratios of Pioneer 34B24 were also greater than observed with Pioneer 34M95. A hybrid by fertility treatment interaction was apparent presumably because root volume and root area during early growth stages were higher for broadcast treatments with Pioneer 34M95 as compared to the results with Pioneer 34B24.

Samples taken from the largest diameter category of roots (those greater then 4 mm) showed that the large diameter typically resulted in shorter root lengths, higher volumes and fewer tips. So although there were not as many of these roots and they were shorter in length, they made up for it in volume with their larger diameters. The only fertility treatment differences seen were within the >4 mm root diameter category, and only for Pioneer hybrid 34M95. In this largest diameter class, the broadcast treatment had a higher root area than all other fertility treatments.

Root system measurements from both years generally revealed that the broadcast treatment was always as good as, or better than, a banded P plus K placement. Overall root volume was highest with the broadcast and 15-cm band placements in 2002. Root weights from 2001 also followed this same trend, with the broadcast having significantly higher weights than all other treatments.

Likewise, early season shoot weights from 2002 were also highest with the broadcast and lowest with the band P alone treatment. As expected, banded P plus K and band K alone treatments resulted in higher shoot K concentrations than the banded P alone treatment. Hybrids differed in their shoot to root ratios, but fertility treatments had no impact on shoot to root ratios.

Chlorophyll readings, although often non-significant during the peak of the grain filling period, tended to show higher values with broadcast treatment when significant differences were seen. The band K alone and control treatments were usually the lowest on these dates.

Despite the early season advantages noted with the broadcast P plus K, it was interesting to note than grain yields were never higher with broadcast treatment. In fact, in 2002, the yield from the broadcast treatment was significantly less than that of the band P plus K, the band P alone, and the band K alone treatments. Positive yield responses to banding P alone were even more surprising in 2002 because of the very high soil test P concentrations. Grain nutrient concentrations were not significantly affected by fertility treatments in either year. These comparisons need to be continued for more years to better understand the complex responses of corn to deep banding of phosphorus and potassium.

CHAPTER THREE. GENERAL DISCUSSION

Corn responses to deep placement of P and K fertilizers from this research endeavor prove that it is a very complex issue. Hybrids often differed in their growth and development, but we did not see as many fertility treatment interactions as we might have expected. Likewise, population density caused differences in corn growth and development, but the interactions between population and fertility treatments were rarely significant. Corn grain yields were never increased by planting at the higher plant density; thus, attempts to explore possible nutrient placement differences at normal versus high population levels were somewhat constrained.

Although the two hybrids were not the primary focus of our investigations, there were numerous confirmations that the hybrids were indeed different from each other. In Study 1, hybrids were often were significantly different in nutrient concentration (with whole plants and in grain), leaf area, and yields. Hybrid differences were also apparent in Study 2, with Pioneer 34B24 having higher root area, surface area, diameter, and volume than Pioneer 34M95. The root length, shoot weight and shoot to root ratios of Pioneer 34B24 were also greater than observed with Pioneer 34M95. Hybrids differed in their shoot to root ratios even though fertility treatments had no impact on shoot to root ratio.

Differential corn responses to fertility treatments varied considerably in the timing of their onset, and in their longevity. In both studies, treatments resulting in early advantages for corn growth (e.g. deep placement in Study 1 and broadcast in Study 2) did not result in consistent corn development or yield benefits later in the season.

In 2001 (for Study 1) an increased shoot weight was observed at the V4 growth stage with the 30-cm depth P and K placement when compared to the broadcast and 15-cm nutrient placement. For Pioneer 34B24, both the control and the deep band (30-cm) placements resulted in significantly higher shoot weights than all other fertility treatments. However, the early vigor of the 30-cm band treatment did not translate into increased leaf area index (LAI) later in the season (R1 stage). Indeed, the 15-cm band treatment had a significantly higher LAI than the 30-cm band treatment at the R1 growth stage.

Root development interactions between fertility treatments and hybrid choice or root diameter range were relatively infrequent. In Study 2, significant hybrid by fertility treatment interactions for root volume and root area during early growth stages occurred because these root parameters were higher for broadcast treatments when growing Pioneer 34M95, but not for Pioneer 34B24. Fertility treatment by root diameter interactions were observed for roots above 4 mm in diameter, but not for smaller diameter roots. In this largest diameter class, the broadcast treatment resulted in higher root area than all other fertility treatments (but only for Pioneer hybrid 34M95). This latter response could merely indicate that there were more nodal roots with broadcast P and K placement.

Root data from both years generally revealed that the broadcast treatment was always as good as, or better than, a banded P plus K placement. Overall root volume was highest with the broadcast and 15 cm band placements in 2002. Root weights from 2001 also followed this same trend, with the broadcast having significantly higher weights than all other treatments. Likewise, early season shoot weights from 2002 were also highest with the broadcast and lowest with the band P alone treatment.

Despite the early season advantages noted with the broadcast P plus K in Study 2, it was interesting to note than grain yields were never higher with broadcast treatment. In fact, in 2002, the yield from the broadcast treatment was significantly less than that of the band P plus K, the band P alone, and the band K alone treatments. The early season vigor of the broadcast P and K did not show any advantage at harvest.

In both studies in both years, the chlorophyll readings exhibited significant differences with regard to nutrient placement. When differences were significant, the broadcast P and K application always showed the highest levels of chlorophyll. In Study 1 in 2001, the broadcast treatment had significantly higher chlorophyll readings than did the 30-cm band treatment. For 2002, chlorophyll readings were again highest for the broadcast treatment. As we would expect, the control had the lowest readings. The broadcast treatment tended to display higher chlorophyll readings than other fertility treatments towards the end of grain fill. The band K alone and control treatments were usually the lowest on these dates.

In the environments we tested, we conclude that, generally, broadcast placement is as effective as deep placement when pursuing high corn yields. The very deep 30-cm placement did not create any yield advantage over traditional broadcast applications.

Corn responses to deeper placement of P and K fertilizers were seen in some of the measurements taken, but the data shown for two years of study do not show obvious trends.

Occasionally significant and positive corn growth responses to the 30-cm placement depth of P and K were observed. However, overall, results do not indicate that the deeper placement of P and K is preferable to broadcasting. Early shoot weights were higher when P and K fertilizers were deep-banded as compared to a broadcast or shallow-banded placement. The early vigor observed in the deep-banded treatment did not translate into higher leaf area indices. The 15-cm banded treatment resulted in significantly higher LAI than the 30 cm band.

Chlorophyll readings from both studies indicated that the broadcast placement had better “stay-green” ability than deep-banded treatments. Corn yields were not affected by fertility treatments in 2001; in 2002 both the deep-band and combined shallow plus deep band treatments resulted in significantly higher yields than the control, but not relative to broadcasting. Positive yield responses were seen with the 15-cm P plus K, P alone and K alone banded treatments (versus broadcast) for study 2 in 2002 only. This was surprising because it was not only a wet year, but the soil-test P levels were higher.

Root data from both years generally revealed that the broadcast treatment was always as good as, or better than, a banded P plus K placement. Overall root volume was highest with the broadcast and 15-cm P plus K placements in 2002. Samples taken from the largest diameter category of roots (those greater then 4 mm) showed that the broadcast treatment had a higher root area than all other fertility treatments when observing Pioneer hybrid 34M95. Shoot and root weights from 2001 also followed this same trend, with the broadcast having significantly higher weights than all other treatments.

The results observed in these studies demonstrate that corn response to P and K fertilizer placement is not straightforward. Deep in-row placement of P and K was not typically superior to broadcast placement even at very high plant densities. Corn responses to deeper placement of P and K fertilizers were seen in some of the measurements taken, but the data shown for two years of study do not show obvious trends.

There were some mitigating factors that might have influenced our corn response data to the varying fertility placement treatments. Possible mitigating factors are the following:

(1) We applied a uniform starter fertilizer application on each fertility treatment, including the control. The rate was high enough that, in combination with spring-applied fertilizer treatments, there appeared to be fertilizer burn issues in 2001. The high levels of starter may have made the effects of deep-banded P and K less apparent.

(2) In the first study, the soil test values showed that there was no apparent stratification of P or K in 2001. Positive corn results with deeper placement would have been much more likely with highly stratified P and K soils.

(3) Soil variability is present in almost any field, and our sites were no exception. The soil P and K levels were not uniform throughout the experimental area in any of the site-years. Occasionally high P and K levels in “control” plots would render it difficult to show corn advantages associated with any fertilizer addition.

(4) The precision of planting corn rows directly over the deep fertilizer bands may have been sufficiently imprecise so that corn plants may not have derived as full a benefit as they might have with precise row positioning over the bands. The corn planter operator tried to follow the strip tilled berms as well as humanly possible, but the precision obtained in that operation was decidedly less than what is now possible with the most precise automatic guidance systems available in 2005. Precision planting of corn rows directly on top is potentially very important for corn farmers who rely on deep-banded fertilizer as their sole banded nutrient source (especially if they have no starter fertilizer capability on planters).

(5) One large variable in all field research is weather. As discussed earlier, deep banding is often more effective in dry conditions. In our studies, we had a normal to somewhat dry spring in 2001, and a very wet spring in 2002. Perhaps in a year with less rainfall, more corn yield benefit would have been observed with deep banding relative to surface broadcast application.

(6) The high soil test levels in our fields probably also impacted our results. We thought that the concentrated bands would still create an advantage over broadcast placement, even in fields with high soil fertility. Prior studies had shown that banded K could increase yields even in soils that tested high for exchangeable K, although most research indicates that yield responses to P and K placement are rare when soil test levels are high.

The results from our studies did not show correlation between early growth measurements and yield. This is similar to prior research. Previous research has varied in corn responses reported in response to banding either P or K alone, but we saw no consistent benefit to any banding combination or depth placement.

Part of the purpose of this research was an attempt to increase yield; we pursued fertility management approaches that potentially would decrease the “yield gap” between average yields and high yield contest winners. However, there is a need to remember that high yields are not always the most profitable. In future studies, it would be beneficial to see an analysis to determine if the management practices investigated are economically favorable. For the advancement of science, pursuing high yields is fascinating indeed; however, attaining the most efficient yield is what will provide maximum impact for sustainable agriculture.

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APPENDICES

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APPENDIX A: Unanalyzed root core data

Appendix A-1. Root core data by year and fertilizer treatment at growth stage V-10 for a composite of in-row and between-row samples

Year	Fertilizer Placement	Length cm	Area cm^2	SurfArea cm^2	Diameter mm	Len/Vol cm/m^3	Volume cm^3	Tips	Forks	Crossings
2001	Control	73	5.6	17.5	0.70	73	0.35	146	250	15
	Broadcast	77	6.8	21.4	0.83	77	0.52	140	228	13
	15 cm P&K	72	5.9	18.5	0.73	72	0.42	138	227	15
	15 cm Band P	69	5.1	16.1	0.69	69	0.33	138	200	14
	15 cm Band K	82	7.4	23.2	0.83	82	0.57	162	279	14
2002	Control	147	13.1	41.0	0.77	147	1.10	288	644	49
	Broadcast	157	13.7	43.1	0.76	157	1.09	305	692	52
	15 cm P&K	166	13.4	42.2	0.73	166	0.99	325	694	59
	15 cm Band P	161	13.2	41.4	0.76	161	0.96	304	748	60
	15 cm Band K	143	10.7	33.5	0.70	143	0.74	285	584	53

Appendix A-2. Root core data by year and hybrid at growth stage V-10 for a composite of in-row and between-row samples

Year	Hybrid	Length cm	Area cm^2	SurfArea cm^2	Diameter mm	Len/Vol cm/m^3	Volume cm^3	Tips	Forks	Crossings
2001	Pioneer 34B24	78	6.1	19.1	0.72	78	0.42	152	238	17
	Pioneer 34M95	71	6.2	19.5	0.80	71	0.46	138	234	12
2002	Pioneer 34B24	147	11.5	36.2	0.73	147	0.81	304	628	55
	Pioneer 34M95	163	14.1	44.3	0.76	163	1.14	298	717	55

APPENDIX B: Chlorophyll data

Appendix B-1. Average chlorophyll readings for 2001 in study 1.

	17-Jul	Jul. 25	Aug. 7	Aug. 15	Aug. 23	Aug. 31	Sep. 7	Sep. 14
Pioneer 34B25	56.1 a	60.0 a	60.0 a	60.6 a	57.9 a	56.5 a	54.2 a	46.3 a
Pioneer 34M96	54.4 b	56.7 b	58.1 b	57.7 b	55.5 b	54.3 b	51.3 b	40.6 b
79,000 plants ha^{-1}	56.1 a	59.6 a	60.1 a	60.3 a	57.9 a	56.6 a	54.3 a	46.7 a
104,000 plants ha^{-1}	54.4 b	57.0 b	58.0 b	58.0 b	55.5 b	54.1 b	51.2 b	40.2 b
Control	54.9	58.4	59.1	59.0	56.8 ab	55.4 ab	52.3	40.8
Broadcast	55.5	58.6	59.0	59.6	57.4 a	55.9 a	53.4	45.9
6-Inch Band	.	58.4	58.7	59.2	56.8 ab	55.8 a	53.3	44.1
12-Inch Band	.	57.8	59.0	58.7	56.0 b	54.4 b	52.0	42.0
6+12-Inch Bands	55.3	58.5	59.3	59.2	56.3 ab	55.3 ab	52.6	44.5
Treatment‡				Significance Level				
Hyb	**	**	**	**	**	**	**	**
Pop	**	**	**	**	**	**	**	**
Fert	ns	ns	ns	ns	*	*	ns	ns
Hyb x Pop	ns	ns	ns	ns	ns	ns	ns	ns
Hyb x Fert	ns	ns	ns	ns	ns	ns	ns	ns
Pop x Fert	ns	ns	ns	ns	ns	ns	ns	ns
Hyb x Pop x Fert	ns	ns	ns	ns	ns	ns	ns	ns

Appendix B-2. Average chlorophyll readings for 2002 in study 1.

	Sep. 11	Sep. 18	Sep. 25	Oct. 2
Pioneer 34B24	59.8	57.9	54.0	42.5
Pioneer 34M95	56.5	55.7	53.2	44.9
79,000 plants ha^{-1}	58.6	57.4 a	54.4 a	45.4 a
104,000 plants ha^{-1}	57.5	56.2 b	52.7 b	42.1 b
Control	57.7	56.3	52.7	39.1 b
Broadcast	58.3	56.8	53.5	45.6 a
6-Inch Band	57.6	56.0	54.1	43.0 a
12-Inch Band	57.8	57.6	53.6	45.4 a
6+12-Inch Bands	58.8	57.3	54.1	45.6 a
Treatment	Significance Level			
Hyb				
Pop	ns	**	**	**
Fert	ns	ns	ns	**
Hyb x Pop				
Hyb x Fert				
Pop x Fert	ns	ns	ns	ns
Hyb x Pop x Fert				

Apendix C: Nutrient data

Appendix C-1. Shoot concentration of nutrients at the V6 Growth Stage in 2001.

	N (%)	P (%)	K (%)	Mg (%)	S (%)	B (ppm)	Fe (ppm)	Mn (ppm)	Cu (ppm)	Zn (ppm)
Pioneer 34B24	4.32	0.36	3.65	0.45 a	0.35 a	7.50 b	2617	153 b	7.32 a	34.0
Pioneer 34M95	4.39	0.37	3.79	0.41 b	0.33 b	8.27 a	2651	195 a	6.28 b	33.3
79,000 plants ha^{-1}	4.40	0.38 a	3.72	0.43	0.35 a	8.04	2744	196 a	6.79	34.6
104,000 plants ha^{-1}	4.31	0.35 b	3.72	0.43	0.34 b	7.74	2523	152 b	6.82	32.8
Control	4.37	0.36	3.71	0.43	0.33	7.46	2469	178	6.35	32.5
Broadcast	4.31	0.36	3.82	0.42	0.34	8.07	2615	147	6.86	35.0
6-Inch Band	4.30	0.37	3.80	0.44	0.35	8.29	2669	170	6.91	33.7
12-Inch Band	4.43	0.37	3.68	0.44	0.35	8.00	2710	189	7.44	35.0
6+12-Inch Bands	4.35	0.36	3.59	0.43	0.34	7.60	2705	187	6.45	32.1
Treatment‡					Significance Level					
Hyb	ns	ns	ns	**	**	**	ns	*	**	ns
Pop	ns	**	ns	ns	*	ns	ns	**	ns	ns
Fert	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Hyb x Pop	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
Hyb x Fert	ns	ns	ns	ns	ns	*	ns	ns	ns	ns
Pop x Fert	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Hyb x Pop x Fert	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Appendix C-2. Nutrient concentrations from ear leaf in 2001 and 2002.

	P		K		Ca	S	Zn
	2001	2002	2001	2002	2002	2002	2002
Pioneer 34B25	0.22	0.27	2.04	1.44	0.34	0.184	18.6
Pioneer 34M96	0.20	0.26	2.30	1.88	0.34	0.165	20.2
79,000 plants ha^{-1}	0.23	0.27	2.13	1.63	0.36 a	0.178 a	19.7
104,000 plants ha^{-1}	0.20	0.27	2.22	1.73	0.32 b	0.170 b	19.3
Control	0.21	0.26	2.01	1.69	0.33	0.169 b	18.2
Broadcast	0.21	0.26	2.26	1.59	0.34	0.170 b	21.4 a
6-Inch Band	0.23	0.26	2.25	1.71	0.33	0.170 b	18.3
12-Inch Band	0.21	0.26	2.17	1.68	0.35	0.179 a	18.9
6+12-Inch Bands	0.21	0.28	2.17	1.78	0.35	0.180 a	20.4
Treatment‡			Significance Level				
Hyb	ns		ns				
Pop	ns	ns	ns	ns	**	**	ns
Fert	ns	ns	ns	ns	ns	**	*
Hyb x Pop	ns		ns				
Hyb x Fert	ns		ns				
Pop x Fert	ns	ns	ns	ns	ns	ns	ns
Hyb x Pop x Fert	ns		ns				

Appendix C-3. Nutrient concentration from grain at harvest in 2001.

	N (%)	Mg (%)	S (%)	B (ppm)	Fe (ppm)	Mn (ppm)	Cu (ppm)	Zn (ppm)
Pioneer 34B24	1.39	0.18 a	0.13 a	2.49 a	27.3	6.40	1.39	28.7 a
Pioneer 34M95	1.32	0.16 b	0.11 b	3.07 b	26.9	6.69	1.55	26.1 b
79,000 plants ha^{-1}	1.35	0.17	0.12	2.88 a	27.5	6.90 a	1.46	27.9
104,000 plants ha^{-1}	1.35	0.16	0.12	2.69 b	26.7	6.19 b	1.49	26.9
Control	1.36	0.17	0.12	2.76	24.9	6.21 b	1.43	26.8 ab
Broadcast	1.30	0.16	0.12	2.87	27.2	6.29 b	1.29	26.0 b
6-Inch Band	1.41	0.18	0.12	2.88	28.0	7.29 a	1.65	29.2 a
12-Inch Band	1.26	0.17	0.12	2.67	27.8	6.61 ab	1.52	28.3 ab
6+12-Inch Bands	1.43	0.17	0.12	2.75	27.6	6.33 b	1.47	26.6 ab
Treatment‡	Significance Level							
Hyb	ns	**	**	**	ns	ns	ns	**
Pop	ns	ns	*	*	ns	**	ns	ns
Fert	ns	ns	ns	ns	ns	*	ns	*
Hyb x Pop	ns	ns	ns	ns	ns	ns	ns	ns
Hyb x Fert	ns	ns	ns	*	ns	ns	ns	ns
Pop x Fert	ns	ns	ns	ns	ns	ns	ns	ns
Hyb x Pop x Fert	ns	ns	ns	ns	*	ns	ns	*

Appendix C-4. Nutrient concentration from grain at harvest in 2002.

	N (%)	Mg (%)	S (%)	B (ppm)	Fe (ppm)	Mn (ppm)	Cu (ppm)	Zn (ppm)
Pioneer 34B24	1.64	0.18	0.13	7.71	32.9	6.78	1.47	29.3
Pioneer 34M95	1.56	0.17	0.11	8.47	34.9	7.03	1.50	27.9
79,000 plants ha^{-1}	1.59 b	0.17	0.12	7.66	32.7	6.69	1.38	28.3
104,000 plants ha^{-1}	1.61 a	0.18	0.12	8.52	35.1	7.12	1.59	28.8
Control	1.57	0.17	0.12	6.93	32.1	6.36 b	1.32	27.3 b
Broadcast	1.63	0.19	0.12	8.51	36.5	7.52 a	1.88	31.0 a
6-Inch Band	1.60	0.17	0.12	8.67	34.4	6.70 b	1.53	27.6 b
12-Inch Band	1.61	0.17	0.12	8.31	34.0	7.04 ab	1.34	28.2 b
6+12-Inch Bands	1.60	0.17	0.12	8.04	32.5	6.91 ab	1.37	28.8 b
Treatment‡								
Hyb								
Pop	ns	ns	ns	ns	ns	ns	ns	ns
Fert	ns	ns	ns	ns	ns	*	ns	*
Hyb x Pop								
Hyb x Fert								
Pop x Fert	ns	ns	ns	ns	ns	ns	ns	ns
Hyb x Pop x Fert								