ENHANCED EFFICIENCY PHOSPHORUS APPLICATION FOR CORN

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CHAPTER 1-LITERATURE REVIEW, OBJECTIVES, AND HYPOTHESES

Phosphorus in soil and plants

Phosphorus (P) is an essential plant nutrient that is an important structural element in nucleic acids (RNA and DNA), serves as an energy transfer element (ATP), and has a critical role in cellular regulation and carbon partitioning. The concentration of P in plants ranges from 0.5 to 5 g kg^{-1} dry weight (Vance et al., 2003). Characteristic visual symptoms of P deficiency include overall stunting of the plant and a darker green to purple coloration of leaves (Westermann, 2005). The purple coloration in some species is due to accumulation of sugars that enhance synthesis of anthocyanin (a purple pigment) in the leaf. The leaves may also contain small necrotic spots. Additional symptoms may include the production of slender stems and delayed maturity of the plant. Symptoms will be observed in older leaves since P is mobile in plants and translocated from older to newly developing tissues.

Inorganic phosphorus

The total amount of P in soils does not always correspond to the amount available for P uptake by plants. Plants mainly absorb P dissolved in the soil solution as orthophosphate ions (HPO_4^{-2} and $H_2PO_4^{-1}$). In general, the amount of P in soil solution at a given time is on the order of less than 1 kg ha^{-1}, or less than 1% of the total quantity of P in the soil (Pierzynski, 1991). The monovalent anion, $H_2PO_4^{-1}$, dominates in acid soils (pH 4 to 7.2), while alkaline soils (greater than pH 7.2) are characterized by the divalent anion, HPO_4^{-2}. Both monovalent and divalent anions are available in near-neutral soils (Pierzynski et al., 2005).

The major soil inorganic P transformations are precipitation/dissolution and adsorption/desorption reactions. Precipitation reactions and surface adsorption are collectively called P sorption (Pierzynski et al., 2005). Precipitation is defined as the formation of discrete insoluble compounds in soils. Precipitation reactions include secondary minerals. The common secondary P minerals are the products of reactions between soluble P and iron (Fe), aluminum (Al), or calcium (Ca) (Barber, 1984). Some common soil phosphate minerals are fluoroapatite, hydroxyapatite, dicalcium phosphate, variscite, berlinite, and strengite. Adsorption of P is the attraction of phosphorus ions or compounds to the surface of a solid. Adsorption solids include metal oxides, metal hydrous oxides, and other clay minerals. Phosphorus adsorption primarily involves the removal of HPO_4^{-2} and $H_2PO_4^{-1}$ from solution through chemical reactions, subsequently, resulting in pretention on reactive surfaces of the soil solid phase. Clay mineralogy is a key factor governing P sorption occurs (Sample et al., 1980). Clay minerals that contain greater anion exchange capacity (due to positive surface charge) have a greater affinity for P ions. A few examples are kaolinite, gibbsite, goethite, and allophane.

Phosphorus precipitation reactions and adsorption on mineral surfaces largely depends on soil pH. In acidic soils, Al, Fe, or Mn, either as dissolved ions, oxides, or hydrous oxides have a net positive charge and attract anionic P. Large quantities of Al or Fe oxides and hydroxides are found in highly weathered soils and require application of several times the quantity of P ferilizer compared to less weathered soils with lower Al and Fe contents (Wild, 1950). In alkaline soils, Ca quickly reacts with soluble $H_2PO_4^{-1}$ to form a sequence of Ca phosphate compounds with decreasing solubility and plant availability (Barber, 1984). As much as 25 to 90% of P can become unavailable for plant uptake depending on soil composition, pH, and Ca concentration (Brandon and Mikkelsen, 1979).

Organic phosphorus

The relative amounts of inorganic and organic forms of P vary greatly among soils. Generally, the organic fraction constitutes 30 to 65% of the total P in soils, although high organic matter soils can contain up to 90% organic P (Harrison, 1987) There are three broad groups of organic P compounds known to exist in soils including: (1) inositol phosphate, often called phytins or phytic acids; (2) nucleic acids; and (3) phospholipids (Condron et al., 2005). Inositol phosphates tend to be stable in acid and alkaline conditions, making them very abundant (1 to 100% of the total organic P). Together, nucleic acids and phospholipids make up 0 to 7% of the organic P in most soils. The rate at which organic P is converted into soluble, stable inorganic forms of P is highly dependent on the nature of the organic matter as well as environmental factors such as soil moisture, temperature, and pH (Stevenson, 1986). Immobilization, the incorporation of P into microbial biomass, occurs if the C:P ratio of the organic matter is greater than 300:1, while mineralization, the conversion of organic P to inorganic P, usually occurs rapidly if the C:P ratio is less than 200:1.

Phosphorus fertilizers

Phosphorus sources

Phosphorus fertilizers are used in large quantities in agriculture, horticulture, and yard care. The U.S. used 202,527,000 Mg of P_2O_5 from 1960 to 2010 (USDA, 2012). In

Missouri alone, P fertilizer use for corn (*Zea mays* L.) production increased from 44,000 Mg P_2O_5 in 1990 to 80,000 Mg P_2O_5 in 2010 (USDA, 2011). Many different sources of P fertilizers are available on the market today. Three of the most popular fertilizers used by farmers are triple superphosphate (TSP), monoammonium phosphate (MAP), and diammonium phosphate (DAP).

Differences between these fertilizers revolves around solubility and nutrient concentration. Monocalcium phosphate (the main P form in TSP) has been found to be more soluble and plant available than DAP in an alkaline soil, but slightly less soluble in an acidic soil (Bouldin and Sample, 1959). MAP and DAP are popular with producers because they provide the soil not only with P but also nitrogen (N) which could potentially reduce application time and cost. However, limited research has evaluated DAP as a source of N and P. A greenhouse study using corn evaluated the effectiveness of DAP as a dual source of N and P. DAP was compared with urea plus single superphosphate (SSP) placed at different depths (surface broadcast, incorporation, and deep banding) in a calcareous clay soil. Soil treated with urea plus SSP had higher Olsen P than soil treated with DAP regardless of fertilizer placement. With both fertilizers, surface broadcasting apparently reduced the accessibility of P to the plant roots and resulted in a lower P uptake and plant yield than incorporation treatments. When the fertilizers were either incorporated or deep-placed, N uptake was as high with DAP as with urea plus SSP. However, surface application resulted in lower N uptake from DAP than from urea plus SSP. Urea plus SSP produced higher plant yields than those obtained with DAP regardless of the method of fertilizer placement (Lu et al., 1987). Other research has shown little to no difference in grain yields and soil P levels between P fertilizer sources (Reid et al. 2004). Garcia et al. (1997) tested phosphate availability of several P fertilizers in calcareous soils with a high P sorption capacity. Available P levels did not increase when SSP, TSP, or DAP were applied. This was due to the sorption of P by the formation of Ca phosphates in these high pH and Ca content soils.

Other research has shown interactions between Zn and P where a high rate of P decreased zinc (Zn) tissue concentrations (Warnock, 1970; Safaya, 1976). Singh et al. (1986) observed that Zn tissue concentrations in wheat (*Triticum aestivum* L.) decreased 3.0 mg kg^{-1} and 6.7 mg kg^{-1} as P fertilizer application increased from 0 kg ha^{-1} to 80 and 160 kg ha^{-1}, respectively. A greenhouse study found total Zn accumulation in corn shoots increased 175 µg pot^{-1} and Zn tissue concentration decreased 21 µg g^{-1} as P fertilizer application increased from 0 to 300 mg kg^{-1}. The dilution of Zn to deficiency levels as the plant growth rate increased in response to applied P was considered the primary reason for these results (Friesen et al., 1980).

Deep placement

When evaluating the effectiveness of fertilizers, placement is a key variable. The hypothesis behind deep P fertilizer placement is that less P is lost from surface erosion and more P is available for early season crop growth. Research has shown an increase in plant growth and yields with deep placement compared to a broadcast application (Hairston et al., 1990). A study compared the effectiveness of broadcast compared to deep banding of annual and one-time P fertilizer applications to alfalfa (*Medicago sativa* Leyss). In annual and one-time applications, banding increased dry matter yield (DMY) (742 to 954 kg ha^{-1}) and protein yield (173 to 205 kg ha^{-1}) relative to broadcast application. Banding compared to broadcast produced greater P-use efficiency of applied

P (58 kg DMY kg^{-1} P ha^{-1}) for the annual application and for the one-time application (47 kg DMY kg^{-1} P ha^{-1}). Recovery of fertilizer P with deep banding was 16% greater for an annual application and 12% greater for the one-time application compared to a broadcast application (Malhi et al., 2001).

However, response to deep placement of P fertilizers has been inconsistent (Patrick et al. 1959; Mallarino et al., 1999; Borges and Mallarino, 2001). Plant growth and yield response to P placement could be dependent on the crop. A study in Kansas found that subsurface P application had a positive effect on early season crop growth and generally increased P uptake for corn and sorghum [*Sorghum bicolor* (L.) Moench]. Deep-banded P generally increased P uptake and yields of corn and sorghum. However, subsurface placement of P had little effect on soybean [*Glycine max* (L.) Merr.] yields (Schwab et al., 2006). Plant response to deep P placement can also be affected by climatic conditions. Robertson et al. (1958) found significant corn yield increases with deep placement when residual P was present in the surface soil and total rainfall was adequate with dry periods during early growth. However, deep placement did not affect yields when soil contained residual P and rainfall was above average and well distributed.

Phosphorus enhancers

With high fertilizer costs, farmers are interested in reduced application rates and use of P enhancers. Avail® (Specialty Fertilizer Products, Leawood, KS) and P_2O_5-Max®(P-Max, Rosen's Inc., Fairmont, MN) are commercial products that have been promoted to enhance the efficiency of P-based fertilizers. Avail® is a P enhancer for granular phosphate fertilizers such as DAP and MAP as well as other liquid phosphate fertilizers. It was designed to reduce the impact of cations (i.e., Ca, Fe, Mn, and Al) in the soil around the fertilizer granule on P sorption and plant P uptake. This product binds with Ca, Fe, Mn, and Al to prevent precipitation of P (SFP, 2009). The active ingredient from the material safety data sheet is a maleic-itaconic copolymer (SFP, 2005). P_2O_5-Max® increases P uptake and improves root surface area resulting in better nutrient absorption and higher yields (Rosen's Inc, 2012). Industry reports provide a number of instances where application of Avail® treated P to crops either in granular or liquid form resulted in yield increases in corn, potato (*Solanum tuberosum*), sugar beet (*Beta vulgaris*), and soybean (Tindall, 2007). Similarly, rice yields increased 502 kg ha^{-1} when reduced rates of TSP were applied (28 kg P_2O_5 ha^{-1}) with Avail (Dunn, 2008).

In other research, there have been limited effects of Avail® on plant growth and yields. A study conducted in 2008 and 2009 at five locations throughout Kansas evaluated the effectiveness of Avail® under both corn and wheat cropping systems (Ward, 2010). There was no significant effect of Avail® on plant biomass, tissue P concentration, or grain yields for corn and wheat. In Canada, two trials evaluated a nonfertilized control and three rates of seed-placed MAP at 6.5, 13, and 19.5 kg P ha^{-1} with and without Avail® (Karamanos and Puurveen, 2011). The results showed neither a significant effect of treating MAP with Avail® nor a significant interaction between Avail® treatment and rate of P on the yield of wheat and P uptake.

Plant response to P deficiency

If P is not in the right form, it will not be able to be taken up by plants no matter how much how P is applied to the soil. Adaptations have been developed in plants to acquire more P from soil, when it is limiting. A few examples would be changes in root development and function, release of organic acids by roots, and the formation of symbiotic associations with soil fungi (Gilbert et al., 2000; Lynch and Brown, 2001; Ryan et al., 2001; Vance et al, 2003; Schnepf et al., 2008).

Roots

Roots are the primary source of nutrient uptake for plants. One adaption plants have for dealing with P deficiency is to alter root development and function. Since P is relatively immobile in soils, increasing the amount and area of roots can increase P uptake. The typical plant response to P deficiency is to allocate more carbon to the roots which increased root growth, enhanced lateral root formation, and increased the length and number of root hairs (Lynch, 1995; Gilroy and Jones, 2000; Liao et al., 2001; Lynch and Brown, 2001). The greatest P concentration was typically found in topsoil, thus plants have adapted by redistributing root growth from primary roots to lateral roots. This concentrated roots near the soil surface (Lynch and Brown, 2001; Williamson et al 2001). Root surface area can be increased by an increase in root hairs (Vance et al, 2003). Root hairs are specialized for nutrient uptake and can form as much as 77% of the root surface area of field crops (Parker et al., 2000).

One of the major root adaptations of plants is cluster root formation (Skene, 1998; Pate et al., 2001). Cluster roots are made composed of single clusters of very densely packed determinate lateral rootlets. They are initiated in waves and are in multiples opposite every protoxylem point within the wave of differentiation (Skene, 2000). Cluster roots also produce an abundance of root hairs which resulted in an increase in surface area greater than 100-fold compared with normal roots (Vance et al., 2003). Cluster roots are thought to mobilize sparingly soluble inorganic P more effectively by localized concentration of root exudates (Grierson and Attiwill, 1989).

Plant growth regulators, such as auxin, ethylene, and cytokinin, are involved in P deficiency alterations in root hair formation and cluster root development. Auxin stimulates the formation of cluster roots in many species (Gilbert et al., 2000). Gilbert et al. (2000) showed that auxin transport inhibitors added to P deficient plants reduced the formation of cluster roots. Ethylene synthesis caused an increase in root hair length and density. At least eight of the forty genes affecting root hair development acted directly or indirectly on ethylene biosynthesis (Grierson et al., 2001). Cytokinin, on the other hand, inhibited root growth while stimulating shoot growth (Skoog and Miller, 1995). Under P deficiency conditions, auxin and ethylene concentrations increased, while cytokinin decreased.

Organic acids

The release of organic acids by roots affects P deficiency by altering rhizoshpere chemistry and plant growth (Jones, 1998; Hinsinger, 2001; Ryan et al., 2001; Yan et al., 2002; Vance et al., 2003). Malate and citrate are two organic acids that are the principle mechanism in alleviating P deficiency. Organic acids released by root hairs allow for the chelation of Al^{3+}, Fe^{3+}, and Ca^{2+}, and the subsequent displacement of inorganic P from bound or precipitated forms (Jones, 1998; Hinsinger, 2001; Ryan et al., 2001). Organic acids can enhance the dissolution of P-bearing minerals. Organic acids caused organic P to be more susceptible to hydrolysis by acid phosphates (Braum and Helmke, 1995). Protons and organic acid anions (OA^-) were also released under P deficiency. Yan et al. (2002) showed increased proton release from younger clusters while OA^- release was increased under prolonged P deficiency conditions in white lupin (*Lupinus albus*). The release of protons into the rhizosphere is a way to counteract intracellular acidity.

Mycorrhiza

Plants obtain P under P-stressed conditions by forming symbiotic associations between plant roots and specific soil fungi (Schnepf et al., 2008). The most widespread terrestrial symbiosis is arbuscular mycorrhizal (AM), which was is formed by 70-90% of land plant species (Parniske, 2008). Arbuscular mycorrhizal fungi provide plants with an additional pathway for P uptake and allowed plants to obtain P that was outside their root area (Zhu et al, 2001). Phosphorus is first taken up from the soil by external fungal mycelium. It is then transported toward the soil surface and transferred into the root cortical cells (Raghothama, 2005). The benefits of this symbiotic association are dependent on the P concentration in the soil. Studies on mycorrhizae inoculated corn showed that there was an increase in P acquisition under low P conditions, while the amount of increased P acquisition decreased with higher P concentrations (Kaeppler et al., 2000).

Liming

The concentration of plant available forms of P is largely affected by adsorption-desorption and precipitation reactions. These reactions may be influenced by increases in pH and Ca concentrations resulting from lime application. The speciation of phosphate and the electrostatic potential of adsorbing surfaces are two key factors in adsorption reactions that change with an increase in pH. Increasing pH increases the concentration of divalent phosphate ion (HPO_4^{2-}), which promotes adsorption. At the same time, when variable charge is present, the soil surface becomes more negatively charged as pH increases and retains less phosphate ions (Barrow, 1984). This resulted in an increase in plant available P in the soil solution. An application of lime can also decrease plant available P by increasing the concentration of Ca, which resulted in an increase in P precipitation as Ca phosphate (Naidu et al., 1990). The result of these competing affinities was expected to determine whether lime increased (Friesen et al. 1980) or decreased (Amarasiri and Olsen, 1973; Westermann, 1992) P uptake.

Exchangeable cations

Calcium deficiency (Ritchey et al., 1982) and Al toxicity (Pavan et al., 1982) are considered major yield limiting factors resulting from acid soils. Liming has been shown to resolve these issues by increasing soil pH and adding Ca. The application of lime increased exchangeable Ca, exchangeable Mg, and decreased exchangeable Al (Lim and Shen, 1978). Moschler et al. (1973) evaluated how liming affected exchangeable Ca and exchangeable Al in the upper 10 cm between no-tilled (NT) and conventional tilled (CT) corn in Virginia. In the limed NT soil, exchangeable Al comprised only 0.2% of the exchangeable cations, compared to 29.9% in non-limed NT soil. Aluminum saturation in tilled soil that received lime was 0.8% compared to 14.0% in non-limed, CT soil. More exchangeable Ca and higher soil pH were present in the limed, NT soil than in limed, CT soil. The higher exchangeable Al and less favorable rooting environment in the nonlimed soils reduced early growth of corn. An increase in corn maturity at harvest with limed soil resulted in an increase in corn yields.

Yields results from lime application

The increase in soil pH, exchangeable Ca, and decreased exchangeable Al resulted in increased corn yields between 718 to 828 kg ha^{-1} from a surface application of lime on NT (Blevins et al., 1978). However, the application method of the lime also determined its effectiveness. Moschler et al. (1973) compared continuous NT corn to continuous CT corn with or without lime. In NT corn, lime was surface applied, while the lime was incorporated into the soil in CT corn. The application of lime increased corn grain yield more than twice as much in NT (31.3%) as in CT (13.5%). In both tillage systems, lime was essential for the highest yields.

A greenhouse study evaluated the placement of lime in the Ap or A2 of a Norfolk loamy sand (Estrada and Cummings, 1968). The application of lime in either horizon increased root growth (0.8 g pot^{-1} for the Ap and 0.4 g pot^{-1} for the A2) in the horizon to which it was applied. When lime was only applied to the Ap horizon, the root weight increased 0.3 g pot^{-1} in the A2 horizon. However, there was no increase in root weight in the Ap horizon when lime was added to the A2 horizon. When lime was applied to either horizon, there was an increase in total plant above ground biomass, total plant P uptake, and a decrease in exchangeable Al concentration (Estrada and Cummings, 1968).

Other research has shown no effect of lime or a decrease in grain yields in some instances (Estes, 1972; Woodruff et al., 1987). In central Iowa, only one of five site-years increased grain yield (230 kg ha^{-1}) in response to a lime application. The most likely reason for this lack of response was due to the presence of high-pH (calcareous) subsoils (Bianchini and Mallarino, 2002). Caires et al. (2005) also found limited results from the application of lime in Brazil. Only one site-year of soybeans out of eight and one site-year of wheat out of two increased in grain yields.

Tillage

No-till

Conservation tillage practices, such as no-till (NT), may have a positive effect on reducing erosion and lowering production costs. Increased soil fertility, structure, and reduced potential for soil erosion occurs primarily due to the minimum soil disturbance associated with NT (Triplett and Dick, 2008). Yield response to NT systems depended upon good soil drainage and previous crop characteristics (Dick and van Doren, 1985; Guy and Oplinger, 1989). Well-drained soils, crop rotation, and more southern latitudes generally benefited from NT soybean production compared with poorly drained soils, continuous corn cropping systems, and northern latitudes (Griffith and Wollenhaupt, 1994). In a 10-year Iowa study, Chase and Duffy (1991) found that NT and moldboard plow produced similar soybean grain yields in a corn-soybean rotation on a moderately well-drained and moderately permeable loam soil. Brown et al. (1989) also found no difference in soybean yields between NT and moldboard plow when averaged over an eight year tillage study on a silt clay loam soil in Iowa. On a Houston Black clay soil (fine, smectitic, thermic Udic Haplusterts), NT produced higher corn yields than chisel tillage system without beds and chisel tillage system with raised wide beds (Torbert et al., 2001).

No-till has reduced yields in some instances compared to CT due to lower soil temperatures and higher soil moisture early in the growing season which reduced seedling emergence and slowed early growth (Burrows and Larson, 1962; Fortin and Pierce, 1990; Vyn and Raimbault, 1993; Uri, 2000). Higher residue levels on the soil surface could limit plant emergence by maintaining low soil temperatures and increasing soil moisture. Mehdi et al. (1999) conducted research on corn response to CT, reduced tillage, and NT with two residue levels (with or the residue totally remove) in southwestern Quebec. In all the treatments with residue, residue cover hindered the emergence of corn seedlings. No-till with residue had slower emergence rates two weeks after the planting date compared to other tillage systems. Greater soil compaction in NT may have also contributed to delayed seedling emergence in NT with residue. However, NT treatments had significantly higher amounts of seedling emergence at four weeks after planting. While there were no significant grain yield differences between tillage or residue treatments, the highest grain and stover water contents were consistently found in NT.

Studies have shown that NT corn yields can be reduced by as much as 35% compared with CT for moderately well to poorly drained soils (Erbach et al., 1992; Hussain et al., 1999). Halvorson et al. (2006) found CT produced 16% higher yields than NT in Colorado. The lower grain yields of NT resulted from slow early-spring development and delayed tasseling compared with CT system as a result of cooler spring soil temperatures in NT. Residue cover on the soil surface was greater in NT (89%) than in the CT system (14%). Howard et al. (2002) studied yield response between disk-till and NT in Tennessee. Disk-till yields were 0.59 to 1.34 Mg ha^{-1} greater than NT in 5 of the 11 site-years. However, P response was greater with NT production. No-till with P at 20 kg ha^{-1} increased yields 0.62 Mg ha^{-1}, while disk-till yields increased 0.44 Mg ha^{-1} with P at 39 kg P ha^{-1}.

Lower yields with NT did not always result in lower economic returns. No-till reduced time commitment by 35.9% and fuel cost by 36% compared to CT which ultimately lowered input cost (Lithourgidis et al., 2005). Yin and Al-Kaisi (2004) evaluated soybean yields under different tillage systems. In a well drained soil, NT had yields that were 5.4% less than CT. However, the economic returns of NT were $23.07 ha^{-1} yr^{-1} greater than CT. On a poorly drained soil, CT increased yields 8.2% and increased the economic return \$18.98 ha^{-1} yr^{-1} compared to the NT system. Lithourgidis et al. (2005) studied different tillage systems under a corn-wheat double cropping system. Only one of four growing seasons showed a 4.35 Mg ha^{-1} reduction in corn silage yields with NT compared to CT. However, there were no significant differences observed in wheat yield among tillage practices. Even with no yield benefits with using NT, reduced labor and fuel consumption with NT has resulted in an economic advantage for farmers.

Strip-till

Strip-tillage (ST), also referred to as zone tillage (ZT), is another conservation tillage practice that aims to combine the yield benefits of tillage with the environmental improvements of NT. It is a tillage practice that isolates soil tillage to a narrow band, generally 15 to 20 cm wide and 15 to 20 cm deep, while keeping the remaining soil surface undisturbed. Strip-till systems were first developed for use on Coastal Plain soils as a method to manage soil compaction in the Southeastern United States by combining deep tillage, while maintaining crop residue cover (Busscher and Sojka, 1987).

Strip-till has been shown to increase corn yields compared to NT (Vetsch et al., 2007) and equal to CT (Griffith et al., 1973; Randall et al., 2001). Vetsch and Randall (2002) evaluated tillage effects on continuous corn and corn following soybean production in Minnesota. With continuous corn, yields increased 0.4 Mg ha^{-1} with ST and 0.7 Mg ha^{-1} with CT compared to NT. No-till and ST maintained surface residue coverage between 54 and 87%. However, corn grain yields were not affected by tillage system in a corn-soybean rotation when averaged across years.

Research has also shown limited yield differences between NT and ST (Mallarino et al., 1999; Al-Kaisi and Lichet, 2004; Al-Kaisi and Kwaw-Mensah, 2007; Archer and

Reicosky, 2009). In Iowa, Licht and Al-Kaisi (2005a) found that ST had no effect on N uptake, dry matter production, and corn grain yields compared to chisel plow and NT. Vetsch and Randall (2004) showed that CT increased corn grain yields 0.3 and 0.5 Mg ha^{-1} compared to ST and NT, respectively. However, silage yields were 0.8 and 0.9 Mg ha^{-1} greater for ST and CT compared to NT. Nitrogen uptake was also greater for ST (193 kg ha^{-1}) and CT (198 kg ha^{-1}) compared with NT (181 kg ha^{-1}). Perez-Bidegain et al. (2007) evaluated different tillage effects on corn and soybean yields in Iowa. However, no differences were observed for soybean yields between tillage systems, while corn planted with disk-chisel tillage yielded 0.8 Mg ha^{-1} more than the mean yield of ST and NT.

Soil physical properties

The differences in yield response to NT and ST are a result of differences in soil bulk density and soil strength. No-till soils generally had the highest bulk density and penetrometer resistance (PR) (Bauder et al. 1981; Hill, 1990; Pierce et al. 1992), which could restrict root growth. Drury et al. (2003) evaluated the effect of CT, ZT, and NT on different soil physical properties. Zone tillage had the lowest overall PR in a low rainfall year and intermediate overall PR in a normal rainfall year. No-till tended to produce the greatest overall PR in the normal and low rainfall years, while CT produced lowest overall soil PR under normal rainfall and intermediate PR under low rainfall. Generally, the NT treatments also had higher bulk densities (1.41 Mg m^{-3} in 1998, 1.42 Mg m^{-3} in 1999, and 1.29 Mg m^{-3} in 2000) compared to ZT (1.31 Mg m^{-3} in 1998 and 1.30 Mg m^{-3} in 1999 and 2000) and CT (1.41 Mg m^{-3} in 1998, 1.30 Mg m^{-3} in 1999, and 1.35 Mg m^{-3} in 2000).

Overstreet and Hoyt (2008) evaluated differences in soil properties between the row, interrow, and edge locations of ST. Soil bulk density was 0.3 to 0.5 g cm^{-3} lower in the row position than between the row. No differences were found between the row and interrow positions for soil water content, total organic carbon, total N, and potentially mineralizable N. Soil respiration was greatest in the interrow position and least in the row position. Microbial biomass carbon was observed to be the greatest in the interrow location followed by the edge, and the lowest values came from the row location. This suggested that the increased level of year long residue cover and reduced disturbance in the interrow enhanced the biological community supported in this region of the soil.

Soil temperature

Changes in soil temperature due to tillage alter the seedbed environment has resulted in differences in plant growth and emergence. Compared to NT, ST can improve the seedbed environment in poorly drained soils due to increased evaporation and higher soil temperature in the row (Bolton and Booster, 1981; Al-Kaisi and Hanna, 2002). This improved seedbed environment is particularly important early in the growth season. In general, NT soils had lower soil temperatures than CT (Johnson and Lowery, 1985) and ST (Al-Kaisi and Hanna, 2002). Beyaert et al. (2002) found lower soil temperatures with NT compared to CT in southwestern Ontario, Canada. At a 4 cm depth, mean soil temperatures were lower in NT than in CT on 75% of the days during emergence and when averaged over the emergence period. Conventional tillage had higher mean soil temperatures than ZT in the warmer and drier planting season, but was similar during the cooler planting seasons. Licht and Al-Kaisi (2005b) evaluated the effect of tillage on soil temperature. In the top 5 cm, ST increased soil temperature 1.2 to 1.4°C over NT which was similar to the chisel plow soil temperature. This caused the corn emergence rate index (ERI) of both ST and chisel plow to be slightly greater ranging from 0.2 to 1.5 ERI than NT throughout the four site years.

Weed emergence

Weed emergence is another factor that is affected by tillage systems. Reduced yields from NT could be due to poorer weed control (Randall et al., 1996). No-till crops generally required more intensive weed management compared with CT since a greater concentration of weed seed was present at the soil surface (Buhler, 1995). However, a study in southern Illinois observed different results (Hendrix et al., 2004). In 2000, emergence of giant foxtail (*Setaria faberi* Herrm.), common waterhemp (*Amaranthus rudis* Sauer), velvetleaf (*Abutilon theophrasti* Medicus), and common cocklebur (*Xanthium strumarium* L.) was greater in CT than NT or ST two weeks after planting. At two weeks after planting, total weed emergence was 2.5 times greater with CT (678 plants m^{-2}) than NT (261 plants m^{-2}), while ST had the lowest total weed emergence with (167 plants m^{-2}).

Research Objectives and Hypotheses

Increased fertilizer costs, new P enhancer products available on the market, and challenges of corn production with NT prompted this research for enhancing the effectiveness of P fertilizers. Very little research has been done on P enhancers. Past research has not evaluated interactions of P enhancers with different tillage/fertilizer placements, P sources, or lime applications. The motivation of this research was to evaluate P enhancers across different management practices and locations.

Objectives

1. Evaluate the effect of P fertilizer placement (strip-tillage/deep banding and no-tillage/surface broadcast), MAP rate (0, half the recommended rate, and recommended rate), and P enhanced efficiency products [Avail®(Specialty Fertilizer Products, Leawood, KS) and P_2O_5-Max® (P-Max, Rosen's Inc., Fairmont, MN)] on grain yield, P uptake, and apparent P recovery efficiency in corn.
2. Evaluate the effect of P source (non-treated control and a broadcast application of DAP or TSP), P enhancer [Avail®(Specialty Fertilizer Products, Leawood, KS) and P_2O_5-Max® (P-Max, Rosen's Inc., Fairmont, MN)], and ag lime (0 or the recommended rate) on grain yield, P uptake, and apparent P recovery efficiency in corn.

Hypotheses

1. Phosphorus enhancers will not improve corn grain yields or P uptake or apparent P recovery efficiency.
2. Strip-till with deep banding placement will increase corn yields, P uptake and apparent P recovery efficiency compared to no-till with surface broadcast of MAP.
3. Application of recommended amount of lime will increase corn yields, P uptake, and apparent P recovery efficiency compared to when no lime is applied, while DAP and TSP will have similar corn yields and P uptake.

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CHAPTER 2-CORN PRODUCTION AS AFFECTED BY PHOSPHORUS ENHANCERS AND TILLAGE

ABSTRACT

With high fertilizer costs, farmers are interested in reduced phosphorus (P) fertilizer application rates and use of enhanced efficiency P fertilizer applications or treatments. A two year study was initiated to determine the effects of tillage/fertilizer placement [no-till (NT)/surface broadcast or strip-till (ST)/deep banding], monoammonium phosphate (MAP) rate [0 kg ha^{-1}, half the recommended rate (56 kg ha^{-1}), and the recommended rate (112 kg ha^{-1})], and the presence or absence of two enhanced phosphorus efficiency products (Avail® and P_2O_5-Max®) on corn (*Zea mays* L.) production. The study was conducted in 2010 and 2011 at Novelty and Albany, MO. The P enhancers did not affect plant population, silage dry weights, grain moisture, yield, grain protein, grain starch, plant nitrogen (N), potassium (K) uptake, or apparent P recovery efficiency (APRE) at either location. In the NT/broadcast and ST/deep banding treatments, the addition of Avail® or P_2O_5-Max® did not increase P uptake over the non-treated controls. Strip-till/deep banding increased plant populations 3,500 to 15,500 plants ha^{-1} compared to NT/broadcast. Yields increased 1.57 Mg ha^{-1} with use of strip-till/deep banding over NT/broadcast at Novelty, but yields at Albany were affected by placement and MAP rate. Monammonium phosphate fertilizer rate had a significant effect on yields with P_2O_5 at 0 kg ha^{-1} yielding 0.30 to 0.36 Mg ha^{-1} more than MAP at 56 or 112 kg P_2O_5 ha^{-1}.

INTRODUCTION

Phosphorus (P) is an essential plant nutrient that is an important structural element in nucleic acids (RNA and DNA), serves as an energy transfer element (ATP), and has a critical role in cellular regulation and carbon partitioning. Phosphorus fertilizers are used in large quantities in agriculture, horticulture, and turf grass. The U.S. used $2.03\text{x}10^8$ Mg of P_2O_5 from 1960 to 2010 (USDA, 2012). In Missouri alone, P fertilizer use for corn production has increased from $4.4\text{x}10^4$ Mg P_2O_5 in 1990 to 80,000 Mg P_2O_5 in 2010 (USDA, 2011).

With high fertilizer costs, farmers are interested in reduced P fertilizer application rates and use of P enhancers. Avail® (Specialty Fertilizer Products, Leawood, KS) and P_2O_5-Max®(P-Max, Rosen’s Inc., Fairmont, MN) are commercial products that haves been promoted to enhance the efficiency of P-based fertilizers on several soil types. Avail® is a P enhancer for granular phosphate fertilizers such as DAP and MAP as well as other liquid P fertilizers. Avail® was designed to reduce the impact of cations (i.e., Ca, Fe, Mn, and Al) in the soil around the fertilizer granule on soil P sorption and plant P uptake. This product binds with Ca, Fe, Mn, and Al in soil to prevent precipitation of P (SFP, 2009). The active ingredient in Avail® is a maleic-itaconic copolymer (SFP, 2005). P_2O_5-Max® increases P uptake and improves root surface area resulting in better nutrient absorption and higher yields. The active ingredient is poly-amino acid (L-aspartic acid), sodium salt (Rosen's Inc, 2012).

There has been limited published research on plant growth and yields in the presence of Avail®. A study conducted in 2008 and 2009 at five locations throughout Kansas evaluated the effectiveness of Avail® under both corn and wheat cropping systems (Ward, 2010). There was no significant effect of Avail® on plant biomass, P uptake, or grain yields for corn and wheat. In Canada, two trials evaluated a nonfertilized control and three rates of seed-placed MAP at 6.5, 13, and 19.5 kg P ha^{-1} with and without Avail® (Karamanos and Puurveen, 2011). The results showed significant effect of treating MAP with Avail®, nor a significant interaction between Avail® treatment and rate of P on wheat yield and P uptake.

When evaluating fertilizer effectiveness, placement is a variable that can increase efficiency. Less P is lost from surface erosion when P is deep placed or incorporated. Research has shown an increase in plant growth and yields with deep placement compared to a broadcast surface application (Hairston et al., 1990; Malhi et al., 2001). Malhi et al. (2001) compared the effectiveness of broadcast compared to deep banding of annual and one-time applications of P fertilizer on alfalfa (*Medicago sativa* Leyss) (Malhi et al., 2001). In annual and one-time applications, banding increased dry matter yield (DMY) between 742 to 954 kg ha^{-1} and protein yield between 173 to 205 kg ha^{-1} compared to a broadcast application. Banding compared to broadcast produced greater P-use efficiency of applied P (58 kg DMY kg^{-1} P ha^{-1}) for the annual application and 47 kg DMY kg^{-1} P ha^{-1} for the one-time application. Similarly, recovery of fertilizer P with deep banding was 16% greater for an annual application and 12% greater for the one-time application compared to broadcast application. However, response to deep placement of P fertilizers has been inconsistent (Patrick et al. 1959; Mallarino et al., 1999; Borges and Mallarino, 2001). Response of plant growth and yields to P placement could be dependent on the crop. A study in Kansas found that subsurface applications of P generally increased P uptake and yields of corn and sorghum [*Sorghum bicolor* (L.)

Moench]. However, subsurface placement of P had no effect on soybean [*Glycine max* (L.) Merr.] yields (Schwab et al., 2006). Plant response to deep P placement can also be affected by climatic conditions. Robertson et al. (1958) found significant corn yield increases with deep placement when residual P was present in the surface soil and total rainfall was adequate with dry periods during early growth. However, deep placement did not affect yields when soil contained residual P and rainfall was above average and well distributed throughout the growing season.

Conservation tillage practices, such as NT, have reduced erosion and lowered production costs. Increased soil fertility, structure, and reduced potential for soil erosion occurred primarily due to minimum soil disturbance associated with NT (Triplett and Dick, 2008). Yield response to NT systems depended upon adequate soil drainage and previous crop characteristics (Dick and van Doren, 1985; Guy and Oplinger, 1989). Well-drained soils, crop rotation, and more southern latitudes generally benefited from NT soybean production compared with poorly drained soils, continuous corn cropping systems, and northern latitudes (Griffith and Wollenhaupt, 1994). In a 10-year Iowa study, Chase and Duffy (1991) found that NT and moldboard plow produced similar soybean grain yields in a corn-soybean rotation on moderately well-drained and moderately permeable loam soil. Brown et al. (1989) also found no difference in soybean yields between NT and moldboard plow when averaged over an eight year tillage study on a silt clay loam soil in Iowa. On a Houston Black clay soil (fine, smectitic, thermic Udic Haplusterts), NT produced higher corn yields than chisel tillage system without beds and chisel tillage system with raised wide beds (Torbert et al., 2001).

No-till has reduced yields in some instances compared to conventional tillage (CT) due to lower soil temperatures and higher soil moisture early in the growing season which reduced seedling emergence and slowed early growth (Burrows and Larson, 1962; Fortin and Pierce, 1990; Vyn and Raimbault, 1993; Uri, 2000). No-till soils generally have higher bulk densities and penetrometer resistance (Bauder et al. 1981; Hill, 1990; Pierce et al. 1992), which could restrict root growth and affect fertilizer uptake. Studies have shown that NT corn yields were reduced by as much as 35% compared with CT for moderately well to poorly drained soils (Erbach et al., 1992; Hussain et al., 1999). Halvorson et al. (2006) found CT produced 16% higher yields than NT in Colorado. Lower grain yields associated with NT resulted from slow early-spring growth and delayed tasseling compared with the CT system as a result of cooler spring soil temperatures in NT. Cooler soil temperatures were due to greater residue cover on the soil surface in NT (89%) than in the CT system (14%). Howard et al. (2002) studied yield response between disk-till and NT in Tennessee. Disk-till yields were 0.59 to 1.34 Mg ha^{-1} greater than NT in 5 of the 11 site-years. However, P yield response was greater with NT production. No-till with P at 20 kg ha^{-1} increased yields 0.62 Mg ha^{-1}, while disk-till yields increased 0.44 Mg ha^{-1} with P at 39 kg P ha^{-1}.

Strip-till (ST) is another conservation tillage practice that aims to combine the yield benefits of tillage with the environmental improvements of NT. It is a tillage practice that is isolated to a narrow band, generally 15 to 20 cm wide and 15 to 20 cm deep, while keeping the remaining soil surface undisturbed. Strip-till can improve the seedbed environment in poorly drained soils due to increased soil moisture evaporation, increased soil temperature (Bolton and Booster, 1981) and decreased soil bulk densities in the row compared with NT (Drury et al., 2003; Overstreet and Hoyt, 2008). Strip-till has been shown to increase corn yields compared to NT (Vetsch et al., 2007) and was equal to CT (Griffith et al., 1973; Randall et al., 2001). Vetsch and Randall (2002) evaluated tillage effects on continuous corn production in Minnesota. In continuous corn, yields increased 0.4 Mg ha^{-1} with ST compared to NT. Strip-till/deep fertilizer banding has also been shown to produce less soil nitrous oxide (N_2O) emissions per unit of grain yield compared to NT/surface broadcast (Nash et al., 2012). In Missouri, ST/deep banding averaged 0.52 kg N_2O-N Mg grain^{-1}, which was lower than NT/surface broadcast (0.72 kg N_2O-N Mg grain^{-1}) (Nash et al., 2012).

However, other research has also shown limited yield differences between NT and ST (Mallarino et al., 1999; Al-Kaisi and Lichet, 2004; Al-Kaisi and Kwaw-Mensah, 2007; Archer and Reicosky, 2009). In Iowa, Licht and Al-Kaisi (2005a) found that ST had no effect on N uptake, dry matter production, and corn grain yields compared to chisel plow and NT. Vetsch and Randall (2004) showed that CT increased corn grain yields 0.3 and 0.5 Mg ha^{-1} compared to ST and NT, respectively. However, silage yields were 0.8 and 0.9 Mg ha^{-1} greater for ST and CT compared to NT, respectively. Nitrogen uptake was also greater for ST (193 kg ha^{-1}) and CT (198 kg ha^{-1}) compared with NT (181 kg ha^{-1}). Perez-Bidegain et al. (2007) evaluated different tillage effects on corn and soybean yields in Iowa. No differences were observed for soybean yields between tillage systems, while corn planted with disk-chisel tillage yielded 0.8 Mg ha^{-1} more than the mean yield of ST and NT.

Increased fertilizer costs, new P enhancer products available on the market, and challenges of corn production with NT prompted this research investigating techniques to enhance P fertilizer efficience. The objective of this study was to evaluate the effect of tillage/fertilizer placement, P rate, and two P enhancer products on corn production, grain quality, P uptake, and apparent P recovery efficiency.

MATERIALS AND METHODS

Field research was conducted in 2010 and 2011 at the Greenley Memorial Research Center (40°01'N, 92°11'W) near Novelty, MO on a Kilwinning silt loam (fine, smectitic, mesis, Vertic Epiaqualfs) and at the Hundley-Whaley Center (40°14'N, 94°20'W) near Albany, MO on a Bremer silty clay loam (fine, smectitic, mesic, Typic Argiaquolls). Each site was arranged as a factorial randomized complete block design with four replications. Corn was planted following soybean. Initial soil samples were randomly collected to a 15 cm depth from each replication and analyzed by the University of Missouri Soil and Plant Testing Laboratory using standard methods (Nathan et al., 2006) including soil pH (0.01 M $CaCl_2$), Bray-1 P, exchangeable potassium, calcium, magnesium (1 M NH_4OA_C), zinc (DTPA extraction), soil organic matter (loss-on-ignition), neutralizable acidity (Woodruff buffer), and effective cation exchange capacity (Table 2.1).

Treatments included a 3-factor arrangement of application placement (NT/surface broadcast or strip-till/deep banding), monoammonium phosphate (MAP) rate [0, half the recommended rate (56 kg P_2O_5 ha^{-1}), and recommended rate (112 kg P_2O_5 ha^{-1})], and the presence or absence of two enhanced phosphorus efficiency products [non-treated control, Avail®(Specialty Fertilizer Products, Leawood, KS) at 2.1 L Mg^{-1}, and P_2O_5 Max® (P-Max, Rosen's Inc., Fairmont, MN) at 4.2 L Mg^{-1}]. Phosphorus treatments were deep banded using a Yetter® 2984 strip-till system equipped with high residue Maverick®

units (Yetter Manufacturing, Inc., Colchester, IL), a rolling basket, and dry fertilizer application tubes at the Novelty site. At the Albany site, phosphorus treatments were also deep banded using a Yetter® 2984 strip-till system equipped with residue manager wheels (Yetter Manufacturing, Inc., Colchester, IL), B-33 mole knife, and opposing closing wheel disks. A Gandy Orbit Air® (Gandy Company, Owatonna, MN) dry fertilizer applicator was used to meter and deliver fertilizer behind the applicator knife in the strip till system. Phosphorus was broadcast applied with a hand spreader in the NT surface broadcast treatment. Ammonium nitrate fertilizer was broadcast-applied for the appropriate treatments to balance the N contribution of MAP as the rate was reduced. The planter was equipped with Shark-tooth® (Yetter Manufacturing, Inc., Colchester, IL) residue cleaners used in tandem with a NT coulter. The residue cleaners performed well in heavy residue of the NT plots and provided a smooth seedbed above strip-tilled plots. The row spacing was 0.76-m. Management information is available in Table 2.2.

Corn grain yield and moisture content were measured by harvesting the two center rows with a plot combine (Wintersteiger Delta, Salt Lake City, UT). Grain samples were collected from each plot and evaluated for starch, protein, and oil concentration (Foss Infratec, Eden Prairie, MN). Grain yields were adjusted to 155 g kg^{-1} moisture prior to analysis. Corn silage yield was measured by harvesting 1.5 m of one row at physiological maturity with data expressed on a dry matter basis. The silage samples underwent a H_2SO_4-H_2O_2 digestion and were analyzed for total N (colorimetric Indophenols blue), P (colorimetric ammonium molybdate), and K (atomic absorption) uptake. Apparent P recovery efficiency (APRE) was calculated as [((kg P uptake ha^{-1} of treated - kg P uptake ha^{-1} of control)/(kg fertilizer applied P ha^{-1}))*100]. All data were subjected to analysis of variance and means separated using Fisher's Protected LSD (*P*=0.1). Data were combined over factors and locations when appropriate as indicated by the analysis of variance (data not presented). Plant population at Novelty, plant population at Albany, and grain oil concentration at Novelty were subjected to an *F Max* test for homogeneity (Kuehl, 1994) and combined over site-years when variances were homogenous.

RESULTS AND DISCUSSION

The 2010 season had 265 to 523 mm higher precipitation at both locations than in 2011 (Figure 2.1). The 2010 growing season at Novelty received the highest precipitation (1082 mm) of all four site years. Average precipitation for the past decade was 720 mm (Nelson et al., 2010). The soil temperatures at 5.1 cm under soybean cover were similar at between locations for each year but differed by year (Figure 2.2). Since no four-way interactions (year*P enhancer*placement*MAP rate) existed for all the parameters evaluated, main effects were reported and interactions present when appropriate.

Phosphorus enhancer

The P enhancers did not affect plant population (*P*=0.51), silage dry weights (*P*=0.81), grain moisture (*P*=0.54), yield (*P*=0.83), grain protein (*P*=0.74), grain starch (*P*=0.63), N uptake (*P*=0.42), K uptake (*P*=0.82), or APRE (*P*=0.32) during the four site-years (Tables 2.3 and 2.4). The non-treated control oil concentration at Albany was 1.3 g kg^{-1} greater than P_2O_5-Max® (Table 2.3). In the NT/broadcast and ST/deep banding, the addition of Avail® or P_2O_5-Max® did not increase P uptake over the non-treated controls (Table 2.4). Avail® increased P uptake 5.7 kg ha^{-1} over P_2O_5-Max® with ST/deep banding, while no differences between products were observed with NT/broadcast.

Phosphorus uptake increased 5.9 kg ha^{-1} when P fertilizer was applied with P_2O_5-Max® and NT/broadcast instead of ST/deep banding. Ward (2010) found similar results with Avail® in Kansas for both corn and wheat where there was no significant effect of Avail® on biomass production, P uptake, or grain yields of both crops. In Canada, Karamanos and Puurveen (2011) showed neither a significant effect of treating MAP with Avail®, nor a significant interaction between Avail® treatment and rate of P on the yield of wheat and P uptake.

Phosphorus placement

Strip-till/deep banding increased plant populations 15,500 plants ha^{-1} at Novelty and 3,500 plants ha^{-1} at Albany compared to NT/broadcast (Table 2.5). The claypan soil at Novelty has poorer internal drainage than the Bremer silt loam at Albany. An improved seedbed environment likely caused the higher plant populations with ST. Strip-till can improve the seedbed environment in poorly drained soils due to increased soil moisture evaporation and increased soil temperature in the row compared with NT (Bolton and Booster, 1981). This was particularly important early in the growth season. Licht and Al-Kaisi (2005b) evaluated the effect of tillage on soil temperature. In the top 5 cm, ST increased soil temperature 1.2 to 1.4°C over NT. This caused the corn emergence rate index (ERI) of ST to be slightly greater 0.2 ERI than NT throughout the four site years. This effect could have been important in maintaining a good corn stand during April and early May when rainfall was great (Figure 1) and soil temperatures were cool (Figure 2).

There was no effect of fertilizer placement on silage dry weights, N, or K uptake, but grain moisture was 3.3 g kg^{-1} greater in NT/broadcast compared to ST/deep banding

(Table 2.5). No-till/broadcast increased APRE 20.7% over ST/deep banding. Yields increased 1.57 Mg ha^{-1} with use of ST/deep banding over NT/broadcast at Novelty, but yields at Albany were affected by fertilizer placement and MAP rate. When no MAP was added at Albany, NT/broadcast increased grain yields 0.55 Mg ha^{-1} over ST/deep banding. However, no difference was observed between NT/broadcast and ST/deep banding with MAP at 56 or 112 kg P_2O_5 ha^{-1}. MAP at 0 kg P_2O_5 ha^{-1} yielded 0.71 Mg ha^{-1} more than MAP at 56 kg P_2O_5 ha^{-1} rate under NT/broadcast, but no difference was observed with MAP at 112 kg P_2O_5 ha^{-1}. This difference may be due to the ammonium nitrate that was added to balance the N contribution as the MAP rate increased. The lack of response to the addition of MAP at Albany could also be a result of the higher initial Bray-1 P found at Albany compared to Novelty (Table 2.1).

Strip-till has been shown to increase corn yields compared to NT (Vetsch et al., 2007), but was equal to CT in other research (Griffith et al., 1973; Randall et al., 2001). Vetsch and Randall (2002) found in continuous corn that yield increased 0.4 Mg ha^{-1} with ST compared to NT in Minnesota. However, research has also shown no to limited yield differences between NT and ST (Mallarino et al., 1999; Al-Kaisi and Lichet, 2004; Al-Kaisi and Kwaw-Mensah, 2007; Archer and Reicosky, 2009). In Iowa, Licht and Al-Kaisi (2005a) found that ST had no effect on N uptake, dry matter production, and corn grain yields compared to chisel plow and NT. Perez-Bidegain et al. (2007) evaluated different tillage effects on corn and soybean yields in Iowa. However, no differences were observed for soybean yields between tillage systems, while corn planted with disk-chisel tillage yielded 0.8 Mg ha^{-1} more than the mean yield of ST and NT.

Grain protein and starch concentrations had an interaction between year and placement at Novelty, but not Albany (Table 2.6). NT/broadcast had 14 g kg^{-1} higher protein concentration in 2010 than ST/deep banding and 6 g kg^{-1} higher protein concentration in 2011. In 2010, ST/deep banding increased starch by 8 g kg^{-1}, while starch increased 3 g kg^{-1} with ST/deep banding in 2011. Grain oil concentration was affected by location, placement, and MAP rate. At Novelty, NT/broadcast with MAP at 0 kg P_2O_5 ha^{-1} had at least 1.7 g kg^{-1} lower oil concentration than any other placement-MAP rate combination. At Albany, ST/deep banding with MAP at 0 kg P_2O_5 ha^{-1} had a lower oil concentration than any other placement-MAP rate combination except for NT/broadcast MAP at 112 kg P_2O_5 ha^{-1}. The effect of tillage on plant stand was less pronounced at Albany compared to Novelty which may have affected grain quality.

Monoammonium phosphate rate

Plant population, silage dry weights, and grain moisture were not affected by MAP rate at the four site-years evaluated in this research (Table 2.7). MAP rate had a significant effect on yields with at 0 kg P_2O_5 ha^{-1} yielding 0.30 to 0.36 Mg ha^{-1} more than MAP at 56 or 112 kg P_2O_5 ha^{-1}. This difference may be due to the ammonium nitrate that was added to balance the N contribution as the MAP rate increased to 112 kg ha^{-1}. There were no significant differences between MAP rates for N uptake, but the MAP rate at 0 kg P_2O_5 ha^{-1} indicated higher N uptake than MAP at 56 or 112 kg P_2O_5 ha^{-1} (Table 2.8). A greenhouse study using corn evaluated the effectiveness of DAP as a dual source of N and P (Lu et al., 1987). Diammonium phosphate was compared with urea plus single superphosphate (SSP) placed at different depths (surface broadcast, incorporation, and deep banding) on a calcareous clay soil. Soil treated with urea plus SSP had higher Olsen

P than soil treated with DAP regardless of fertilizer placement. With both fertilizers, surface broadcasting apparently reduced the accessibility of P to the plant roots and resulted in lower P uptake and plant yield than incorporation treatments. When the fertilizers were either incorporated or deep-placed, N uptake was as high with DAP as with urea plus SSP. However, surface application resulted in lower N uptake from DAP than from urea plus SSP. Urea plus SSP produced higher plant yields than those obtained with DAP regardless of the method of fertilizer placement.

Grain protein concentration increased 3 g kg^{-1} with MAP at 56 and 112 kg P_2O_5 ha^{-1} compared to the non-treated control at Novelty in 2011, but no differences were observed at Novelty in 2010 or Albany (Table 2.7). MAP at 0 and 112 kg P_2O_5 ha^{-1} increased starch concentration 2 g kg^{-1} over MAP at 56 P_2O_5 ha^{-1} at Novelty, but not at Albany. Plant N, P, K uptake, or APRE were not affected by MAP rate at the four site-years evaluated in this research (Table 2.8).

CONCLUSIONS

The two P enhanced efficiency products studied in this research did not consistently increase agronomic performance, including apparent P recover efficiency, at the sites and environmental conditions in interaction with several fertilization rates and tillage practices evaluated in this research. The addition, the P enhancers did not affect plant population, silage dry weights, grain moisture, yield, grain protein, grain starch, N, K uptake, or apparent P recovery efficiency. In both NT/broadcast and ST/deep banding, the addition of Avail® or P_2O_5-Max® did not increase P uptake over the non-treated controls. Since in this trial the soils tested were acidic, more research needs to done on alkaline soils.

Strip-till/deep banding showed an increase in plant populations of 3,500 to 15,500 plants ha^{-1} compared to NT/broacast. An improved seedbed environment with lower soil moisture and higher soil temperatures likely caused the higher plant populations with ST. The higher plant populations of ST resulted in increased grain yields 1.57 Mg ha^{-1} compared to NT at Novelty. Poorly drained claypan soils in Northeast Missouri responded greater to strip-till than silty clay soils in Northwest Missouri. MAP rate had a significant effect on yields with P_2O_5 at 0 kg ha^{-1} yielding 0.30 to 0.36 Mg ha^{-1} more than MAP at 56 or 112 kg P_2O_5 ha^{-1}. This difference may be due to the ammonium nitrate that was added to balance the N contribution as the MAP rate increased to 112 kg ha^{-1}.

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Table 2.1. Selected initial soil properties for the P placement, rate, and enhancer experiments at Novelty and Albany in 2010 and 2011.

	Novelty		Albany	
	2010	2011	2010	2011
pHs (0.01 M $CaCl_2$)	6.8 ± 0.3[†]	6.6 ± 0.2	6.4 ± 0.4	6.0 ± 0.3
Bray-1 P (kg ha^{-1})	50 ± 26	27 ± 8	90 ± 48	90 ± 11
Exchangeable (1 M NH_4OA_C)				
Potassium (kg ha^{-1})	275 ± 41	158 ± 25	293 ± 25	315 ± 44
Calcium (kg ha^{-1})	6039 ± 528	5585 ± 242	6466 ± 417	6513 ± 692
Magnesium (kg ha^{-1})	470 ± 83	502 ± 54	713 ± 200	779 ± 109
Zinc (mg kg^{-1}) (DTPA Extraction)	0.75 ± 0.24	0.35 ± 0.13	0.80 ± 0.24	0.88 ± 0.17
Soil organic matter (g kg^{-1})	24 ± 8	26 ± 1	25 ± 1	27 ± 7
Neutralizable acidity ($cmol_c$ kg^{-1})	0.25 ± 0.5	0.75 ± 0.29	1.25 ± 1.19	2 ± 0.82
Cation exchange capacity ($cmol_c$ kg^{-1})	16 ± 1	15 ± 1	19 ± 2	20 ± 3

[†] Standard deviation

Table 2.2. Field and management information for P placement, rate, and enhancer experiments at Novelty and Albany in 2010 and 2011.

Management information	Novelty		Albany	
	2010	2011	2010	2011
Plot size	3 by 23 m	3 by 23 m	4.6 by 23 m	4.6 by 23 m
Hybrid	DK 62-54 VT3	DK 62-54 VT3	DK 63-84 VT3	DK 63-84 VT3
Planting Date	14 Apr.	31 Mar.	30 May	13 Apr.
Seeding rate	74,100 seeds ha^{-1}	74,100 seeds ha^{-1}	74,100 seeds ha^{-1}	72,900 seeds ha^{-1}
Tissue harvest date	7 Sep.	25 Aug.	9 Sep.	26 Aug.
Harvest date	30 Oct.	8 Sep.	15 Oct.	27 Sep.
P fertilizer application date	13 Apr.	30 Mar.	15 Apr.	15 Nov.
Additional fertilizer (date, source, & rate)	6 May, Urea (202 kg N ha^{-1}) + NBPT (4 L Mg^{-1})	31 Oct. 2010, Anhydrous ammonia (179 kg N ha^{-1}) + Nitrapyrin (0.56 kg a.i. ha^{-1})	19 Apr., Urea (168 kg N ha^{-1}) + NBPT (4 L Mg^{-1})	14 Apr., Urea (168 kg ha^{-1})
Weed management[‡]				
Burndown	NA	11 Apr., Glyphosate (1.06 kg a.i. ha^{-1}) + DS (0.36 kg a.i. ha^{-1}) + DAS (512 mL ha^{-1})	NA	NA
Preemergence	16 Apr., S-metolachlor (2.25 kg a.i. ha^{-1}) + Atrazine (0.84 kg a.i. ha^{-1}) + Mesotrione (0.23 kg a.i. ha^{-1}) + DSD (0.56 kg a.i. ha^{-1})	13 Apr., Acetochlor (2.35 kg a.i. ha^{-1}) + Atrazine (1.77 kg a.i. ha^{-1})	15 Apr., S-metolachlor (2.4 kg a.i. ha^{-1}) + Atrazine (0.9 kg a.i. ha^{-1}) + Mesotrione (0.24 kg a.i. ha^{-1}) ; 30 May, Isoxaflutole (0.14 kg a.i. ha^{-1})	16 Apr., S-metolachlor (2.4 kg a.i. ha^{-1}) + Atrazine (0.9 kg a.i. ha^{-1}) + Mesotrione (0.24 kg a.i. ha^{-1})
Postemergence	22 June, Glyphosate (1.45 kg a.i. ha^{-1}) + DAS (0.04 kg a.i. ha^{-1})	NA	21 June, Glyphosate (1.16 kg a.i. ha^{-1})	7 June, Glyphosate (1.16 kg a.i. ha^{-1})

[†] Abbreviations: DAS, Diammonium sulfate; DS, Dimethylamine salt; DSD, Dimethylamine salt of dicamba; NA, None applied;

[‡] acetochlor (2-chloro-2'-methyl-6'ethyl-N-ethoxymethylacetanilide); atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine); diammonium sulfate ((NH4)2SO4); dimethylamine salt (2,4-Dichlorophenoxyacetic acid); dimethylamine salt of dicamba (3,6-dichloro-0-anisic acid); glyphosate (N-(phosphonomethyl)glycine); isoxaflutole (5-cyclopropyl-4-(2-methylsulfonyl-4-trifluoromethylbenzoyl) isoxazole); mesotrione (2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione); nitrapyrin (2-chloro-6-(trichloromethyl) pyridine); NBPT (N-(n-butyl) thiophosphoric triamide); S-metolachlor (2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl]acctamide).

Table 2.3. The effect of P enhancer on plant population, silage dry weights, grain moisture, yield, oil, protein, and starch. Data were combined over site-year, placement, and MAP rate except for grain oil.

P enhancer	Plant population	Silage dry weights	Grain moisture	Yield	Oil		Protein	Starch
					Novelty[†]	Albany[†]		
	plants ha^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	---------- g kg^{-1} ----------		g kg^{-1}	g kg^{-1}
Non-treated	59,800	14.9	172	8.21	36.8	37.7	83	729
Avail®	58,200	14.6	170	8.28	36 .4	36.9	84	730
P_2O_5-Max®	58,500	14.8	170	8.20	36.9	36.4	84	730
LSD (*P*=0.1)	NS[‡]	NS	NS	NS	NS	0.7	NS	NS
P-value	0.51	0.83	0.54	0.83	0.74	0.01	0.74	0.63

[†] Data were combined over years (2010 and 2011).

[‡] NS = Not significant

Table 2.4. The effect of P enhancer on uptake of N, K, P uptake, and apparent P recovery efficiency (APRE). Data were combined over site-year, placement, and MAP rate except for P uptake.

			P uptake		
			Placement		
P enhancer	N uptake	K uptake	NT/broadcast	ST/deep banding	APRE
	kg ha^{-1}	kg ha^{-1}	----------------kg ha^{-1}----------------		%
Non-treated	420.1	279.8	39.6	38.1	16.1
Avail®	430.7	279.1	38.0	39.8	13.1
P_2O_5-Max®	448.2	285.3	40.0	34.1	3.8
LSD (P=0.1)	NS[†]	NS	------------------4.1------------------		NS
P-value	0.42	0.82	-----------------0.09-----------------		0.32

[†] NS =Not significant

Table 2.5. Phosphorus placement effect on plant population, silage dry weights, grain moisture, yield, N, K uptake, and apparent P recovery efficiency (APRE). Data were combined over site-year, MAP rate, and P stabilizer except for plant population and yield.

					Yield						
	Plant population					Albany†					
			Silage dry	Grain		MAP rate (kg P_2O_5 ha^{-1})					
Placement	Novelty†	Albany†	weights	moisture	Novelty†	0	56	112	N uptake	K uptake	APRE
	----plants ha^{-1}-----		Mg ha^{-1}	g kg^{-1}	--------------------Mg ha^{-1}--------------------				kg ha^{-1}	kg ha^{-1}	%
NT/broadcast	50,600	57,600	14.7	172.2	6.74	9.32	8.61	8.97	430.8	285.7	21.4
ST/deep banding	66,100	61,100	14.9	168.9	8.31	8.77	8.90	9.05	435.2	277.1	0.7
LSD (P=0.1)	2,600	2,900	NS‡	2.4	0.36	---------------0.47---------------			NS	NS	11.5

†Data were combined over years (2010 and 2011).
‡NS = Not significant

Table 2.6. Placement effect on grain protein, starch, and oil. Data were combined over MAP rate and P stabilizer except for grain oil which was combined over site year and P stabilizer.

							Oil					
	Protein			Starch			Novelty†			Albany†		
	Novelty			Novelty			MAP rate(kg P_2O_5 ha^{-1})			MAP rate(kg P_2O_5 ha^{-1})		
Placement	2010	2011	Albany†	2010	2011	Albany†	0	56	112	0	56	112
	------------- g kg^{-1} -------------			------------- g kg^{-1} -------------			---------- g kg^{-1} ----------			---------- g kg^{-1} ----------		
NT/broadcast	84	93	84	739	729	723	34.8	37.3	36.5	37.4	37.3	36.8
ST/deep banding	70	87	85	747	732	722	37.5	37.5	36.7	36.0	37.6	37.0
LSD (P=0.1)	2	2	NS‡	2	2	NS	----------1.4----------			----------1.0----------		

†Data were combined over years (2010 and 2011).
‡NS = Not significant

Table 2.7. Plant population, silage dry weights, grain moisture, yield, protein, and starch as affected by MAP rate. Data were combined over site-year, location, placement, and P stabilizer except for grain protein and starch.

					Protein				
	Plant	Silage dry	Grain		Novelty			Starch	
MAP Rate	population	weights	moisture	Yield	2010	2011	Albany[†]	Novelty[†]	Albany[†]
kg P_2O_5 ha^{-1}	plants ha^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	----------- g kg^{-1} ----------			------- g kg^{-1} -------	
0	58,800	15.2	171	8.44	77	88	85	737	723
56	59,000	14.5	170	8.08	77	91	84	735	722
112	58,700	14.6	170	8.14	76	91	84	737	723
LSD (*P*=0.1)	NS[‡]	NS	NS	0.25	NS	2	NS	2	NS

[†] Data were combined over years (2010 and 2011).

[‡] NS = Not significant

Table 2.8. The effect of MAP rate on N, P, K uptake, and apparent P recovery efficiency (APRE).

MAP rate	N uptake	P uptake	K uptake	APRE
kg P_2O_5 ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	%
0	440.7	37.2	289.2	
56	429.6	38.2	270.0	12.9
112	428.7	39.5	285.1	9.1
LSD (*P*=0.1)	NS[‡]	NS	NS	NS

[†] Data were combined over years (2010 and 2011).

[‡] NS = Not significant

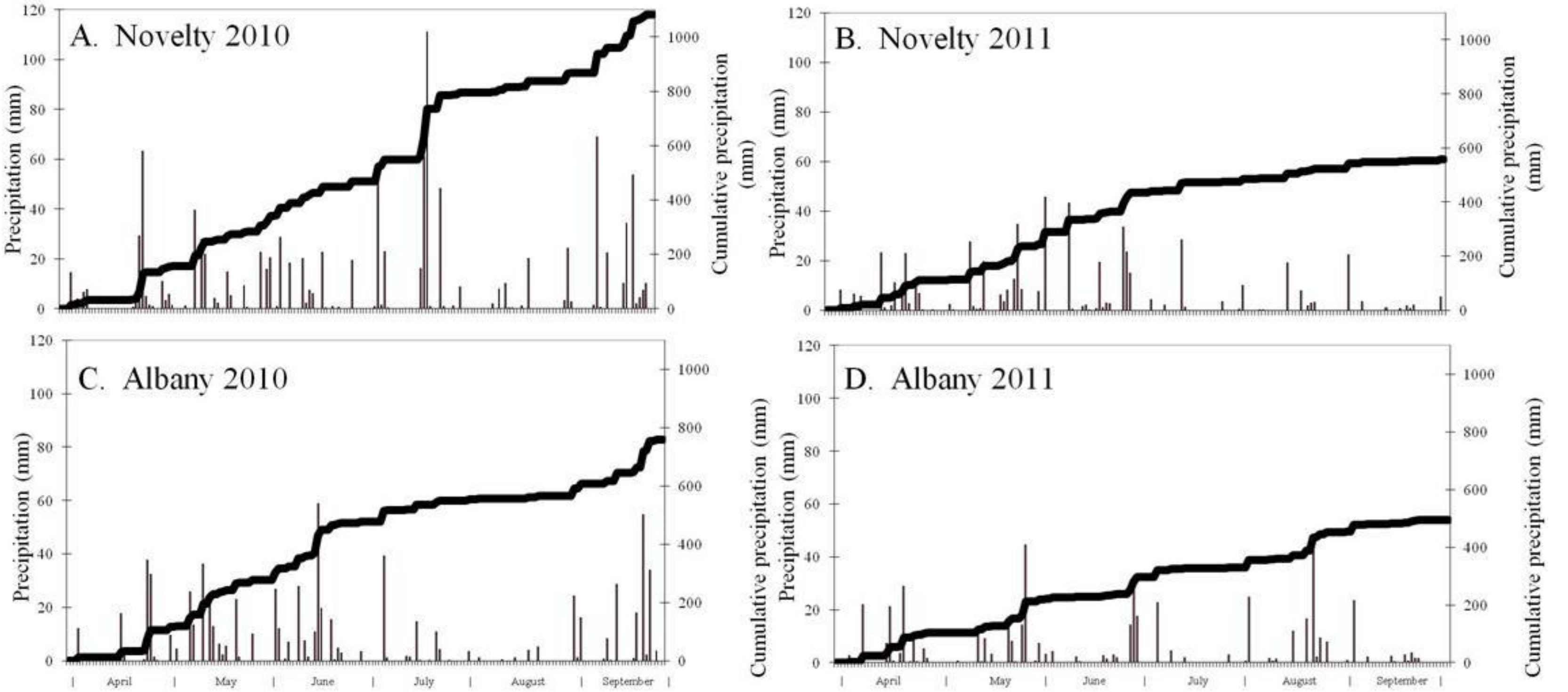

Figure 2.1. Daily (bars) and cumulative (line) precipitation from March through September of 2010 and 2011 at Novelty (A and B) and Albany (C and D).

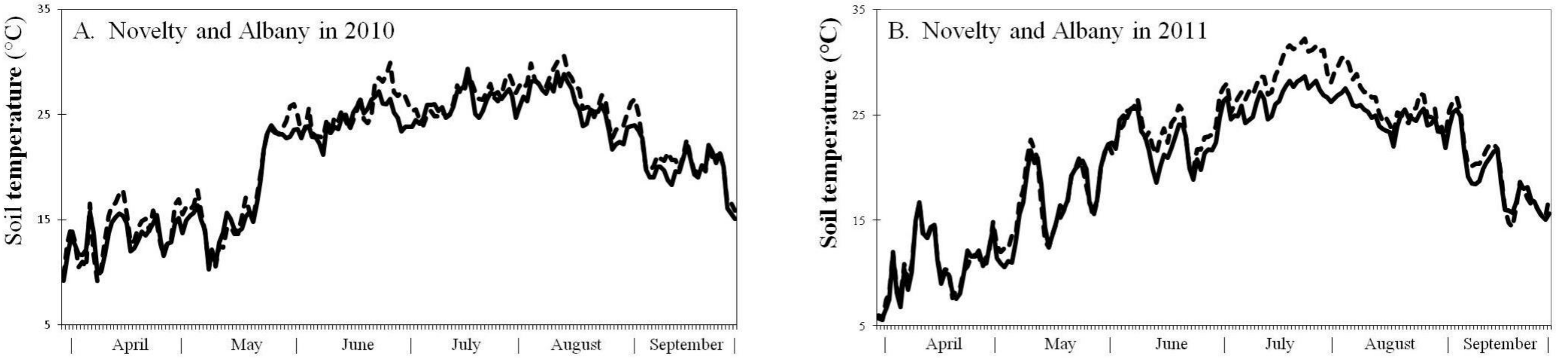

Figure 2.2. Average daily soil temperature at 51 mm depth under soybean residue from March through September in 2010 (A) and 2011 (B) at Novelty and Albany. The solid line is Novelty and the dashed line is Albany.

CHAPTER 3-CORN PRODUCTION AS AFFECTED BY PHOSPHORUS ENHANCERS, PHOSPHORUS SOURCE, AND LIME

ABSTRACT

With high fertilizer costs, farmers are interested in enhancing the efficiency of their P fertilizers. A study was initiated to determine the effects of liming application (0 and recommended rate), P source [non-treated control and a broadcast application of diammonium phosphate (DAP) or triple superphosphate (TSP)], and the presence or absence of two commercial enhanced phosphorus efficiency products (Avail$^{®}$ and P_2O_5-Max$^{®}$) on corn (*Zea mays* L.) production. The study was conducted at Novelty in northeastern Missouri and Portageville in southeastern Missouri. The P enhancers did not affect plant population, silage dry weights, grain moisture, yield, protein, oil, or starch concentrations at either location. Plant N, P, K uptake, and apparent P recovery efficiency (APRE) were not affected by P enhancers at Portageville. At Novelty, neither P enhancer paired with DAP increased P uptake over the non-treated control. Triple superphosphate treated with Avail$^{®}$ increased P uptake 8.6 kg ha^{-1} compared to the non-treated control and 7.1 kg ha^{-1} compared to P_2O_5-Max$^{®}$. In 2010 at Novelty, TSP treated with Avail$^{®}$ increased K uptake 150 kg ha^{-1} compared to the non-treated TSP and 100 kg ha^{-1} compared to P_2O_5-Max$^{®}$. Plant population was 4,800 plants ha^{-1} greater in the non-limed control compared to the recommended rate in 2011 at Novelty, while plant population was not affected at Portageville. The recommended amount of lime increased grain yields 0.77 Mg ha^{-1} at Portageville, but there was no effect at Novelty. Plant P uptake increased

3.4 kg ha^{-1}with the application of lime at Novelty, but was not affected at Portageville. Grain yield increased 0.34 Mg ha^{-1} with TSP compared to the non-treated control.

INTRODUCTION

Phosphorus (P) is an essential plant macronutrient. Phosphorus fertilizers are used in large quantities in agriculture, horticulture, and turf grass. The U.S. used 2.03x10^{8} Mg of P_2O_5 from 1960 to 2010 (USDA, 2012). In Missouri alone, P fertilizer use for corn production has increased from 4.4x10^{4} Mg P_2O_5 in 1990 to 8.0x10^{4} Mg P_2O_5 in 2010 (USDA, 2011).

With high fertilizer costs, farmers are interested in reduced P application rates and use of P enhancers. Avail® (Specialty Fertilizer Products, Leawood, KS) and P_2O_5-Max® (P-Max, Rosen’s Inc., Fairmont, MN) are commercial products that are claimed to enhance the efficiency of P-based fertilizers on several soil types. Avail® is a P enhancer for granular phosphate fertilizers, such as DAP and MAP, as well as other liquid phosphate fertilizers. It was designed to reduce the impact of cations (i.e., Ca, Fe, Mn, and Al) in the soil around the fertilizer granule on P sorption and plant P uptake. This product binds with Ca, Fe, Mn, and Al to prevent precipitation of P (SFP, 2009). The active ingredient is a maleic-itaconic copolymer (SFP, 2005). P_2O_5-Max® is claimed to increase P uptake and improve root surface area resulting in better nutrient absorption and higher yields. The active ingredient is poly amino acid (L-aspartic acid), sodium salt (Rosen's Inc, 2012).

There have been limited published research on the effects of Avail® on plant growth and yields. A study conducted in 2008 and 2009 at five locations throughout Kansas evaluated the effectiveness of Avail® under corn and wheat cropping systems

(Ward, 2010). There was no significant effect of Avail® on plant biomass, P uptake, or grain yields for corn and wheat. In Canada, two trials evaluated four rates of seed-placed MAP at 0, 6.5, 13, and 19.5 kg P ha^{-1} with and without Avail® (Karamanos and Puurveen, 2011). The results showed neither a significant effect of treating MAP with Avail®, nor a significant interaction between Avail® treatment and rate of P on yield of wheat and P uptake.

Many different sources of P fertilizers are available on the market. Three of the most popular fertilizers used by farmers are triple superphosphate (TSP), MAP, and diammonium phosphate (DAP). Some of the differences between these fertilizers are their solubility and nutrient concentration. Monocalcium phosphate (main P form in TSP) has been found to be more soluble and plant available than DAP in an alkaline soil, but slightly less soluble in an acidic soil (Bouldin and Sample, 1959). MAP and DAP are popular with producers because they provide the soil not only with P but also nitrogen (N) which could potentially reduce application time and cost. However, limited research has evaluated DAP as a source of N and P. A greenhouse study using corn evaluated the effectiveness of DAP as a dual source of N and P. DAP was compared with urea plus single superphosphate (SSP) placed at different depths (surface broadcast, incorporation, and deep banding) in a calcareous clay soil. Soil treated with urea plus SSP had higher Olsen P than soil treated with DAP regardless of fertilizer placement. With both fertilizers, surface broadcasting apparently reduced the accessibility of P to the plant roots and resulted in a lower P uptake and plant yield than incorporation treatments. When the fertilizers were either incorporated or deep-placed, N uptake was as high with DAP as with urea plus SSP. However, surface application resulted in lower N uptake from DAP than from urea plus SSP. Urea plus SSP produced higher plant yields than those obtained with DAP regardless of the method of fertilizer placement (Lu et al., 1987). Other research has shown little to no difference in grain yields and soil P levels between P fertilizer sources (Reid et al. 2004). Garcia et al. (1997) tested phosphate availability of several P fertilizers in calcareous soils with a high P sorption capacity. Available P levels did not increase when SSP, TSP, or DAP were applied. This was due to the sorption of P by the formation of Ca phosphates in these high pH and Ca content soils.

Other research has shown interactions between Zn and P where a high rate of P decreased zinc (Zn) tissue concentrations (Warnock, 1970; Safaya, 1976). Singh et al. (1986) observed wheat Zn tissue concentrations decreased 3.0 mg kg^{-1} and 6.7 mg kg^{-1} as the P fertilizer application increased from 0 kg ha^{-1} to 80 and 160 kg ha^{-1}, respectively. A greenhouse study found total Zn accumulation in corn shoots increased 175 µg pot^{-1} and Zn tissue concentration decreased 21 µg g^{-1} as P fertilizer application increased from 0 to 300 mg kg^{-1} (Friesen et al., 1980). The dilution of Zn to deficiency levels as the plant growth rate increased in response to applied P was considered the primary reason for these results.

The concentration of plant available forms of P is largely affected by adsorption-desorption and precipitation reactions. These reactions may be influenced by increases in pH and Ca concentrations resulting from lime application. The speciation of phosphate and electrostatic potential of adsorbing surfaces are two key factors in adsorption reactions that change with an increase in pH. Increasing pH increases the concentration of divalent phosphate ion (HPO_4^{2-}), which promotes adsorption. At the same time, when variable charge is present, the soil surface becomes more negatively charged as pH increases and retains fewer phosphate ions (Barrow, 1984). This resulted in an increase in plant available P in the soil solution. An application of lime can also decrease plant available P by increasing the concentration of Ca which resulted in an increase in P precipitation as Ca phosphate (Naidu et al., 1990). The result of these competing affinities was expected to determine whether lime increased (Friesen et al. 1980) or decreased (Amarasiri and Olsen, 1973; Westermann, 1992) P uptake.

Calcium deficiency (Ritchey et al., 1982) and Al toxicity (Pavan et al., 1982) are considered major yield limiting factors resulting from acid soils. Liming has been shown to resolve these issues by increasing soil pH and adding Ca. The application of lime increased exchangeable Ca, exchangeable Mg, and decreased exchangeable Al (Lim and Shen, 1978). Moschler et al. (1973) evaluated how liming affected exchangeable Ca and exchangeable Al in the upper 10 cm between no-tilled (NT) and conventional tilled (CT) corn in Virginia. In the limed NT soil, exchangeable Al comprised only 0.2% of the exchangeable cations, compared to 29.9% in non-limed NT soil. Aluminum saturation in tilled soil that received lime was 0.8% compared to 14.0% in non-limed, CT soil. More exchangeable Ca and higher soil pH were present in the limed, NT soil compared to limed, CT soil. The higher exchangeable Al and less favorable rooting environment in the nonlimed soils reduced early growth of corn. An increase in corn maturity at harvest with limed soil resulted in an increase in corn yields.

The increase in soil pH, exchangeable Ca, and decreased exchangeable Al resulted in increased corn yields between 718 to 828 kg ha^{-1} from a surface application of lime on NT (Blevins et al., 1978). However, the application method of the lime also determined its effectiveness. Moschler et al. (1973) compared continuous NT corn to continuous CT corn with or without lime. In NT corn, lime was surface applied, while the lime was incorporated into the soil in CT corn. The application of lime increased corn grain yield more than twice as much in NT (31.3%) as in CT (13.5%). In both tillage systems, lime was essential for the highest yields. Other research has shown no effect of lime or a decrease in grain yields in some instances (Estes, 1972; Woodruff et al., 1987). In central Iowa, only one of five site-years increased grain yield (230 kg ha^{-1}) in response to a lime application. The most likely reason for this lack of response was due to the presence of high-pH (calcareous) subsoils (Bianchini and Mallarino, 2002). Caires et al. (2005) also found limited results from the application of lime in Brazil. Only one site-year of soybeans out of eight and one site-year of wheat out of two increased in grain yields.

Increased fertilizer costs, new P enhancer products available on the market, and challenges of corn production with NT prompted this research for enhancing the effectiveness of P fertilizers. The objective of this study was to evaluate the effect of liming, P source, and P enhancer products on corn production and P uptake.

MATERIALS AND METHODS

Research trials were established at the Greenley Memorial Research Center (40°01'N, 92°11'W) near Novelty, MO on a Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs) in 2010 and 2011, and the Delta Center (36°23'N, 89°36'W) near Portageville, MO on a Tiptonville silt loam (fine-silty, mixed, superactive, thermic Oxyaquic Argiudolls) in 2010. Each site was arranged as a factorial randomized complete block design with four replications. Initial soil samples were collected from each replication to a 15 cm depth using a stainless steel push probe and characterized for soil pH (0.01 M $CaCl_2$), Bray-1 P, exchangeable (1 M NH_4OA_C) potassium, calcium, magnesium, zinc (DTPA extraction), soil organic matter (loss-on-ignition), neutralizable acidity (Woodruff buffer), and cation exchange capacity using standard methods of the University of Missouri Soil and Plant Testing Laboratory (Nathan et al., 2006) (Table 3.1).

Treatments included a 3-factor arrangement of P source (non-treated control and a broadcast application of DAP or TSP), presence or absence of the phosphorus efficiency products [non-treated control, Avail®(Specialty Fertilizer Products, Leawood, KS) at 2.1 L Mg^{-1}, and P_2O_5-Max® (P-Max, Rosen's Inc., Fairmont, MN) at 4.2 L Mg^{-1}], and broadcast surface application of ag calcitic limestone [0 and recommended (8.1 Mg ha^{-1} at Novelty in 2010, 3.4 Mg ha^{-1} at Novelty in 2011, and 4.5 Mg ha^{-1} at Portageville in 2010)] based on University of Missouri lime recommendations (Buchholz, 1992). Plots were 3 by 14 m. The Novelty site was no-till and rain fed, while the Portageville was conventional tillage with furrow irrigation and application of irrigation water (25 mm) when no rainfall events occurred. Management information is available in Table 3.2.

Corn grain yield and moisture content were measured by harvesting the two center rows with a plot combine (Wintersteiger Delta, Salt Lake City, UT). Grain samples were collected from each plot and evaluated for starch, protein, and oil concentration (Foss Infratec, Eden Prairie, MN) at Novelty. Grain yields were adjusted to 155 g kg^{-1} moisture prior to analysis. Corn silage yield was measured by harvesting 1.5 m of one row at physiological maturity with data expressed on a dry matter basis. The silage samples underwent a H_2SO_4-H_2O_2 digestion and were analyzed for total N (colorimetric

Indophenols blue), P (colorimetric ammonium molybdate), and K (atomic absorption) concentration. Plant N, P, and K uptake were calculated by multiplying silage dry matter yield times tissue nutrient concentration. Apparent phosphorus recovery efficiency (APRE) was calculated as [((P $\text{uptake}_{\text{treated}}$-P $\text{uptake}_{\text{control}}$)/(P fertilizer applied))*100]. All data were subjected to analysis of variance and means separated using Fisher's Protected LSD (P=0.1). Data were combined over factors and locations when appropriate as indicated by the analysis of variance (data not presented).

RESULTS AND DISCUSSION

The 2010 growing season at Novelty received the highest cumulative precipitation of the three growing seasons (Figure 3.1). From March 30 to September 27, the cumulative precipitation at Novelty was 1082 mm in 2010 and 559 mm in 2011, while Portageville received 405 mm in 2010. In Missouri, the long term (1895-1998) average growing season (April through September) cumulative precipitation was 612 mm (Hu and Buyanovsky, 2003). Although there were environmental differences among years, no 4-way interactions (year*liming*P source*P enhancer) existed for the parameters evaluated, and main effects were reported and interactions present when appropriate.

Phosphorus enhancer

Enhanced efficiency P products did not affect plant population (P=0.31), silage dry weights (P=0.48), grain moisture (P=0.69), yield (P=0.65), grain oil (P=0.44), protein (P=0.97), or starch (P=0.48) concentration compared to the non-treated control (Table 3.3). Plant P uptake was affected by P source and P enhancer at Novelty, while P uptake was not affected at Portageville (Table 3.4). When the fertilizer was not treated with a P enhancer, DAP plant P uptake was 8.2 to 8.9 kg ha^{-1} greater than the non-treated control and TSP. Neither of the P enhancers combined with DAP increased P uptake over the non-treated control. Triple superphosphate treated with Avail® increased P uptake 8.6 kg ha^{-1} compared to non-treated TSP and 7.1 kg ha^{-1} compared to P_2O_5-Max®. The lack of response in P uptake at Portageville may be a result of its higher Bray 1-P levels (118 kg ha^{-1}) compared to Novelty (10 to 30 kg ha^{-1}) (Table 3.1). The differences in P uptake between TSP and DAP applied with Avail® could be a result of their differences in solubility. Monocalcium phosphate (the main P form in TSP) has been found to be more soluble and plant available than DAP in an alkaline soil, but less soluble in an acidic soil (Bouldin and Sample, 1959). The soils in this experiment were slightly acidic (pH 5.4 to 5.8), so TSP was probably less soluble than DAP (Table 3.1). More P from TSP was able to stay in area of protection provided by Avail® resulting in the higher P uptake.

Plant K uptake was not affected by P enhancers at Portageville or the 2011 growing season at Novelty (Table 3.4). The 2010 growing season at Novelty showed an interaction between P source and P enhancer for K uptake. TSP treated with Avail® increased K uptake over all other P source-P enhancer combinations except for P_2O_5-Max® applied with the non-treated P-source. When TSP was the P source, Avail® increased K uptake 151.1 kg ha^{-1} compared to the non-treated TSP and 99.9 kg ha^{-1} compared to P_2O_5-Max®. The non-treated P source had higher plant K uptake 75.7 kg ha^{-1} than TSP when no P enhancer was applied. There was no effect of P enhancer on N uptake (P=0.45) or APRE (P=0.43) (Table 3.5). Ward (2010) found similar results with Avail® in Kansas for both corn and wheat. There was no significant effect of Avail® on biomass production, tissue P concentration, or grain yields. Similar in Canada, Karamanos and Puurveen (2011) showed neither a significant effect of treating MAP with Avail®, nor a significant interaction between Avail® treatment and rate of P on wheat yield and P uptake.

Liming application

Plant population was 4,800 plants ha^{-1} greater in the non-limed control compared to the recommended rate in 2011 at Novelty, while plant population was not affected at Portageville (Table 3.6). The recommended amount of lime increased grain yields 0.77 Mg ha^{-1} at Portageville, but there was no effect at Novelty. Grain moisture, oil, protein, and starch concentrations were not affected by the lime treatment at either location.

Blevins et al. (1978) found that surface application of lime on NT increased corn yields between 718 to 828 kg ha^{-1} because of the subsequent increase in soil pH, exchangeable Ca, and decreased exchangeable Al. Other research has shown no effect of lime or a decrease in grain yields in some instances (Estes, 1972; Woodruff et al., 1987). In central Iowa, only one of five site-years increased grain yield (230 kg ha^{-1}) in response to a lime application. The most likely reason for this lack of response was due to the presence of high-pH (calcareous) subsoils (Bianchini and Mallarino, 2002).

Lime application had no effect on N and K uptake (Table 3.7). Phosphorus uptake increased 3.4 kg P ha^{-1}with the application of lime at Novelty, but was not affected at Portageville. The lack of response in P uptake at Portageville may be a result of higher Bray 1-P soil levels (118 kg ha^{-1}) compared to Novelty (10 to 30 kg ha^{-1}) (Table 3.1). The increased P uptake with application of lime could be due to adsorption-desorption and precipitation reactions in the soil (Barrow, 1984). These reactions are influenced by increased pH and Ca concentrations resulting from lime application (Barrow, 1984). The speciation of phosphate and the electrostatic potential of adsorbing surfaces are two key factors in adsorption reactions that change with an increase in pH. A higher pH increased the concentration of divalent phosphate ion (HPO_4^{2-}) and which promoted adsorption. At the same time, when variable charges are present, the soil surface becomes more negatively charged as pH increases and therefore it retain less phosphate ions. This results in an increase in plant available P in the soil solution. However, the lime application in this research decreased APRE 13.4 %.

Phosphorus source

Silage dry weights increased 2.2 Mg ha^{-1} with an application of lime in the non-treated control, but no dry weight differences between lime treatments were observed in the presence of DAP or TSP (Table 3.8). Triple superphosphate increased silage dry weights 2.0 Mg ha^{-1} over the non-treated control when no lime was applied. An application of TSP or DAP had a grain moisture that was 9 to 13 g kg^{-1} lower than the non-treated control. Grain yield increased 0.34 Mg ha^{-1} with TSP compared to the non-treated control. However, N uptake, grain oil, protein, starch and APRE were not affected by P source. Other research has shown little to no difference in grain yields and soil P levels between P fertilizer sources (Reid et al. 2004). Garcia et al. (1997) tested P availability of several P fertilizers in calcareous soils with a high P sorption capacity. Available P levels did not increase when single superphosphate, TSP, or DAP were applied. This was due to the sorption of P by the formation of Ca phosphates in these high pH and Ca content soils.

CONCLUSIONS

This research indicated that the two P enhanced efficiency products studied in this research did not consistently increase agronomic performance, including apparent P recover efficiency, at the sites and environmental conditions in interaction with several P fertilizers and liming practices evaluated in this research. Enhanced efficiency P products did not affect plant population, silage dry weight, grain moisture, yield, oil, protein, starch, or N uptake compared to the non-treated control. Triple superphosphate treated with Avail® increased P uptake 8.6 kg ha^{-1} compared to the non-treated control and 7.1 kg ha^{-1} compared to P_2O_5-Max® at Novelty, but not at Portageville. Since in this trial the soils tested were acidic, more research needs to done on alkaline soils.

The application of lime resulted in mixed production results for the first year corn production after application, at the sites and environmental conditions in this research. Lime application decreased plant population 4,800 plants ha^{-1} in 2011 at Novelty, and increased grain yields 0.77 Mg ha^{-1} at Portageville. Plant P uptake increased 3.4 kg ha^{-1}with the application of lime at Novelty, but was not affected at Portageville. This study showed no significant production differences between TSP and DAP at either location. The application of TSP increased grain yield 0.34 Mg ha^{-1} compared to the non-treated control, while no differences were observed between DAP and the no-treated control.

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Table 3.1. Soil analysis for the P source, P enhancer, and ag lime experiment at Portageville in 2010 and Novelty in 2010 and 2011.

	Novelty		Portageville
	2010	2011	2010
pH_s (0.01 M $CaCl_2$)	5.4 ± 0.1[†]	5.8 ± 0.1	5.2 ± 0.3
Bray-1 P (kg ha^{-1})	30 ± 8	10 ± 2	118 ± 30
Exchangeable (1 M NH_4OA_C)			
Potassium (kg ha^{-1})	285 ± 27	80 ± 13	278 ± 86
Calcium (kg ha^{-1})	5008 ± 155	3918 ± 344	1935 ± 383
Magnesium (kg ha^{-1})	451 ± 84	325 ± 33	344 ± 95
Zinc (mg kg^{-1})	0.78 ± 0.15	0.35 ± 0.06	NA
Soil organic matter (g kg^{-1})	26 ± 2	22 ± 1	14 ± 2
Neutralizable acidity ($cmol_c$ kg^{-1})	4 ± 0.8	1.9 ± 0.3	2.9 ± 0.8
Cation exchange capacity ($cmol_c$ kg^{-1})	17 ± 1	12 ± 1	9 ± 1

[†] Standard deviation

[‡] NA = Not available

Table 3.2. Management information for the P source, P enhancers, and ag lime experiment at Portageville in 2010 and Novelty in 2010 and 2011.

	Novelty		Portageville
Management information	2010	2011	2010
Previous crop	Corn	Wheat	Corn
Hybrid or cultivar	DK 61-69 VT3	DKC 63-42 VT3	Cropland Genetics 68-31
Planting date	26 May	10 May	7 Apr.
Seeding rate	74,100 seeds ha^{-1}	76,100 seeds ha^{-1}	74,100 seeds ha^{-1}
Tissue harvest date	7 Sep.	25 Aug.	16 Aug.
Harvest date	1 Oct.	14 Sep.	8-9 Sep.
Fertilizer			
P application (date & rate)	27 Apr. 118 kg P$_2$O$_5$ ha^{-1}	31 Mar., 112 kg P$_2$O$_5$ ha^{-1}	6 Apr. 56 kg P$_2$O$_5$ ha^{-1}
Lime application (date & rate)	1 Apr., 8.1 Mg ha^{-1}	29 Mar., 3.4 Mg ha^{-1}	1 Apr., 4.5 Mg ha^{-1}
Additional fertilizer (date, source, & rate)	12 Apr., Anhydrous ammonia (263 kg N ha^{-1})	31 Mar., Anhydrous ammonia (202 kg N ha^{-1})	7 Apr., Urea (56 kg N ha^{-1}) + NBPT (4 L Mg^{-1})
Sidedress N (date & rate)	11 June, 32% UAN (168 kg N ha^{-1})	NA	5 May, Urea (168 kg N ha^{-1}) + NBPT (4 L Mg^{-1})
Weed management (date & rate)			
Burndown	21 Apr., Glyphosate (0.72 kg a.i. ha^{-1})	11 Apr., Glyphosate (1.06 kg a.i. ha^{-1}) + DS (0.36 kg a.i. ha^{-1}) + DAS (512 mL ha^{-1})	5 Apr., Glyphosate (1.12 kg a.i. ha^{-1})
Preemergence	21 Apr., Atrazine (1.43 kg a.i. ha^{-1}) + S-metolachlor (1.11 kg a.i. ha^{-1})	13 Apr., Atrazine (2.17 kg a.i. ha^{-1}) + S-metolachlor (1.68 kg a.i. ha^{-1})	9 Apr., Atrazine (3.5 kg a.i. ha^{-1}) + S-metolachlor (1.01 kg a.i. ha^{-1})
Postemergence	22 June, Glyphosate (1.06 kg a.i. ha^{-1})	NA	8 May, Atrazine (1.1 kg a.i. ha^{-1}) + Glyphosate (1.5 kg a.i. ha^{-1})

[†] Abbreviations: DAS, Diammonium sulfate; DS, Dimethylamine salt; NA, None applied.

[‡] Acetochlor (2-chloro-2'-methyl-6'ethyl-N-ethoxymethylacetanilide); atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine); dimethylamine salt (2,4-Dichlorophenoxyacetic acid); glyphosate (N-(phosphonomethyl)glycine); NBPT (N-(n-butyl) thiophosphoric triamide); S-metolachlor (2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl]acctamide).

Table 3.3. Effect of phosphorus enhancer on plant population, silage dry weights, grain moisture, yield, grain oil, protein, and starch concentration. Data were combined over years, location, liming rate, and P source.

P enhancer	Plant population	Silage dry weights	Grain moisture[†]	Yield	Oil[†]	Protein[†]	Starch[†]
	plants ha^{-1}	Mg ha^{-1}	g kg^{-1}	Mg ha^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}
Non-treated	52,300	16.2	256	135	39	90	718
Avail®	52,800	16.0	256	134	39	91	717
P_2O_5-Max®	50,400	15.5	253	136	39	90	717
LSD (*P*=0.1)	NS[‡]	NS	NS	NS	NS	NS	NS
P-value	0.31	0.48	0.69	0.65	0.44	0.97	0.48

[†] Novelty location only.

[‡] NS = Not significant

Table 3.4. Phosphorus and K uptake results based on P enhancers. Data were combined over 2010 and 2011 at Novelty, and at Portageville in 2010, liming rate, and P source.

					K uptake				
	P uptake				Novelty				
	Novelty[‡]				2010				
	P source				P source				
P enhancer	Non-treated	DAP[†]	TSP[†]	Portageville	Non-treated	DAP[†]	TSP[†]	2011	Portageville
	kg ha^{-1}				kg ha^{-1}				
Non-treated	32.1	40.3	31.4	53.1	289.6	283.7	213.9	303.2	278.0
Avail®	29.2	36.8	40.0	47.1	220.6	269.9	365.0	320.8	271.9
P_2O_5-Max®	35.3	32.5	32.9	49.4	292.0	256.4	265.1	333.3	257.2
LSD (P=0.1)	6.7			NS[§]	74.2			NS	NS
P-value	0.033			0.365	0.010			0.438	0.563

[†] DAP and TSP was applied at a 117 kg P_2O_5 ha^{-1} at Novelty in 2010, 112 kg P_2O_5 ha^{-1} at Novelty in 2011, and 56 kg P_2O_5 ha^{-1} at Portageville in 2010.

[‡] Data were combined over years (2010 and 2011).

[§] NS = Not significant

Table 3.5. Phosphorus enhancer effect on N uptake and apparent P recovery efficiency (APRE). Data were combined over 2010 and 2011 at Novelty, and at Portageville in 2010, liming rate, and P source except for apparent P recovery efficiency.

P enhancer	N uptake	APRE
	kg ha^{-1}	%
Non-treated	494.9	6.1
Avail®	472.9	1.7
P_2O_5-Max®	463.6	-6.3
LSD (P=0.1)	NS[§]	NS
P-value	0.45	0.43

[†] DAP and TSP was applied at a 117 kg P_2O_5 ha^{-1} at Novelty in 2010, 112 kg P_2O_5 ha^{-1} at Novelty in 2011, and 56 kg P_2O_5 ha^{-1} at Portageville in 2010.

[‡] The recommended liming rate was 8.1 Mg ha^{-1} at Novelty 2010, 3.4 Mg ha^{-1} at Novelty 2011, and 4.5 Mg ha^{-1} at Portageville 2010.

[§] NS = Not significant

Table 3.6. Plant population, grain moisture, yield, grain oil, protein, and starch results as affected by recommended lime rate. Data were combined over 2010 and 2011 at Novelty, and at Portageville in 2010 except for yield and plant population.

	Plant population				Yield				
	Novelty			Grain					
Liming Rate	2010	2011	Portageville	moisture[†]	Novelty	Portageville	Oil[†]	Protein[†]	Starch[†]
	-------------------plants ha^{-1}-------------------			g kg^{-1}	-----Mg ha^{-1}-----		g kg^{-1}	g kg^{-1}	g kg^{-1}
None	59,700	58,100	37,600	254	10.15	7.07	39	91	717
Recommended[‡]	64,500	55,600	35,400	255	9.78	7.84	39	90	718
LSD (*P*=0.1)	NS[§]	2,000	NS	NS	NS	0.20	NS	NS	NS

[†] Novelty location only.

[‡] The recommended liming rate was 8.1 Mg ha^{-1} at Novelty 2010, 3.4 Mg ha^{-1} at Novelty 2011, and 4.5 Mg ha^{-1} at Portageville 2010.

[§] NS = Not significant

Table 3.7. Nitrogen, P, K uptake, and apparent P recovery efficiency (APRE) results based on liming rate. Data were combined over 2010 and 2011 at Novelty, and at Portageville in 2010 P source and P stabilizer except for P uptake.

		P uptake			
Liming rate	N uptake	Novelty[‡]	Portageville	K uptake	APRE
	kg ha^{-1}	---------------kg ha^{-1}---------------		kg ha^{-1}	%
None	472.2	32.8	50.5	284.5	7.2
Recommended[†]	482.0	36.2	49.2	289.6	-6.2
LSD (*P*=0.1)	NS[§]	3.1	NS	NS	13.0

[†] The recommended liming rate was 8.1 Mg ha^{-1} at Novelty 2010, 3.4 Mg ha^{-1} at Novelty 2011, and 4.5 Mg ha^{-1} at Portageville 2010.

[‡] Data were combined over years (2010 and 2011).

[§] NS = Not significant

Table 3.8. P source effects on silage dry weights, grain moisture, yield, N uptake, grain oil, protein, starch, and and apparent P recovery efficiency (APRE). Data were combined over 2010 and 2011 at Novelty, and at Portageville in 2010, liming rate, and P stabilizer except for silage dry weight.

	Silage dry weights								
	Liming rate		Grain						
P source[†]	None	Recommended[‡]	moisture[§]	Yield	N uptake	Oil[§]	Protein[§]	Starch[§]	APRE
	-------------Mg ha^{-1}-------------		g kg^{-1}	Mg ha^{-1}	kg ha^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	%
Non-treated	14.6	16.8	262	8.90	468.7	39	91	717	
DAP	15.3	16.2	253	9.10	471.0	39	90	718	4.8
TSP	16.6	16.0	249	9.24	491.6	39	90	719	-3.8
LSD (*P*=0.1)	--------------1.4--------------		7	0.27	NS[¶]	NS	NS	NS	NS

[†] DAP and TSP was applied at a 117 kg P_2O_5 ha^{-1} at Novelty in 2010, 112 kg P_2O_5 ha^{-1} at Novelty in 2011, and 56 kg P_2O_5 ha^{-1} at Portageville in 2010.

[‡] The recommended liming rate was 8.1 Mg ha^{-1} at Novelty 2010, 3.4 Mg ha^{-1} at Novelty 2011, and 4.5 Mg ha^{-1} at Portageville 2010.

[§] Novelty location only

[¶] NS= Not significant

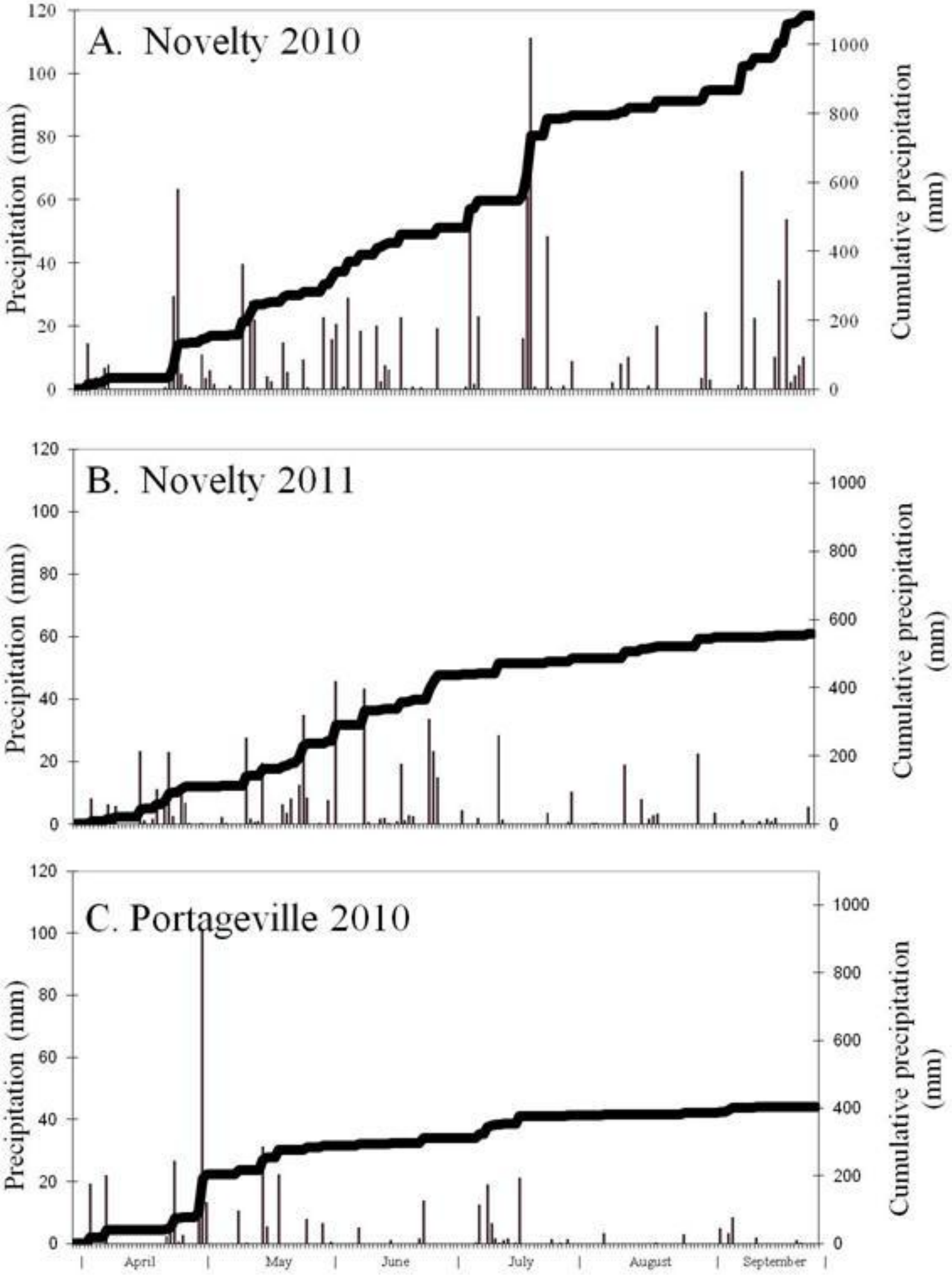

Figure 3.1. Daily (bars) and cumulative (line) precipitation from March through September of 2010 and 2011 at Novelty (A and B) and 2010 at Portageville (C), MO.

CHAPTER 4-OVERALL CONCLUSIONS

Phosphorus (P) is an essential plant nutrient that has several important functions in plants. Phosphorus fertilizers are used in large quantities in agriculture, horticulture, and turf grass. With high fertilizer costs, farmers are interested in reduced P application rates and use of P enhancers. Avail® (Specialty Fertilizer Products, Leawood, KS) and P_2O_5-Max®(P-Max, Rosen's Inc., Fairmont, MN) have been promoted commercially as products that enhance the efficiency of P-based fertilizers on several soil types. The overall objectives of these two research projects were to determine if these P enhancers would increase crop production, grain quality, plant P uptake and apparent P recovery efficiency (APRE) and study the interaction between these enhancers and other factors such as fertilizer placement, P rate, lime application, and P source.

SUMMARY-OBJECTIVE 1

The first objective of this field research trial was conducted as a 3-factor arrangement of application placement [NT/surface broadcast or strip-till/deep banding], monoammonium phosphate (MAP) rate [0 kg P_2O_5 ha^{-1}, half the recommended rate (56 kg P_2O_5 ha^{-1}), and recommended rate (112 kg P_2O_5 ha^{-1})], and the presence and absence of two enhanced phosphorus efficiency products [non-treated control, Avail®(Specialty Fertilizer Products, Leawood, KS) at 2.1 L Mg^{-1}, and P_2O_5 Max® (P-Max, Rosen's Inc., Fairmont, MN) at 4.2 L Mg^{-1}]. The P enhancers did not affect plant population, silage dry weights, grain moisture, yield, grain protein, grain starch, N, K uptake, or APRE for all four site-years. In both NT/broadcast and ST/deep banding, the addition of Avail® or P_2O_5-Max® did not increase P uptake over the non-treated controls. Strip-till/deep banding is a competitive tillage system to NT/broadcast especially at Novelty. Results from this study showed an increase in plant populations 3,500 to 15,500 plants ha^{-1} with ST/deep banding compared to NT. Strip-till/deep banding increased grain yields 1.57 Mg ha^{-1} compared to NT at Novelty, but yields at Albany were affected by placement and MAP rate. Strip-till/deep banding had lower grain protein concentrations and higher grain starch concentrations than NT/broadcast at Novelty, but not at Albany. MAP rate had a significant effect on yields with P_2O_5 at 0 kg ha^{-1} yielding 0.30 to 0.36 Mg ha^{-1} more than MAP at 56 or 112 kg P_2O_5 ha^{-1}. Plant P uptake and APRE was not affected by MAP rate. Grain protein concentration increased 3 g kg^{-1} with MAP at 56 and 112 kg P_2O_5 ha^{-1} compared to the non-treated control only at Novelty in 2011, while MAP at 0 and 112 kg P_2O_5 ha^{-1} increased starch concentration 2 g kg^{-1} over MAP at 56 kg P_2O_5 ha^{-1} only at Novelty.

SUMMARY-OBJECTIVE 2

The second objective was a field trial that included a 3-factor arrangement of P source (non-treated control and a broadcast application of DAP or TSP), presence or absence of the phosphorus efficiency products [non-treated control, Avail® (Specialty Fertilizer Products, Leawood, KS) at 2.1 L Mg^{-1}, and P_2O_5-Max® (P-Max, Rosen's Inc., Fairmont, MN) at 4.2 L Mg^{-1}], and broadcast surface application of ag lime [0 Mg ha^{-1} and recommended (8.1 Mg ha^{-1} at Novelty in 2010, 3.4 Mg ha^{-1} at Novelty in 2011, and 4.5 Mg ha^{-1} at Portageville in 2010)]. Enhanced efficiency P products did not affect plant population, silage dry weight, grain moisture, yield, oil, protein, starch, N uptake, or P fertilizer efficiency compared to the non-treated control. Triple superphosphate treated with Avail® increased P uptake 8.6 kg ha^{-1} compared to the non-treated control and 7.1 kg ha^{-1} compared to P_2O_5-Max® at Novelty, but not at Portageville. The application of lime resulted in mixed production results depending on the location. Lime application decreased plant population 4,800 plants ha^{-1} in 2011 at Novelty, and increased grain yields 0.77 Mg ha^{-1} at Portageville. Plant P uptake increased 3.4 kg ha^{-1} with the application of lime at Novelty, but was not affected at Portageville. This study showed no significant production differences between TSP and DAP, the application of TSP increased grain yield 0.34 Mg ha^{-1} compared to the non-treated control.

CONCLUSIONS

The two P enhanced efficiency products studied in this research did not consistently increase agronomic performance, including apparent P recover efficiency, at the sites and environmental conditions in interaction with several fertilization, liming, and tillage practices evaluated in this research. However, triple superphosphate treated with Avail® increased P uptake 8.6 kg ha^{-1} compared to the non-treated control at Novelty, but not at Portageville. In this trial the soils tested were acidic, so more research needs to done on alkaline soils in Missouri.

Strip-till/deep banding is a competitive tillage system to NT/broadcast especially in soils with poor internal drainage. This study showed an increase in plant populations of 3,500 to 15,500 plants ha^{-1} with ST/deep banding compared to NT/broadcast which indicated a benefit for corn plant establishment especially on claypan soils in Northeast Missouri. An improved seedbed environment with lower soil moisture and higher soil temperatures likely caused the higher plant populations with ST. The higher plant populations of ST resulted in increased grain yields 1.57 Mg ha^{-1} compared to NT at Novelty. The application of lime had in mixed production results for the first year corn production after application, at the sites and environmental conditions in interaction with several P fertilizers and P enhancers that were evaluated in this research. Lime application decreased plant population 4,800 plants ha^{-1} in 2011 at Novelty, and increased grain yields 0.77 Mg ha^{-1} at Portageville. This study showed also no significant production difference between P source (TSP and DAP) at either location. Future research evaluating the production of soybeans following corn treatments will determine if the P enhancers, tillage/fertilizer placement, P rate, and/or lime had any residual effects on a subsequent crop in the rotation.