# EFFECTS OF DEEP VERTICAL PLACEMENT OF LIME ON CORN AND SOYBEAN RESPONSE AND SOIL CHEMICAL PROPERTIES IN CONSERVATION TILLAGE SYSTEMS

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The undersigned, appointed by the dean of the Graduate School,

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A candidate for the degree of

Masters of Science

And hereby certify that, in their opinion, it is worthy of acceptance.

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This thesis is dedicated to my wife

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# LITERATURE REVIEW

## Extent of Soil Acidity

Soil acidity is one of the most influential factors in limiting crop production around the world. Roughly 30% of the Earth's total land area and as much as 70% of potentially farmable land is affected by soil acidity (Rengel, 2003). Soil acidity is common worldwide and can be found across almost all soil orders. However, acidity occurs predominantly in soils formed from acidic parent material or areas where weathering has occurred over a long period of time, such as Oxisols, Ultisols, Alfisols and Andisols (Jayawardane and Stewart, 1995). As a soil naturally weathers in humid climates, it will often result in an increasingly acidic profile due to the loss of base cations. In addition to naturally occurring weathering, soils under degradative management practices will often lead to an increased in soil acidity (Adams, 1984). A highly weathered or degraded soil often results in an acidic soil environment with hard and infertile subsoils that prove to be resistant and sometimes impenetrable to plant roots (Sumner et al., 1986). Similar studies conducted by Marsh and Grove (1992) and Caires et al. (2008) found strong correlations between both corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) root growth and yield response to soil acidity.

A large amount of agronomic land worldwide is often affected by "soil acidity syndrome" which results in severely restricted crop production due to a retardation of root growth paired with reduced nutrient availability (Sumner et al., 1986). With an ever increasing global population and losses of arable land due to urbanization, agricultural production will need to deliver increasing quantities of food and fiber on a diminishing available land area. This pressure to produce more on less land has led to an anthropogenic degradation of up to 40% of the world's arable soils (Jie et al., 2002). For example, in some Australian soils, where fertility relies heavily on nitrogen (N) fertilizer inputs, naturally occurring alkaline and basic soils have been acidified resulting in adverse effects on the food and fiber production in the area (Rengel, 2003).

One of the most important soil orders in terms of food and fiber production affected by anthropogenic soil acidification are Alfisols (NRCS, 2016). In the U.S. Alfisols constitute 13.9% of the land area and over 10% world wide of ice free land (NRCS, 2016). Due to a relatively larger base saturation of 35% or greater at specific depths, Alfisols are widely utilized for crop production around the world (NRCS, 2016). However, intensive agricultural production of these soils can still lead to an acidification that negatively affects crop production.

In the United States alone, almost 100 million hectares of crops were harvested in 2014 (FAOUN, 2014). Over 1.4 billion kilograms of Ca are removed from soils due to harvesting annually (FAOUN, 2014). The removal of Ca from the soil can lead to a significant increase in soil acidity, as exchangeable Ca is replaced by acid components, such as hydrogen ions and exchangeable Al, on soil cation exchange sites. Harvest removal of Ca and other base-forming nutrients, such as Mg, K and Na, in conjunction with other acidifying processes has led to a stratification of subsoil pH in many agronomic areas.

An area greatly affected by subsoil stratification of pH is the central claypan major land research area (MLRA 113) in the Midwestern region of the United States. Claypan soils in this region belong to the Alfisol soil order. Some claypan soils are formed when exchangeable sodium (Na) ions cause dispersion of clay mineral particles, resulting in the development of small particles (0.2 µm) of individual clay minerals. These particles are then able to move freely in the soil solution and migrate downwards with the movement of water. The particles collect in small pores in the subsoil eventually leading to a dense argillic subsoil horizon that is referred to as a claypan. A claypan can be defined as dense subsoil layer with an abrupt increase in content, roughly 100% greater than previous horizons (White and Gartner, 1981). Clay content of the claypan is greater than 450 g $ha^{-1}$ and the top of this claypan can range from 130 to 460 mm deep in the soil profile (Blanco-Canqui et al., 2002). This claypan region contributes to 2.9 million ha of farmable land between Missouri and Illinois (NRCS, 2016). Long time cultivation and removal of base forming cations, such as Ca, led to severely acidic subsoils in parts of this region. For some Northeastern Missouri claypan soils, such as the Putnam, Mexico and Armstrong silt loam soil series, acidification of the soil profile has resulted in subsoil pH as low as 3.6, 4.5, and 4.5, respectively (Ferguson, 1995).

To reduce soil acidity, amendments of calcium carbonate (calcitic limestone) or calcium and magnesium carbonates (dolomitic limestone) can be added to the soil to help raise pH. It is estimated that as much as 172 million metric tons of agricultural limestone equivalent (85% pure $CaCO_3$) is required annually to neutralize the acidity generated from accelerated erosion, use of acid fertilizers, crop removal, and acid precipitation (Follett et al., 1981).

Many developing countries have reduced soil fertility due to acidic surface and subsoil horizons (Rengel, 2003). In addition, developing countries may not have sources of readily available liming materials and may face challenges in the availability, processing, transport and cost of liming materials (Follett et al., 1981). These barriers to use of liming materials in developing countries has led to inadequate lime application which in turn may result in decreasing food production.

A principal problem associated with application of calcitic and dolomitic limestone to acid soils is the immobility of this liming material within the soil profile. Slow solubilities of calcitic and dolomitic limestones lead to slow movement within the soil profile that is largely dependent on soil moisture and temperature. In some cases, lime amendments can take years to fully react and show measurable effects on crop yields (Adams, 1984). The insolubility of calcium carbonate ($CaCO_3$), the active component of calcitic agricultural lime, leads to the slow movement of lime through the soil profile. This causes surface-applied liming materials to show measurable effects almost exclusively in the surface horizon of the soil, leaving the subsoil unamended. In order to obtain desired neutralizing effects in the subsoil from surface amendments many times the recommended amount of lime are needed, making the process impractical and uneconomical (Caires et al., 2008).

This effect of surface lime applications can cause elevated levels of acidity to persist within the subsoil even after lime applications, making amending the subsoil where amelioration is often most needed, a particularly challenging process. To address this issue, several studies have been conducted to explore various methods of subsoil remediation in attempts to adequately and efficiently deliver appropriate lime amendments directly into the subsoil while maintaining the integrity of the soil structure. Factors, such as depth of application, source or type of carbonate used, and delivery mechanism, have been investigated in hopes of examining the issue in more detail.

Often treatments of gypsum are included in these studies for comparison since gypsum can provide a similar addition of Ca to the soil and may reduce aluminum toxicity (Sumner et al., 1986; Farina et al., 2000a, 2000b; Caires et al., 2011). Surface treatments of gypsum ($CaSO_4$) can provide additions of Ca, disperse sodium ions off soil exchange sites and often penetrate deeper than calcitic lime into the subsoil, however do not have an effect on the soil pH (Caires et al., 2011). The deeper movement of calcium from gypsum applications compared to that of calcitic limestone may be related to the differences in mobility of the sulfate contained in gypsum compared to the carbonate contained in lime (Delhaize and Ryan, 1995).

## Causes of Soil Acidity

Soil acidity is defined as a soil with a pH value less than 7. The Natural Resource Conservation Service (NRCS) differentiates soils into 11 categories of acidity or alkalinity based on pH value ranges. For example, the NRCS classification of soil acidity pH ranges denote pH 6.1 – 6.5 as slightly acidic, 5.6 – 6.1 as moderately acidic, 5.1 – 5.5 as strongly acidic, 4.5 – 5.0 as very strongly acidic, 3.5 – 4.4 as extremely acidic and any value below 3.5 as an ultra-acidic soil (USDA-NRCS, 1998).

Many factors may account for the development of soil acidity. The first and most rudimentary cause of acidic soils is formation under an acidic parent material. Acidic parent material, such as consolidated rock granites or some unconsolidated glacial materials including shales and sandstones, all have small base concentration which leads to the formation of soils with low base saturations. The majority of acidic glacial parent material in the United States occurs primarily in the northeast regions, stretching from

Ohio to Maine. Other acidic parent materials, such as granite, occur in the western to northwestern regions of the United States (Follett et al., 1981).

Although an acidic parent material can be the initial cause of soil acidity, one of the most predominant factors leading to soil acidity is leaching with weathering in humid climates. Weathering of soil as a result of leaching is generally the main factor for the formation of an acidic soil and occurs at faster rates if the soil is well-drained. In addition, this process can often be accelerated with anthropogenic practices such as irrigation and fertilization. As rain or irrigation water moves through the soil profile, base cations in mineral solids (i.e., Ca, Mg, K, and Na) dissolve in the soil solution and can be transported downward in the soil profile. Decomposing organic matter and $CO_2$ from the atmosphere combine with water to form carbonic acid ($H_2CO_3$). Aqueous $H_2CO_3$ reacts with Ca and Mg on the soil colloids forming a more soluble bicarbonate product, which allows the nutrients to be easily leached. Leaching primarily occurs when precipitation is greater than evapotranspiration allowing for downward flow of water through the soil profile.

Acidic precipitation also influences soil acidity. Although all rainfall is generally acidic from dissolved atmospheric $CO_2$, air pollution from the burning of fossil fuels, including $NO_x$ and $SO_2$ gases, can increase the acidity of the rain far beyond that caused by dissolved $CO_2$. Currently coal deposits globally are commonly used as an energy resource through its combustion. When combusted, coal will release numerous pollutants into the atmosphere, such as sulfur and nitrogen oxides. For example, sulfur dioxide ($SO_2$), when released into the atmosphere will react with water molecules to form sulfuric acid ($H_2SO_4$). Along with sulfur oxides from coal combustion, nitrogen oxides ($NO_x$), predominantly released from gasoline combustion, react with atmospheric water to form acid compounds (Kennedy, 1992). These compounds are then transferred to the earth through acidic precipitation. Once the acidic precipitation enters the soil, these compounds can decrease the soil solution pH and result in a greater dissolution of bases within the soil solution, subsequently promoting further leaching of base cations out of the rooting zone.

Another factor lowering soil pH globally is the application of acid-forming fertilizers, such as N fertilizer sources (urea, anhydrous ammonia), monoammonium phosphate (MAP) and diammonium phosphate (DAP) (Follett et al., 1981). Because the N fertilizers are much cheaper per unit weight of nutrient content and phosphorous additions from MAP and DAP, they are widely used in modern cropping systems. Additions of these fertilizers may satisfy N needs, but they can ultimately lead to other nutrient deficiencies and toxicities as a result of their largely acidic components lowering soil pH (Follett et al., 1981).

A less significant and more localized cause of soil acidity can come from plant root exudation of hydrogen. This is caused by the discharge of hydrogen ions and carbon dioxide in the rhizosphere during respiration. This results in hydrogen ions (acid) exchanged in the soil solution for base cations so they can be taken up by the plant, along with the addition of $CO_2$ from respiration reacting with water to form carbonic acid ($H_2CO_3$). Both processes lead to a decrease in soil pH and base content in the soil. The base cations can be returned to the soil through decomposition, but if organic matter is reduced it will lead to acidification of soil due to removal of base cations taken up by the plants. As nutrients are removed from the soil system at harvest, they are replaced by hydrogen and exchangeable aluminum ions which subsequently decreases the soil pH. In 2014, roughly 357 million kg of Ca was removed from the soil just by the combined corn and soybean grain harvests in the United States alone (FAOUN, 2014).

The predominant soil orders that include acidic soils are Oxisols, Ultisols, Alfisols, and Andisols. These soils contain variable charge surfaces on kaolinite, sesquioxides, amorphous minerals and organic matter. Through natural or anthropogenic processes, decreases in soil pH has led to substantial reductions in pH dependent cation exchange capacity (CEC) of these soils (Jayawardane and Stewart, 1995).

Soil pH is defined as the inverse log of the hydrogen ion ($H^+$) concentration in the soil solution. As a solution decreases in pH, the concentration or activity of hydrogen ions in water increases (Kennedy, 1992). Hydrogen ion concentration or activity in the soil solution is dependent on a number of reactions within the soil over a period of time and can be illustrated by the simplified equation (Jayawardane and Stewart, 1995):

$$\begin{aligned}&\Delta[H_3O] = (pH \rightleftharpoons CEC) + (Al\ solid \rightleftharpoons Al^{+3}) + (Mn^{+4} \rightleftharpoons Mn^{+2}) + \\ &(\text{reaction of } CaC0_3 \text{ and other amendments}) + \\ &(M^{x+}, Al \text{ silicates} \rightleftharpoons Al \text{ silicates and oxides}) + (\text{organic } C \text{ cycle} \\ &\text{reactions}) + (N \text{ cycle reactions}) + (\text{acid/alkali in precipitation and} \\ &\text{leaching})\end{aligned}$$

[Equation 1.1]

## Effects of Acidic Soils

As a hydrogen ions replace soil base cations, such as calcium, magnesium, potassium and sodium on clay mineral exchange sites, the excess cations are solubilized into the soil solution. These base cations can then a be leached deeper or out of the soil profile, which causes an increase in soil acidity. The scope and severity of base removal paired with an inability to amend the subsoil often leads to infertile acidic subsoils. These acidic subsoils can act as a drastic limiting factor for plant growth and production. In some cases, the presence of an acidic subsoil may create a greater barrier to root growth than that of physical limitations, such as the relatively dense claypan found in many Missouri soils when. A generally acceptable soil pH for corn and soybean production in the Midwest United States is 5.5 to 6.5 (Brown and McLean, 1984). As the pH of the soil solution becomes more acidic, the relative availability of many of the essential plant nutrients become less available for plant uptake due to decreases in their solubility or changes in their chemical forms (Follett et al., 1981). For example, availability of plant essential nutrients nitrogen, phosphorus, potassium, sulfur, calcium, magnesium, boron, copper and zinc all increase as a soil moves from acidic to neutral (Sumner and Yamada, 2002).

Calcium deficiency induced by soil acidity is of great concern for agronomic crops. Available calcium has been known to be crucial for membrane stability in all plants. The role of Ca is vital to the regulation of cell membranes. Presence of Ca ions can effectively reduce interference of sodium for potassium uptake (Pierre et al., 1966). Calcium plays an important role in the structure of cells and is an essential requirement in the binding of root cells (Pierre et al., 1966).

Decreases in available Ca and other vital nutrients resulting from acidic soil pH are crucial reasons why acidic soils inhibit plant growth. With a lesser solubility of nutrients, a plant’s water demand increases in order to take up the required amount of nutrients. Elevated levels of acidity in soils can be a limiting factor on many sensitive crops grown around the world leading to limited growth and low yields.

Adverse effects of soil acidity on plant growth are not limited to nutrient deficiencies. Acid soil pH levels can also often lead to nutrient and chemical toxicities as a result of increased solubility of certain ions and changes in chemical forms. One of the most prominent toxicities resulting from soil acidification is that of aluminum toxicity. Many plant species are sensitive to exchangeable aluminum ($Al^{+3}$) at micromolar concentrations (Delhaize and Ryan, 1995). Aluminum contributes roughly 7% of the Earth's crust mass and the dissolution of many types of parent materials can result in soluble Al in the soil solution (Robson, 1989). Most Al found in soils is either bound by ligands or in non-phytotoxic forms such as mineral oxides or oxyhydroxides (Robson, 1989; Delhaize and Ryan, 1995). Generally speaking, $Al^{+3}$ toxicity rarely occurs above pH 5.5 due to the transformation of $Al^{+3}$ into other Al forms above this pH. However, when pH levels descend below 5.5 solubilization of Al containing minerals increases at an exponential rate and $Al^{+3}$ may become a major limiting factor to plant production (Delhaize and Ryan, 1995). Typically, at a fixed pH the concentration of Al in the soil solution will also remain stable. This results in $Al^{+3}$ supply to plant roots being affected by mass flow and diffusion processes in the soil solution (Rengel, 2003). The concentration of Al in the soil solution is maintained through mineral dissolution and cation exchange. This dissolution and exchange can take place in the direct vicinity of the root, resulting in a constant supply of Al to the plant root hindering the plants ability to overcome Al toxicity (Rengel, 2003).

To fully understand the extent of Al toxicity in a soil, it is important to understand the mechanisms controlling the distribution of Al between solid and aqueous forms. Competition between Al and other cations has an effect on the abundance of the soluble species of Al (Robson, 1989). The Al species $Al^{3+}$ is thought to have the greatest toxicity amongst plants. The hydrolysis of $Al^{+3}$ in solution can be represented by the following simplified reactions (Adams, 1984):

$$Al^{3+} + H_2O \rightleftharpoons AlOH^{2+} + H^{+} \qquad \text{[Equation 1.2]}$$
$$AlOH^{2+} + H_2O \rightleftharpoons Al(OH)_2^{+} + H^{+}$$
$$Al(OH)_2^{+} + H_2O \rightleftharpoons Al(OH)_3 + H^{+}$$
$$\textit{Net Reaction: } Al^{+3} + 3H_2O \rightleftharpoons Al(OH)_3 + 3H^{+}$$

Solubilization of mineral Al not only leads to plant toxicity, but can also add to the acidification of the soil environment. For instance, the complete hydrolysis of $Al^{3+}$ results in the liberation of three hydrogen ions into the solution which further decreases the soil pH.

**Effects of Al Toxicity**

Many plants and crops around the world are sensitive to excessive levels of exchangeable Al and plant growth can become negatively affected when this occurs (Göttlein et al., 1999). As one of the most important limiting factors for plant growth in acid soils, Al toxicity in a soil can lead to drastic decreases in crop production and yield. Aluminum toxicity becomes increasingly severe with decreasing pH and becomes a predominant issue at pH values less than 5.0 (Göttlein et al., 1999). Studies conducted by Adams and Hathcock (1979) found the least level of toxicity ranged from <0.3 – 10 μM, <0.3 – 98 μM and "nontoxic horizons" for $Al^{3+}$, $AlOH^{2+}$, and $Al(OH)_2^{+}$ species, respectively.

Symptoms of Al toxicity are not easily identified because these toxic effects mainly occur in the root systems of the plants (Foy et al., 1978). In some cases, plants may exhibit foliar symptoms that resemble phosphorous (P) deficiency with small, dark green leaves and late maturity, an overall stunting of the plant, purpling of stems, leaves, and leaf veins; and a yellowing and or death leaf tips (Clark et al., 1981). Al toxicity in can also appear as an induced Ca deficiency (i.e. curling or rolling of young leaves and collapse of growing points or petioles) due to reduced Ca transport problems within the plant (Foy et al., 1978).

Excess Al can lead to an inhibition of root growth and elongation resulting in short stubby roots, which limits the plant’s uptake of water because of a reduced and damaged root system (Jamison and Thornton, 1960). With the decrease in root growth and exploration caused by Al toxicity, crop development is impacted due to a diminished ability of the plant to absorb water and nutrients (Jamison and Thornton, 1960). In addition, lack of an extensive root system will cause areas in the vicinity of the roots to become depleted of nutrients more rapidly due to a decreased area of uptake. This in part, can lead to unpredicted deficiencies as much of the soil profile will remain fertile (Pierre et al., 1966).

Examination of plant roots can lead to an initial diagnosis of Al toxicity issues. The easiest recognizable symptom of Al toxicity is the inhibition of root growth, which is a widely accepted measurement for Al stress or toxicity in plants (Delhaize and Ryan, 1995). In simple nutrient solutions, small Al concentrations (μM) can initiate root growth inhibition within a matter of 60 minutes (Delhaize and Ryan, 1995). Aluminum-injured roots generally are often described as being stubby and brittle. Thickening and browning of root tips and lateral roots will occur under Al toxicity stress. Further Al toxicity can cause the root system as a whole to appear coralloid, with a large number of stubby lateral roots that will lack fine branching. Roots damaged by Al toxicity become insufficient in absorbing nutrients and water (Marschner, 2012). Damaged or underdeveloped root systems generally affect younger plants more drastically due to the inherent lack of an initial root system (Foy, 1974).

Underdeveloped and damaged root systems as a result of Al toxicity also may cause many deficiencies in crops making crops highly susceptible to drought. In wetter periods, drought stress caused by Al toxicity is difficult to detect because, even with an underdeveloped root system there is enough water movement present to satisfy the plants nutrient and water demands. Aluminum toxicity becomes more predominant in drier periods when water potentials become more negative, requiring extensive root systems to fulfill the plant’s water and nutrient demands. During drought periods, crops with underdeveloped root systems in acidic soils are no longer able to absorb the required amount of water and nutrients, resulting in stunted growth, damage or even death. However, a normally developed root system with extensive root exploration has a greater ability to absorb water in dry soils. Therefore, crops with Al toxicity require greater amounts of water and nutrients in the soil solution to maintain growth, leading to a greater possibility of the occurrence of limiting factors, such as nutrient deficiencies and water stress.

## Management of Acidic Soils

### *Plant Tolerance*

One commonly used method to increase production on land with surface and subsoil acidity problems is the use of Al-tolerant genotypes. For example, plants such as wheat have a considerable variability in Al tolerance with up to a 10-fold difference in Al tolerance between genotypes. This variation in Al tolerance can allow plant breeders to develop cultivars with an ability to withstand greater levels of exchangeable Al in the soil solution while still maintaining high yields. In wheat, several independent studies show strong evidence that Al-tolerant genotypes can exude Al from their root apices, allowing the Al concentration in the plant tissue to remain low (Delhaize and Ryan, 1995). However, in areas where Al toxicities are small and soil nutrient availability is a greater yield limiting factor, Al-tolerant genotypes may not be as beneficial.

### ***Liming Material***

When growing acid sensitive crops, such as corn and soybean, agricultural lime amendments can be an effective management practice to reduce surface and subsoil acidity. Limestone is mined from naturally occurring deposits in quarries with large concentrations of the active neutralizing mineral calcium carbonate ($CaCO_3$). Limestone is a sedimentary rock comprised of various minerals with a large amount of calcite, the crystalline form of calcium carbonate ($CaCO_3$) (Follett et al., 1981). Another regularly used source of limestone is dolomite, which is composed of large fractions of the crystalline form of magnesium carbonate [$CaMg(CO_3)_2$]. Dolomitic limestone is often used as a soil amendment when addition of the macronutrient magnesium is desired, or of if nearby quarries contain this type of limestone.

In order to classify the contents of the source, lime deposits can be placed into four categories: calcitic limestone, which contains greater than 90% calcite and less than 10% dolomite; dolomitic limestone, which contains 50 to 90% calcite and 10 to 50% dolomite; calcitic dolomite, which contains 10 to 50% calcite and 50 to 90% dolomite; and lastly dolomite, which contains less than 10% calcite and greater than 90% dolomite (MDNR, 2015).

Due to the insoluble nature of $CaCO_3$, lime sources need to be ground into a fine powder to increase reactivity. Once adequately ground to a fineness and purity level specified by each state, the liming material can legally be considered an agriculture limestone amendment or aglime for short.

To evaluate aglime's chemical effectiveness two factors are taken into consideration. The first factor is the calcium carbonate equivalence (CCE). This relationship is the acid-neutralizing capacity by weight of the material in relation to pure $CaCO_3$. The second factor taken into account is the particle size distribution of the ground limestone. Together these factors can be used to calculate the effective calcium carbonate equivalence (ECCE), which suppliers are often required by law to disclose to the public (Adams, 1984; Beegle and Lingenfelter, 2001).

In the determination of the particle size of aglime, the pulverized lime source is passed through a series of sieves with known opening widths to separate finer limestone from courser limestone. Once separated, the particle size of the lime powder can be evaluated and is known as the fineness factor (Follett et al., 1981). In the United States, fineness factor is measured by using a number of standard sieve widths with designated numbers, whereas the higher the sieve number the smaller the openings. For example, in the State of Missouri sieve size No. 8 (2.36 mm), No. 40 (425 µm), and No. 60 (250 µm) are used in separating particle sizes. Fineness factor is then determined using the following equation: (Missouri Statutes, 1999)

***Fineness Factor*** *= (% of materials passing U.S. No. 8 and remaining on 40 X 0.25) + (% of materials passing U.S. No. 40 and remaining on 60 X 0.60) +(% of materials passing U.S. No. 60 X 1.00)* [Equation 1.3]

Once fineness factor is determined the value is multiplied by the CCE to determine the ECCE. Minimum requirements of ECCE are determined at the state level. Most agricultural lime sources contain a mix of particles that are much finer than that required to meet the minimum established standards. One study conducted found that in most cases 20 to 50% of the ground limestone passed through the number 100 sieve (150 µm) (Whittaker and Chichilo, 1964).

Slow movement and reactivity of lime amendments can be attributed to the small solubility of calcium sources, $OH^-$ ions liberated from $CaCO_3$ reacting with the exchangeable hydrogen, $OH^-$ reacting with soil Al and Iron (Fe) oxide minerals, and the lack of an accompanying anion (Liu and Hue 2001). Because of lime's slow movement though the soil, limited effects are observed after application. A general rule of thumb for lime application is to allow at several months for the $CaCO_3$ to begin chemically reacting with the soil colloids (Beegle and Lingenfelter, 2001).

However, because of the slow reaction time, lime amendments can remain active in the soil for relatively long periods of time, giving long-term effects of treatments (Sumner et al., 1986). Amendments with lesser fineness factor generally react slower but have longer lasting effects than that of greater fineness factors. Generally, dolomitic limestone has a higher CCE than calcitic limestone but takes longer to react on acidic soils (Peters et al., 1999) Though calcitic and dolomitic limestone are the main sources of liming material, liming materials can include various other sources. For example, sources such as shell meal, hydrated lime, burned lime, sugar beet lime and calcium silicate can also be used as amendments (Univ. CA. Extension 2011). Table 1.1 indicates the source, chemical formula, and calcium carbonate equivalence percentage of some commonly used lime amendment sources.

Once applied to the soil, lime reacts with the acidic components in the soil solution. Dissolved Ca replaces hydrogen and Al on the soil surfaces leaving $H^+$ and $Al^{+3}$ ions in the soil solution. Hydrogen and Al ions then react with the carbonate ($CO_3^{-2}$) component of limestone to form $CO_2$, $H_2O$ and $Al_2O_3$, resulting in an overall decrease in acidity (Ball, 1999). When applying lime, it is important to know the lime requirement of the soil. This is an estimated amount of lime needed to raise the pH of the soil and neutralize it to a desired level. The first factor taken into account when determining lime requirement is the crop that will be grown. The target pH of the soil after amelioration should be within the most productive range of the crop. A general range for corn and soybean production in the Midwest is pH 5.5 to 6.5 (Sumner and Yamada, 2002).

Secondly, soil texture affects the lime requirement. As clay content increases in a soil and in turn the soils CEC, the amount of lime required to neutralize the soil also increases. The greater fraction of clay results in a greater surface area of that soil with more exchange sites to adsorb hydrogen and exchangeable Al ions (Follett et al., 1981). Lime requirements to raise soil pH from 4.5 to 6.5 based solely on soil textural class are shown in Table 2 (Univ. CA. Extension 2011).

Clay mineralogy is also important in determining lime requirement. Soil clays ordered in increasing lime required to neutralize equal amounts of clay are Fe and Al sesquioxides, kaolinite, illite, montmorillonite, and vermiculite (Follett et al., 1981). Differences in clay mineralogy can largely affect the neutralizable acidity of a soil which is also taken into account when determining lime requirements.

Organic matter will also affect the lime requirement for a soil. The organic content of a soil is directly related to the amount of lime required with a general rule of thumb being for every 1% increase in organic matter a 10% increase in required lime is recommended (Follett et al., 1981). Each factor needs to be accounted for when calculating lime requirements.

### *Gypsum Amendments*

In contrast or sometimes in parallel with limestone applications, applications of gypsum have proven to be beneficial for issues associated with Ca and S deficiencies and improving soil aggregation. Much like limestone, gypsum is a common naturally occurring mineral that is mined from the earth or results as a byproduct from phosphorus fertilizer production. Mineral gypsum is comprised of a calcium attached to a sulfate group and has a much greater solubility than calcitic limestone. Because of this, surface applied gypsum applications penetrate far deeper into the subsoil than limestone carbonates (Hammel et al., 1985; McLay et al., 1994; Delhaize and Ryan, 1995; Liu and Hue 2001). However, because gypsum ($CaSO_4$) is lacking a carbonate ion and the ligand exchange of $SO_4$ for hydroxyl, it remains pH neutral and has no effect on soil pH (Sumner et al., 1986). Nevertheless, gypsum treatments are excellent amendments for soils with deficiencies in either Ca or S as it can supply the nutrients to the subsoil while maintaining the structural integrity of the soil via surface applications (Liu and Hue, 2001).

Perhaps the most important use for applying gypsum to acidic soils is the effect it has on subsoil Al. As soil acidity and Al toxicity often occur together, many producers around the world use gypsum to alleviate Al toxicity in subsoil horizons. Previous studies indicate that surface applications of gypsum can effectively decrease the levels of phytotoxic $Al^{+3}$ present in the subsoil up to 1 m depth resulting in increased crop yields (McLay et al., 1994; Delhaize and Ryan, 1995; Liu and Hue, 2001; Caires et al., 2011)

**Management Practices**

Amendments of gypsum and limestone are known to actively reduce levels of exchangeable Al within a soil as well as adding nutrients such as Ca, Mg and S. Furthermore, lime amendments can also increase cation exchange capacity (CEC), base saturation (BS) and nutrient availability by raising soil pH. For over 100 years, Al toxicity has been recognized as a yield-limiting factor in acidic soils, but the sequence of events that leads to its effects on plant growth remains largely speculative (Delhaize and Ryan, 1995). This gap in understanding has resulted in numerous studies with the objectives to identify plant-specific effects of Al toxicity and to possibly use this insight to increase crop production on acidic soils. A study conducted by Brady et al. (1993) concluded that the presence of exchangeable Al species, $Al^{+3}$, $Al(OH)_2^{+}$, and $Al(OH)^{+2}$ within the soil solution reduced root growth and root hair development in soybean. In that study, a scanning electron microscope (SEM) was used to evaluate root hair growth on Al-treated and non-treated soybean plants along with possible ameliorations by means of calcium carbonate amendments. Roots treated with small concentrations of exchangeable Al (<5 µM) appeared normal without magnification, but the roots exhibited cracks in the epidermis below the zone of root hair formation when viewed by SEM. Other replications and treatments displayed a 90% decrease in the length of the root hair zone compared to roots grown in the absence of Al. At small concentrations of exchangeable Al (<5 µM), evidence of detrimental effects on nodule formation of soybean roots were observed, which was attributed to the impeded development of root hairs. With the addition of exchangeable Ca to the Al-treated roots, the presence of Ca greatly reduced the damaging effects that Al had on root elongation and lateral root development (Brady et al., 1993).

Conventional application of lime has been primarily surface-applied with or without mechanical incorporation in the plow layer. Deeper incorporation of liming materials into the subsoil is less frequent due to the high cost and mechanical power requirements for deep tillage. A review of efforts to ameliorate the subsoil though surface application of lime investigated 20 different research studies assessing downward movement of lime treatments. In summary, varied results were found on the rate and intensity that soil chemical properties was altered but in most cases little to no downward movement of lime was observed, even after considerable amounts of time up to 20 years (Sumner, 1995). In some cases, downward movement of Ca was relatively rapid but was attributed to the downward movement of salt ($CaCl_2$) in the soil profile rather than neutralizing exchangeable Ca (Jayawardane and Stewart, 1995).

Alternatively, surface applied gypsum shows effective downward movement of calcium when surface applied. In a recent study, on soils with large levels of $Al^{+3}$, surface applied gypsum increased Ca and effectively reduced levels of $Al^{+3}$ within the subsoil resulting in a significant increase in corn grain yields by up to 8% 10 years after application (Caires et al., 2011). However, soil pH remained unchanged by gypsum treatments.

Faced with increasing subsoil acidity and the difficulty of reaching subsequent horizons, many attempts have been made to effectively and efficiently ameliorate subsoil acidity (Jamison and Thornton 1960; Gonzalez-Erico et al., 1979; Anderson and

Hendrick 1983; Rechcigl et al., 1985; Sumner et al., 1986; Farina et al., 1998; Adcock et al., 1999; Farina et al., 2000a, 2000b). The focus of most of these studies were aimed to explore the effects of depth, amount and delivery method of lime and gypsum treatments on yield response and changes in soil chemical and physical properties within the profile. An earlier method of deep incorporation of lime conducted by Sumner et al. (1986) considered methods that incorporated lime by broadcasting lime followed by a mixing of the soil down to a meter depth using deep plowing. Plots were then evaluated over the course of four years. Results showed that mixing the lime to a 1 m depth increased alfalfa yields by up to 50%. Although yields increased with the incorporation of lime, the energy costs required to incorporate the lime and destruction of soil structure were considered impractical for large scale use.

Research has shown that the long-term effects, such as hard pans and loss of soil structure, of conventional tillage outweigh the short-term gains (Blevins et al., 1978). This has led to the development of minimum tillage systems with less soil disturbance to help reduce the degradative processes caused by conventional tillage (Jayawardane and Stewart, 1995). In an attempt to minimize these disturbances, several studies investigated the feasibility and functionality of lime application using conservation tillage systems. Doss et al. (1979) tested deep incorporation of lime using a chisel plow in combination with a rotary tiller into the subsoil at depths of 15, 30, and 45 cm on a claypan soil. The experiment resulted in increased yield and rooting depth, and a neutralization of acidity, with increasing effects as the depth of incorporation increased. A study conducted by Farina and Channon (1988) evaluated various methods of deep placement of lime into the subsoil in South Africa which deep placement and incorporation methods that resulted in greater yields than that of conventional surface application techniques. The most successful method consisting of a subsoiler equipped with a lime applicator delivering lime into a 7 cm slot at a depth of 0.75 m. Fuel requirements of each method were also evaluated which indicated that the subsoiler treatments was far more efficient than incorporation methods (Farina and Channon, 1988). Other research demonstrated a greater benefit of deep lime placement onto a hard pan increased alfalfa root penetration from 30 to 60 cm and increased yields from 7.1 to 11.7 Mg ha$^{-1}$ while also decreasing acidity and exchangeable Al below the zone of placement 5 years after treatment (Rechcigl et al., 1985). In a subsequent investigation by Rechcig et al. (1991), further residual effects were observed from the lime application up to 13 years after lime application. The investigation discovered that further downward movement of lime was taking place below the zone of placement more than 13 years after application, demonstrating the residual benefits of lime placement methods.

### Research Objectives and Hypotheses

Soil acidity including Al toxicity, is one of the world’s major constraints on crop production. With increasing variation in climate including more extreme weather events and higher temperatures around the world, it is imperative that adaptive solutions be sought out to prevent agricultural production losses. Though various research has been conducted on remediation of acidic subsoil though minimal disturbance application of lime, there is little information on the effects of deep lime placement into the subsoils. It is thought that subsoil horizons with greater acidity found in many Missouri soils can be the greatest barrier to root growth into the subsoil. Furthermore, the delivery system developed to distribute lime into the subsoil for this project is of unique design and has yet to be evaluated. The objective of this research was to assess the effectiveness of lime or gypsum placement including a deep application method while also investigating the impacts of lime amendments on the concentrations and spatial distribution of soil pH, exchangeable Al, and exchangeable Mn in the soil profile.

### ***Objectives***

1. To determine the effects of lime and gypsum placement (deep vertical placement/surface broadcast) and application rate (0, 0.5x the recommended rate for the subsoil, and the recommended rate for the subsoil) on grain yields of corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.)
2. To assess the effects of lime placement (deep vertical placement/surface broadcast) and amount (0, 0.5x the recommended rate for the subsoil, and the recommended rate for the subsoil) on subsoil acidity and chemical properties.
3. To evaluate the spatial effects of deep lime placement methods (0 and recommended subsoil rate) on soil acidity and neutralizable acidity spatial distribution.

### ***Hypotheses***

1. Deep vertical placement of lime will increase subsoil pH and subsequently increase grain yields of corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) while decreasing levels of exchangeable Al and manganese compared to surface applied lime.
2. Deep vertical placement of lime will effectively deliver lime at depths of 13, 25, 38 and 51 cm and increase pH and decrease neutralizable acidity around the application band.

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Table 1.1. Different types of lime amendments and the calcium source chemical formula, calcium carbonate equivalence (CCE) and source of amendment *(Univ. CA. Extension, 2011).*

| Type of Lime | Chemical Formula | CCE % | Lime Source |
|---|---|---|---|
| Shell Meal | $CaCO_3$ | 95 | Natural shell deposit |
| Limestone | $CaCO_3$ | 100 | Pure form, finely ground |
| Hydrated lime | $Ca(OH)_2$ | 120-135 | Steam burned |
| Burned lime | $CaO$ | 150-175 | Kiln Burned |
| Sugar beet lime | $CaCO_3$ | 80-90 | Sugar beet by-product lime |
| Calcium silicate | $CaSiO_3$ | 60-80 | Slag |
| Dolomite | $CaCO_3$-$MgCO_3$ | 110 | Natural Deposit |

Table 1.2. Lime requirements to raise soil pH from 4.5 to 6.5 based solely on soil texture *(Univ. CA. Extension, 2011).*

| | Lime requirements | |
|---|---|---|
| Soil texture | From pH 4.5 to 5.5 | From pH 5.5 to 6.5 |
| | -------------------- Mg ha$^{-1}$ ------------------- | |
| Sandy and loamy sand | 1.1 | 1.3 |
| Sandy loam | 1.8 | 2.9 |
| Loam | 2.7 | 3.8 |
| Silt Loam | 3.4 | 4.5 |
| Clay Loam | 4.3 | 5.2 |
| Muck | 8.5 | 9.6 |

## CHAPTER 2

# EFFECTS OF DEEP VERTICAL PLACEMENT OF LIME ON SOIL PROPERTIES

## ABSTRACT

Midwestern claypan soils managed for corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) production often have optimum surface pH for crop growth, but are characterized by acidic subsoils. Stratification of soil acidity may inhibit root growth leading to decreased drought tolerance and grain yields. Lime application can increase soil pH, improve soil structure and provide calcium and magnesium to the soil, but these amendments rarely affect the subsoil leaving potential chemical and physical restrictions to root growth. The objectives of this study were to determine the effects of surface and deep vertical placement of lime at various rates on subsoil characteristics under corn and soybean production. Field trials were conducted from 2012 to 2016 in Northeast Missouri with treatments of lime broadcast to the surface soil or incorporated as a vertical band to a depth of 51 cm into the subsoil at 0, 3.4, and 6.7 Mg ha$^{-1}$. Soil pH results indicated that the top 13 cm of soil was not affected by deep lime placement, but at depths of 13 to 25 cm soil pH increased up to 0.6 and 0.7 units for deep vertical placed lime at 3.4 and 6.7 Mg ha$^{-1}$ respectively. When compared with control treatments, vertical placement of lime at 3.4, and 6.7 Mg ha$^{-1}$ increased subsoil pH at depths of 13 to 25 and 25 to 38 cm, respectively one year after application. A similar comparison with the control treatment indicated that deep vertical placement at 6.7 Mg ha$^{-1}$ increased subsoil pH at 13 to 25 cm depths by 6.5 and 5.7% two and three years after application, respectively. No differences in soil pH were observed 38 to 51 cm deep in the soil profile one, two, or three years after

application. Analysis of the spatial distribution of soil $pH_s$ and neutralizable acidity in the soil profile indicate penetration of liming effects up to 38 cm into the subsoil but showed slight evidence of movement away from the initial vertical placement band over a seven-month period.

## INTRODUCTION

For centuries, mankind has observed the effects liming materials can have on altering soil acidity and alkalinity and on improving crop production. Surface and subsoil acidity are among the foremost limiting factors in crop production around the world with up to 70% of arable land having some level of soil acidity (Rengel, 2003). In the U.S. alone, agronomists estimate that up to 73 million Mg of lime should be applied each year to neutralize generated soil acidity (Adams, 1984). Current management practices only apply a fraction of this amount, with estimates ranging from 20 to 30 million Mg of lime applied each year (West and McBride, 2005). Due to the initially great soil fertility across the United States Midwest, liming did not become a standard practice in the area until the early 1900s, after years of land use began to deplete nutrients and acidify the soil (Adams, 1984). Furthermore, as manmade fertilizers became a common practice soil acidity continued to intensify, due to greater nutrient removal as a result of increased yields and additions of acidic components from the fertilizers (Doss et al., 1979).

Today, agricultural lime amendments are commonly used throughout the Midwest to help neutralize elevated acidity within the soil, but rarely meet the required quantities to fully neutralize acidity to the recommended target pH for optimal crop growth. It is estimated that, depending on the nitrogen (N) fertilizer source, it may require 0.8 to 2.5 kg of calcium carbonate ($CaCO_3$) per pound of N fertilizer to neutralize the acidity generated. Furthermore, as more agricultural professionals move towards no-till management practices to prevent losses from erosion and degradation of soil structure, ameliorating subsoil acidity has become increasingly more difficult.

Due to the slow downward movement of lime, conventional surface application of lime generally does not penetrate into the subsoil horizons under no-till practices. The slow movement of lime can be attributed to the slow solubility of $CaCO_3$, the principal component in limestone. Additionally, the reaction of $CaCO_3$ with $H^+$ and $Al^{+3}$ within the soil solution along with iron (Fe) and aluminum (Al) oxide minerals within the soil matrix can further decrease the movement of lime amendments within a soil (Liu and Hue, 2001). Stratification of subsoil acidity within a soil profile can also lead to a dramatic decrease in plant nutrient availability with depth and increases in Al toxicity (Ebelhar et al., 2011). Acidic subsoil has also been shown to lead to a decrease in plant water uptake due to reduced root length and density caused by Al toxicity (Gonzales-Erico et al., 1979). Additionally, acidic conditions can result in a decrease in microbial activity, reducing the effectiveness of soil rhizobia and soybean nodulation formation (Acosta-Martínez et al., 2003).

As conventional surface applications of lime have proven to be unable to effectively reduce subsoil acidity, various researchers have examined several management methods to effectively alter subsoil chemistry. Early attempts to amend subsoil acidity consisted of a complete mixing of lime within the soil profile though conventional tillage and inversion practices to depths ranging anywhere from 10 cm to 1 m (Doss et al., 1979; Sumner et al., 1986; Farina and Channon 1988; Farina et al., 2000a, 2000b). Methods of incorporation though inversion increased grain yields, but required large amounts of energy and lime to effectively move the soil and alter soil properties, plus the economic value was unclear (Sumner et al., 1986; Farina et al., 2000a). A study investigating the effects of incorporation of varying quantities up to 18.0 Mg ha$^{-1}$ of lime at 15 and 30 cm into the subsoil of an acidic Oxisol observed grain yield increases in corn as great as 2.7 Mg ha$^{-1}$ and decreased exchangeable Al saturation of exchange sites from 70% saturation to <5%. Yield response to deep incorporation was greatest at a 30 cm depth (Gonzales-Erico et al., 1979). Furthermore, a study by Farina et al. (2000) found that the long-term effects of subsoil amelioration indicated beneficial impacts on subsoil pH that extended 10 years past application.

Due to the infertile nature of the soil, the majority of research on deep placement of lime placement has been conducted on highly weathered soils. These soils were generally very acidic with toxic levels of exchangeable Al in the soil solution (Joris et al., 2012; Pagani and Mallarino, 2015). With a great severity in acidity and toxicities, benefits of lime amendments on these soils have shown to be a necessary management practice to increase soil fertility. However, there is little research on the effects of subsoil lime amendments on soil acidity as a way to maintain or improve diminished fertility on less weathered soils.

This research aims to further evaluate the effects of deep vertical placement on subsoil acidity in poorly drained claypan soils. It is estimated that roughly 4 million ha of the Midwest is comprised of claypan soil, spanning across Kansas, Missouri and Illinois, with smaller regions found in Nebraska, Oklahoma, and Iowa (Jamison et al., 1968). Of these soils, 2.9 million ha of farmable land between Missouri and Illinois make up the Central Claypan Major Land Resource Area (NRCS, 2016). Claypan soils managed for corn and soybean production often have surface pH optimum for crop growth, but largely acidic subsoils. Acid subsoil pH can inhibit root growth leading to reduced drought tolerance and grain yields (Doss et al., 1979; Sumner et al., 1986; Flower and Crabtree 2011; Joris et al., 2012). Soil Survey publications show that Missouri claypan soils exhibit a sudden stratification in soil pH with an optimal surface horizon and acidic subsoil from 20 to 50 cm with pH values as acid as 3.6, 4.5, and 4.5 for the Putnam, Mexico and Armstrong soil series, respectively (Ferguson, 1995).

To remediate subsoil acidity in a timely fashion, it may be necessary to incorporate lime directly into the soil profile (Toma et al., 1999). Deep vertical placement of lime utilizing conservation-type tillage could accomplish an increase in grain production, provide zone-tillage, maintain surface residue, while also increasing subsoil pH. This research initiated a long-term evaluation of the impact of addressing subsoil pH correction in reduced tillage cropping systems. The objective of this research was to evaluate the impacts of lime placement at differing amounts on the soil pH, spatial distribution of subsoil pH, and other soil properties within the soil profile for soils cropping corn-soybean rotation.

## MATERIALS AND METHODS

### Site Description and Experimental Design

Three trials were established on poorly-drained claypan soils over the course of three growing seasons starting in 2012 at the Greenley Memorial Research Center (40°02’N, 92°20’W) near Novelty, MO. The first and third trials were established in the spring of 2012 and the fall of 2013 on a Putnam silt loam (Fine, smectitic, mesic Vertic Albaqualfs), respectively. The second trial was established in the fall of 2012 on a

Kilwinning silt loam (fine, smectitic, mesic, Vertic Epiaqualfs). Prior to the study, the experimental sites were under continuous no-till production for over 13 years. Sites with acidic surface and subsoils were utilized for this experiment. Initial soil characteristics were prior to the establishment of each trial (Table 2.1), and field management information is reported in Tables 2.2A to 2.5B.

The experiment was arranged as a split-split-plot with crop (corn or soybean) as the main plot, placement as the sub-plots and lime or gypsum as the sub-sub-plots with four replications for each trial. The sub-plots included: a non-treated control, surface application of lime at 3.4 Mg ha$^{-1}$, surface application of lime at 6.7 Mg ha$^{-1}$, deep vertical tillage with no application of lime, deep vertical placement of lime at 3.4 Mg ha$^{-1}$, deep vertical placement of lime at 6.7 Mg ha$^{-1}$, surface application of gypsum at 2.9 Mg ha$^{-1}$, surface application of gypsum at 5.2 Mg ha$^{-1}$, deep vertical tillage placement with no application of gypsum, deep vertical placement of gypsum at 2.9 Mg ha$^{-1}$ and deep vertical placement of gypsum at 5.2 Mg ha$^{-}$1. Plot sizes were 4.6 × 24.4 m for Trials #1 and #3, and 4.6 × 22.9 m for Trial #2. Deep vertical placement and surface-applied strips were then divided into plots of varying rates of lime, giving a split-split randomized complete block design. The long-term effects of trials established 2012, 2013 and 2014 were evaluated and corn plots rotated into soybean while soybean was rotated into corn for subsequent years. The crops were planted in rotation for subsequent years. Deep vertical placement was accomplished using a conservation subsoiler (Case IH Ecolo-Til® 2500, Goodfield, IL) with a custom built shank designed to deliver lime simultaneously at four depths (0-13, 13-25, 25-38 and 38-51 cm) (Figure 2.1). Depths were selected to be approximately equivalent with past literature (Tupper et al., 1987; Farina et al., 2000a, 2000b). Lime application amounts of 0, 3.4 and 6.7 Mg $ha^{-1}$ were selected based on the average lime recommendation for the subsoil (6.7 Mg $ha^{-1}$) and the average lime recommendation for the top 15 cm of soil (3.4 Mg $ha^{-1}$).

For mechanical application purposes, pelletized lime and gypsum were used in replacement of traditional powder amendments. The limestone source was comprised of pelletized lime (Kelly's Pelletized Lime, Kirksville, MO) derived from mined calcitic limestone containing 36.4% Ca and 1% Mg with a Calcium Carbonate Equivalence (CCE) of 90.7% and an Effective Neutralizing Material (ENM) of 300 kg ENM $Mg^{-1}$. The concept and calculations for ENM are provided in Buchholz et al. (1983). Particle size distribution of the liming material before pelletizing consisted of 99.9% passing through a 2.36 mm mesh sieve, 97.0% passing through a 0.841 mm mesh sieve, 88.0% passing through a 0.420 mm mesh sieve, 63.0% passing through a 0.297 mm mesh sieve and 61.0% passing through a 0.250 mm mesh sieve. A 2% lignosulfonate material was utilized as the binding agent for palletization (Kelly's Pelletized Lime, Kirksville, MO).

Application amounts of lime were achieved using a commercial Montag dry fertilizer air delivery system (MonTag Manufacturing, Inc., Emmetsburg, IA). Conservation zone tillage knifes were spaced 76 cm apart, in accordance with standard corn row spacing. Uniform broadcast surface applications were achieved by running the conservation tillage unit with the custom shank above the soil surface to ensure consistency of application. Strips of corn or soybean were randomly assigned at trial establishment and rotated for subsequent years. Each crop strip was randomly divided into two additional strips of surface-applied and deep vertically placed lime.

## Management

Lime treatments were applied to Trial #1 in the spring of 2012 followed by planting of corn and soybean shortly after the treatment application. The timing of the lime applications was changed to the fall for Trial #2 and #3 in subsequent years. In the spring of 2013, corn and soybean were planted in Trial #2 which had received the fall lime treatments and in Trial #1 to assess the residual effects of the previous year's lime treatments. In the fall of 2013, lime treatments for Trial #3 were applied and corn and soybean were planted the following spring of 2014 for Trials #1, #2 and #3 to assess the effects of the recent lime treatments in Trial #3 and the residual effects of the previous lime treatments in Trials #1 and #2. Management practices, such as row spacing, seeding rate, hybrid or varieties, weed and pest control, tillage and maintenance fertilization for each trial are presented in Tables 2.2a to 2.5b.

## Soil Sampling and Analysis

Initial soil samples were evaluated prior to the establishment of each trial at depths of 0-13, 13-28, 25-38, and 38-51 cm using a Giddings hydraulic probe (Giddings Machine Company, Windsor, CO) and compositing three cores plot$^{-1}$. Samples were air-dried and ground in a hammer mill to pass through a stainless steel sieve with 2-mm openings. All samples were analyzed by the University of Missouri Soil and Plant Testing Laboratory using standard methods described in Nathan et al. (2006). Methods included soil $pH_s$ (0.01 M $CaCl_2$), neutralizable acidity (Woodruff buffer), soil organic matter (loss-on-ignition), soil test Bray-1 P, exchangeable calcium, magnesium and potassium (1 M $NH_4OAc$) and cation exchange capacity.

Soil samples were collected in the fall after harvest in 2012, 2013, and 2014 from corn and soybean plots every year. In 2015, soil samples were only collected from Field Trials #2 and #3. Core samples were collected after harvest using a Giddings probe and divided into depth ranges of 0-13, 13-28, 25-38, and 38-51 cm, corresponding to the different distribution depths of lime during deep vertical banding. Three core samples were collected from each treatment plot, one core from the center of the fertilizer band, another 38 cm to the left of the band, and a third 38 cm to the right of the band, which corresponds to halfway between bands. The three core samples were divided with respect to the depth ranges and combined together to make one sample per depth per treatment plot. All samples were air-dried and ground to pass through a 2-mm sieve.

Samples were analyzed by the University of Missouri Soil and Plant Testing Laboratory for analysis identical to that of initial soil tests. Additional soil testing was conducted on the control plots of each trial to determine the background levels of exchangeable aluminum for each trial. Exchangeable Al content of the soil was determined using 1 M KCl (Bertsch and Bloom, 1996). Extracts were then subject to Atomic Absorption Spectroscopy (AAS) analysis (SOLAAR S Series AA spectrometer, Thermo Scientific, Cambridge U.K.).

A spatial analysis of effects of deep vertical banding on $pH_s$ and neutralizable acidity was initiated in late summer of 2015 on similar, but on a more acidic Leonard silt loam (Fine, smectitic, mesic Vertic Epiaqualfs). Two replicate treatments of deep vertical banding at amounts of 0 and 6.4 Mg $ha^{-1}$ were applied to the soil. Trenches were excavated to expose a vertical plane of 76 × 51 cm within a band of each treatment with the band in the center of the plane. Samples were collected from the vertical wall of the trench perpendicular to the deep band based on a grid template with an increasing frequency of samples near the band (Figure 2.2). Push probe soil samples were collected zero, three and seven months after treatment from each point and analyzed for $pH_s$ and neutralizable acidity (Nathan et al., 2006).

All GIS mapping spatial interpolations were performed using the Inverse Distance Weighting (IDW) tool in ArcMap 10.3. The IDW tool calculated weighted distance averages, and the averages would not go beyond the value range (min and max) of sampling points. Power was set to 2, and search radius was variable.

Data were analyzed using analysis of variance (ANOVA) and comparisons among treatment means were made using Fisher's protected least significant difference (LSD) at $P< 0.10$. Statistical procedures were carried out with SAS statistical software (SAS Institute Inc., 2013). Soil data were analyzed on the basis of treatment effects for individual trials and treatment effects for residual years of combined trials. Having trials established in subsequent years from 2012 to 2014, evaluating the residual effect of treatments proved problematic as residual years after treatment for each trial did not take place during the same time span. Some initial soil chemical characteristics varied significantly between field trials. With climatic conditions differing greatly between years after treatments and reaction time of lime depending heavily on moisture and temperature, direct comparisons between trials resulted in large levels of variation. Residual effects presented as percent differences were calculated by comparing the means of treatment plots within each replication of a trial with the non-treated control means of the same replications within the trial. Percent differences from control plots were grouped into years after application and averaged for each treatment.

# RESULTS AND DISCUSSION

## Climatic Conditions

From the initiation of the first experimental plot in May 2012 to the last collection of soil samples in November 2015, climatic widely conditions varied. In 2012, an extreme seasonal drought occurred over the growing season (The National Drought Mitigation Center, 2012). Precipitation in 2012 from January 1st to December 31st was 297 mm below the 10-year average (Figure 2.3). Annual precipitation in 2013, was only 16 mm below the 10-year average but extended periods of drought were experienced throughout the season with over half of the recorded precipitation occurring over two events. Precipitation in 2014 was 54 mm below normal, whereas 2015 was a very wet year, with precipitation 272 mm above the 10-year average.

## Initial Soil Characteristics

Initial soil sample results (Table 2.1) taken prior to P and K fertilization indicated relatively small amounts of Bray P1-phosphorus and exchangeable potassium in Trials #1 and #3 compared to the University of Missouri recommendations for row crops (Buchholz, 2004). Adequate levels of exchangeable magnesium existed at all trials. In general, Ca, Mg, K and CEC values increased with depth for all trials, indicating deep leaching of base cations into the subsoil which is characteristic of claypan soils (Jamison et al., 1968). Adequate calcium levels existed at all depths of each trial. Trials #1 and #3, established in 2012 and 2014, had greater initial soil $pH_s$ levels in the 0 to 25 cm depth than Field Trial 2 established in 2013. Trials 1 and 3 had a greater degree of stratification of $pH_s$ in the subsoil, with smaller values at the 25 to 51 and 38 to 51 cm depths, respectively. Soil exchangeable aluminum was detected at depths of 25 to 51 cm which ranged from zero to 74 mg $kg^{-1}$. The presence of exchangeable Al has shown to restrict root growth of corn and soybeans and is known to phytotoxic effects on soybean root hair growth at concentrations as small as 2 µM (Brady et al., 1993; Delhaize and Ryan, 1995) Exchangeable Al at lower depths may have an effect on deep rooting corn plants. In areas where there was large exchangeable Al, lime amendments can effectively reduce levels of Al toxicity by raising soil pH above 5.5, resulting in significant yield responses (Caires et al., 2008; Flower and Crabtree 2011). However, areas where Al toxicities are small, crop responses to a change of pH in the subsoil may be unnoticed as Al toxicity can be a greater limiting factor than soil acidity.

### Effects on Soil Properties

Based on visual observation, the custom built shank effectively delivered the desired amounts of lime into the subsoil; however, excavation of the band after placement indicated a lack of soil disruption below 38 cm. (Figure 2.4). The modified shank resulted in greater soil disturbance than normal deep tillage (Figure 2.5). However, surface tillage via a Tilloll 875 (Landoll Corp., Marysville, KS) following deep vertical placement treatments was utilized to smooth the surface prior to planting. When withdrawn from the soil, the custom built shank delivered a uniform broadcast of pelletized lime over the soil surface. Due to spring application, reaction time for the lime and gypsum treatments was reduced by five months for Trial #1 compared to other trials. Differences in time after application of Trial #1 may have resulted in lesser effects from treatments in the initial experimental year compared to other trials. Since as reactivity of lime treatments are affected by time and soil moisture (Adams, 1984), less than normal precipitation observed over 2012 may have further limited the reaction of lime treatments during the first year of Trial #1

**Calcium**

After the first year, soil exchangeable Ca levels in the 0 to 13 cm depth were 542 kg Ca $ha^{-1}$ greater than the control for the 3.4 Mg $ha^{-1}$ rate of surface-applied lime a for Trial #1 (Table 2.6). Surface-applied lime at 6.7 Mg $ha^{-1}$ raised soil Ca levels at the 0 to 13 cm depth by 719 and 626 kg Ca $ha^{-1}$ one year after treatment applications for Trials #2 and #3, respectively. Surface lime treatments of 3.4 Mg $ha^{-1}$ raised soil Ca at the 0 to 13 cm depth 407 and 473 kg Ca $ha^{-1}$ two years after application for Trials #2 and #3, respectively.  Surface-applied lime at 6.7 Mg $ha^{-1}$ for all three trials raised soil Ca levels by as much as 881 kg Ca $ha^{-1}$ larger than the control at the 0 to 13 cm depth two years after application. Three years after application surface lime treatments raised soil Ca levels by as much as 1032 kg Ca $ha^{-1}$ over non-treated controls (Table 2.6). No significant differences from the control were observed at the 13 to 51 cm depth range for surface applications in all three trials at any time. Lack of increases in subsoil exchangeable Ca from surface treatments indicated little to no downward movement of lime when surface broadcasted. Past research on the effects of surface applications of lime on no-till production showed that lime amendments did not readily penetrate into the subsurface when surface-applied (Sumner et al., 1986; Farina and Channon 1988; Ebelhar et al., 2011). Furthermore, research done by Caires et al. (2011) indicated that surface-applied lime may penetrate as little as 5 cm into the soil under no-till conditions.

One year after application, all deep banding lime placement treatments except at 6.4 Mg $ha^{-1}$ for Trial #3 had no significant effect on soil Ca levels at the 13 to 25 cm depths (Table 2.6). Two years after treatment at the 13 to 25 cm depths deep vertical placement at 6.7 Mg ha$^{-1}$ increased soil Ca by as much as 1631 kg Ca ha$^{-1}$ for all three trials and as much as 1313 kg Ca ha$^{-1}$ three years after application. One year after application at the 25 to 38 depth range, deep lime placement at 6.7 Mg ha$^{-1}$ increased soil Ca levels up to 2504 kg Ca ha$^{-1}$ for Trials #2 and #3. At the 25 to 38 cm depth, deep lime placement at 3.4 Mg ha$^{-1}$ increased soil Ca levels 1440 kg ha$^{-1}$ two years after application in the 2nd trial. Deep lime placement at 6.7 Mg ha$^{-1}$ increased soil Ca at the 25 to 38 depth 1620 and 1241 kg ha$^{-1}$ for Trial #2 one and two years after application, respectively. No significant differences were observed among treatments at the 38 to 51 cm depth ranges (Table 2.6).

To evaluate residual effects, treatment differences from non-treated control plots were combined for all trials and separated into years after treatment. (Figure 2.6A-C). During the first year surface lime treatments at 3.4 and 6.7 Mg ha$^{-1}$ had soil Ca levels at 0 to 13 cm that were 12 and 16% above the control and at least 11 and 8% greater than all deep vertical placement treatments, respectively (Figure 2.6A). Two years after application surface treatments of 3.4 and 6.7 Mg ha$^{-1}$ exhibited an increase in soil test Ca 13 and 22% above the control, respectively, for the top 13 cm of soil (Figure 2.6B). Soil Ca levels at the 13 to 51 cm depth range were unaffected by surface treatments, which was similar to research by Liu and Hue (2001), where Ca from surface applied lime did not penetrate beyond 10 cm into the subsoil. Deep banded lime placement at 6.7 Mg ha$^{-1}$ increased soil Ca levels in the 13 to 25 cm depth range compared to non-treated plots by 20, 28 and 24% one, two and three years after application, respectively (Figure 2.6A-C). Significant increases compared to control plots in soil calcium from deep vertical placement treatments of 6.7 Mt ha$^{-1}$ may indicate that deep vertical placed lime at recommended rates can successfully add Ca directly into the subsoil. Increasing soil exchangeable Ca levels at depths in the subsoil can result in an increase of pH, reduction of exchangeable Al and possible increases in subsoil fertility resulting in greater drought tolerance and yields (Sumner et al., 1986; Flower and Crabtree, 2011; Joris et al., 2012).

**Neutralizable acidity**

Large levels of soil neutralizable acidity (NA) with increasing depth is often an indication of increasing soil exchangeable Al. As indicated by Delhaize and Ryan (1995), the hydrolysis of Al results in the production of three hydronium ions, which leads to an increase in the soil NA. Aluminum toxicity can cause smaller rooting systems in several crops resulting in decreased yields (Foy et al., 1978). Lime amendments applied to the soil surface significantly reduced NA in the top 13 cm of soil in the first year for all three trials (Table 2.7). Lime applied to the surface at 6.7 Mg ha$^{-1}$ reduced NA in the surface soil by as much as 2.1 cmol$_c$ kg$^{-1}$ two and three years after treatment for all trials. Little significance between treatments was observed for depths of 13 to 51 cm; however, deep banded lime placement reduced soil NA at the 13 to 25 and 25 to 38 cm depth ranges for Trial #3 one year after application.

Residual effects of treatment differences from non-treated plots showed some changes in surface and subsurface soil NA (Figure 2.7A-C). When compared to non-treated controls, soil NA had an average 32% decrease for surface-applied lime at 3.4 Mg ha$^{-1}$ and a 46% decrease for surface-applied lime at 6.7 Mg ha$^{-1}$ at the 0 to 13 cm depth in the first year of treatment (Figure 2.7A). At the 13 to 25 cm depth, deep vertical placement of lime at 3.4 Mg ha$^{-1}$ resulted in a 38% decrease in soil NA. No significant differences from the control were observed at 25 to 51 cm depths in the first year of treatment.

In the second year of surface lime applications, 3.4 and 6.7 Mg ha$^{-1}$ resulted in a 28 and 49% decrease in soil NA compared to non-treated controls (Figure 2.7B). Deep vertical placement at 0 Mg ha$^{-1}$ raised NA by 28% compared to controls at 13 to 25 cm in the second year of treatment, but soil NA decreased 24% by the vertical deep lime placement treatment of 6.7 Mg ha$^{-1}$. No significant differences in soil NA from the non-treated means were observed between treatments at 25 to 51 cm depths in the soil profile for the second year.

In the third year after treatment in trial #1, surface lime treatments at 3.4 and 6.7 Mg ha$^{-1}$ lowered soil NA at the surface by 36 and 54%, respectively, compared to non-treated means (Figure 2.7C). No significant differences in soil NA from the non-treated means were observed between treatments at depths of 13 to 51 cm in the soil profile for the second year.

A lack of significance among treatments in soil NA at depths below 25 cm may be a further indication that the custom built shank may not be effectively deliver treatments to the lower two depths. Other possible causes for non-significance at these depths could be due to the acidic pH observed in the subsoils. Various researchers suggest that lime amendments applied to acidic soil move very slowly due to their great interaction with the acidic components in the soil (Delhaize and Ryan, 1995). Research done by Lollato et al. (2013) found that dolomitic pelletized lime, when placed in furrow migrates very slowly though the soil profile. Additionally, it was observed that effects of dolomitic pelletized lime amendments were restricted to within roughly 1.3 cm of placement and pellets maintained their spherical structure 220 days after placement. Similarly, in this research, visual observation of soil probe samples and excavated pits found indications of lime pellets maintaining their structure up to a year after application. Furthermore, soil sampling method used in this research collected an average value from areas in and around the band, and if much of the band is not included in the sample, the sample will contain largely unamended soil thereby providing a less representative determination of the effect on soil NA within the band.

### Soil pH$_s$

Soil pH$_s$ in the top 13 cm was increased by surface lime treatments at 3.4 and 6.7 Mg ha$^{-1}$ in the first year after treatment for all trials (Table 2.8). Surface pH$_s$ continued to increase and remained greater than the control in the second and third residual year for all trials. In the second residual year, deep vertical placement at 6.7 Mg ha$^{-1}$ increased pH$_s$ in the 13 to 25 cm depth by 0.5 units for Trial #1. By the third residual year, treatments of 3.4 and 6.7 Mg ha$^{-1}$ for Trial #1 significantly increased subsoil pH$_s$ at the 13 to 25 depth by 0.4 and 0.6 units, respectively. Deep vertical placement of lime at 6.7 Mg ha$^{-1}$ were also greater than surface treatments for the second and third residual year of Trial #1. In Trial #3, deep lime placement treatments at 3.4 and 6.7 Mg ha$^{-1}$ increased subsoil pH$_s$ by 0.6 and 0.7 units at the 13 to 25 cm depth and by 0.4 and 1.0 units at the 25 to 38 cm depth, respectively, one year after application. Two years after application at the 13 to 25 depth, Trial #3 deep vertical placed lime at 3.4 and 6.7 Mg ha$^{-1}$ increased pH$_s$ by 0.3 and 0.4 units, respectively.

Combined residual effects of all trials showed that the top 13 cm of soil pH$_s$ was raised 9.0% over the control by broadcasted lime at 3.4 Mg ha$^{-1}$ (Figure 2.8A)

Additionally, surface applied lime at 6.7 Mg ha$^{-1}$ raised soil pH$_s$ 12.8% over the control. At the 13 to 25 depth, deep lime placement treatments at 3.4 Mg ha$^{-1}$ raised soil pH$_s$ by 5.0% over the control, while there was a 6.4 and 5.3% increase over surface-applied treatments at 3.4 and 6.7 Mg ha$^{-1}$, respectively, during the first residual year. At the 25 to 38 cm depth, deep vertical placement at 6.4 Mg ha$^{-1}$ raised subsoil pH$_s$ 7.5% over the control, and 9.0 and 8.2% over surface treatments at 3.4 and 6.7 Mg ha$^{-1}$, respectively. No significant differences were observed at the 38 to 51 cm depth.

In the second residual year, soil pH$_s$ in the top 13 cm of soil was significantly greater for surface lime applications than the control and all deep vertical placement treatments (Figure 2.8B). At the 13 to 25 cm depth, deep vertical placement of lime at 3.4 and 6.7 Mg ha$^{-1}$ increased subsoil pH$_s$ by 4 and 6.5% above the non-treated control. No significant differences between treatments were observed at the 25 to 51 cm depths in the second year.

Surface-applied lime continued to raise surface soil pH$_s$ compared to the control three years after treatment (Figure 2.8C). Deep vertical placement at 3.4 Mg ha$^{-1}$ raised subsoil pH$_s$ by 6.2 and 4.8% above the control for 13 to 25 cm and 25 to 38 cm depths, respectively. Deep vertical placement at 6.7 Mg ha$^{-1}$ raised subsoil pH$_s$ by 5.7% at the 13 to 25 cm depth range three years after application. No significant differences compared to control plots were observed at the 25 to 51 cm depths, indicating lack of downward movement of amendments and that lime treatments were not being effectively delivered at the lower depths.

## Spatial analysis

Spatial analysis of the soil profile for the control showed that the tillage only control treatment had little differences between sampling points for $pH_s$ and NA while differences appeared to be random at all three sampling times (Figure 2.9 A, C and E; 2.10 A, C and E). Three months after placement, deep banded lime treatments increased soil $pH_s$ while decreasing soil NA within the band at 13 to 38 cm depths and 6 cm to the right of the band at the 13 cm depth (Figure 2.9 D; 2.10 D). Soil $pH_s$ and soil NA was once again noticeably increased within the band from the 13 to 38 cm depth (Figure 2.9 F; 2.10 F). These results indicate that the deep banded lime amendments had a limited spatial effect over time within the soil profile and were not influencing soil acidity beyond the 38 cm depth and remained to stay localized around the band. Precipitation and temperature data over the course of this analysis are presented in Figure 2.11.

As indicated by Lolleto et al. (2013), use of pelletized lime in deep placement treatments results in less movement than surface applied treatments. The physical characteristics of pelletized lime may have added to the lack of movement observed from treatments. Furthermore, research conducted by Farina and Charana (1988) on deep banding of lime observed root growth only in the area of placement, indicating little alteration in soil pH and exchangeable Al levels outside the area of treatment in the first four years of study. It should also be noted that $pH_s$ for the spatial analysis in the soil profile were consistently smaller than that of the soils utilized for the field trials. This difference could lead to a greater buffering effects of the soil, which could impede the movement of lime in the soil profile. Long-term analysis of treatments will better indicate how the pelletized lime reacts and moves within the soil profile. Research by Doss et al.

(1979) suggests that lime treatments may need 10 to 14 years to effectively alter subsoil pH from surface applications. If reaction time of pelletized lime is significantly reduced when injected into the subsoil, movement of treatments though the subsoil may take many years to have full effects. In concordance with this theory, a later study on the long-term effects of treatments, indicated that deep placed lime increased yields over a decade after treatment (Farina et al., 2000b).

## CONCLUSIONS

Differences in soil properties of the top 13 cm of soil were greatly affected by surface applications of lime, with greater soil $pH_s$, increased exchangeable Ca levels, and decreased soil test NA. Deep band lime placement methods had little to no effects on the top 13 cm of soil as lime amendments had little contact with the soil depth. Deep vertical placement treatments appeared to have the greatest effect on the subsoil when compared to surface treatments. Deep vertical placement treatments performed best at the 13 to 25 cm depth but varied in effectiveness among liming rates.

Differences in climatic conditions may have impacted chemical interactions within the soil profile, as reactions are affected by water and temperature conditions. Furthermore, treatments of lime applied to Trial #1 were applied in the spring, giving less time for treatments to react in the subsoil during the first year. Since lime does not move readily though the soil, significant changes in soil properties from surface placement treatments were difficult to observe.

As other have observed, the effects of lime may be restricted to the area of application when injected into the subsoil. Spatial analysis maps of the changes in soil chemistry of the soil profile confirm this lack of lateral movement. This result may indicate that the vertically banded lime application method have limited effects on plant growth since only a small portion of the subsoil volume was affected, unless plant roots follow the injection pathway and are able to penetrated the soil deeper. Furthermore, obtaining representative samples from the soil surface may be difficult since they were combined from areas in and around the band. This may have resulted in samples being diluted with portions of amended and unamended subsoil, which could result in greater variation in soil properties.

However, deep banded lime placement did result in reductions in soil acidity and Ca levels at the 13 to 38 cm depth ranges for various treatments. Significant residual effects of the deep banded liming treatments were also observed several years after application, possibly due to the greater time for reaction with the soil to take place. Further research may be needed to determine if the custom deep lime shank attachment can be redesigned to distribute the lime over a more extensive subsoil volume while still maintaining reduced surface soil disturbance in fields under conservation tillage management. A surface application of lime may be needed to accompany the subsurface deep vertical placement.

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Table 2.1. Initial soil characteristics (mean ± 1 standard deviation) at different depths for Trial #1, Trial #2 and Trial #3.

| Soil characteristics | 0 – 13 cm | 13 – 25 cm | 25 – 38 cm | 38 – 51 cm |
|---|---|---|---|---|
| Trial #1 (Established in 2012) | | | | |
| pH$_s$ | 5.6 ± 0.2 | 5.6 ± 0.4 | 4.6 ± 0.2 | 4.6 ± 0.2 |
| Neutralizable acidity (cmol$_c$ kg$^{-1}$) | 3.5 ± 2 | 2.9 ± 1 | 8.5 ± 1.6 | 6.8 ± 1.0 |
| Organic matter (%) | 2.7 ± 0.3 | 2.3 ± 0.1 | 2.3 ± 0.3 | 2.2 ± 0.2 |
| Bray 1P (kg ha$^{-1}$) | 17.4 ± 9.8 | 5.0 ± 1.4 | 3.9 ± 1.9 | 14.6 ± 4.5 |
| Ca (kg ha$^{-1}$) | 4,427 ± 347 | 5,200 ± 661 | 5,257 ± 706 | 4,988 ± 673 |
| Mg (kg ha$^{-1}$) | 494 ± 98 | 689 ± 189 | 981 ±138 | 996 ± 158 |
| K (kg ha$^{-1}$) | 178 ± 12 | 173 ± 28 | 226 ± 32 | 231 ± 16 |
| CEC (cmol$_c$ kg$^{-1}$) | 15.4 ± 2.3 | 17.3 ± 3.2 | 24.2 ± 3.2 | 22.0 ± 2.3 |
| Trial #2 (Established in 2013) | | | | |
| pH$_s$ | 5.0 ± 0.1 | 5.0 ± 0.5 | 4.9 ± 0.7 | 4.9 ± 0.8 |
| Neutralizable acidity (cmol$_c$ kg$^{-1}$) | 5.1 ± 0.5 | 4.9 ± 1.9 | 6.9 ± 4.0 | 6.8 ± 3.8 |
| Organic matter (%) | 3.0 ± 0.6 | 1.9 ± 0.4 | 1.8 ± 0.3 | 1.4 ± 0.4 |
| Bray 1P (kg ha$^{-1}$) | 127.2 ± 46.2 | 19.1 ± 10.7 | 11.5 ± 4.0 | 30.8 ± 19.4 |
| Ca (kg ha$^{-1}$) | 2,841 ± 312 | 263 ± 690 | 4,138 ± 1,828 | 4,144±1,678 |
| Mg (kg ha$^{-1}$) | 307 ± 91 | 415 ± 192 | 739 ± 452 | 848 ± 420 |
| K (kg ha$^{-1}$) | 594 ± 240 | 159 ± 47 | 179 ± 77 | 233 ± 85 |
| CEC (cmol$_c$ kg$^{-1}$) | 13.3 ± 1.4 | 13.9 ± 3.3 | 19.1 ± 6.4 | 19.4 ± 4.8 |
| Trial #3 (Established in 2014) | | | | |
| pH$_s$ | 6.1 ± 0.1 | 6.2 ± 0.1 | 5.0 ± 0.2 | 4.6 ± 0.1 |
| Neutralizable acidity (cmol$_c$ kg$^{-1}$) | 1.8 ± 0.5 | 1.9 ± 0.3 | 7.1 ± 1.9 | 12.3 ± 1.9 |
| Organic matter (%) | 2.3 ± 0.5 | 2.1 ± 0.2 | 2.3 ± 0.4 | 2.7 ± 0.3 |
| Bray 1P (kg ha$^{-1}$) | 10.4 ± 4.7 | 5.6 ± 2.2 | 2.0 ± 0.6 | 1.1 ± 0 |
| Ca (kg ha$^{-1}$) | 3,954 ± 957 | 3,646 ± 289 | 4,497 ± 434 | 5,223 ± 384 |
| Mg (kg ha$^{-1}$) | 398 ± 158 | 377 ± 58 | 749 ± 142 | 1,226 ± 80 |
| K (kg ha$^{-1}$) | 154 ± 30 | 136 ± 12 | 220 ± 36 | 349 ± 28 |
| CEC (cmol$_c$ kg$^{-1}$) | 12.2 ± 3.2 | 11.6 ± 0.8 | 20.2 ± 3.2 | 28.9 ± 2.7 |

Table 2.2A. Field and management information for Trial #1 corn sites from 2012 to 2014.

| Management information | 2012 | 2013 | 2014 |
|---|---|---|---|
| Plot size (m) | 4.6 by 24.4 | 4.6 by 24.4 | 4.6 by 24.4 |
| Hybrid or cultivar | DKC 63-25 VT3 | DKC 63-25 VT3 | P1151 AM |
| Planting date | 30 May | 14 May | 16 April |
| Row spacing (cm) | 76.2 | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 12,140 | 12,140 | 13,350 |
| Harvest date | 12 Oct. | 19 Sep. | 30 Sep. |
| Maintenance fertilizer | None | None | 20-80-140-20S-2Zn MESZ |
| Nitrogen | 67 kg N ha$^{-1}$ (Urea) and 146 kg N ha$^{-1}$ (PCU) | 224 kg N ha$^{-1}$ (AA) | 202 kg N ha$^{-1}$ (AA) |
| Lime | 29 May | None | None |
| Tillage | Tilloll 2x 30 May<br>Cultipacked 30 May in deep tilled treatments | None | None |
| Weed management | | | |
| Burndown | 5 June, Verdict (0.23 kg a.i. ha$^{-1}$) + Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) + UAN (2.34 L ha$^{-1}$) | 22 May, Lexar (2.37 kg a.i. ha$^{-1}$) + Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + COC (2.34 L ha$^{-1}$) | 9 May, Warrant (1.15 kg a.i. ha$^{-1}$)<br>23 May, Lexar EZ (2.84 kg a.i. ha$^{-1}$) + Roundup PowerMAX (0.79 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) |
| Postemergence | 22 June, Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + COC (2.34 L ha$^{-1}$) + Callisto (0.09 kg a.i. ha$^{-1}$) + Atrazine (1.15 kg a.i. ha$^{-1}$) | 27 June, Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + COC (2.34L ha$^{-1}$) + Callisto (0.09 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) | 18 June, Roundup PowerMAX (0.79 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) |
| Insect management | NA | NA | NA |
| Disease management | NA | NA | NA |

[†]Abbreviations: AA, anhydrous ammonia; COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

[††]Herbicide chemical nomenclature used in burndown and postemergence listed in Table 2.9

Table 2.2B. Field and management information for Trial #1 corn sites from 2015 to 2016.

| Management information | 2015 | 2016 |
|---|---|---|
| Plot size (m) | 4.6 by 24.4 | 4.6 by 24.4 |
| Hybrid or cultivar | DKC 63-25 VT3 | DKC 62-97 VT3 |
| Planting date | 18 April | 5 April |
| Row spacing (cm) | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 12,140 | 12,140 |
| Harvest date | 17 Sept. | 29 Sept. |
| Maintenance fertilizer | None | None |
| Nitrogen | 235 kg N ha$^{-1}$ (AA) | 190 kg N ha$^{-1}$ (AA) |
| Lime | None | None |
| Tillage | None | None |
| Weed management | | Tilloll 1x |
| Burndown | 23 April, Sharpen (0.02 kg a.i. ha$^{-1}$) + Touchdown Total (75.0 kg a.i. ha$^{-1}$) + MSO (1% v/v) + UAN (2.34 L ha$^{-1}$) | 14 April, Roundup PowerMAX (1.14 kg a.i ha$^{-1}$) + Verdic (0.36 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + MSO (1% v/v) |
| | 27 May, Roundup PowerMAX (0.82 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 18 May, Zidua (0.25 kg a.i. ha$^{-1}$) + Atrazine (2.3 kg a.i. ha$^{-1}$) NIS (0.25% v/v) + DAS (2.04 kg L$^{-1}$) |
| Postemergence | 6 June, Halex GT (2.01 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + Boundary (2.09 kg a.i. ha$^{-1}$) + UAN (2.34 L ha-1) | NA |
| Insect management | NA | NA |
| Disease management | NA | NA |

[†] Abbreviations: AA, anhydrous ammonia; COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

[††] Herbicides chemical nomenclature used in burndown and postemergence listed in Table 2.9

Table 2.3A. Field management information for Trial #2 corn sites from 2013 to 2016.

| Management information | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|
| Plot size (m) | 4.6 by 22.9 | 4.6 by 22.9 | 4.6 by 22.9 | 4.6 by 24.4 |
| Hybrid or cultivar | DKC 63-87 | GH G09E98-3000GT | DKC 63-25 VT3 | DKC 62-97 VT3 |
| Planting date | 14 May | 5 May | 18 April | 5 April |
| Row spacing (cm) | 76.2 | 76.2 | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 12,140 | 12,220 | 12,140 | 12,140 |
| Harvest date | 19 Sep. | 30 Sep. | 14 Sept. | 29 Sept. |
| Maintenance fertilizer | None | 20-80-140-20S-2Zn MESZ | None | None |
| Nitrogen | 135 kg N ha$^{-1}$ (PCU) | 202 kg N ha$^{-1}$ (AA) + nitrapyrin (2.34 L ha$^{-1}$) | 235 kg N ha$^{-1}$ (AA) | 190 kg N ha$^{-1}$ (AA) |
| Lime | 27 Nov | None | None | None |
| Tillage | Tilloll 2x, 1 May | None | None | None |
| Weed management | | | | Tilloll 1x |
| Burndown | 22 May, Lexar (2.36 kg a.i. ha$^{-1}$) + Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + COC (2.34 L ha$^{-1}$) | 9 May, Sharpen (0.02 kg a.i. ha$^{-1}$) + Warrant (1.16 kg a.i. ha$^{-1}$) + MSO (1% v/v) + UAN (2.34 L ha-1)<br>23 May, Lexar EZ (2.84 kg a.i. ha$^{-1}$) + Roundup PowerMAX (0.79 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 23 April, Sharpen (0.02 kg a.i. ha$^{-1}$) + Touchdown Total (75.0 kg a.i. ha$^{-1}$) + MSO (1% v/v) + UAN (2.34 L ha$^{-1}$)<br>27 May, Roundup PowerMAX (0.82 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 14 April, Roundup PowerMAX (1.14 kg a.i ha$^{-1}$) + Verdic (0.36 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + MSO (1% v/v)<br>18 May, Zidua (0.25 kg a.i. ha$^{-1}$) + Atrazine (2.3 kg a.i. ha$^{-1}$) NIS (0.25% v/v) + DAS (2.04 kg L$^{-1}$) |
| Postemergence | 27 June, Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + COC (2.34 L ha$^{-1}$) + Callisto (0.09 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) | 18 June, Roundup PowerMAX (0.79 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 6 June, Halex GT (2.01 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + Boundary (2.09 kg a.i. ha$^{-1}$) + UAN (2.34 L ha-1) | NA |
| Insect management | NA | NA | NA | NA |
| Disease management | NA | NA | NA | NA |

†Abbreviations: AA, anhydrous ammonia; COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; PCU, polymer-coated urea; UAN, 32% urea ammonium nitrate.

††Herbicides chemical nomenclature used in burndown and postemergence listed in Table 2.9

Table 2.3B. Field management information for Trial #3 corn sites from 2014 to 2016.

| Management information | 2014 | 2015 | 2016 |
|---|---|---|---|
| Plot size (m) | 4.6 by 24.4 | 4.6 by 24.4 | 4.6 by 24.4 |
| Hybrid or cultivar | GH G09E98-3000GT | DKC 63-25 VT3 | DKC 63-25 VT3 |
| Planting date | 5 May | 23 April | 15 April |
| Row spacing (cm) | 76.2 | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 12,220 | 12,140 | 12,140 |
| Harvest date | 7 Oct. | 17 Sept. | 29 Sept. |
| Maintenance fertilizer | 20-80-140-20S-2Zn MESZ | None | None |
| Nitrogen | 224 kg N ha$^{-1}$ (AA) | 235 kg N ha$^{-1}$ (AA) | 190 kg N ha$^{-1}$ (AA) |
| Lime | 15 Nov | None | None |
| Tillage | Tilloll 2x 23 April | None | None |
| Weed management | | | |
| Burndown | 9 May, Sharpen (0.02 kg a.i. ha$^{-1}$) + Warrant (1.16 kg a.i. ha+-1) + MSO (1% v/v) + UAN (2.34 L ha$^{-1}$) | 23 April, Sharpen (0.02 kg a.i. ha$^{-1}$) + Touchdown Total (75.0 kg a.i. ha$^{-1}$) + MSO (1% v/v) + UAN (2.34 L ha$^{-1}$) | 14 April, Roundup PowerMAX (1.14 kg a.i ha$^{-1}$) + Verdict (0.36 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + MSO (1% v/v) |
| Postemergence | 23 May, Lexar EZ (2.84 kg a.i. L ha$^{-1}$) + Roundup PowerMAX (0.79 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$)<br>18 June, Roundup PowerMAX (0.79 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 27 May, Roundup PowerMAX (0.82 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$)<br>6 June, Halex GT (2.01 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 18 May, Zidua (0.25 kg a.i. ha$^{-1}$) + Atrazine (2.3 kg a.i. ha$^{-1}$) NIS (0.25% v/v) + DAS (2.04 kg L$^{-1}$) |
| Insect management | NA | NA | NA |
| Disease management | NA | NA | NA |

[†]Abbreviations: COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

[††]Herbicides chemical nomenclature used in burndown and postemergence listed in Table 2.9

Table 2.4A. Field and management information for Trial #1 soybean sites from 2012 to 2014.

| Management information | 2012 | 2013 | 2014 |
|---|---|---|---|
| Plot size (m) | 4.6 by 24.4 | 4.6 by 24.4 | 4.6 by 24.4 |
| Hybrid or cultivar | AG3730 RR2 | AG3730 RR2 | P93Y92 |
| Planting date | 30 May | 8 May | 8 May |
| Row spacing (cm) | 19 | 19 | 19 |
| Seeding rate (seeds ha$^{-1}$) | 80,940 | 80,940 | 72,840 |
| Harvest date | 4 Oct. | 9 Sep. | 20 Oct. |
| Maintenance fertilizer | None | None | 20-80-140-20S-2Zn MESZ |
| Urea and PCU | | | |
| Lime | 29 May | None | None |
| Tillage | Tilloll 2x 30 May<br>Cultipacked 30 May in deep tilled treatments | None | None |
| Weed management | | | |
| Burndown | 5 June, Verdict (0.22 kg a.i. ha$^{-1}$) + Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) + UAN (2.34 L ha$^{-1}$) | NA | 9 May, Warrant (1.16 kg a.i. ha$^{-1}$) |
| Preemergence and/or Postemergence | 22 June, Reflex (0.35 kg a.i. ha$^{-1}$) + Roundup PowerMAX (0.78 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + NIS (0.25% v/v) | 22 May, Prefix (2.42 kg a.i. ha$^{-1}$) + Roundup PowerMAX (1.14 kg a.i.) + COC (2.34 L ha$^{-1}$) + UAN (2.34 L ha$^{-1}$) | 23 May, Prefix (15.23 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + NIS (0.25% v/v)<br>18 June, Roundup PowerMAX (0.78 kg a.i. L ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) |
| Insect management | NA | NA | NA |
| Disease management | NA | NA | NA |

[†] Abbreviations: COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

[††] Herbicides chemical nomenclature used in burndown and postemergence listed in Table 2.9

Table 2.4B. Field and management information for Trial #1 soybean sites from 2015 to 2016.

| Management information | 2015 | 2016 |
|---|---|---|
| Plot size (m) | 4.6 by 24.4 | 4.6 by 24.4 |
| Hybrid or cultivar | AG3731 RR2 | AG3731 RR2 |
| Planting date | 3 June | 15 April |
| Row spacing (cm) | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 80,940 | 80,940 |
| Harvest date | 10 Oct. | 19 Oct. |
| Maintenance fertilizer | None | 15-73-129 (MAP) |
| Urea and PCU | | |
| Lime | None | None |
| Tillage | None | None |
| Weed management | | |
| Burndown | 24 April, Touchdown Total (0.72 kg a.i. ha$^{-1}$) + Sharpen (0.02 kg a.i. ha$^{-1}$) + UAN (2.34 L ha$^{-1}$) + MSO (1% v/v)<br>27 May, Roundup PowerMAX (0.78 kg a.i. ha$^{-1}$) + Dual II Magnum (0.78 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 14 April, Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + Verdict (0.36 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + MSO (1% v/v) |
| Preemergence and/or Postemergence | 6 June, Boundary (2.09 kg a.i. ha$^{-1}$) + UAN (2.34 L ha-1)<br>17 Aug., Roundup PowerMAX (1.04 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 19 May, Prefix (1.65 kg a.i. ha$^{-1}$) + First Rate (.03 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) + DAS (2.04 kg L$^{-1}$) |
| Insect management | NA | NA |
| Disease management | NA | NA |

[†] Abbreviations: COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

[††] Herbicides chemical nomenclature used in burndown and postemergence listed in Table 2.9

Table 2.5A. Field and management information for Trial #2 soybean sites from 2013 to 2016.

| Management information | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|
| Plot size (m) | 4.6 by 22.9 | 4.6 by 22.9 | 4.6 by 22.9 | 4.6 by 22.9 |
| Hybrid or cultivar | AG3731 RR2 | AG3932 | AG3932 | AG3731 RR2 |
| Planting date | 16 May | 8 May | 3 June | 15 April |
| Row spacing (cm) | 19 | 19 | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 80,940 | 52,690 | 12,140 | 80,940 |
| Harvest date | 9 Sep. | 19 Oct. | 9 Oct. | 16 Oct. |
| Maintenance fertilizer | None | 20-80-140-20S-2Zn MESZ | None | 15-73-129 (MAP) |
| Urea and PCU | | | | |
| Lime | 27 Nov | None | None | None |
| Tillage | Tilloll 2x, 1 May | None | None | None |
| Weed management | | | | |
| Burndown | NA | 9 May, Sharpen (0.02 kg a.i. ha$^{-1}$) + Warrant (1.04 kg a.i. ha$^{-1}$) + MSO (1% v/v) + UAN (2.34 L ha$^{-1}$) | 24 April, Touchdown Total (0.72 kg a.i. ha$^{-1}$) + Sharpen (0.02 kg a.i. ha$^{-1}$) + UAN (2.34 L ha$^{-1}$) + MSO (1% v/v)<br>27 May, Roundup PowerMAX (0.78 kg a.i. ha$^{-1}$) + Dual II Magnum (0.78 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 14 April, Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + Verdict (0.36 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + MSO (1% v/v) |
| Preemergence and/or Postemergence | 22 May, Prefix (2.42 kg a.i. ha$^{-1}$) + Roundup PowerMAX (1.14 kg a.i.ha$^{-1}$) + COC (2.34 L ha$^{-1}$) + UAN (2.34 L ha$^{-1}$) | 23 May, Prefix (1.52 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + NIS (0.25% v/v)<br>18 June, Roundup PowerMAX (0.78 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 17 Aug., Roundup PowerMAX (1.04 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 19 May, Prefix (1.65 kg a.i. ha$^{-1}$) + FirstRate (.03 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) + DAS (2.04kg L$^{-1}$) |
| Insect management | NA | NA | NA | |
| Disease management | NA | NA | NA | |

[†]Abbreviations: COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

[††]Herbicides chemical nomenclature used in burndown and postemergence listed in Table 2.9

Table 2.5B. Field management information for Trial #3 soybean sites from 2014 to 2016.

| Management information | 2014 | 2015 | 2016 |
|---|---|---|---|
| Plot size (m) | 4.6 by 24.4 | 4.6 by 24.4 | 4.6 by 24.4 |
| Hybrid or cultivar | P93Y92 | AG3932 | AG3931 |
| Planting date | 8 May | 23 April | 14 April |
| Row spacing (cm) | 19 | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 72,840 | 72,840 | 72,840 |
| Harvest date | 20 Oct. | 10 Oct. | 19 Oct. |
| Maintenance fertilizer | 20-80-140-20S-2Zn MESZ | None | None |
| Urea and PCU | | | |
| Lime | 15 Nov | None | None |
| Tillage | Tilloll 2x 23 April | None | None |
| Weed management | | | |
| Burndown | 9 May, Sharpen (0.02 kg a.i. ha$^{-1}$) + Warrant (1.16 kg a.i. ha$^{-1}$) + MSO (1% v/v) + UAN (2.34 L ha$^{-1}$) | 24 April, Touchdown Total (0.72 kg a.i. ha$^{-1}$) + Sharpen (0.02 kg a.i. ha$^{-1}$) + UAN (2.34 L ha$^{-1}$) + MSO (1% v/v) | 14 April, Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + Verdict (0.36 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + MSO (1% v/v) |
| Postemergence | 23 May, Prefix (1.52 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + NIS (0.25% v/v)<br>18 June, Roundup PowerMAX (0.78 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 27 May, Roundup PowerMAX (0.78 kg a.i. ha$^{-1}$) + Dual II Magnum (0.78 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$)17 Aug., Roundup PowerMAX (1.04 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 19 May, Prefix (1.65 kg a.i. ha$^{-1}$) + First Rate (.03 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) + DAS (2.04kg L$^{-1}$) |
| Insect management | NA | NA | NA |
| Disease management | NA | NA | NA |

†Abbreviations: COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

††Herbicides chemical nomenclature used in burndown and postemergence listed in Table 2.9

Table 2.6. Soil test calcium values for lime treatments at 0 to 13, 13 to 25, 25 to 38 and 38 to 51 cm depths for 2012, 2013,2014, and 2015 for Trials #1, #2 and #3.

| | | Trial #1 | | | Trial #2 | | | Trial #3 | |
|---|---|---|---|---|---|---|---|---|---|
| Depth | Treatment | 2012 | 2013 | 2014 | 2013 | 2014 | 2015 | 2014 | 2015 |
| | | kg ha$^{-1}$ | | | | | | | |
| 0 to 13 cm | CTRL[†] | 4,267 | 4,633 | 4,745 | 3,003 | 2,667 | 2,930 | 4,088 | 3,592 |
| | S-LO | 4,809 | 4,963 | 5,547 | 3,520 | 3,074 | 3,579 | 4,387 | 4,165 |
| | S-HI | 4,592 | 5,128 | 5,777 | 3,723 | 3,548 | 3,638 | 4,714 | 4,401 |
| | D-NO | 3,919 | 4,541 | 5,315 | 3,220 | 2,907 | 3,307 | 4,624 | 3,612 |
| | D-LO | 4,212 | 4,661 | 5,393 | 3,131 | 2,640 | 3,402 | 4,375 | 3,778 |
| | D-HI | 3,806 | 4,324 | 5,146 | 3,409 | 3,008 | 3,306 | 4,537 | 3,746 |
| | LSD$_{(0.10)}$[††] | 532 | 488 | 716 | 395 | 373 | 500 | 491 | 519 |
| 13 to 25 cm | CTRL | 4,712 | 4,832 | 5,343 | 3,872 | 4,202 | 3,857 | 3,526 | 3,844 |
| | S-LO | 4,928 | 5,269 | 5,605 | 4,488 | 4,778 | 4,435 | 3,344 | 4,062 |
| | S-HI | 5,012 | 4,980 | 5,626 | 4,173 | 4,839 | 4,252 | 3,357 | 4,327 |
| | D-NO | 4,986 | 5,883 | 5,934 | 4,365 | 4,798 | 4,563 | 3,696 | 3,959 |
| | D-LO | 4,998 | 6,208 | 6,053 | 4,481 | 4,239 | 4,427 | 3,952 | 4,001 |
| | D-HI | 5,144 | 6,463 | 6,656 | 4,389 | 5,517 | 4,789 | 4,794 | 4,539 |
| | LSD$_{(0.10)}$ | NS[†††] | 1218 | 903 | NS | 1,055 | 695 | 695 | 553 |
| 25 to 38 cm | CTRL | 5,866 | 5,802 | 5,650 | 4,086 | 4,426 | 3,926 | 5,230 | 4,704 |
| | S-LO | 5,683 | 6,221 | 6,049 | 5,100 | 5,390 | 5,001 | 4,980 | 4,343 |
| | S-HI | 5,698 | 5,672 | 5,736 | 4,759 | 4,738 | 4,371 | 5,577 | 4,594 |
| | D-NO | 6,034 | 5,525 | 6,115 | 4,580 | 4,878 | 4,695 | 5,378 | 4,464 |
| | D-LO | 6,330 | 5,577 | 5,924 | 5,011 | 5,866 | 4,895 | 5,806 | 4,535 |
| | D-HI | 6,233 | 5,968 | 6,178 | 5,706 | 5,667 | 4,692 | 7,734 | 4,989 |
| | LSD$_{(0.10)}$ | NS | NS | NS | 1,066 | 1285 | NS | 1373 | NS |
| 38 to 51 cm | CTRL | 5,790 | 5,589 | 5,517 | 3,951 | 4,659 | 3,744 | 6,589 | 5,006 |
| | S-LO | 6,043 | 5,733 | 5,912 | 5,328 | 6,000 | 5,332 | 6,267 | 5,299 |
| | S-HI | 6,465 | 5,599 | 5,838 | 4,671 | 5,769 | 4,662 | 5,786 | 5,135 |
| | D-NO | 5,766 | 5,958 | 5,558 | 4,495 | 4,874 | 4,432 | 6,203 | 4,466 |
| | D-LO | 6,023 | 5,385 | 5,459 | 4,997 | 5,780 | 4,996 | 6,309 | 3,785 |
| | D-HI | 6,062 | 6,020 | 5,591 | 4,543 | 5,805 | 4,788 | 6,313 | 5,342 |
| | LSD$_{(0.10)}$ | NS | NS | NS | NS | NS | NS | NS | NS |

[†] Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$

[††] LSD$_{(0.10)}$ denotes least significant difference at α=0.10

[†††] NS denotes no significant differences between treatments at α=0.10

Table 2.7. Soil test neutralizable acidity values for lime treatments at 0 to 13, 13 to 25, 25 to 38 and 38 to 51 cm depths for 2012, 2013,2014, and 2015 for Trials #1, 2 and 3.

| | | Trial #1 | | | Trial #2 | | | Trial #3 | |
|---|---|---|---|---|---|---|---|---|---|
| Depth | Treatment | 2012 | 2013 | 2014 | 2013 | 2014 | 2015 | 2014 | 2015 |
| | | ------------------------------ cmol$_c$ kg$^{-1}$ -------------------------------- | | | | | | | |
| 0 to 13 cm. | CTRL† | 2.3 | 2.1 | 2.9 | 6.9 | 5.7 | 7.1 | 2.9 | 2.4 |
| | S-LO | 1.5 | 1.2 | 1.1 | 5.6 | 4.4 | 6.4 | 1.8 | 1.9 |
| | S-HI | 1.3 | 0.8 | 0.4 | 4.8 | 3.6 | 5.4 | 1.0 | 1.3 |
| | D-NO | 2.5 | 2.3 | 2.2 | 6.9 | 6.1 | 7.1 | 2.4 | 2.8 |
| | D-LO | 2.3 | 2.1 | 2.4 | 7.4 | 6.3 | 7.0 | 2.4 | 2.1 |
| | D-HI | 3.3 | 1.9 | 2.2 | 6.9 | 6.4 | 8.1 | 2.7 | 2.2 |
| | LSD$_{(0.1)}$ †† | 1.0 | 0.6 | 0.6 | 1.3 | 1.1 | 1.4 | 1.0 | 0.8 |
| 13 to 25 cm. | CTRL | 2.1 | 2.4 | 2.4 | 6.1 | 5.9 | 6.9 | 0.5 | 2.1 |
| | S-LO | 2.4 | 1.7 | 2.1 | 7.8 | 6.6 | 8.2 | 0.1 | 2.0 |
| | S-HI | 2.1 | 2.7 | 2.1 | 6.9 | 5.3 | 7.3 | 0.3 | 1.6 |
| | D-NO | 2.2 | 3.3 | 2.9 | 7.3 | 8.3 | 7.9 | 0.1 | 2.3 |
| | D-LO | 2.1 | 1.9 | 1.9 | 5.5 | 5.8 | 6.3 | 0.0 | 1.4 |
| | D-HI | 2.9 | 1.4 | 1.4 | 7.1 | 5.7 | 7.2 | 0.1 | 1.6 |
| | LSD$_{(0.1)}$ | NS††† | NS | NS | NS | NS | NS | 0.3 | NS |
| 25 to 38 cm. | CTRL | 8.8 | 9.9 | 8.5 | 8.4 | 8.9 | 8.0 | 5.0 | 6.9 |
| | S-LO | 8.9 | 9.8 | 8.3 | 11.9 | 10.9 | 10.6 | 4.6 | 5.6 |
| | S-HI | 9.3 | 9.3 | 8.3 | 10.8 | 9.5 | 8.6 | 4.8 | 5.4 |
| | D-NO | 8.5 | 8.3 | 9.4 | 9.3 | 9.3 | 9.3 | 5.3 | 6.3 |
| | D-LO | 6.6 | 9.9 | 7.7 | 11.5 | 9.6 | 7.6 | 3.5 | 5.9 |
| | D-HI | 9.8 | 9.3 | 8.1 | 8.0 | 10.3 | 10.2 | 2.4 | 5.4 |
| | LSD$_{(0.1)}$ | NS | NS | NS | 2.6 | NS | NS | 1.8 | NS |
| 38 to 51 cm. | CTRL | 11.7 | 10.9 | 10.3 | 8.4 | 9.5 | 7.6 | 11.2 | 12.8 |
| | S-LO | 11.6 | 11.6 | 10.2 | 10.8 | 11.1 | 11.5 | 10.0 | 11.2 |
| | S-HI | 12.1 | 12.8 | 11.1 | 10.9 | 10.1 | 9.9 | 9.3 | 11.8 |
| | D-NO | 11.8 | 11.7 | 10.4 | 9.6 | 9.1 | 9.2 | 10.5 | 12.4 |
| | D-LO | 11.3 | 11.4 | 9.8 | 11.9 | 11.4 | 9.7 | 10.8 | 12.6 |
| | D-HI | 12.3 | 12.1 | 10.2 | 9.6 | 10.8 | 10.1 | 9.9 | 11.7 |
| | LSD$_{(0.1)}$ | NS | NS | NS | NS | NS | NS | NS | NS |

† Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$

††LSD(0.10) denotes least significant difference at α=0.10

††† NS denotes no significant differences between treatments at α=0.10

Table 2.8. Soil test pH$_s$ values for lime treatments at 0 to 13, 13 to 25, 25 to 38 and 38 to 51 cm depths for 2012, 2013,2014, and 2015 for Trials #1, #2 and #3.

| Depth | Treatment | Trial #1 | | | Trial #2 | | | Trial #3 | |
|---|---|---|---|---|---|---|---|---|---|
| | | 2012 | 2013 | 2014 | 2013 | 2014 | 2015 | 2014 | 2015 |
| | | pH$_s$ units | | | | | | | |
| 0 to 13 cm. | CTRL[†] | 5.6 | 5.8 | 5.5 | 4.7 | 4.6 | 4.6 | 5.6 | 5.5 |
| | S-LO | 6.2 | 6.3 | 6.3 | 5.2 | 5.2 | 4.9 | 6.1 | 5.8 |
| | S-HI | 6.3 | 6.5 | 6.6 | 5.3 | 5.5 | 5.2 | 6.4 | 6.2 |
| | D-NO | 5.7 | 5.8 | 5.9 | 4.8 | 4.6 | 4.6 | 5.7 | 5.4 |
| | D-LO | 5.7 | 6.0 | 5.8 | 4.7 | 4.6 | 4.8 | 5.7 | 5.7 |
| | D-HI | 5.6 | 6.0 | 5.9 | 4.8 | 4.6 | 4.6 | 5.7 | 5.6 |
| | LSD$_{(0.1)}$[††] | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.4 | 0.3 |
| 13 to 25 cm. | CTRL | 6.1 | 5.9 | 5.9 | 5.0 | 4.9 | 4.9 | 5.9 | 5.9 |
| | S-LO | 6.0 | 6.0 | 6.0 | 4.7 | 4.9 | 4.8 | 6.1 | 5.9 |
| | S-HI | 6.0 | 5.8 | 6.1 | 4.9 | 5.0 | 4.9 | 6.1 | 6.0 |
| | D-NO | 6.1 | 5.8 | 5.9 | 4.9 | 4.7 | 4.9 | 6.2 | 5.8 |
| | D-LO | 6.2 | 6.2 | 6.3 | 5.2 | 5.0 | 5.2 | 6.5 | 6.2 |
| | D-HI | 5.8 | 6.4 | 6.5 | 5.0 | 5.2 | 5.0 | 6.6 | 6.3 |
| | LSD$_{(0.1)}$ | NS[†††] | 0.4 | 0.4 | 0.3 | NS | 0.4 | 0.4 | 0.3 |
| 25 to 38 cm. | CTRL | 4.8 | 4.7 | 4.8 | 4.8 | 4.7 | 4.7 | 5.0 | 5.0 |
| | S-LO | 4.7 | 4.7 | 4.7 | 4.6 | 4.6 | 4.5 | 5.1 | 5.2 |
| | S-HI | 4.7 | 4.7 | 4.9 | 4.6 | 4.7 | 4.6 | 5.1 | 5.2 |
| | D-NO | 4.7 | 4.9 | 4.7 | 4.7 | 4.7 | 4.6 | 5.0 | 5.1 |
| | D-LO | 5.1 | 4.7 | 5.2 | 4.6 | 4.9 | 4.8 | 5.4 | 5.3 |
| | D-HI | 4.6 | 4.8 | 4.9 | 5.1 | 4.7 | 4.5 | 6.0 | 5.4 |
| | LSD$_{(0.1)}$ | NS | NS | NS | NS | NS | 0.2 | 0.4 | NS |
| 38 to 51 cm. | CTRL | 4.5 | 4.6 | 4.4 | 4.6 | 4.6 | 4.6 | 4.5 | 4.4 |
| | S-LO | 4.5 | 4.6 | 4.4 | 4.6 | 4.6 | 4.5 | 4.7 | 4.4 |
| | S-HI | 4.5 | 4.5 | 4.4 | 4.6 | 4.7 | 4.5 | 4.8 | 4.4 |
| | D-NO | 4.5 | 4.5 | 4.4 | 4.6 | 4.6 | 4.6 | 4.6 | 4.4 |
| | D-LO | 4.5 | 4.6 | 4.5 | 4.6 | 4.6 | 4.5 | 4.6 | 4.4 |
| | D-HI | 4.4 | 4.5 | 4.5 | 4.7 | 4.6 | 4.5 | 4.7 | 4.4 |
| | LSD$_{(0.1)}$ | NS | NS | NS | NS | NS | NS | NS | NS |

[†] Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$

[††] LSD$_{(0.10)}$ denotes least significant difference at $\alpha$=0.10

[†††] NS denotes no significant differences between treatments at $\alpha$=0.10

Table 2.9. Chemical nomenclature of herbicides used in management of trials from 2012 to 2016.

| **Herbicide** | **Chemical Name** |
|---:|:---|
| Atrazine | 1-Chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine |
| Boundary | Metribuzin: 2-chloro-4-ethylamino-6-isopropylamino-s-triazine; *S*-metolachlor |
| Callisto | Mesotrione: 2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione |
| Dual II Magnum | *S*-metolachlor: 2-Chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl]acetamide |
| FirstRate | Cloransulam-methyl: N-(2-carbomethoxy-6-chlorophenyl)-5-ethoxy-7-fluoro(1,2,4)triazolo-[1,5-c]pyrmidine-2-sulfonmide |
| Halex GT | Mesotrione; S-metolachlor; Glyphosate, N-(phosphonomethyl) glycine |
| Lexar | Atrazine; Mesotrione; Acetamide, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl]-,(S) |
| Prefix | *S*-metolachlor; Sodium Salt of Fomesafen, 5-[2-chloro-4-(trifluoromethyl)phenoxy]-N-(methylsulfonyl)-2-nitrobenzamide |
| Reflex | Sodium Salt of Fomesafen, 5-[2-chloro-4-(trifluoromethyl)phenoxy]-N-(methylsulfonyl)-2-nitrobenzamide |
| Roundup PowerMAX | Glyphosate, N-(phosphonomethyl)glycine |
| Sharpen | Saflufenacil, N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3,6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide |
| Touchdown | Glyphosate: N-(phosphonomethyl) glycine |
| Verdict | Saflufenacil, N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3,6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide; Dimethenamid-P, (S)-(2-chloro-N-[(1-methyl-2-methoxy)ethyl]-N-(2,4-dimethyl-thien-3-yl)-acetamide |
| Warrant | Acetochlor, 2-Chloro-N-(ethoxymethyl)-N-(2-ethyl-6-methylphenyl)acetamide |
| Zidua | Pyroxasulfone, 3-[[[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)-1H-pyrazol-4-yl]methyl]sulfonyl]-4,5-dihydro-5,5-dimethylisoxazole |

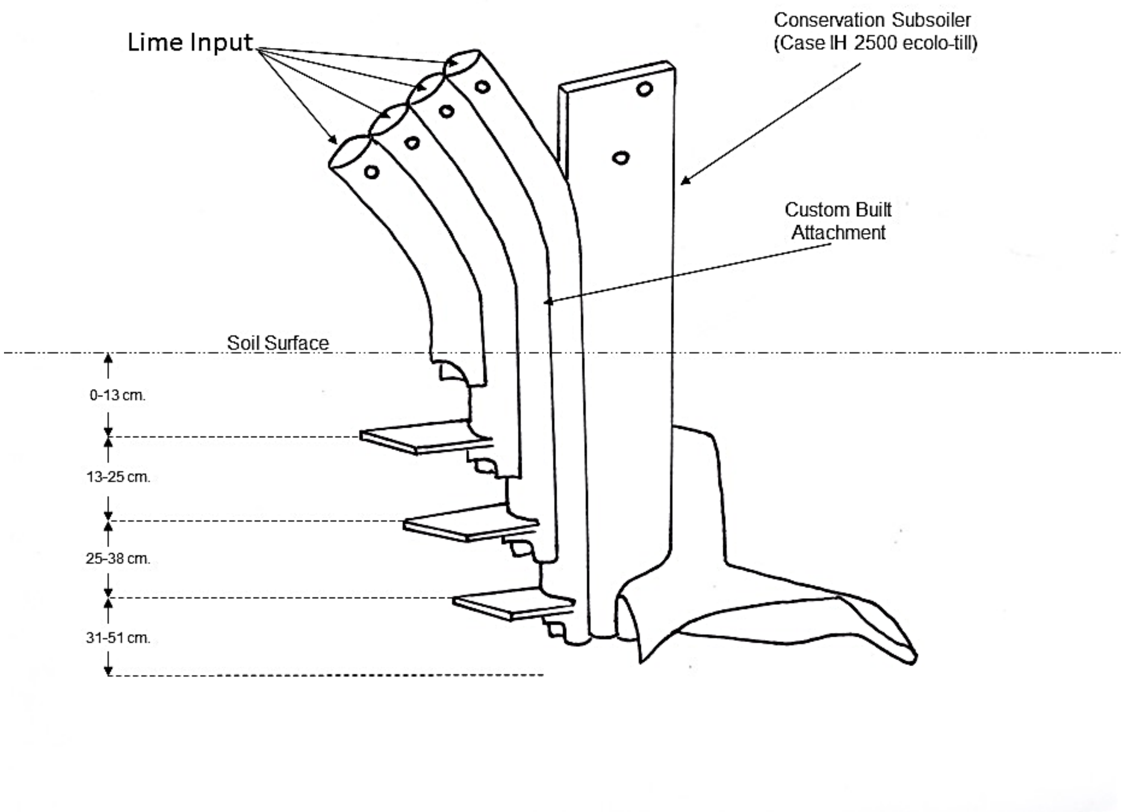

Figure 2.1. Custom built shank attachment schematics showing the tool and the depths of lime placement.

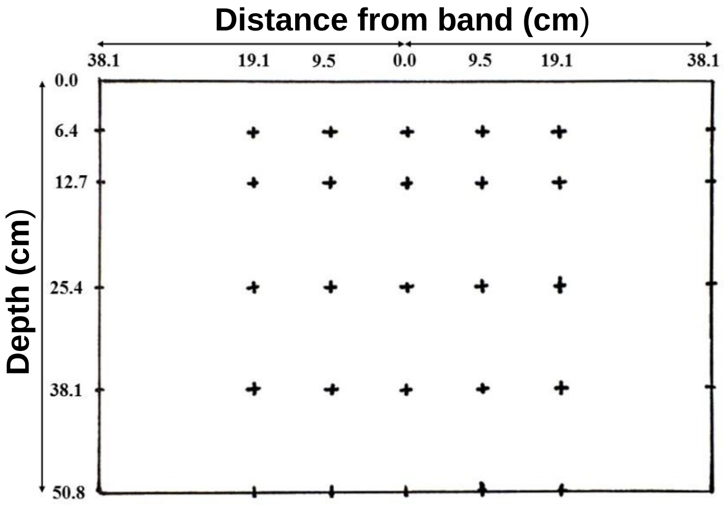

Figure 2.2. Diagram showing the soil sampling template used for assessing spatial variation in the soil profile with depth and distance from the deep lime injection analysis sampling

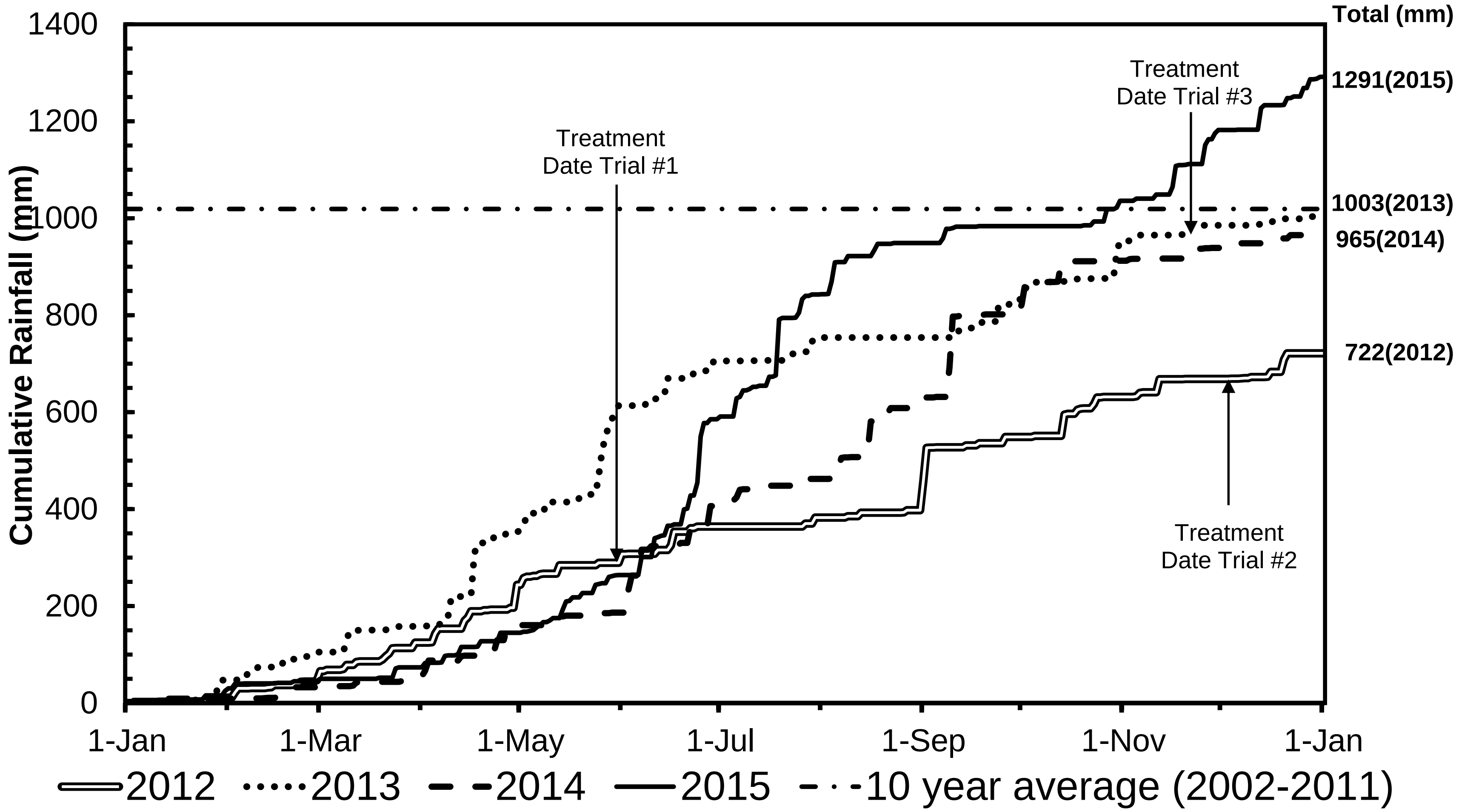

Figure 2.3. Cumulative precipitation during the 2012, 2013, 2014 and 2015 growing seasons and the 10-year average (1019 mm) at Greenley Memorial Research Center in Novelty, Missouri. Lime treatment dates for individual trials were identified for each year.

Figure 2.4. Depth of deep vertical placement treatments into the subsoil.

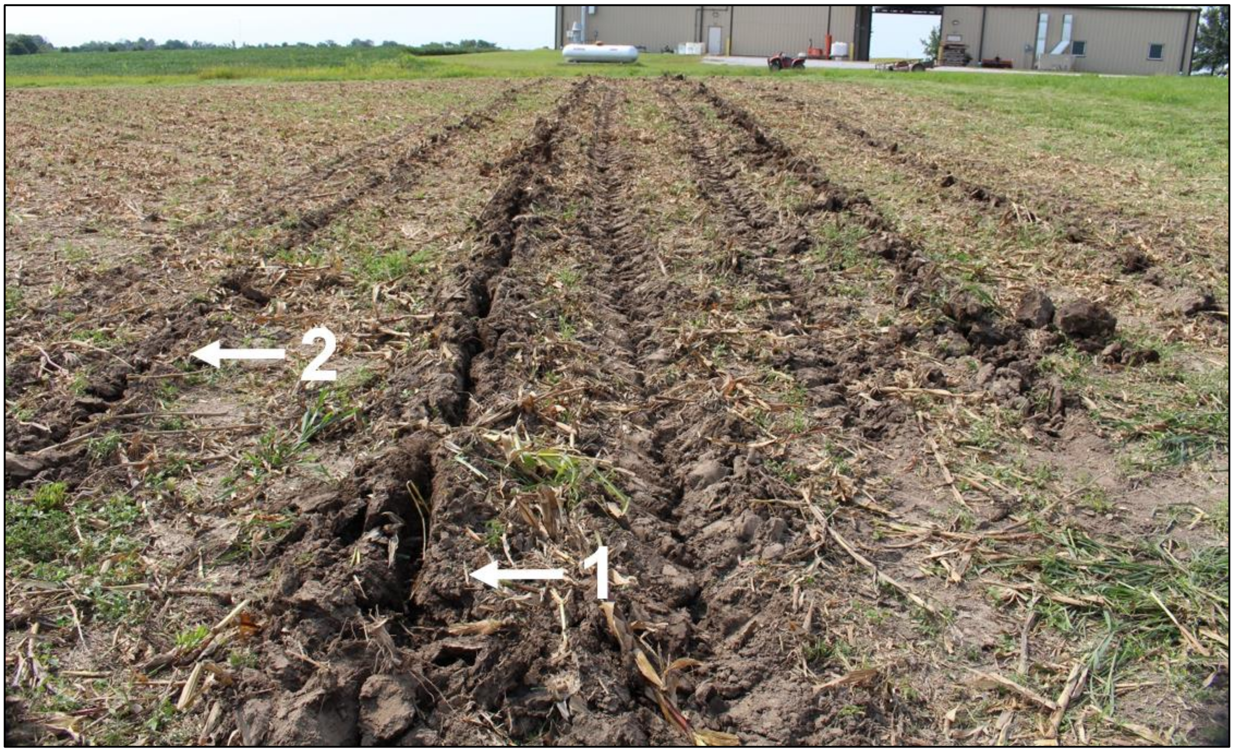

Figure 2.5. Increased surface soil disturbance caused by the custom build shank (1) compared to that of zone tillage (2).

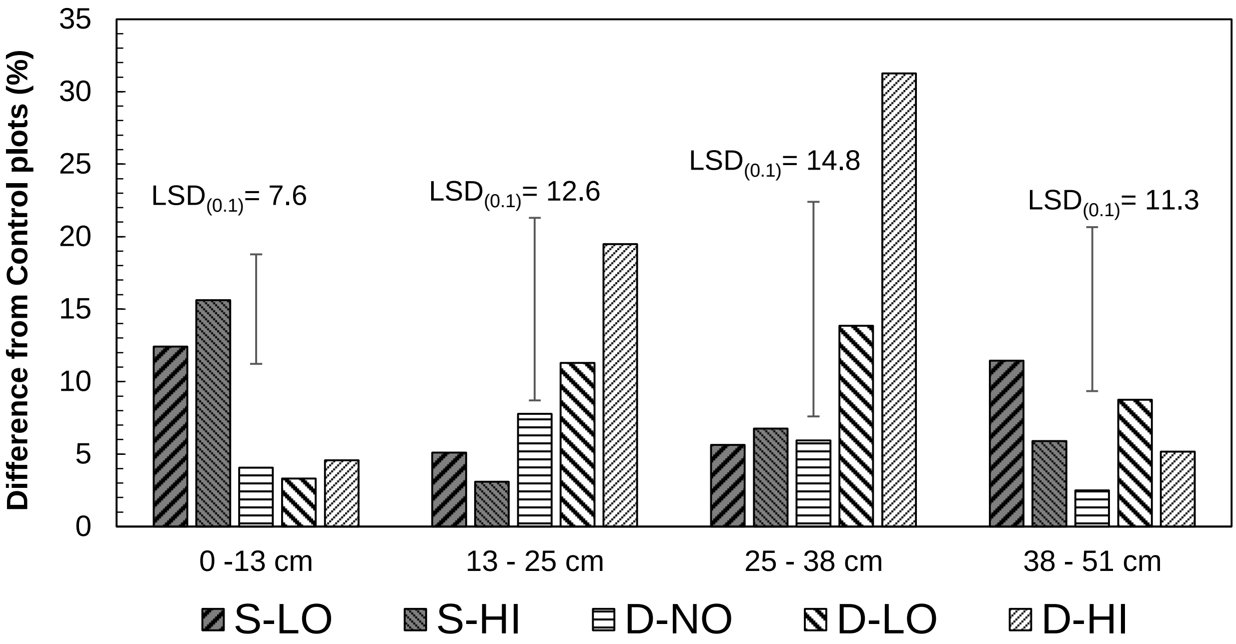

Figure 2.6A. Soil calcium percent difference of treatments from control plots at 0 to 13, 13 to 25, 25 to 38 and 38 to 51cm depths one year after treatment. (Abbreviations: LSD$_{(0.10)}$, least significant differences at $p \leq 0.10$; NS, No statistical difference at $p \leq 0.10$; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

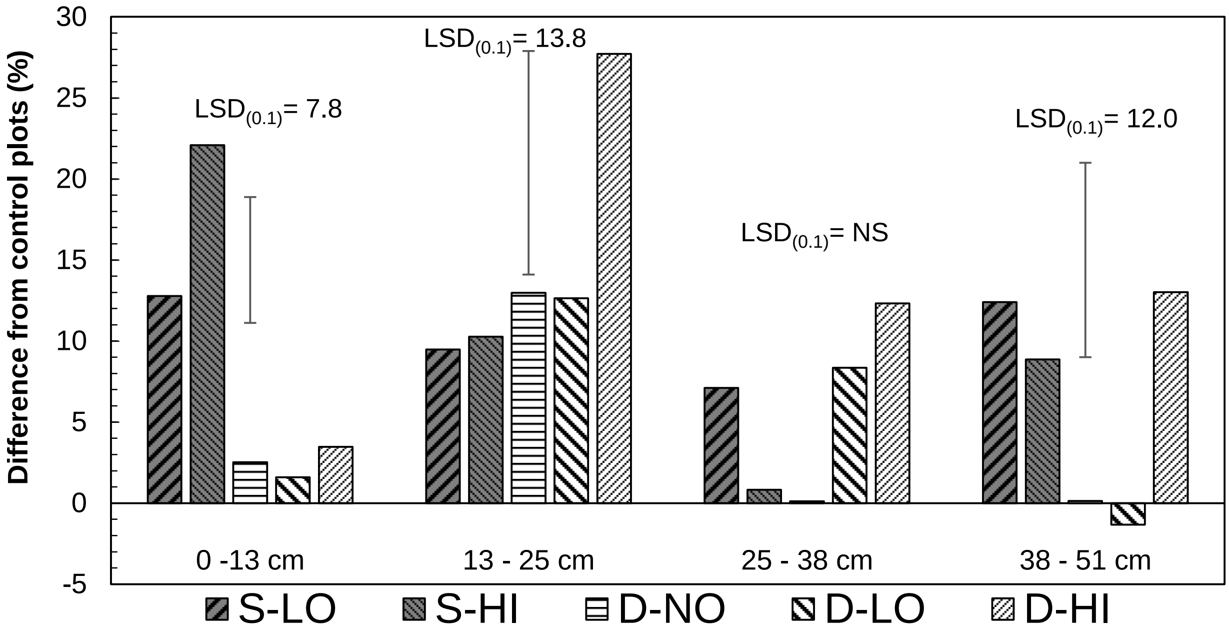

Figure 2.6B. Calcium percent difference of treatments from control plots at 0 to 13, 13 to 25, 25 to 38 and 38 to 51cm depths two years after treatment. (Abbreviations: LSD$_{(0.10)}$, least significant differences at $p \leq 0.10$; NS, No statistical difference at $p \leq 0.10$; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

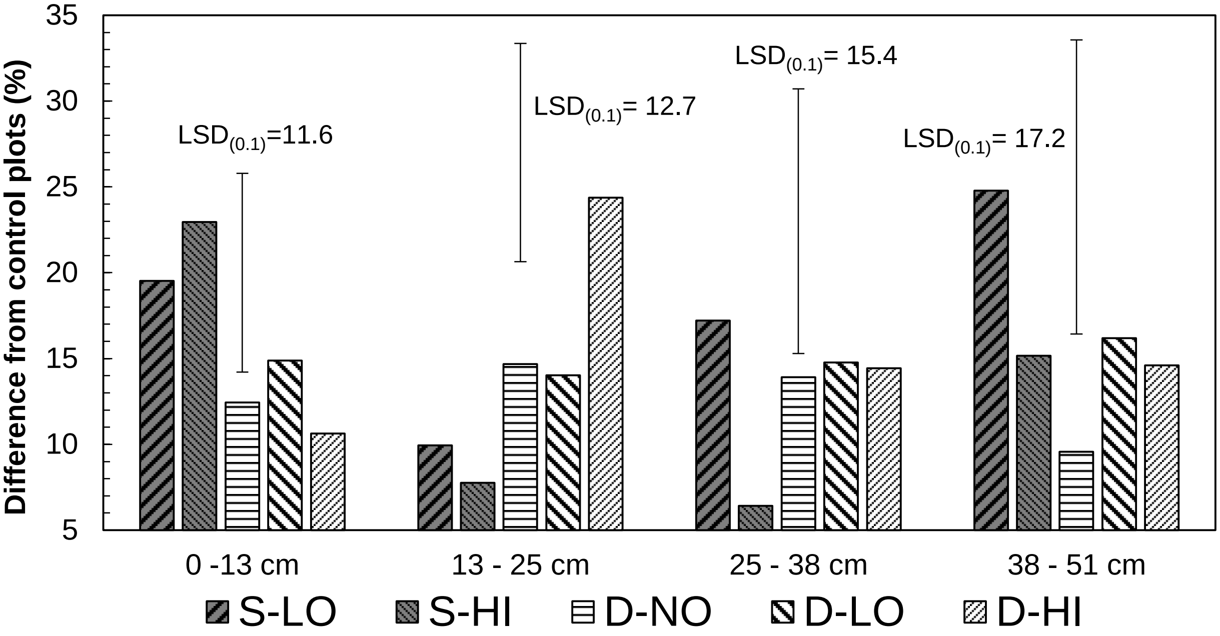

Figure 2.6C. Calcium percent difference of treatments from control plots at 0 to 13, 13 to 25, 25 to 38 and 38 to 51cm depths three years after treatment. (Abbreviations: LSD$_{(0.10)}$, least significant differences at $p \leq 0.10$; NS, No statistical difference at $p \leq 0.10$; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

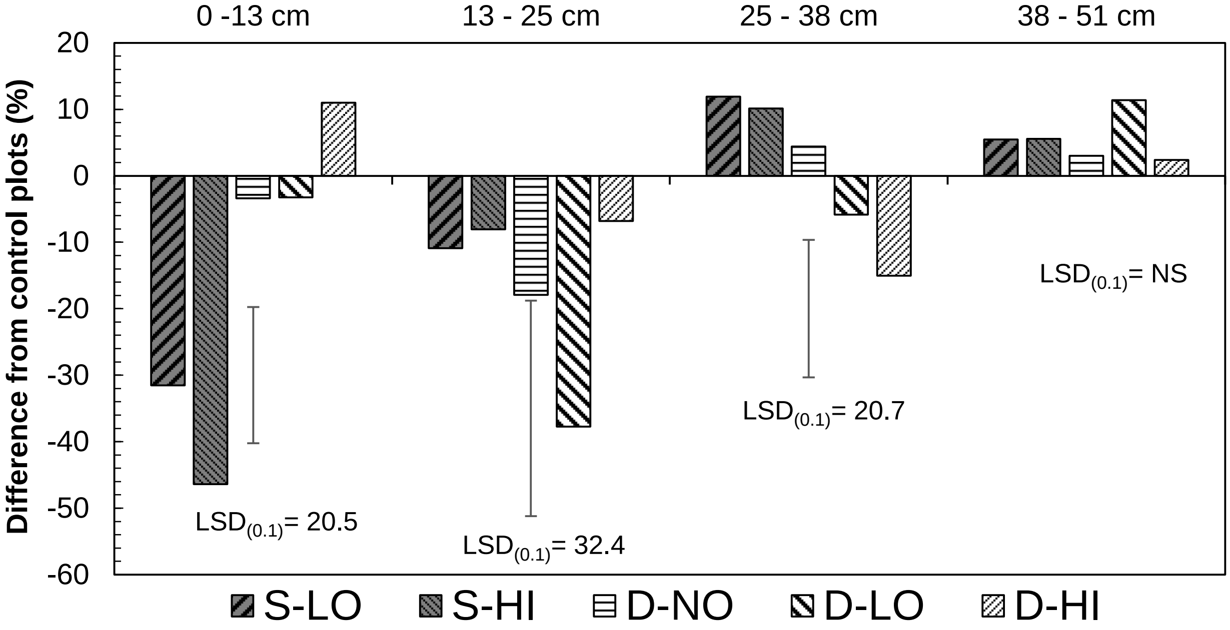

Figure 2.7A. Soil neutralizable acidity percent difference of treatments from control plots at 0 to 13, 13 to 25, 25 to 38 and 38 to 51cm depths one year after treatment. (Abbreviations: LSD$_{(0.10)}$, least significant differences at $p \leq 0.10$; NS, No statistical difference at $p \leq 0.10$; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

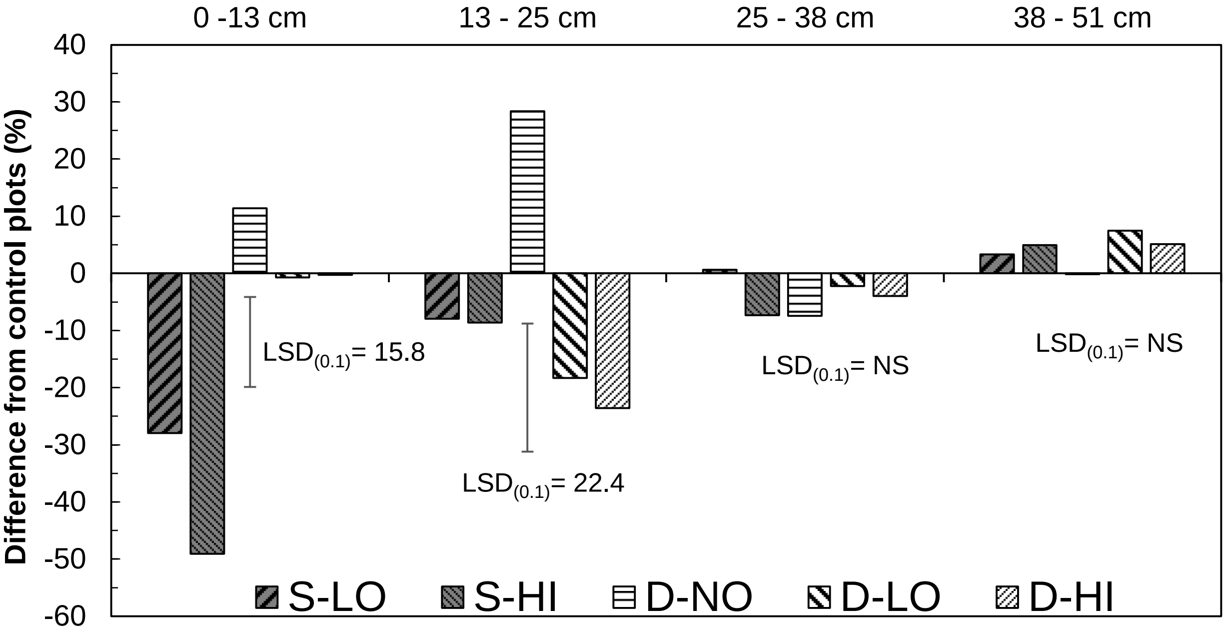

Figure 2.7B. Soil neutralizable acidity percent difference of treatments from control plots at 0 to 13, 13 to 25, 25 to 38 and 38 to 51cm depths two year after treatment. (Abbreviations: $LSD_{(0.10)}$, least significant differences at $p \leq 0.10$; NS, No statistical difference at $p \leq 0.10$; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

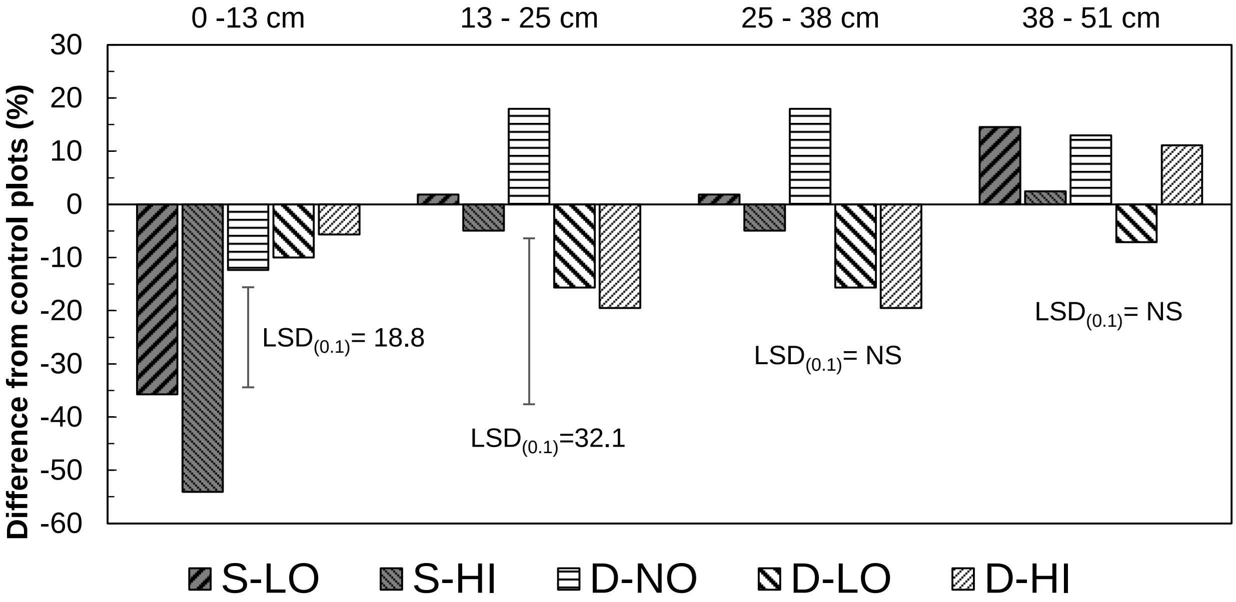

Figure 2.7C. Soil neutralizable acidity percent difference of treatments from control plots at 0 to 13, 13 to 25, 25 to 38 and 38 to 51cm depths three year after treatment. (Abbreviations: $LSD_{(0.10)}$, least significant differences at $p \leq 0.10$; NS, No statistical difference at $p \leq 0.10$; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

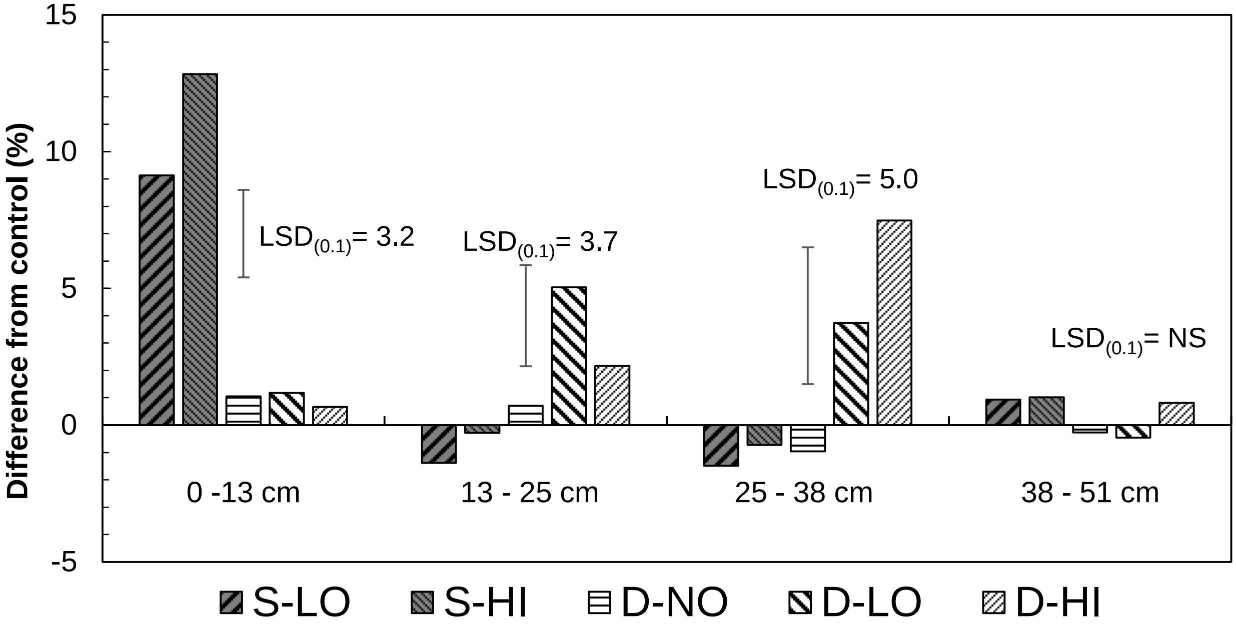

Figure 2.8A. Soil $pH_s$ percent difference of treatments from control plots at 0 to 13, 13 to 25, 25 to 38 and 38 to 51cm depths one year after treatment. (Abbreviations: $LSD_{(0.10)}$, least significant differences at $p \leq 0.10$; NS, No statistical difference at $p \leq 0.10$; S-LO, Surface 3.4 Mg $ha^{-1}$; S-HI, Surface 6.7 Mg $ha^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg $ha^{-1}$; D-HI, Deep placement 6.7 Mg $ha^{-1}$).

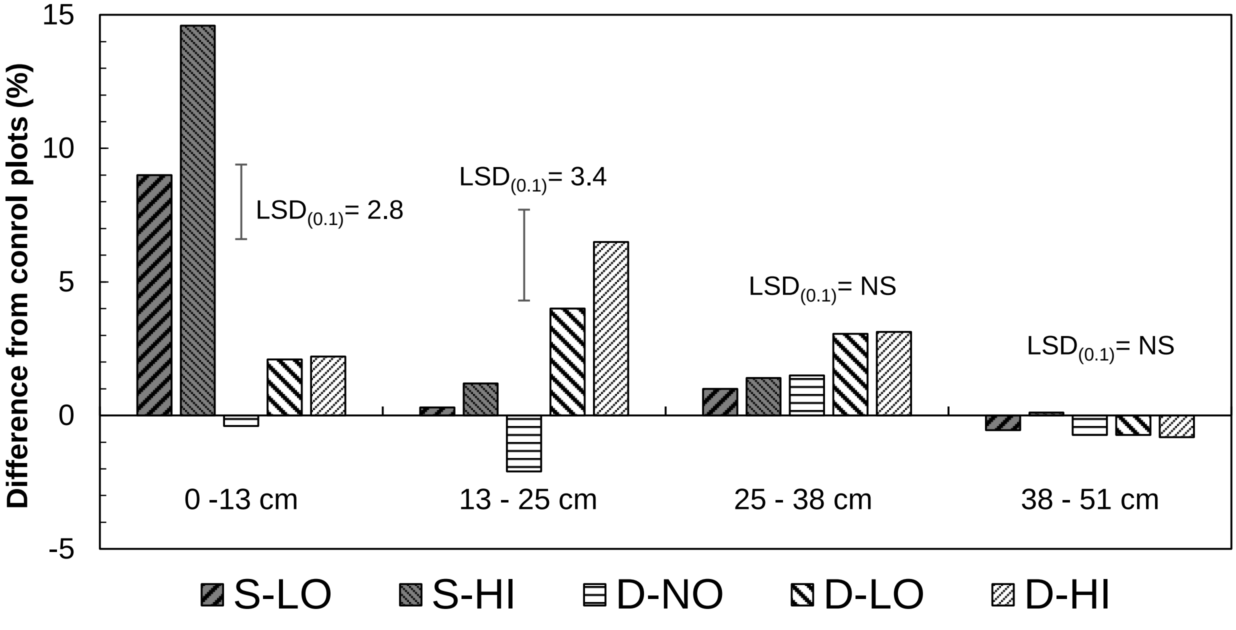

Figure 2.8B. Soil $pH_s$ percent difference of treatments from control plots at 0 to 13, 13 to 25, 25 to 38 and 38 to 51cm depths two year after treatment. (Abbreviations: $LSD_{(0.10)}$, least significant differences at $p \leq 0.10$; NS, No statistical difference at $p \leq 0.10$; S-LO, Surface 3.4 Mg $ha^{-1}$; S-HI, Surface 6.7 Mg $ha^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg $ha^{-1}$; D-HI, Deep placement 6.7 Mg $ha^{-1}$).

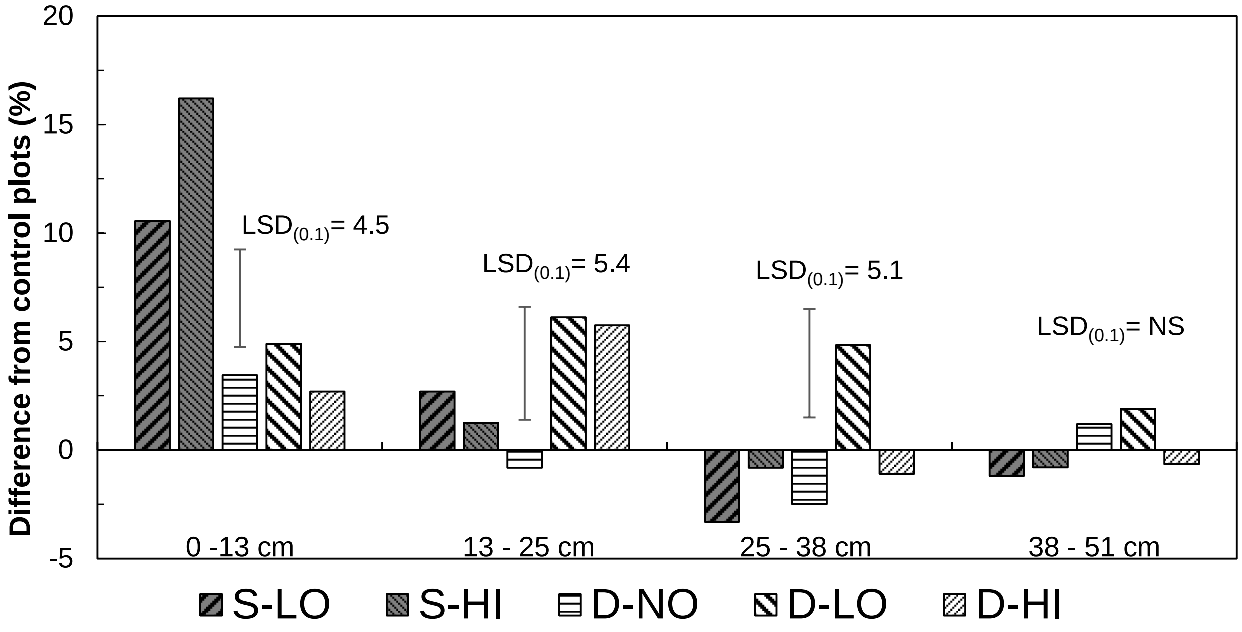

Figure 2.8C. Soil pH$_s$ percent difference of treatments from control plots at 0 to 13, 13 to 25, 25 to 38 and 38 to 51cm depths three years after treatment. (Abbreviations: LSD$_{(0.10)}$, least significant differences at $p \leq 0.10$; NS, No statistical difference at $p \leq 0.10$; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

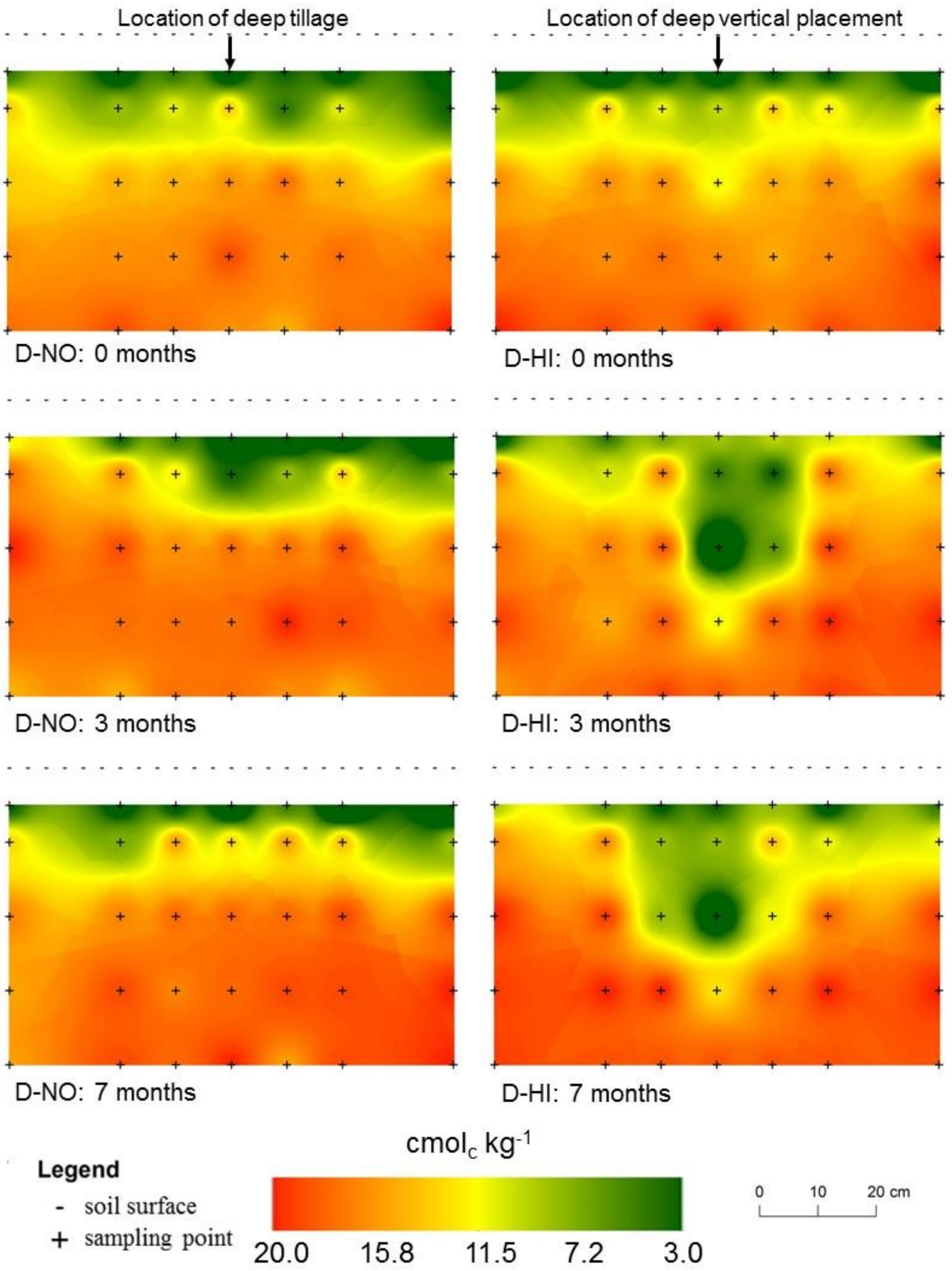

Figure 2.9. Spatial distribution of soil neutralizable acidity in the soil profile after deep vertical placement control at 0 Mg ha$^{-1}$ (D) and a deep vertical placement treatment at 6.7 Mg ha$^{-1}$ (treated) showing changes occurring 0, 3 and 7 months after treatment.

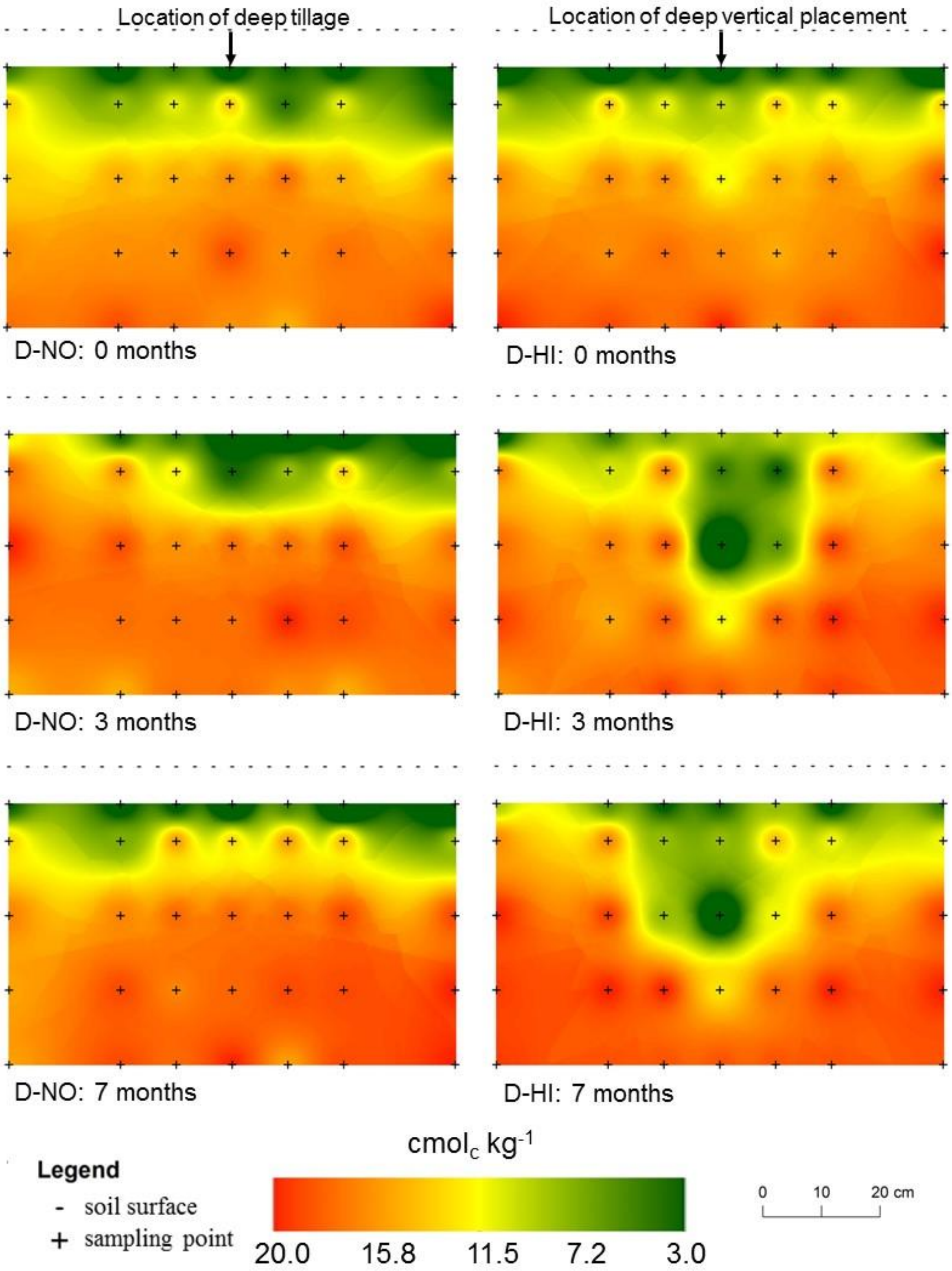

Figure 2.10. Spatial distribution of soil pH$_s$ in the soil profile after deep vertical placement control at 0 Mg ha$^{-1}$ (D-NO) and a deep vertical placement treatment at 6.7 Mg ha$^{-1}$ (D-HI) showing changes occurring 0, 3 and 7 months after treatment.

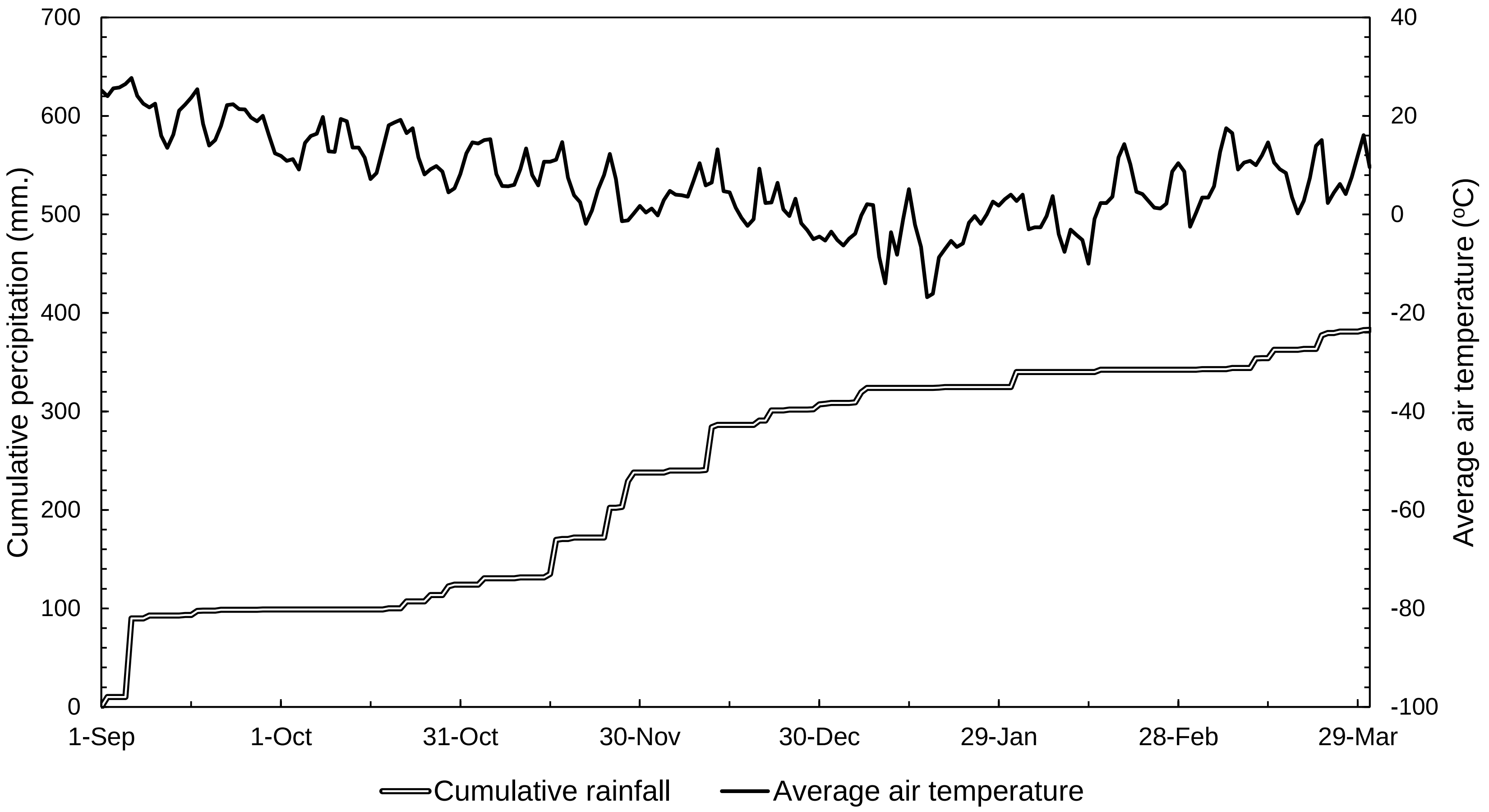

Figure 2.11. Cumulative rainfall and average air temperature of Greenley Memorial Research Center during spatial analysis sampling conducted in 2015/2016.

# CHAPTER 3

## EFFECTS OF DEEP VERTICAL PLACEMENT OF LIME AND GYPSUM ON CORN AND SOYBEAN PRODUCTION

### ABSTRACT

Central claypan soils utilized for corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) production often have been managed to have adequate surface pH for crop growth, but the presence of acidic subsoils may limit crop production. Subsoil acidity may inhibit root growth leading to decreased drought tolerance and grain yields. A lime application can increase soil pH, improve soil structure and provide calcium and magnesium to the soil, but surface amendments that often occur in no-till systems rarely affect the subsoil, resulting in potential chemical and physical barriers to root growth. Surface applications of gypsum also may alleviate aluminum toxicities in acidic soils, increase calcium levels, and alter soil properties in the subsoil. The objective of this study was to determine the effects of surface and deep vertical placement of lime and gypsum at several application rates on corn and soybean plant growth and yields in a conservative tillage system. Field trials were conducted from 2012 to 2014 in Northeast Missouri with treatments of lime (0, 3.4, and 6.7 Mg ha$^{-1}$) and gypsum (0, 2.9, and 5.2 Mg ha$^{-1}$) broadcast on the soil surface or applied as a deep vertical band to a depth of 51 cm. When precipitation was below average, compared to control plots, deep vertical placed lime at 6.7 Mg ha$^{-1}$ significantly raised corn yields by 1.3 Mg ha$^{-1}$ four years after treatment for Trial #2, of which had the lowest initial pH$_s$ of the trials. In years with adequate moisture, no significant increases in corn yield were observed with deep lime placement treatments compared to control plots. Treatments of lime had a greater effect on corn yield than soybean. Deep vertical placement of lime resulted in no significant

increase in soybean yield compared to the controls for all trials. Inconsistent results for corn and soybean yields from gypsum treatments made it unclear on the benefits of adding gypsum. Longer observation time may be needed to fully evaluate the effects of these treatments.

## INTRODUCTION

Effects of subsoil acidity on agronomic production is of great concern in multiple regions around the world (Sumner et al., 1986; Tupper et al., 1987; Mclay et al., 1994; Farina et al., 2000a, 2000b; Godsey et al., 2007), with roughly 70% of the worlds arable land having some level of soil acidity (Rengel, 2003). Acidic conditions in the subsoil horizons have shown to affect nutrient availability and root growth of many agronomic crops (Tupper et al., 1987; Sumner and Yamada, 2002; Yang et al., 2013). Furthermore, soils under intense cropping systems may have substantial increases in subsoil acidity with depth (Abruña et al., 1964; Adeoye and Singh, 1984).

Amendments of agriculture limestone have the ability to alleviate soil acidity (Sumner et al., 1986; Tupper et al., 1987; Mclay et al., 1994; Farina et al., 2000a, 2000b; Godsey et al., 2007, Flower and Crabtree, 2011; Lollato et al., 2013). Liming additions have shown to increase grain yields of many crops through increased rooting systems, nutrient availability and uptake, drought resistance, and reduction of aluminum and manganese toxicities (Sumner et al., 1986; Farina et al., 2000a, 2000b; Joris et al., 2012) In the U.S. alone, it is estimated that roughly 73 million Mg of agricultural lime is required each year to neutralize acidity generated from crop removal (Adams, 1984). However, it is estimated that under current management practices in the U.S. only around 20 to 30 Mg of agriculture lime is applied each year, making up a fraction of the required recommendation (West and Mc Bride, 2005). Issues associated with surface and subsoil acidity are of increasing concern as rising global population pressures producers to cultivate more food on less land area which increases the potential of soil acidity.

Conventional applications of lime have generally been restricted to surface amendments followed by shallow conventional tillage. Surface-applied lime is shown to effectively alleviate soil acidity but is generally restricted to the plow layer (Blevins et al., 1978; Farina and Channon, 1988; Liu and Hue, 2001). Previous research has shown that soil acidity can be successfully reduced at lower depths by simply increasing the plowing depth. Doss et al. (1979) found an increase in subsoil pH when incorporating treatments of lime through rotary tillage up to 45 cm. Treatments of lime increased rooting depth, plant height and grain yield for corn. Sumner et al. (1986) found a 50% increase in alfalfa (*Medicago sativa* L.) yields when lime incorporated via moldboard plow to a 1 m depth over a 4-year period. However, effects from mixing alone significantly decreased yields.

Although conventional tillage has been a primary practice in agriculture for over 3000 years (Hobbs et al., 2008), recent developments in agricultural technology and concerns over soil erosion and degradation of soil structure caused by conventional tillage have begun to shift the average farmer in the United States toward no-till conservation tillage practices. Soils maintained under no-till conditions have shown increases in soil aggregation and aggregate stability as well as increases in organic carbon (Six et al., 1999). However, due to the slow downward movement of lime, the use of no-till or conservation tillage practices has caused difficulty in effectively reaching subsoil horizons with current lime amendments (Caires et al., 2011).

In areas with small soil calcium (Ca) levels and elevated exchangeable aluminum ($Al^{+3}$) resulting from acid soil pH, treatments of gypsum ($CaSO_4$) have shown to be effective in ameliorating these limitations to crop growth and development (Sumner et al., 1987; Farina et al., 2000a, 2000b). Solubility of gypsum is roughly 200 times greater than the calcium carbonate found in limestone allowing surface applications to affect subsoil properties (Rengel, 2003). Tropical regions with highly weathered soils have shown greater response to surface application and incorporation of gypsum in overcoming limitations brought on by subsoil acidity as compared to less weathered soils in more temperate regions (Sumner, 1995).

Increased crop yield responses to gypsum are largely credited to reduction of soluble $Al^{+3}$ and additions of Ca to the soil after gypsum was applied. Although gypsum has little to no effect on soil acidity, gypsum applications greatly reduce $Al^{+3}$ toxicities in the soil (Mclay et al., 1994). The precise mechanism behind the immobilization of $Al^{+3}$ is not well understood, but it is suggested to occur through various complex reactions (Mclay et al., 1994). For example, the sulfate in gypsum may react with $Al^{+3}$ to form aluminum hydroxyl sulfate minerals that precipitate out of the soil solution (Nordstrom, 1982). Others propose that decreases in Al:Ca ratios from additions of calcium from gypsum resulted in higher calcium – aluminum complexes causing a reduction of $Al^{+3}$ in the soil solution (Ritchey et al., 1980).

Regardless of the pathway for $Al^{+3}$ reduction caused by gypsum application, it is essential that surface amendments leach downward into the subsoil for subsoil amelioration to occur (Mclay et al., 1994). In a study by Toma et al. (1999), the long term beneficial effects of incorporated and surface-applied gypsum on ferruginous and aluminous soils under corn and alfalfa management continued to occur 16 years after application. Furthermore, corn grain yields increased 29 to 50% over the period of 16 years after treatment.

Successful improvements to soil fertility from gypsum amendments on highly weathered tropical soils are not often observed on less weathered, but equally acidic soils (Farina, 1997; Farina et al., 2000a, 2000b). Greater soil fertility and small levels of active $Al^{+3}$ found in less weathered soils results in little to no beneficial effects from gypsum treatments. Soil orders, such as Alfisols, Oxisols, and Ultisols, are often characterized by a stratification of increasing soil acidity with depth in the soil profile resulting in low and sometimes unsustainable crop yields (Farina et al., 2000a, 2000b; Sumner and Yamada 2002; Rengel, 2003).

Furthermore, the greater levels of neutralizable acidity of less weathered soils, require greater quantities of lime to raise surface pH sufficiently to successfully promote downward movement of alkalinity (Farina et al., 2000a). A study to evaluate recently acidified soils under no-till production applied limestone at amounts up to 10 Mg $ha^{-1}$ found little to no effects on subsoil pH 5 cm below the surface. (Edwards and Beegle, 1988). Furthermore, lime treatments generally did not have an effect on corn grain yield; however, calcium uptake increased significantly while manganese uptake decreased.

In order to effectively reduce subsoil acidity under no till and conservation tillage practices, lime amendments must be directly applied to the subsoil. Farina and Channon (1988) evaluated various methods of subsoil amelioration which involved directly injecting lime into the subsoil at depths up to 70 cm. A long-term study of lime treatments (Farina et al., 2000a, 2000b) found beneficial effects of these treatments up to

10 years after application. Much like gypsum research, the majority of research on deep placement of lime occurs on highly weathered soils in tropical regions. There has been little research investigating the effects of deep lime and gypsum placement on less weathered, but equally acidic soils. To our knowledge, no research has been conducted on the effects of lime and gypsum vertical placement on yield response of corn and soybean for claypan soils. The objective of this research was to evaluate the impacts of lime and gypsum placement at differing rates on corn and soybean plant growth and grain yields in a conservation tillage system.

## MATERIALS AND METHODS

### Site Description and Experimental Design

Three field trials were established on Northeast Missouri Central Claypan soils over the course of 2012 to 2014 at the Greenley Memorial Research Center (40°02’N, 92°20’W) near Novelty, MO. Field Trials #1 and #3 were established in the spring of 2012 and the fall of 2013 on a Putnam silt loam (Fine, smectitic, mesic Vertic Albaqualfs). Field Trial #2 was established in the fall of 2012 on a Kilwinning silt loam (fine, smectitic, mesic, Vertic Epiaqualfs) (Figure 3.1). Prior to the study, experimental sites were under continuous no-till production for over 13 years. Sites with acidic surface and subsoil horizons were utilized for this experiment. Initial soil characteristics were taken at the establishment of each trial and are presented in Table 3.1.

A randomized complete block design was used for the three field trials with 12 treatments replicated four times. Plot sizes were 4.6 × 24.4 m for trials 1 and 3, and 4.6 × 22.9 m for trial 2. A factorial arrangement of treatments included two crops, two placement methods, and rates of lime (0, 3.4 and 6.7 Mg $ha^{-1}$) and gypsum (2.9 and 5.2

Mg ha$^{-1}$). The crops evaluated in this experiment were corn and soybean planted in rotation for subsequent years. Methods of placement included a surface broadcasted or a deep banding incorporation of calcitic pelletized lime or pelletized gypsum at four depths (0-13, 13-25, 25-38 and 38-51 cm) simultaneously (Figure 3.2). Depths were selected to be similar to past literature (Tupper et al., 1987; Farina et al., 2000a, 2000b). For mechanical application purposes, pelletized lime and gypsum were used in replacement of traditional powder amendments.

Deep banding was accomplished using a conservation subsoiler (Case IH Ecolo-Til® 2500, Goodfield, IL) with a custom built shank attachment designed to deliver lime at desired depths (Figure 3.2). Lime application rates were selected based on the average subsoil recommendation (6.7 Mg ha$^{-1}$) and the average top 15 cm of soil recommendation (3.4 Mg ha$^{-1}$). Gypsum application rates were selected based on the average subsoil recommendation (5.2 Mg ha$^{-1}$) and the average top 15 cm of soil recommendation (2.9 Mg ha$^{-1}$). The limestone source was comprised of pelletized lime (Kelly's Pelletized Lime, Kirksville MO) derived from quarried calcitic limestone containing 36.4% Ca and 1% Mg with a Calcium Carbonate Equivalence (CCE) of 90.7% and an Effective Neutralizing Material (ENM) of 300 kg ENM Mg$^{-1}$. The concept and calculations for ENM are provided in Buchholz et al. (1983). Particle size distribution of the liming material before pelletizing consisted of 99.9% passing through a 2.36 mm mesh sieve, 97.0 % passing through a 0.841 mm mesh sieve, 88.0% passing through a 0.420 mm mesh sieve, 63.0% passing through a 0.297 mm mesh sieve and 61.0% passing through a 0.250 mm mesh sieve. A 2% lignosulfonate was added as the binding agent for palletization. The gypsum source was comprised of pelletized gypsum (Kelly's Gypsum, Kirksville MO) derived from mined gypsum containing 76.0% calcium sulfate dihydrate ($CaSO_4 – 2H_2O$).

Lime and gypsum treatments were applied using a commercial Montag dry fertilizer air delivery system (Emmetsburg, IA). Conservation zone tillage knives were spaced 76 cm apart, congruent with standard corn row spacing. Greater soil disturbance from vertical lime and gypsum placement was observed compared to normal conservation vertical tillage. Surface tillage with a Tilloll 875 (Landoll Corp., Marysville, KS) followed deep vertical placement treatments to smooth the soil surface prior to planting; however, no additional tillage was performed the following years after application of treatments. Uniform broadcast surface applications were achieved by running a conservation tiller with custom shank above the soil surface to ensure consistency. Strips of corn or soybean were randomly assigned at trial establishment and rotated for subsequent years. Each crop strip was randomly divided into two additional strips of surface-applied and deep vertical placement lime. Deep vertical placement and surface applied strips were then divided into plots of varying rates of lime, resulting in a split-split randomized complete block design.

Treatment abbreviations used in the following text and all figures and tables for lime treatments sections are as follows:

CTRL: No application of lime/no tillage

S-LO: Surface application of lime at 3.4 Mg $ha^{-1}$

S-HI: Surface application of lime at 6.7 Mg $ha^{-1}$

D-NO: Deep vertical tillage with no application of lime

D-LO: Deep vertical lime placement at 3.4 Mg $ha^{-1}$

D-HI: Deep vertical lime placement at 6.7 Mg $ha^{-1}$

Treatment abbreviations used in the following text and on all figures and tables for gypsum treatments sections are as follows:

CTRL: No application of gypsum/no tillage

S-LO: Surface application of gypsum at 2.9 Mg $ha^{-1}$

S-HI: Surface application of gypsum at 5.2 Mg $ha^{-1}$

D-NO: Deep vertical tillage with no application of gypsum

D-LO: Deep vertical gypsum placement at 2.9 Mg $ha^{-1}$

D-HI: Deep vertical gypsum placement at 5.2 Mg $ha^{-1}$

### Management

In the spring of 2012, lime treatments were applied to Trial #1 followed by planting of corn and soybean. In the fall 2012, lime treatments were applied to Trial #2 with planting of corn and soybean the following spring of 2013 for Trials #1 and #2. In the fall of 2013, lime treatments for Trial #3 were applied with corn and soybean being planted the following spring of 2014 for Trials #1, #2 and #3. Management practices, such as row spacing, seeding rate, hybrid or varieties, weed and pest control, tillage and maintenance fertilization for each trial are presented in Tables 3.2A to 3.5B.

### Soil Sampling and Analysis

Initial soil samples were taken at the establishment of each trial using a Giddings hydraulic probe (Giddings Machine Company, Windsor, CO) prior to P and K fertilizer and treatment applications and were separated into depths of 0-13, 13-28, 25-38, and 38-51 cm. Samples were analyzed by the University of Missouri Soil and Plant Testing Laboratory using standard methods (Nathan et al., 2006).

### Plant Data

The center two rows of corn plots were harvested using a plot combine (Wintersteiger Delta, Salt Lake City, UT) and grain yields were adjusted to 15% moisture.  For plots planted to soybean, the center 1.5 m of the soybean plot was harvested using a plot combine (Wintersteiger Delta, Salt Lake City, UT) and yields adjusted to 13% moisture. Grain samples were collected and analyzed for protein and oil (soybean), and starch, protein, and oil (corn) using near-infrared spectroscopy (Foss Infratec 1241 Grain Analyzer, Eden Prairie, MN). Plant populations were calculated based on middle row stand counts for corn and a middle of plot stand count for a 1.2 m length of row for soybean. Yield percent differences were calculated by comparing the means of treatment plots within each replication of a trial with the non-treated control means of the same replications within the trial. Percent differences from control plots were grouped into years after application and averaged for each treatment.

Data were analyzed using analysis of variance (ANOVA) and comparisons among treatment means were made using Fisher's protected least significant difference (LSD) at $P < 0.10$. Statistical procedures were carried out with SAS statistical software (SAS Institute Inc., 2013).

## RESULTS AND DISCUSSION

### Climatic and Environmental Conditions

Climatic conditions at the field sites varied among growing seasons. Rainfall over the growing seasons (Figure 3.3) for 2012, 2013 and 2016 were 275, 26 and 188 mm below the 10-year average of 699 mm, respectively. Although 2013 rainfall over the growing season was only slightly below average, the majority of the precipitation occurred over the course of a few events and an extended dry period persisted from early July to September. Rainfall for 2014 and 2015 was 48 and 212 mm above the 10-year average, respectively. These seasonal differences in rainfall may account for some of the observed differences in grain yields for both corn and soybean over the cropping years.

Additionally, Trials #1 and #3 were conducted on a Putnam silt loam whereas Trial #2 was on a Mexico silt loam, which had very acid surface soil pH. Furthermore, variation in surface and subsoil acidity may explain inconsistent variations in plant growth and yields between treatments. Even within a specific soil series, surface and subsoil acidity can vary greatly in a field (Pagani and Mallarino, 2015).

## Crop Response to Lime

### *Corn*

The effects of lime placement on corn heights taken at or later than VT for all three field trials for 2012 to 2014 are shown in Table 3.6. In Trial #1, plant heights were significantly raised 5 to 21 cm over the control by all deep vertical placement methods in 2012 and 2014. In 2012, surface application at 6.7 Mg ha$^{-1}$ significantly lowered stand heights by 5 cm in Trial #1. However, a surface application at 6.7 Mg ha$^{-1}$ significantly increased heights in 2013 and 2014 over the control by 6 and 16 cm, respectively. For Trial #2, no treatments increased corn stand heights compared to the control in 2013. However, deep tillage effects alone significantly increased plant height by 8 cm in 2014. Plant height for Trial #3 significantly increased by 13 cm compared to the control with a surface application of 3.4 Mg ha$^{-1}$ in 2014.

Corn plant populations for all trials from 2012 to 2016 are reported in Table 3.7. Deep tillage alone and lime at 3.4 Mg ha$^{-1}$ decreased plant populations 2,000 to 17,300 plants ha$^{-1}$ in 2012, 2014 and 2016 for Trial #1. In 2016, deep vertical placement treatments at 6.7 Mg ha$^{-1}$ decreased plant populations by 9,800 plants ha$^{-1}$ for Trial #1. Treatments of deep vertical placement with no lime decreased plant populations in 2014 by 3,100 plants ha$^{-1}$ for Trial #2. No other differences in corn plant populations were observed among lime treatments in Trials #2 and #3.

Significant decreases in corn plant populations from deep vertical placement were observed only in even years (2012, 2014, 2016) for Trial #1. The small populations every other year of Trial #1 may suggest either notable variation in soil properties of individual plots or possibly mechanical differences during initial applications. Furthermore, the higher corn plant heights observed in 2012 and 2014 of Trial #1 could be due to smaller populations during those years, as there would be less competition for sunlight among the individual plants.

Grain yield varied greatly among years, and appeared to be heavily influenced by rainfall. Corn grain yields for Trial #1, #2 and #3 are presented in Figures 3.4, 3.5 and 3.6 respectively. In 2012, a drought year, the effects of deep vertical placement alone increased corn yield by 0.3 Mg ha$^{-1}$ compared to control plots for Trial #1 Figure 3.4). However, no differences were observed when compared with lime. Subsequently, the effects of deep vertical placement in the following wetter years, had decreased corn grain yields compared to control plots by 0.8 and 1.2 Mg ha$^{-1}$ in 2013 and 2014, respectively (Figure 3.4).

Research by Tupper et al. (1987) suggested that deep tillage fracturing of hardpans resulted in greater exposure to soil acidity resulting in greater Al and manganese (Mn) toxicities. Likewise, adverse effects of deep vertical placement with no lime observed in 2013 and 2014 may indicate a greater exposure to soil acidity when tillage is not accompanied by a lime treatment. Additionally, under no-tillage, surface applications of lime at 3.4 Mg ha$^{-1}$ increased corn yield 1.2 Mg ha$^{-1}$ in 2014 for Field Trial #1 (Figure 3.4), indicating possible limitation due to surface acidity. Lack of significant yield increases in wetter years from deep vertical placed lime signifies that under adequate soil moisture subsoil acidity may not be a substantial limiting factor for these soils. Likewise, similar research on correction of soil acidity found less yield responses to lime treatments under non-drought conditions compared to crops under drought stress (Yang et al., 2013). No differences from non-treated plots were observed in 2015 for Field Trial #1; however, deep vertical placement of lime at 3.4 Mg ha$^{-1}$ in 2016 reduced corn yield 1.4 Mg ha$^{-1}$ compared to the control.

For Trial #2, no differences between treatments were observed for the first two years of the trial (Figure 3.5). Slower solubility and reaction time of lime may be a possible cause for no response to the lime treatments for the early years of experimental plots. By the third year of treatment, corn grain yields were 1.8 Mg ha$^{-1}$ less with deep vertical placed lime treatment at 6.7 Mg ha$^{-1}$ for Trial #2 in 2015. However, this large observed reduction in yield may be mainly a result of climatic conditions and environmental variability. Lack of significant reductions in previous years along with heavy precipitation for that year is a possible indication that yield loss is likely affected by environmental factors rather than treatment factors. Nevertheless, deep tillage with no lime and deep vertical placed lime at 6.7 Mg ha$^{-1}$ in 2016 increased corn yield 1.4 and 1.3 Mg ha$^{-1}$, respectively (Figure 3.5). Increased grain yields in Trial #2 from deep vertical placement with no lime and lime placement treatments were observed in 2016, when precipitation was below average, may indicate a beneficial effect of lime on drought tolerance in low moisture environments. As past research has demonstrated, lime treatments can effectively decrease soil acidity, resulting in greater root development and decreased drought sensitivity of a crop. (Caries et al., 2008; Joris et al., 2012; Yang et al., 2013). Furthermore, in wetter years (2014 and 2015), corn yields of deep vertical placed lime were either insignificant or significantly less than the controls. This again signified less of an effect of soil acidity on plant growth under adequate soil moisture environments.

No treatments raised corn yields compared to the control in the first year of Trial #3 (Figure 3.6). Consequently, two years after treatment, surface applied lime at 3.4 Mg ha$^{-1}$ and deep vertical placed lime at 6.7 Mg ha$^{-1}$ had decreased corn yields by 1.8 and 1.6 Mg ha$^{-1}$ in 2015, respectively (Figure 3.6).

To better compare the early residual effects of lime treatments on corn grain yields, percent differences from the control plots were averaged and combined for all three field trials (Figure 3.7). During the first year, deep vertical placement with no lime and vertical lime placement treatments increased grain yields by 6.5 to 15.2% however; only the effects from deep vertical placement with no lime were significant with an increase of 15.2%. No significant changes in corn yield were observed two years after application. Three years after treatment, deep vertical placement methods of 3.4 and 6.7 Mg ha$^{-1}$ significantly decreased grain yields by 8.4 and 12.3%, respectively. Reductions in corn yield three years after treatment could be explained by greater amounts of precipitation observed during the 2014 and 2015 growing season (Figure 3.3) leading to adequate levels of soil moisture during the third residual year of treatment for Trial #1 and #2. Therefore, tillage effects in combination with the success of control plots may have resulted in the observed decreases in yield. No significant differences among treatments were observed for the fourth year after application. Lack of differences in yield response to treatments observed may be attributed to satisfactory levels of moisture over the 2015 and 2016 seasons.

Soil variability between and within the trial sites was indicated by variations in corn yields of lime-treated plots. For example, deep vertical placement of lime treatments appeared to have a greater response in Trial #2 compared to Trials #1 and #3, and once again differing response in odd years compared to even years suggest further variability within the trial. As indicated in the initial soil characteristics table (Table 3.1), Trial #2 had greater surface soil acidity as well as overall more acidic subsoil $pH_s$. Previous research suggests that benefits from deep placed lime only become apparent when subsoil $pH_s$ is a large enough limiting factor to plant growth and development (Pagani and Mallarino, 2015). This can be observed by the increases yield response seen in Trial #2, a plot with greater acidic surface $pH_s$ compared to Trials #1 and #3. Yet, significant increases in grain yield from deep applications of lime similar to those observed in the highly weathered soils of the tropics (Sumner et al., 1986; Farina et al., 2000a, 2000b) were not noticed in this study. This may be attributed to the greater soil base cation concentrations, especially with Ca, and lesser levels of $Al^{+3}$ in the top 15 cm found in the claypan soils of this study (Table 2.6). This suggests that the early effects of deep vertical placement on these soils may be negligible, seen at acid pH, because crop yields may not be as largely impacted by soil acidity limiting factors. However, examining the effects of lime placement often requires long-term evaluation as lime applications may take years to fully react and have a beneficial effect on plant growth many years after application (Farina and Charanan, 1988; Farina et al., 2000a, 2000b).

*Soybean*

Soybean heights were recorded late August to early September each year from 2012 to 2015 (Table 3.8). Deep vertical placement with no lime application for Trial #1 significantly increased soybean height by 2 cm in 2012. Significant differences for soybean heights among treatments were observed in 2014 and 2015 for Trial #1, however no treatments were significantly different from control plots.

For Trial #2, surface application at 6.7 Mg ha$^{-1}$ and deep vertical placement with no lime significantly lowered plant height compared to the control in 2014 by 7 and 8, respectively. No significant differences in soybean heights were observed between treatments in 2013 and 2014 for Trial #2.

Significant differences in soybean plant height between treatments were observed in 2014 for Trial #3; however, all of the treatments were similar to the control. In 2015, deep vertical placement with no lime, placement at 6.7 Mg ha$^{-1}$ and surface application of 6.7 Mg ha$^{-1}$ shortened soybean heights by 8, 10 and 14 cm, respectively in Trial #3.

Soybean plant populations for all trials from 2012 to 2016 are reported in Table 3.9. Significant differences in soybean plant populations between treatments were observed for all experimental years of Trial #1; however, only 2012 and 2014 had treatments with populations greater than the control. For example, surface lime applications at 3.4 Mg ha$^{-1}$ had greater soybean plant populations by 118,500 plants ha$^{-1}$ in 2012 compared to the control. In 2014, deep vertical placement at 3.4 Mg ha$^{-1}$ had plant populations that were 64,600 plants ha$^{-1}$ greater than the control in Trial #1.

No significant differences in soybean plant populations were observed among treatments in Trial #2 for all crop years with the exception of 2014. Compared to the control plots, soybean populations were decreased by 32,300 and 37,700 plants ha$^{-1}$ from surface treatment at 6.7 Mg ha$^{-1}$ and a deep vertical placement treatment at 3.4 Mg ha$^{-1}$, respectively, in 2014.

Broadcasted lime at of 6.7 Mg ha$^{-1}$ in Trial #3 had reduced plant populations by 64,600 plant ha$^{-1}$ compared to control treatments, whereas no differences between treatments were observed in 2014 and 2016.

Similar to corn yields, soybean yields varied amongst years which was largely affected by rainfall (Figure 3.8 to 3.10). During the first and second years after treatment (2012 and 2013), Trial #1 soybean yields were decreased 0.3 and 0.2 Mg ha$^{-1}$, respectively, with deep vertically placed lime at 3.4 Mg ha$^{-1}$ (Figure 3.8). Likewise, the effects of just deep tillage decreased soybean yield by 0.2 Mg ha$^{-1}$ when compared to the control in 2013. There were no observed differences in yield amongst treatments three years after site establishment of Trial #1. Compared to the control plots, deep vertical placed lime at 6.7 Mg ha$^{-1}$ resulted in significant decreases in soybean yield of 0.5 and 0.8 Mg ha$^{-1}$ in 2015 and 2016, respectively (Figure 3.8). Additionally, in 2016, control plots greater yields than all other treatments, except deep vertical placed lime at 3.4 Mg ha$^{-1}$.

Little significance in soybean yield between treatments was observed for Trial #2 for the four years after establishment (Figure 3.9). Deep vertical placement with no lime in 2014 was the only treatment significantly different from control plots, where treatment effects decreased soybean yield by 0.5 Mg ha$^{-1}$. Significant differences in yield were observed between treatments of Trial #2 in 2016, however all treatments were similar the control plots. Similarly, no significance in soybean yields were observed in the first two years for Trial #3. Moreover, treatments failed to significantly increased soybean yield compared to control plots in 2016 (Figure 3.10).

Due to large variations in precipitation, percent differences of treatments from non-treated controls were used to evaluate the residual effects of treatments. Differences from control plots for each trial were combined into residual years after treatment and averaged (Figure 3.11). During the first year of treatment, no significant differences in soybean yields were observed. Two years after application, deep lime placement treatments decreased soybean yields compared to the control by 10.5, 8.4 and 8.4% for 0, 3.4 and 6.7 Mg ha$^{-1}$, respectively. In the third year and fourth year after treatment, no significant changes in soybean yield were observed compared to the control.

When comparing soybean yield with corn yield, it became apparent that the generally shallow rooting nature of soybeans was less affected by deep placed lime. In all three field trials, the only significant effects of deep vertical placement methods were negative. This may be attributed to the lack of lime amendment added to the surface 13 cm of soil in deep vertical placement treatments where the majority of the roots may be found. Furthermore, in addition to adverse effects from tillage on soybean, greater acidity found in the unamended portion of deep vertical placement treatments may hinder early plant development in both corn and soybean, leading to an early stunting of the plant. Nevertheless, surface amendments of lime displayed no significant yield increase over control plots in these trials. This could be a result of the slow reaction time of lime within the surface horizon. Various other studies indicated a lack of yield response of both corn and soybean during the first few years after application and suggested that lime could require over a decade to fully react (Doss et al., 1979; Farina et al., 2000b; Conyers et al., 2003; Caires et al., 2008). Additionally, cation exchange capacity of soybean roots (CECR) is much greater than that of corn (Fernandes and Souza, 2006). With a greater CECR, soybean plants are far more effective at extracting soil nutrients, and may experiences less beneficial effects from lime amendments. Lack of increases in soybean yields may also be attributed to herbicide applications from previous years. For example, in a study conducted by Scharf et al. (2005) saw a decrease in soybean yield of 0.4 Mg ha$^{-1}$ under a 1:1 corn/soybean rotation when the herbicide atrazine was applied to corn the previous year. As atrazine is an active ingredient of many of the herbicides used in management of trials, roll over effects from previous application may have resulted in decreases in soybean production.

Based on observed changes in soil acidity in the soil profile (see Chapter 2), the chemical effects of lime were generally restricted to the zone of application which was similar to past research (Conyers et al., 2003; Farina et al., 2000b). Furthermore, pelletized lime and gypsum were used as the amendment alliteratively to powered sources. Past research has shown that pelletized lime behaves the same as conventional non-pelletized lime when surface applied (Godsey et al., 2007); however, pelletized lime may not react as fast as the non-pelletized counterpart once it was incorporated into the soil. Additionally, past research on in furrow placement of dolomitic pelletized lime found little changes in soil properties less than two cm from placement (Lollato et al., 2013). Furthermore, spherical structure of dolomitic lime pellets was maintained 220 days after application. This physical property of pelletized lime observed in this study may have impacted on the soil chemical reactions that took place after deep vertical placement of the amendments.

## Crop Response to Gypsum

### *Corn*

Corn heights for all the treatments in Trials #1, #2 and #3 from 2012 to 2014 are reported in Table 3.10. All heights were recorded between September and October of each year after corn plants had reached the VT growth stage. There were significant differences in corn plant heights among treatments in 2012 and 2014 for Trial #1. No significant treatment differences compared to the control were observed in 2012, 2013 and 2014 for Trial #1. In Trial #2, surface lime application at 2.9 Mg ha$^{-1}$ increased plant heights 14 cm over the control in 2013. In 2014, no significant differences between treatments were observed for both Trial #2 and #3.

Corn plant populations for gypsum treatments are reported in Table 3.11. Plant populations where decreased by the deep vertical placement of gypsum at 2.9 Mg ha$^{-1}$ by 11,300 plants ha$^{-1}$ in 2012 for Trial #1. No significant differences in plant population were observed among treatments in 2013 and 2014 for Trial #1. During the 2015 growing season, surface applied gypsum at 2.9 Mg ha$^{-1}$ decreased plant populations by 3,400 plants ha$^{-1}$, where as in 2016, deep vertically placed gypsum at 2.9 and 5.2 Mg ha$^{-1}$ decreased plant populations 8,000 and 11,800, respectively. No significant differences in plant populations were observed between the lime treatments and the control plots for Trial #2 from 2012 to 2016. Trial #3 had no significant differences among treatments in 2014 and 2016. However, deep gypsum placement at 5.2 Mg ha$^{-1}$ had reduced plant populations by 3,800 plants ha$^{-1}$ in 2015.

Differences in corn grain yields between treatments for all three field trials are presented in Figures 3.12 to 3.14. In the first and second year of Trial #1, corn grain yields were not affected by deep vertically placed gypsum compared to the control (Figure 3.12). By the third year, deep vertical placed gypsum at 5.2 Mg $ha^{-1}$ had a 1.1 Mg $ha^{-1}$ reduction in corn yields in Trial #1 compared to the control (Figure 3.12). In 2015, no treatments resulted in significant differences in grain yields compared to control plots for Trial #1. Five years after treatment in Trial #1, deep vertically placed gypsum at 2.9 and 5.2 Mg $ha^{-1}$ had corn yields that were 1.4 and 1.1 Mg $ha^{-1}$ less than the control, respectively.

No significant differences from gypsum treatments compared to the control plots were observed for all experimental years of Trial #2 (Figure 3.13). In 2014 surface applied of gypsum at 5.2 Mg $ha^{-1}$ reduced corn yield by 1.8 Mg $ha^{-1}$ in Trial #3 (Figure 3.14). Two years after application, deep vertical placed gypsum at 5.2 Mg $ha^{-1}$ reduced corn yields by 2.4 Mg $ha^{-1}$ in Trial #3. In the third experimental year, corn yields were reduced by 0.9 Mg $ha^{-1}$ from gypsum surface applied at 5.2 Mg $ha^{-1}$ in Trial #3.

To better assess the residual effects of gypsum on corn grain yields, differences from control plots were combined and averaged for all three trials (Figure 3.15). During the first year of application, deep vertical placement had no significant effects on grain yield. Two years after application, only deep vertical placement at 5.2 Mg $ha^{-1}$ significantly decreased yields by 9.9%. Grain yields were similar to control plots three years after application. However, four years after surface applications of gypsum at 2.9 Mg $ha^{-1}$ corn grain yields increased 13.0%.

*Soybean*

Soybean plant heights were recorded in August to September each year and are reported in Table 3.12. Surface applied gypsum at 2.9 Mg $ha^{-1}$ increased soybean plant height by 3 cm for Trial #1 in 2012. However, no gypsum treatments significantly increased soybean height compared to the control from 2013 to 2015. In Trial #2, an 11 cm increase in plant height from a surface application of gypsum at 2.9 Mg $ha^{-1}$ was observed compared to the control in 2013. This same trial had 8 and 10 cm shorter plants from a deep vertical placement of gypsum at 2.9 and 5.2 Mg $ha^{-1}$, respectively, compared to the control. The only significant decreases in plant height compared to the control for Trial #3 were observed in 2015, where surface applications and deep vertical placement of gypsum at 2.9 Mg $ha^{-1}$ were 15 and 14 cm, respectively, shorter than the control.

Trial #1 had no significant differences in soybean plant populations among treatments for all years from 2012 to 2015, but surface application of gypsum at 2.9 Mg $ha^{-1}$ increased plant populations by 269,100 plants $ha^{-1}$ in 2016 (Table 3.13). Trial #2 had a significant decrease in plant population of 37,700 and 32,300 plants $ha^{-1}$ for deep vertical placement treatments of 2.9 and 5.2 Mg $ha^{-1}$, respectively in 2014. However, surface and deep vertical placement treatments of 5.2 Mg $ha^{-1}$ had 53,800 and 64,500 plants $ha^{-1}$, respectively, greater soybean plant populations in 2015. For Trial #3, deep vertically placed gypsum at 5.2 Mg $ha^{-1}$ had decreased plant populations by 43,100 plants $ha^{-1}$ compared to the control in 2014, while a surface application at 2.9 Mg $ha^{-1}$ had a plant population that was 32,300 plants $ha^{-1}$ less than the control in 2016.

Soybean yields varied greatly between crop years depending on seasonal precipitation (Figure 3.3). Yields from gypsum treatments are presented in Figures 3.16

to 3.18. For the first year of Trial #1, deep vertical placement of gypsum at 5.2 Mg $ha^{-1}$ had yields that were 0.3 Mg $ha^{-1}$ (Figure 3.16) lower than the control. However, no significant effects from gypsum treatments were observed in the second, third, or fourth year after application compared to control plots. In 2016, all gypsum treatments had soybean yields that were less than the non-treated control.

For Trial #2, gypsum had no effect on soybean yields the first season after treatment (Figure 3.17). By the second year after treatment, deep vertical placed gypsum at 2.9 and 5.2 Mg $ha^{-1}$ for Trial #2 yields that were 0.7 Mg $ha^{-1}$ less than the control (Figure 3.17). However, no difference among gypsum treatments were observed in the following two years of treatment (2015 and 2016) for Trial #2. Gypsum treatments on Trial #3 had no effects on yield compared to the control for all three experimental years following establishment (Figure 3.18).

Percent differences from control plots were combined by years after application for all field trials to evaluate the residual effects of gypsum treatments (Figure 3.21). In the first year of application, deep vertical placement at 5.2 Mg $ha^{-1}$ had yields that were 9.8% less than the control. In the second year after application, deep vertically placed gypsum at 2.9 and 5.2 Mg $ha^{-1}$ had yields that were 6.4 to 6.5% less than the control. No significant differences among the treatments were observed the third year after application; however, deep vertical placement decreased soybean yields up to 18.5%.

Deep application of gypsum to poorly-drained claypan soils in Northeast Missouri did not consistently increase corn and soybean yields. Lack of response to gypsum was most likely caused by the low levels of $Al^{+3}$ in the surface soil and the limited effect of gypsum in altering the soil $pH_s$. This was supported by Farina and Channon (1988) which concluded that gypsum applications are only effective when $Al^{+3}$ exceeds Ca in the soil. Past successes of Farina et al. (2000a) from deep placement gypsum and lime on acidic soils were not observed in this study. This may in part be due to the initially large soil test Ca levels and greater fertility found in these claypan soils (Table 3.1) along with smaller levels of $Al^{+3}$ in the soil solution. Caries et al. (2011) found no significant increases in soybean yields following gypsum amendments 0 to 10 years after application. Moreover, previous research indicated that soybean production is strongly affected by the gypsum content in soil and yields can be significantly reduced when high levels of gypsum are present (Mardoud, 1980). In addition, past research by Tupper et al. (1987) suggests that deep tillage of soils with dense subsoils can result in greater exposure to subsoil acidity if the acidity is not corrected. Deep tillage effects paired with lack of changes to pH and possible adverse effects from gypsum may have resulted in yield reductions in four of the 12 crop years.

## CONCLUSIONS

Previous research on deep vertical placement of lime and gypsum has indicated possible benefits of this application method to ameliorate subsoil acidity issues and increase crop production, especially in highly-weathered soils. However, less research has established the efficacy of this placement method in less-weathered soils, especially when the lime and gypsum are deep vertically banded. Deep vertical placement of lime was less effective in altering soil acidity throughout the subsoil, but it had a localized effect close to where lime was placed.  Therefore, the lack of a consistent initial first year crop response to liming may be due to the limited soil reaction with lime that could occur around the band and the constraints that a lack of reaction would cause for root growth.

This research also suggests that surface and deep vertical placement application of gypsum to claypan soils had no increase in corn or soybean yields. Deep vertical placement of gypsum may reduce crop yields when this material was placed in a band at the rates evaluated in this experiment.

Yearly rotation between corn and soybean for each plot is typical, but may have affected some differences between treatments as variability between soil characteristics can be large, even on a small scale. The effects of lime applications on soil acidity and crop production can also require many years to fully assess. Continued long-term analysis of field sites could obtain a better understanding of the effects of treatments and how they interact with climate and different depths to the more acidic claypan that occurs across these landscapes.

Alterations in the design of the custom built shank for deep banded placement may be needed to incorporate the lime into a larger soil volume in the subsoil. However, these alterations may require greater energy to pull the shank through the soil. A possible combination of simultaneous shallow and deep lime placement could be explored. Further comparisons between the deep banded lime placement with use of the custom built shank and deep incorporation of lime may also useful to assess possible crop response to amelioration of subsoil acidity in claypan soils. Possible benefits to improved root growth deeper in the soil may include improved drought tolerance, reduced nutrient deficiencies, and higher yields.

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Table 3.1. Initial average soil characteristics (±standard deviation) at different depths for the Trial #1, #2 and #3 established in 2012, 2013, and 2014, respectively.

| | Soil depth | | | |
|---|---|---|---|---|
| Soil characteristics | 0 – 13 cm | 13 – 25 cm | 25 – 38 cm | 38 – 51 cm |
| Trial #1 | | | | |
| pH$_s$ | 5.6 ± 0.2 | 5.6 ± 0.4 | 4.6 ± 0.2 | 4.6 ± 0.2 |
| Neutralizable acidity (cmol$_c$ kg$^{-1}$) | 3.5 ± 2 | 2.9 ± 1 | 8.5 ± 1.6 | 6.8 ± 1.0 |
| Organic matter (%) | 2.7 ± 0.3 | 2.3 ± 0.1 | 2.3 ± 0.3 | 2.2 ± 0.2 |
| Bray 1P (kg ha$^{-1}$) | 17.4 ± 9.8 | 5.0 ± 1.4 | 3.9 ± 1.9 | 14.6 ± 4.5 |
| Ca (kg ha$^{-1}$) | 4,427 ± 347 | 5,200 ± 661 | 5,257 ± 706 | 4,988 ± 673 |
| Mg (kg ha$^{-1}$) | 494 ± 98 | 689 ± 189 | 981 ±138 | 996 ± 158 |
| K (kg ha$^{-1}$) | 178 ± 12 | 173 ± 28 | 226 ± 32 | 231 ± 16 |
| CEC (cmol$_c$ kg$^{-1}$) | 15.4 ± 2.3 | 17.3 ± 3.2 | 24.2 ± 3.2 | 22.0 ± 2.3 |
| Trial #2 | | | | |
| pH$_s$ | 5.0 ± 0.1 | 5.0 ± 0.5 | 4.9 ± 0.7 | 4.9 ± 0.8 |
| Neutralizable acidity (cmol$_c$ kg$^{-1}$) | 5.1 ± 0.5 | 4.9 ± 1.9 | 6.9 ± 4.0 | 6.8 ± 3.8 |
| Organic matter (%) | 3.0 ± 0.6 | 1.9 ± 0.4 | 1.8 ± 0.3 | 1.4 ± 0.4 |
| Bray 1P (kg ha$^{-1}$) | 127.2 ± 46.2 | 19.1 ± 10.7 | 11.5 ± 4.0 | 30.8 ± 19.4 |
| Ca (kg ha$^{-1}$) | 2,841 ± 312 | 3,263 ± 690 | 4,138 ± 1,828 | 4,144 ± 1,678 |
| Mg (kg ha$^{-1}$) | 307 ± 91 | 415 ± 192 | 739 ± 452 | 848 ± 420 |
| K (kg ha$^{-1}$) | 594 ± 240 | 159 ± 47 | 179 ± 77 | 233 ± 85 |
| CEC (cmol$_c$ kg$^{-1}$) | 13.3 ± 1.4 | 13.9 ± 3.3 | 19.1 ± 6.4 | 19.4 ± 4.8 |
| Trial #3 | | | | |
| pH$_s$ | 6.1 ± 0.1 | 6.2 ± 0.1 | 5.0 ± 0.2 | 4.6 ± 0.1 |
| Neutralizable acidity (cmol$_c$ kg$^{-1}$) | 1.8 ± 0.5 | 1.9 ± 0.3 | 7.1 ± 1.9 | 12.3 ± 1.9 |
| Organic matter (%) | 2.3 ± 0.5 | 2.1 ± 0.2 | 2.3 ± 0.4 | 2.7 ± 0.3 |
| Bray 1P (kg ha$^{-1}$) | 10.4 ± 4.7 | 5.6 ± 2.2 | 2.0 ± 0.6 | 1.1 ± 0 |
| Ca (kg ha$^{-1}$) | 3,954 ± 957 | 3,646 ± 289 | 4,497 ± 434 | 5,223 ± 384 |
| Mg (kg ha$^{-1}$) | 398 ± 158 | 377 ± 58 | 749 ± 142 | 1226 ± 80 |
| K (kg ha$^{-1}$) | 154 ± 30 | 136 ± 12 | 220 ± 36 | 349 ± 28 |
| CEC (cmol$_c$ kg$^{-1}$) | 12.2 ± 3.2 | 11.6 ± 0.8 | 20.2 ± 3.2 | 28.9 ± 2.7 |

Table 3.2A. Field and management information for Trial #1 corn sites from 2012 to 2014.

| Management information | 2012 | 2013 | 2014 |
|---|---|---|---|
| Plot size (m) | 4.6 by 24.4 | 4.6 by 24.4 | 4.6 by 24.4 |
| Hybrid or cultivar | DKC 63-25 VT3 | DKC 63-25 VT3 | P1151 AM |
| Planting date | 30 May | 14 May | 16 April |
| Row spacing (cm) | 76.2 | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 12,140 | 12,140 | 13,350 |
| Harvest date | 12 Oct. | 19 Sep. | 30 Sep. |
| Maintenance fertilizer | None | None | 20-80-140-20S-2Zn MESZ |
| Nitrogen | 67 kg N ha$^{-1}$ (Urea) and 146 kg N ha$^{-1}$ (PCU) | 224 kg N ha$^{-1}$ (AA) | 202 kg N ha$^{-1}$ (AA) |
| Lime | 29 May | None | None |
| Tillage | Tilloll 2x 30 May<br>Cultipacked 30 May in deep tilled treatments | None | None |
| Weed management | | | |
| Burndown | 5 June, Verdict (0.23 kg a.i. ha$^{-1}$) + Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) + UAN (2.34 L ha$^{-1}$) | 22 May, Lexar (2.37 kg a.i. ha$^{-1}$) + Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + COC (2.34 L ha$^{-1}$) | 9 May, Warrant (1.15 kg a.i. ha$^{-1}$)<br>23 May, Lexar EZ (2.84 kg a.i. ha$^{-1}$) + Roundup PowerMAX (0.79 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) |
| Postemergence | 22 June, Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + COC (2.34 L ha$^{-1}$) + Callisto (0.09 kg a.i. ha$^{-1}$) + Atrazine (1.15 kg a.i. ha$^{-1}$) | 27 June, Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + COC (2.34L ha$^{-1}$) + Callisto (0.09 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) | 18 June, Roundup PowerMAX (0.79 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) |
| Insect management | NA | NA | NA |
| Disease management | NA | NA | NA |

†Abbreviations: AA, anhydrous ammonia; COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

††Herbicide chemical nomenclature used in burndown and postemergence listed in Table 3.14

Table 3.2B. Field and management information for Trial #1 corn sites from 2015 to 2016.

| Management information | 2015 | 2016 |
|---|---|---|
| Plot size (m) | 4.6 by 24.4 | 4.6 by 24.4 |
| Hybrid or cultivar | DKC 63-25 VT3 | DKC 62-97 VT3 |
| Planting date | 18 April | 5 April |
| Row spacing (cm) | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 12,140 | 12,140 |
| Harvest date | 17 Sept. | 29 Sept. |
| Maintenance fertilizer | None | None |
| Nitrogen | 235 kg N ha$^{-1}$ (AA) | 190 kg N ha$^{-1}$ (AA) |
| Lime | None | None |
| Tillage | None | None |
| Weed management | | Tilloll 1x |
| Burndown | 23 April, Sharpen (0.02 kg a.i. ha$^{-1}$) + Touchdown Total (75.0 kg a.i. ha$^{-1}$) + MSO (1% v/v) + UAN (2.34 L ha$^{-1}$)<br>27 May, Roundup PowerMAX (0.82 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 14 April, Roundup PowerMAX (1.14 kg a.i ha$^{-1}$) + Verdic (0.36 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + MSO (1% v/v)<br>18 May, Zidua (0.25 kg a.i. ha$^{-1}$) + Atrazine (2.3 kg a.i. ha$^{-1}$) NIS (0.25% v/v) + DAS (2.04 kg L$^{-1}$) |
| Postemergence | 6 June, Halex GT (2.01 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + Boundary (2.09 kg a.i. ha$^{-1}$) + UAN (2.34 L ha-1) | NA |
| Insect management | NA | NA |
| Disease management | NA | NA |

[†]Abbreviations: AA, anhydrous ammonia; COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

[††]Herbicides chemical nomenclature used in burndown and postemergence listed in Table 3.14

Table 3.3A. Field management information for Trial #2 corn sites from 2013 to 2016.

| Management information | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|
| Plot size (m) | 4.6 by 22.9 | 4.6 by 22.9 | 4.6 by 22.9 | 4.6 by 24.4 |
| Hybrid or cultivar | DKC 63-87 | GH G09E98-3000GT | DKC 63-25 VT3 | DKC 62-97 VT3 |
| Planting date | 14 May | 5 May | 18 April | 5 April |
| Row spacing (cm) | 76.2 | 76.2 | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 12,140 | 12,220 | 12,140 | 12,140 |
| Harvest date | 19 Sep. | 30 Sep. | 14 Sept. | 29 Sept. |
| Maintenance fertilizer | None | 20-80-140-20S-2Zn MESZ | None | None |
| Nitrogen | 135 kg N ha$^{-1}$ (PCU) | 202 kg N ha$^{-1}$ (AA) + nitrapyrin (2.34 L ha$^{-1}$) | 235 kg N ha$^{-1}$ (AA) | 190 kg N ha$^{-1}$ (AA) |
| Lime | 27 Nov | None | None | None |
| Tillage | Tilloll 2x, 1 May | None | None | None |
| Weed management | | | | Tilloll 1x |
| Burndown | 22 May, Lexar (2.36 kg a.i. ha$^{-1}$) + Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + COC (2.34 L ha$^{-1}$) | 9 May, Sharpen (0.02 kg a.i. ha$^{-1}$) + Warrant (1.16 kg a.i. ha$^{-1}$) + MSO (1% v/v) + UAN (2.34 L ha-1)<br>23 May, Lexar EZ (2.84 kg a.i. ha$^{-1}$) + Roundup PowerMAX (0.79 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 23 April, Sharpen (0.02 kg a.i. ha$^{-1}$) + Touchdown Total (75.0 kg a.i. ha$^{-1}$) + MSO (1% v/v) + UAN (2.34 L ha$^{-1}$)<br>27 May, Roundup PowerMAX (0.82 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 14 April, Roundup PowerMAX (1.14 kg a.i ha$^{-1}$) + Verdic (0.36 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + MSO (1% v/v)<br>18 May, Zidua (0.25 kg a.i. ha$^{-1}$) + Atrazine (2.3 kg a.i. ha$^{-1}$) NIS (0.25% v/v) + DAS (2.04 kg L$^{-1}$) |
| Postemergence | 27 June, Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + COC (2.34 L ha$^{-1}$) + Callisto (0.09 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) | 18 June, Roundup PowerMAX (0.79 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 6 June, Halex GT (2.01 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + Boundary (2.09 kg a.i. ha$^{-1}$) + UAN (2.34 L ha-1) | NA |
| Insect management | NA | NA | NA | NA |
| Disease management | NA | NA | NA | NA |

[†] Abbreviations: AA, anhydrous ammonia; COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; PCU, polymer-coated urea; UAN, 32% urea ammonium nitrate.

[††] Herbicides chemical nomenclature used in burndown and postemergence listed in Table 3.14

Table 3.3B. Field management information for Trial #3 corn sites from 2014 to 2016.

| Management information | 2014 | 2015 | 2016 |
|---|---|---|---|
| Plot size (m) | 4.6 by 24.4 | 4.6 by 24.4 | 4.6 by 24.4 |
| Hybrid or cultivar | GH G09E98-3000GT | DKC 63-25 VT3 | DKC 63-25 VT3 |
| Planting date | 5 May | 23 April | 15 April |
| Row spacing (cm) | 76.2 | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 12,220 | 12,140 | 12,140 |
| Harvest date | 7 Oct. | 17 Sept. | 29 Sept. |
| Maintenance fertilizer | 20-80-140-20S-2Zn MESZ | None | None |
| Nitrogen | 224 kg N ha$^{-1}$ (AA) | 235 kg N ha$^{-1}$ (AA) | 190 kg N ha$^{-1}$ (AA) |
| Lime | 15 Nov | None | None |
| Tillage | Tilloll 2x 23 April | None | None |
| Weed management | | | |
| Burndown | 9 May, Sharpen (0.02 kg a.i. ha$^{-1}$) + Warrant (1.16 kg a.i. ha+-1) + MSO (1% v/v) + UAN (2.34 L ha$^{-1}$) | 23 April, Sharpen (0.02 kg a.i. ha$^{-1}$) + Touchdown Total (75.0 kg a.i. ha$^{-1}$) + MSO (1% v/v) + UAN (2.34 L ha$^{-1}$) | 14 April, Roundup PowerMAX (1.14 kg a.i ha$^{-1}$) + Verdict (0.36 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + MSO (1% v/v) |
| Postemergence | 23 May, Lexar EZ (2.84 kg a.i. L ha$^{-1}$) + Roundup PowerMAX (0.79 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$)<br>18 June, Roundup PowerMAX (0.79 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 27 May, Roundup PowerMAX (0.82 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$)<br>6 June, Halex GT (2.01 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 18 May, Zidua (0.25 kg a.i. ha$^{-1}$) + Atrazine (2.3 kg a.i. ha$^{-1}$) NIS (0.25% v/v) + DAS (2.04 kg L$^{-1}$) |
| Insect management | NA | NA | NA |
| Disease management | NA | NA | NA |

[†]Abbreviations: COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

[††]Herbicides chemical nomenclature used in burndown and postemergence listed in Table 3.14

Table 3.4A. Field and management information for Trial #1 soybean sites from 2012 to 2014.

| Management information | 2012 | 2013 | 2014 |
|---|---|---|---|
| Plot size (m) | 4.6 by 24.4 | 4.6 by 24.4 | 4.6 by 24.4 |
| Hybrid or cultivar | AG3730 RR2 | AG3730 RR2 | P93Y92 |
| Planting date | 30 May | 8 May | 8 May |
| Row spacing (cm) | 19 | 19 | 19 |
| Seeding rate (seeds ha$^{-1}$) | 80,940 | 80,940 | 72,840 |
| Harvest date | 4 Oct. | 9 Sep. | 20 Oct. |
| Maintenance fertilizer | None | None | 20-80-140-20S-2Zn MESZ |
| Urea and PCU | | | |
| Lime | 29 May | None | None |
| Tillage | Tilloll 2x 30 May<br>Cultipacked 30 May in deep tilled treatments | None | None |
| Weed management | | | |
| Burndown | 5 June, Verdict (0.22 kg a.i. ha$^{-1}$) + Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) + UAN (2.34 L ha$^{-1}$) | NA | 9 May, Warrant (1.16 kg a.i. ha$^{-1}$) |
| Preemergence and/or Postemergence | 22 June, Reflex (0.35 kg a.i. ha$^{-1}$) + Roundup PowerMAX (0.78 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + NIS (0.25% v/v) | 22 May, Prefix (2.42 kg a.i. ha$^{-1}$) + Roundup PowerMAX (1.14 kg a.i.) + COC (2.34 L ha$^{-1}$) + UAN (2.34 L ha$^{-1}$) | 23 May, Prefix (15.23 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + NIS (0.25% v/v)<br>18 June, Roundup PowerMAX (0.78 kg a.i. L ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) |
| Insect management | NA | NA | NA |
| Disease management | NA | NA | NA |

[†]Abbreviations: COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

[††]Herbicides chemical nomenclature used in burndown and postemergence and/or Postemergence listed in Table 3.14

Table 3.4B. Field and management information for Trial #1 soybean sites from 2015 to 2016.

| Management information | 2015 | 2016 |
|---|---|---|
| Plot size (m) | 4.6 by 24.4 | 4.6 by 24.4 |
| Hybrid or cultivar | AG3731 RR2 | AG3731 RR2 |
| Planting date | 3 June | 15 April |
| Row spacing (cm) | 76.2 | 76.2 |
| Seeding rate (seeds $ha^{-1}$) | 80,940 | 80,940 |
| Harvest date | 10 Oct. | 19 Oct. |
| Maintenance fertilizer | None | 15-73-129 (MAP) |
| Urea and PCU | | |
| Lime | None | None |
| Tillage | None | None |
| Weed management | | |
| Burndown | 24 April, Touchdown Total (0.72 kg a.i. $ha^{-1}$) + Sharpen (0.02 kg a.i. $ha^{-1}$) + UAN (2.34 L $ha^{-1}$) + MSO (1% v/v)<br>27 May, Roundup PowerMAX (0.78 kg a.i. $ha^{-1}$) + Dual II Magnum (0.78 kg a.i. $ha^{-1}$) + DAS (2.04 kg $L^{-1}$) | 14 April, Roundup PowerMAX (1.14 kg a.i. $ha^{-1}$) + Verdict (0.36 kg a.i. $ha^{-1}$) + DAS (2.04 kg $L^{-1}$) + MSO (1% v/v) |
| Preemergence and/or Postemergence | 6 June, Boundary (2.09 kg a.i. $ha^{-1}$) + UAN (2.34 L ha-1)<br>17 Aug., Roundup PowerMAX (1.04 kg a.i. $ha^{-1}$) + DAS (2.04 kg $L^{-1}$) | 19 May, Prefix (1.65 kg a.i. $ha^{-1}$) + First Rate (.03 kg a.i. $ha^{-1}$) + NIS (0.25% v/v) + DAS (2.04 kg $L^{-1}$) |
| Insect management | NA | NA |
| Disease management | NA | NA |

[†]Abbreviations: COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

[††]Herbicides chemical nomenclature used in burndown and postemergence listed in Table 3.14

Table 3.5A. Field and management information for Trial #2 soybean sites from 2013 to 2016.

| Management information | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|
| Plot size (m) | 4.6 by 22.9 | 4.6 by 22.9 | 4.6 by 22.9 | 4.6 by 22.9 |
| Hybrid or cultivar | AG3731 RR2 | AG3932 | AG3932 | AG3731 RR2 |
| Planting date | 16 May | 8 May | 3 June | 15 April |
| Row spacing (cm) | 19 | 19 | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 80,940 | 52,690 | 12,140 | 80,940 |
| Harvest date | 9 Sep. | 19 Oct. | 9 Oct. | 19 Oct. |
| Maintenance fertilizer | None | 20-80-140-20S-2Zn MESZ | None | 15-73-129 (MAP) |
| Urea and PCU | | | | |
| Lime | 27 Nov | None | None | None |
| Tillage | Tilloll 2x, 1 May | None | None | None |
| Weed management | | | | |
| Burndown | NA | 9 May, Sharpen (0.02 kg a.i. ha$^{-1}$) + Warrant (1.04 kg a.i. ha$^{-1}$) + MSO (1% v/v) + UAN (2.34 L ha$^{-1}$) | 24 April, Touchdown Total (0.72 kg a.i. ha$^{-1}$) + Sharpen (0.02 kg a.i. ha$^{-1}$) + UAN (2.34 L ha$^{-1}$) + MSO (1% v/v)<br>27 May, Roundup PowerMAX (0.78 kg a.i. ha$^{-1}$) + Dual II Magnum (0.78 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 14 April, Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + Verdict (0.36 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + MSO (1% v/v) |
| Preemergence and/or Postemergence | 22 May, Prefix (2.42 kg a.i. ha$^{-1}$) + Roundup PowerMAX (1.14 kg a.i.ha$^{-1}$) + COC (2.34 L ha$^{-1}$) + UAN (2.34 L ha$^{-1}$) | 23 May, Prefix (1.52 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + NIS (0.25% v/v)<br>18 June, Roundup PowerMAX (0.78 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 17 Aug., Roundup PowerMAX (1.04 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 19 May, Prefix (1.65 kg a.i. ha$^{-1}$) + FirstRate (.03 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) + DAS (2.04kg L$^{-1}$) |
| Insect management | NA | NA | NA | |
| Disease management | NA | NA | NA | |

† Abbreviations: COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

†† Herbicides chemical nomenclature used in burndown and postemergence listed in Table 3.14

Table 3.5B. Field management information for Trial #3 soybean sites from 2014 to 2016.

| Management information | 2014 | 2015 | 2016 |
|---|---|---|---|
| Plot size (m) | 4.6 by 24.4 | 4.6 by 24.4 | 4.6 by 24.4 |
| Hybrid or cultivar | P93Y92 | AG3932 | AG3931 |
| Planting date | 8 May | 23 April | 14 April |
| Row spacing (cm) | 19 | 76.2 | 76.2 |
| Seeding rate (seeds ha$^{-1}$) | 72,840 | 72,840 | 72,840 |
| Harvest date | 20 Oct. | 10 Oct. | 19 Oct. |
| Maintenance fertilizer | 20-80-140-20S-2Zn MESZ | None | None |
| Urea and PCU | | | |
| Lime | 15 Nov | None | None |
| Tillage | Tilloll 2x 23 April | None | None |
| Weed management | | | |
| Burndown | 9 May, Sharpen (0.02 kg a.i. ha$^{-1}$) + Warrant (1.16 kg a.i. ha$^{-1}$) + MSO (1% v/v) + UAN (2.34 L ha$^{-1}$) | 24 April, Touchdown Total (0.72 kg a.i. ha$^{-1}$) + Sharpen (0.02 kg a.i. ha$^{-1}$) + UAN (2.34 L ha$^{-1}$) + MSO (1% v/v) | 14 April, Roundup PowerMAX (1.14 kg a.i. ha$^{-1}$) + Verdict (0.36 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + MSO (1% v/v) |
| Postemergence | 23 May, Prefix (1.52 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) + NIS (0.25% v/v)<br>18 June, Roundup PowerMAX (0.78 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 27 May, Roundup PowerMAX (0.78 kg a.i. ha$^{-1}$) + Dual II Magnum (0.78 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$)17 Aug., Roundup PowerMAX (1.04 kg a.i. ha$^{-1}$) + DAS (2.04 kg L$^{-1}$) | 19 May, Prefix (1.65 kg a.i. ha$^{-1}$) + First Rate (.03 kg a.i. ha$^{-1}$) + NIS (0.25% v/v) + DAS (2.04kg L$^{-1}$) |
| Insect management | NA | NA | NA |
| Disease management | NA | NA | NA |

[†] Abbreviations: COC, crop oil concentrate; DAS, diammonium sulfate; NA, None applied; NIS, non-ionic surfactant; UAN, 32% urea ammonium nitrate.

[††] Herbicides chemical nomenclature used in burndown and postemergence listed in Table 3.14

Table 3.6. VT stage or later corn plant heights for lime treatments for all field trials from 2012 to 2014.

| Trial # | Treatment | Cropping season |  |  |
|---|---|---|---|---|
|  |  | 2012 | 2013 | 2014 |
|  |  | ------------------------------- cm ------------------------------- |  |  |
| Trial #1 | CTRL | 164 | 202 | 224 |
|  | S-LO | 163 | 206 | 231 |
|  | S-HI | 159 | 208 | 240 |
|  | D-NO | 171 | 204 | 238 |
|  | D-LO | 172 | 202 | 235 |
|  | D-HI | 170 | 201 | 245 |
|  | LSD$_{(P\leq0.10)}$ | 5 | 5 | 10 |
| Trial #2 | CTRL | ---[†] | 246 | 266 |
|  | S-LO | --- | 252 | 271 |
|  | S-HI | --- | 243 | 270 |
|  | D-NO | --- | 248 | 274 |
|  | D-LO | --- | 246 | 266 |
|  | D-HI | --- | 239 | 268 |
|  | LSD$_{(P\leq0.10)}$ | --- | 10 | 5 |
| Trial #3 | CTRL | --- | --- | 251 |
|  | S-LO | --- | --- | 264 |
|  | S-HI | --- | --- | 251 |
|  | D-NO | --- | --- | 253 |
|  | D-LO | --- | --- | 250 |
|  | D-HI | --- | --- | 259 |
|  | LSD$_{(P\leq0.10)}$ | --- | --- | 10 |

[†] Field site was not established and no data were collected

[††] Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$

Table 3.7. Corn plant populations of lime treatments for all trials from 2012 to 2016.

| Trial # | Treatment | Cropping season 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|
| | | ------------------------------ No. $ha^{-1}$ | ------------------------------ | | | |
| Trial #1 | CTRL | 74,400 | 66,000 | 70,200 | 62,800 | 74,000 |
| | S-LO | 74,200 | 66,900 | 70,500 | 61,600 | 73,400 |
| | S-HI | 72,200 | 67,800 | 68,400 | 61,100 | 74,900 |
| | D-NO | 64,400 | 66,400 | 67,600 | 61,600 | 67,600 |
| | D-LO | 57,100 | 68,400 | 68,200 | 61,600 | 58,800 |
| | D-HI | 69,000 | 70,200 | 66,900 | 62,000 | 64,200 |
| | $LSD_{(P \leq 0.10)}$ | 5,400 | NS[†] | 2,000 | NS | 4,900 |
| Trial #2 | CTRL | ---[††] | 66,600 | 65,500 | 62,100 | 66,100 |
| | S-LO | --- | 63,000 | 63,300 | 64,900 | 65,000 |
| | S-HI | --- | 66,100 | 65,200 | 63,000 | 70,300 |
| | D-NO | --- | 65,900 | 62,400 | 61,300 | 68,300 |
| | D-LO | --- | 67,700 | 64,600 | 64,100 | 72,300 |
| | D-HI | --- | 66,800 | 64,400 | 61,900 | 69,300 |
| | $LSD_{(P \leq 0.10)}$ | --- | 4,200 | 2,500 | NS | NS |
| Trial #3 | CTRL | --- | --- | 61,400 | 75,900 | 74,500 |
| | S-LO | --- | --- | 60,300 | 73,000 | 72,700 |
| | S-HI | --- | --- | 58,800 | 73,700 | 75,300 |
| | D-NO | --- | --- | 62,200 | 74,200 | 77,000 |
| | D-LO | --- | --- | 56,000 | 73,700 | 74,600 |
| | D-HI | --- | --- | 60,000 | 74,000 | 71,200 |
| | $LSD_{(P \leq 0.10)}$ | --- | --- | NS | NS | NS |

[†] NS denotes no significance difference at $P \leq 0.10$

[††] Field site was not established and no data were collected

[†††] Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg $ha^{-1}$; S-HI, Surface 6.7 Mg $ha^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg $ha^{-1}$; D-HI, Deep placement 6.7 Mg $ha^{-1}$

Table 3.8. Late season soybean plant top heights of lime treated plots for all field trials 2012 to 2015

| Trial # | Treatment | Cropping season | | | |
|---|---|---|---|---|---|
| | | 2012 | 2013 | 2014 | 2015 |
| | | cm | | | |
| Trial #1 | CTRL | 53 | 70 | 99 | 83 |
| | S-LO | 54 | 70 | 104 | 74 |
| | S-HI | 53 | 66 | 105 | 84 |
| | D-NO | 55 | 68 | 98 | 79 |
| | D-LO | 53 | 67 | 98 | 86 |
| | D-HI | 54 | 66 | 108 | 72 |
| | LSD$_{(P\leq0.10)}$ | 1 | NS[†] | 10 | 12 |
| Trial #2 | CTRL | ---[††] | 75 | 99 | 61 |
| | S-LO | --- | 74 | 94 | 63 |
| | S-HI | --- | 74 | 92 | 58 |
| | D-NO | --- | 72 | 91 | 57 |
| | D-LO | --- | 77 | 96 | 60 |
| | D-HI | --- | 73 | 94 | 58 |
| | LSD$_{(P\leq0.10)}$ | --- | NS | 6 | NS |
| Trial #3 | CTRL | --- | --- | 98 | 84 |
| | S-LO | --- | --- | 97 | 74 |
| | S-HI | --- | --- | 102 | 70 |
| | D-NO | --- | --- | 100 | 72 |
| | D-LO | --- | --- | 104 | 79 |
| | D-HI | --- | --- | 103 | 74 |
| | LSD$_{(P\leq0.10)}$ | --- | --- | 6 | 10 |

[†] NS denotes no significance difference at P≤0.10

[††]Field site was not established and no data were collected

[†††]Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$

Table 3.9. Soybean plant populations of lime treated plots for all trials 2012 to 2016.

| | | Cropping season | | | | |
|---|---|---|---|---|---|---|
| Trial # | Treatment | 2012 | 2013 | 2014 | 2015 | 2016 |
| | | No ha$^{-1}$ | | | | |
| Trial #1 | CTRL | 462,800 | 376,700 | 226,000 | 269,100 | 592,000 |
| | S-LO | 581,300 | 387,500 | 258,300 | 290,600 | 505,900 |
| | S-HI | 398,300 | 409,000 | 269,100 | 312,200 | 581,300 |
| | D-NO | 484,400 | 355,200 | 236,800 | 269,100 | 742,700 |
| | D-LO | 452,100 | 312,200 | 290,600 | 290,600 | 721,200 |
| | D-HI | 570,500 | 366,000 | 279,900 | 226,000 | 710,400 |
| | LSD$_{(P\leq0.10)}$ | 116,100 | 86,400 | 56,000 | 59,000 | 19,7900 |
| Trial #2 | CTRL | ---[††] | 452,100 | 215,300 | 193,800 | 656,600 |
| | S-LO | --- | 430,600 | 199,100 | 204,500 | 721,200 |
| | S-HI | --- | 366,000 | 183,000 | 226,000 | 699,700 |
| | D-NO | --- | 344,400 | 188,400 | 215,300 | 688,900 |
| | D-LO | --- | 376,700 | 177,600 | 204,500 | 753,500 |
| | D-HI | --- | 409,000 | 199,100 | 215,300 | 581,300 |
| | LSD$_{(P\leq0.10)}$ | --- | NS[†] | 31,700 | NS | NS |
| Trial #3 | CTRL | --- | --- | 269,100 | 290,600 | 839,600 |
| | S-LO | --- | --- | 269,100 | 290,600 | 914,900 |
| | S-HI | --- | --- | 258,300 | 226,000 | 1,065,600 |
| | D-NO | --- | --- | 247,600 | 279,900 | 882,600 |
| | D-LO | --- | --- | 258,300 | 269,100 | 1,097,900 |
| | D-HI | --- | --- | 279,900 | 279,900 | 1,108,700 |
| | LSD$_{(P\leq0.10)}$ | --- | --- | NS | 54,200 | NS |

[†] NS denotes no significance difference at P≤0.10

[††] Field site was not established and no data were collected

[†††] Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$

Table 3.10. VT stage or later corn plant top heights of gypsum treatments for all field trials from 2012 to 2014.

| Trial # | Treatment | Cropping season 2012 | Cropping season 2013 | Cropping season 2014 |
|---|---|---|---|---|
| | | cm | | |
| Trial #1 | CTRL | 164 | 202 | 224 |
| | S-LO | 158 | 208 | 232 |
| | S-HI | 163 | 208 | 227 |
| | D-NO | 171 | 204 | 238 |
| | D-LO | 170 | 201 | 248 |
| | D-HI | 167 | 202 | 181 |
| | LSD $_{(P \leq 0.10)}$ | 10 | NS[†] | 61 |
| Trial #2 | CTRL | ---[††] | 246 | 266 |
| | S-LO | --- | 260 | 271 |
| | S-HI | --- | 233 | 267 |
| | D-NO | --- | 248 | 274 |
| | D-LO | --- | 242 | 273 |
| | D-HI | --- | 244 | 269 |
| | LSD $_{(P \leq 0.10)}$ | --- | 14 | NS |
| Trial #3 | CTRL | --- | --- | 251 |
| | S-LO | --- | --- | 255 |
| | S-HI | --- | --- | 238 |
| | D-NO | --- | --- | 253 |
| | D-LO | --- | --- | 262 |
| | D-HI | --- | --- | 259 |
| | LSD $_{(P \leq 0.10)}$ | --- | --- | NS |

[†] NS denotes no significance difference at $P \leq 0.10$

[††] Field site was not established and no data were collected

[†††] Abbreviations: CTRL, Control; S-LO, Surface 2.9 Mg ha$^{-1}$; S-HI, Surface 5.2 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 2.9 Mg ha$^{-1}$; D-HI, Deep placement 5.2 Mg ha$^{-1}$

Table 3.11. Corn plant populations of gypsum treatments for all trials from 2012 to 2016.

| Trial # | Treatment | Cropping season | | | | |
|---|---|---|---|---|---|---|
| | | 2012 | 2013 | 2014 | 2015 | 2016 |
| | | ------------------------------ No. ha$^{-1}$--------------------------------- | | | | |
| Trial #1 | CTRL | 74,400 | 66,000 | 70,200 | 62,800 | 74,000 |
| | S-LO | 76,900 | 72,300 | 66,800 | 59,900 | 77,300 |
| | S-HI | 76,900 | 70,100 | 69,800 | 61,100 | 72,000 |
| | D-NO | 64,400 | 66,400 | 67,600 | 61,600 | 67,600 |
| | D-LO | 63,100 | 66,000 | 67,600 | 61,600 | 66,000 |
| | D-HI | 70,100 | 68,300 | 67,100 | 62,300 | 62,200 |
| | LSD$_{(P\leq0.10)}$ | 9,300 | NS | NS | 2,100 | 7,400 |
| Trial #2 | CTRL | --- | 66,600 | 65,500 | 62,100 | 66,100 |
| | S-LO | --- | 67,800 | 69,400 | 64,900 | 68,700 |
| | S-HI | --- | 67,800 | 68,300 | 64,600 | 70,800 |
| | D-NO | --- | 65,900 | 62,400 | 61,300 | 68,300 |
| | D-LO | --- | 64,900 | 66,400 | 63,300 | 67,800 |
| | D-HI | --- | 66,500 | 62,400 | 61,800 | 68,900 |
| | LSD$_{(P\leq0.10)}$ | --- | NS | 6,000 | NS | NS |
| Trial #3 | CTRL | --- | --- | 61,400 | 75,900 | 74,500 |
| | S-LO | --- | --- | 50,100 | 75,300 | 73,000 |
| | S-HI | --- | --- | 57,100 | 73,000 | 66,500 |
| | D-NO | --- | --- | 62,200 | 74,200 | 77,000 |
| | D-LO | --- | --- | 61,000 | 73,900 | 74,900 |
| | D-HI | --- | --- | 61,800 | 72,100 | 77,000 |
| | LSD$_{(P\leq0.10)}$ | --- | --- | NS | 3,500 | 8,300 |

[†] NS denotes no significance difference at P≤0.10

[††]Field site was not established and no data were collected

[†††]Abbreviations: CTRL, Control; S-LO, Surface 2.9 Mg ha$^{-1}$; S-HI, Surface 5.2 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 2.9 Mg ha$^{-1}$; D-HI, Deep placement 5.2 Mg ha$^{-1}$

Table 3.12. Late season soybean plant top heights of gypsum treatments for all field trials from 2012 to 2015.

| Trial # | Treatment | Cropping season 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|
| | | cm | | | |
| Trial #1 | CTRL | 53 | 70 | 99 | 83 |
| | S-LO | 56 | 67 | 100 | 87 |
| | S-HI | 55 | 67 | 102 | 83 |
| | D-NO | 55 | 68 | 98 | 79 |
| | D-LO | 55 | 69 | 107 | 83 |
| | D-HI | 54 | 66 | 98 | 77 |
| | LSD$_{(P≤0.10)}$ | 3 | NS[†] | 8 | 9 |
| Trial #2 | CTRL | ---[††] | 75 | 99 | 61 |
| | S-LO | --- | 86 | 98 | 53 |
| | S-HI | --- | 77 | 93 | 58 |
| | D-NO | --- | 72 | 91 | 57 |
| | D-LO | --- | 75 | 91 | 53 |
| | D-HI | --- | 73 | 89 | 61 |
| | LSD$_{(P≤0.10)}$ | --- | 9 | 8 | 8 |
| Trial #3 | CTRL | --- | --- | 98 | 84 |
| | S-LO | --- | --- | 107 | 69 |
| | S-HI | --- | --- | 100 | 75 |
| | D-NO | --- | --- | 100 | 72 |
| | D-LO | --- | --- | 100 | 70 |
| | D-HI | --- | --- | 91 | 74 |
| | LSD$_{(P≤0.10)}$ | --- | --- | 10 | 10 |

[†] NS denotes no significance difference at $P \leq 0.10$

[††] Field site was not established and no data were collected

[†††] Abbreviations: CTRL, Control; S-LO, Surface 2.9 Mg ha$^{-1}$; S-HI, Surface 5.2 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 2.9 Mg ha$^{-1}$; D-HI, Deep placement 5.2 Mg ha$^{-1}$

Table 3.13. Soybean plant population of gypsum treatments for all trials from 2012 to 2016

| Trial # | Treatment | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|
| | | Cropping season | | | | |
| | | No ha$^{-1}$ | | | | |
| Trial #1 | CTRL | 462,800 | 376,700 | 226,000 | 269,100 | 592,000 |
| | S-LO | 538,200 | 376,700 | 247,600 | 258,300 | 861,100 |
| | S-HI | 549,000 | 333,700 | 269,100 | 301,400 | 635,100 |
| | D-NO | 484,400 | 355,200 | 236,800 | 269,100 | 742,700 |
| | D-LO | 538,200 | 344,400 | 236,800 | 247,600 | 753,500 |
| | D-HI | 441,300 | 387,500 | 269,100 | 279,900 | 678,100 |
| | LSD$_{(P\leq0.10)}$ | NS[†] | NS | NS | NS | 225,400 |
| Trial #2 | CTRL | ---[††] | 452,100 | 215,300 | 193,800 | 656,600 |
| | S-LO | --- | 419,800 | 209,900 | 215,300 | 559,700 |
| | S-HI | --- | 387,500 | 204,500 | 247,600 | 710,400 |
| | D-NO | --- | 344,400 | 188,400 | 215,300 | 688,900 |
| | D-LO | --- | 452,100 | 177,600 | 226,000 | 742,700 |
| | D-HI | --- | 387,500 | 183,000 | 258,300 | 678,100 |
| | LSD$_{(P\leq0.10)}$ | --- | 90,400 | 30,600 | 44,000 | NS |
| Trial #3 | CTRL | --- | --- | 269,100 | 290,600 | 839,600 |
| | S-LO | --- | --- | 258,300 | 258,300 | 861,100 |
| | S-HI | --- | --- | 247,600 | 226,000 | 807,300 |
| | D-NO | --- | --- | 247,600 | 279,900 | 882,600 |
| | D-LO | --- | --- | 236,800 | 269,100 | 839,600 |
| | D-HI | --- | --- | 226,000 | 279,900 | 904,200 |
| | LSD$_{(P\leq0.10)}$ | --- | --- | 39,300 | 58,700 | NS |

[†] NS denotes no significance difference at $P\leq0.10$

[††] Field site was not established and no data were collected

[†††] Abbreviations: CTRL, Control; S-LO, Surface 2.9 Mg ha$^{-1}$; S-HI, Surface 5.2 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 2.9 Mg ha$^{-1}$; D-HI, Deep placement 5.2 Mg ha$^{-1}$

Table 3.14. Chemical nomenclature of herbicides used in management of trials from 2012 to 2016.

| **Herbicide** | **Chemical Name** |
|---|---|
| Atrazine | 1-Chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine |
| Boundary | Metribuzin: 2-chloro-4-ethylamino-6-isopropylamino-s-triazine; *S*-metolachlor |
| Callisto | Mesotrione: 2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione |
| Dual II Magnum | *S*-metolachlor: 2-Chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl]acetamide |
| FirstRate | Cloransulam-methyl: N-(2-carbomethoxy-6-chlorophenyl)-5-ethoxy-7-fluoro(1,2,4)triazolo-[1,5-c]pyrmidine-2-sulfonmide |
| Halex GT | Mesotrione; S-metolachlor; Glyphosate, N-(phosphonomethyl) glycine |
| Lexar | Atrazine; Mesotrione; Acetamide, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl]-,(S) |
| Prefix | *S*-metolachlor; Sodium Salt of Fomesafen, 5-[2-chloro-4-(trifluoromethyl)phenoxy]-N-(methylsulfonyl)-2-nitrobenzamide |
| Reflex | Sodium Salt of Fomesafen, 5-[2-chloro-4-(trifluoromethyl)phenoxy]-N-(methylsulfonyl)-2-nitrobenzamide |
| Roundup PowerMAX | Glyphosate, N-(phosphonomethyl)glycine |
| Sharpen | Saflufenacil, N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3,6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide |
| Touchdown | Glyphosate: N-(phosphonomethyl) glycine |
| Verdict | Saflufenacil, N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3,6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide; Dimethenamid-P, (S)-(2-chloro-N-[(1-methyl-2-methoxy)ethyl]-N-(2,4-dimethyl-thien-3-yl)-acetamide |
| Warrant | Acetochlor, 2-Chloro-N-(ethoxymethyl)-N-(2-ethyl-6-methylphenyl)acetamide |
| Zidua | Pyroxasulfone, 3-[[[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)-1H-pyrazol-4-yl]methyl]sulfonyl]-4,5-dihydro-5,5-dimethylisoxazole |

Figure 3.1. Location of Trials #1, #2 and #3 and spatial analysis at the Greenley Memorial Research Center near Novelty, Missouri.

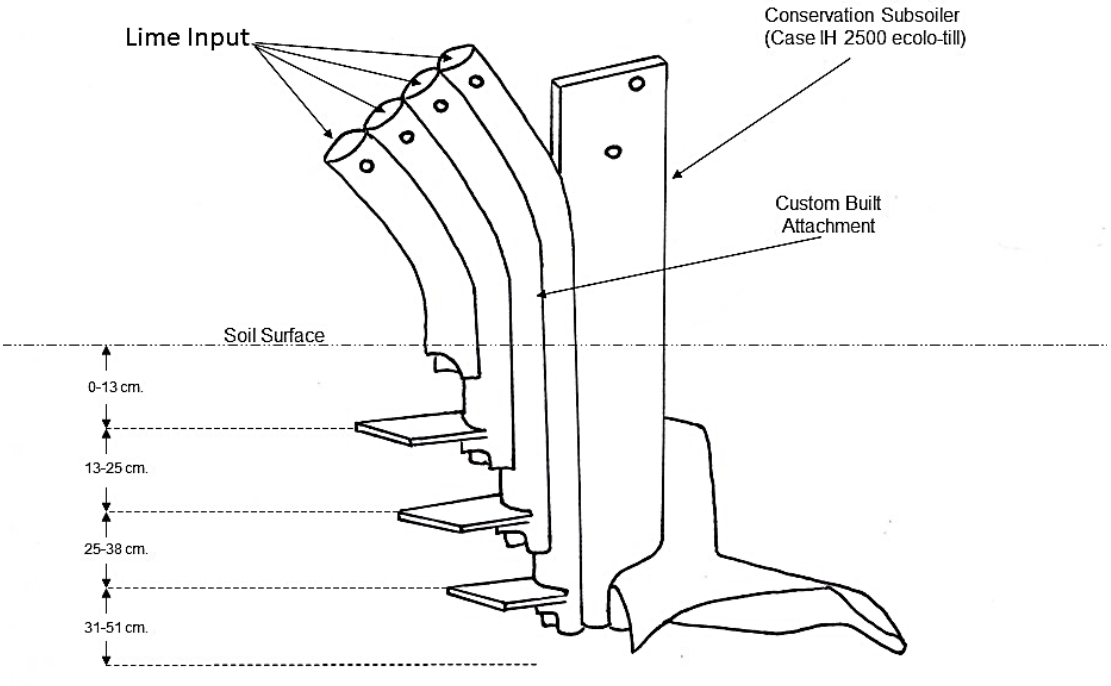

Figure 3.2. Custom built shank attachment schematics showing the depths at which the lime is placed in the soil in relation to the soil surface.

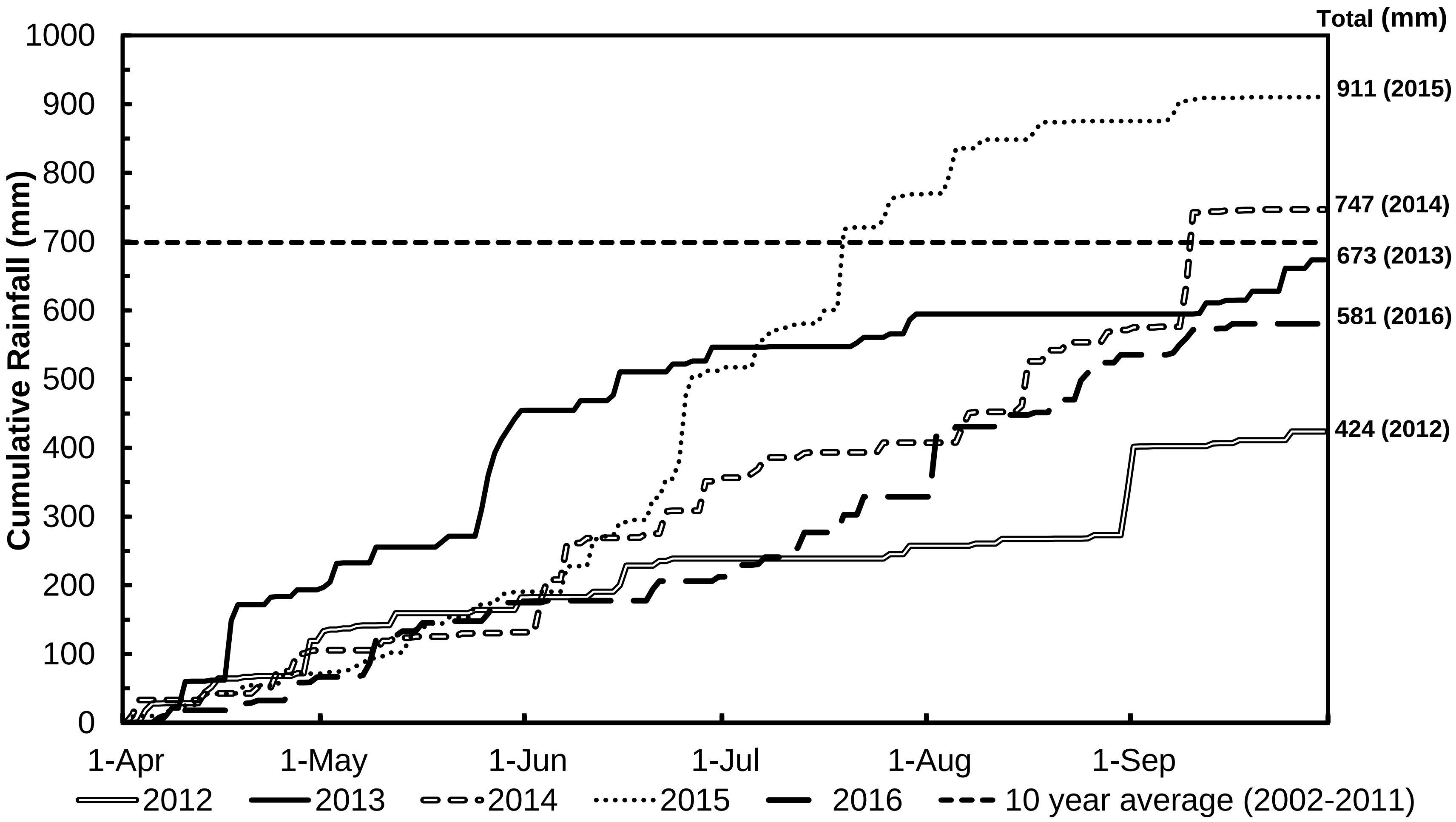

Figure 3.3. Cumulative precipitation during the 2012 to 2016 growing seasons and the 10 (2002 to 2011) year average (699 mm) at the Greenley Memorial Research Center near Novelty, Missouri.

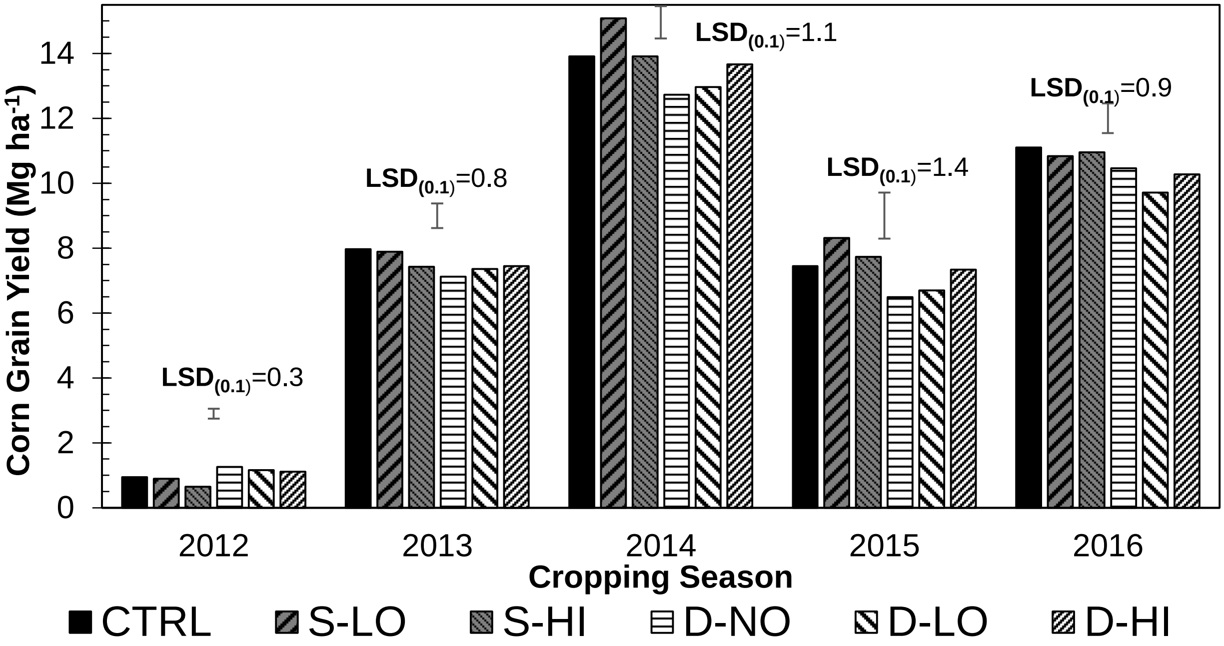

Figure 3.4. Trial #1 corn grain yields (Mg ha$^{-1}$) for lime treatments from 2012 to 2016 cropping season. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

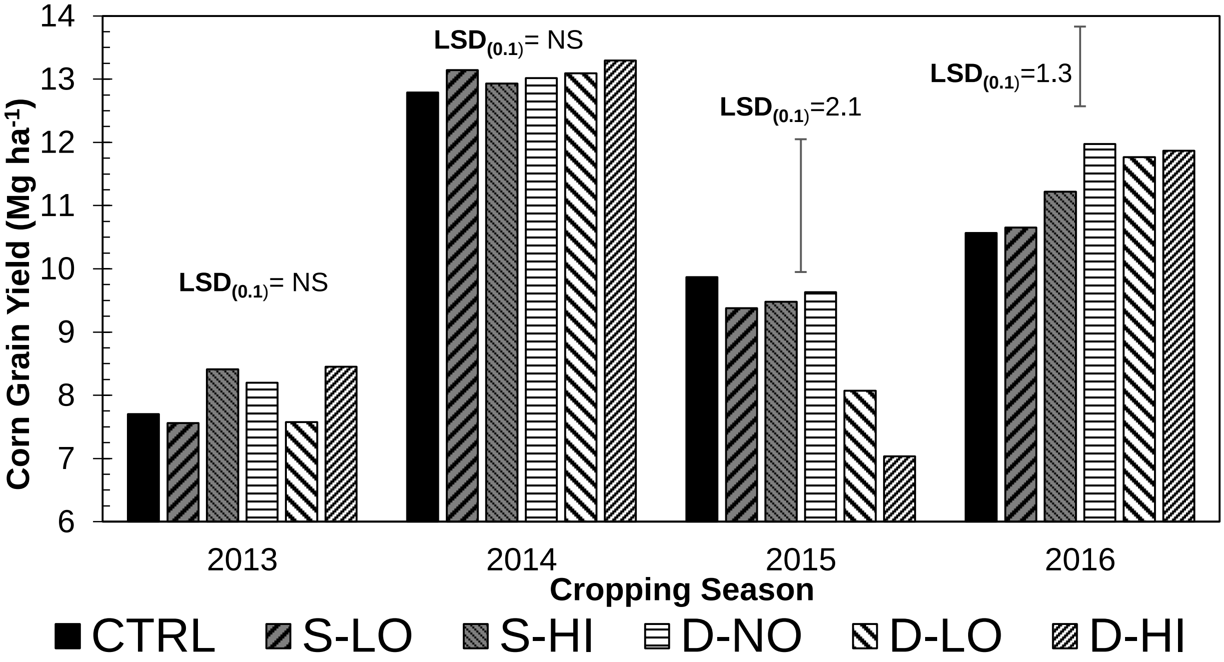

Figure 3.5. Trial #2 corn grain yields (Mg ha$^{-1}$) for lime treatments from 2013 to 2016 cropping season. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

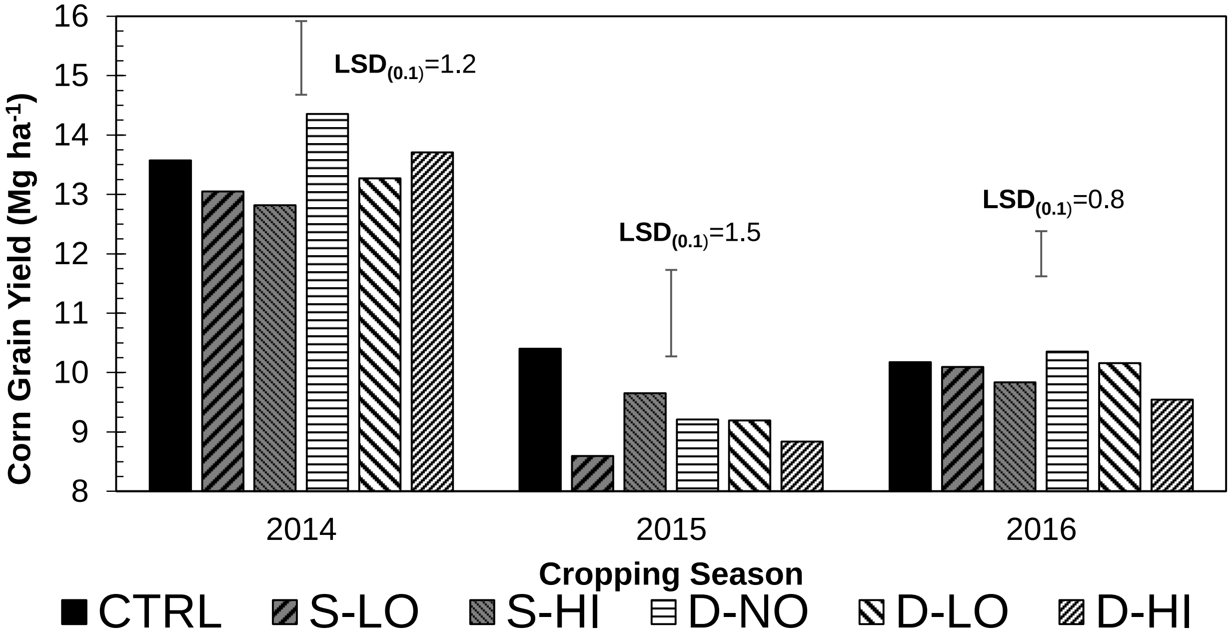

Figure 3.6. Trial #3 corn grain yields (Mg ha$^{-1}$) for lime treatments from 2014 to 2016 cropping season. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

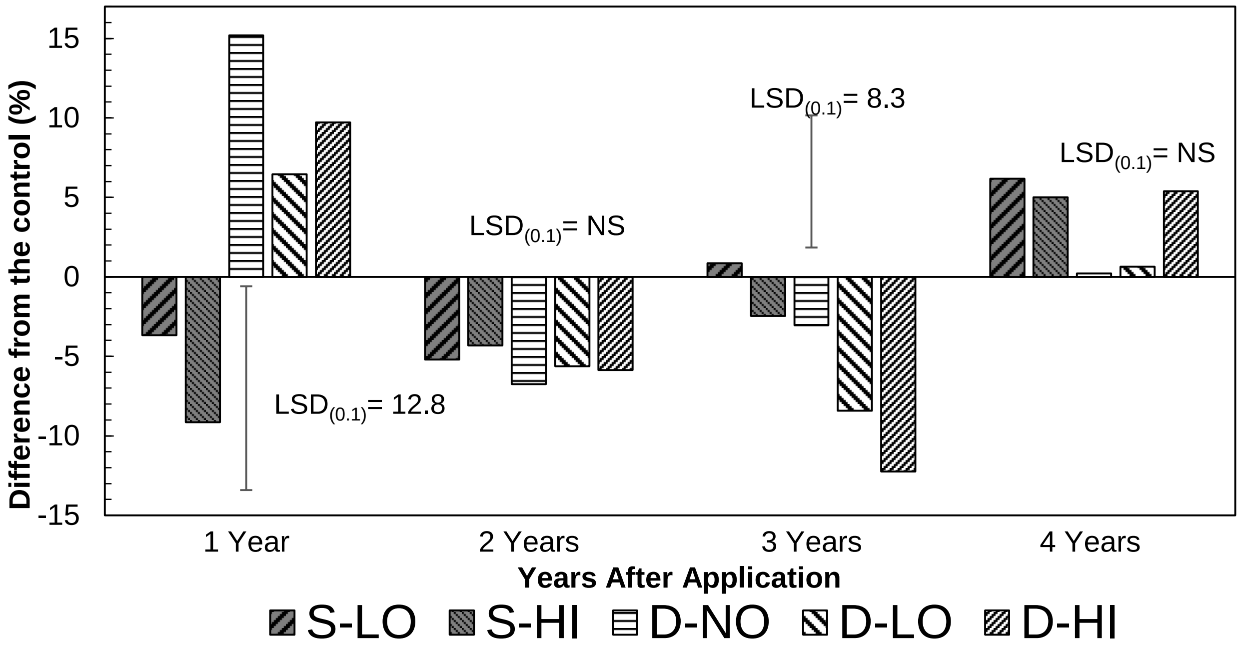

Figure 3.7. Corn yield difference from control plots (%) of lime treatments for all trials 1 to 4 years after treatments. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

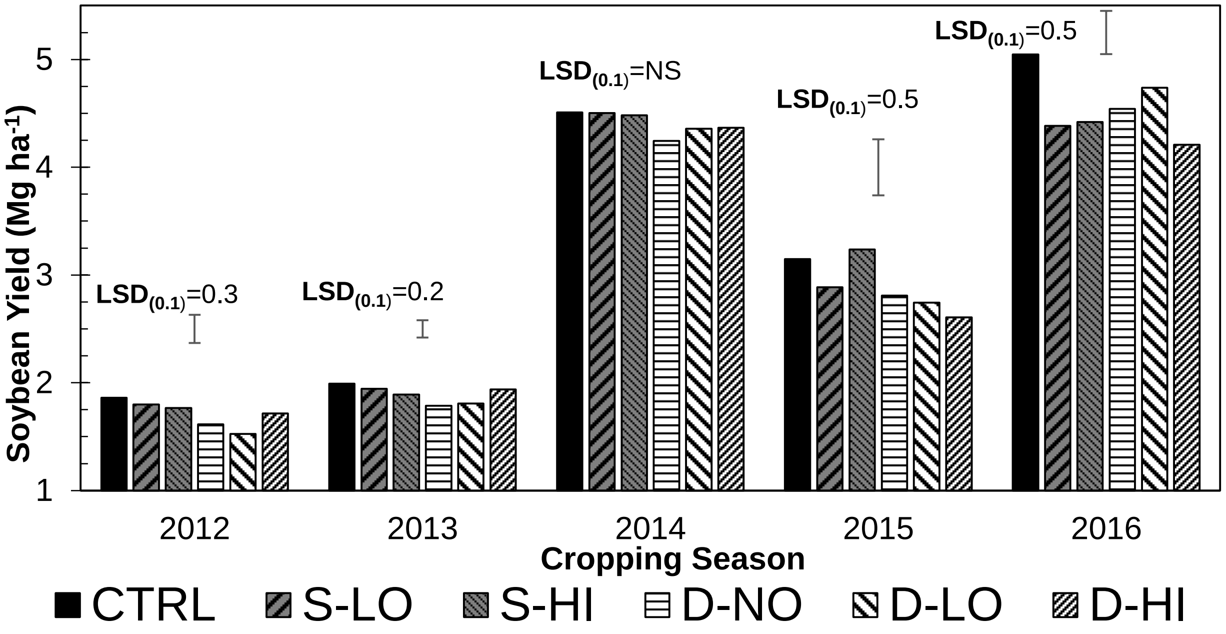

Figure 3.8. Trial #1 soybean yields (Mg ha$^{-1}$) for lime treatments from 2012 to 2016 cropping season. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

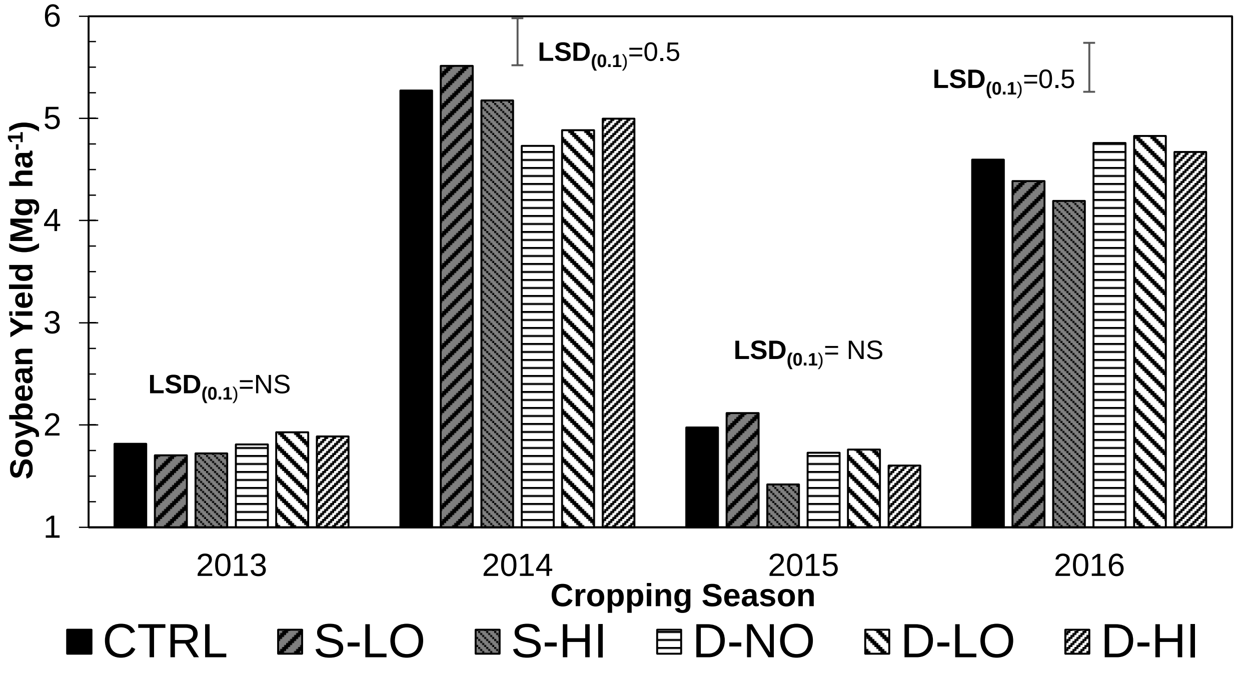

Figure 3.9. Trial #2 soybean yields (Mg ha$^{-1}$) for lime treatments from 2013 to 2016 cropping season. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg ha$^{-1}$; S-HI, Surface 6.7 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg ha$^{-1}$; D-HI, Deep placement 6.7 Mg ha$^{-1}$).

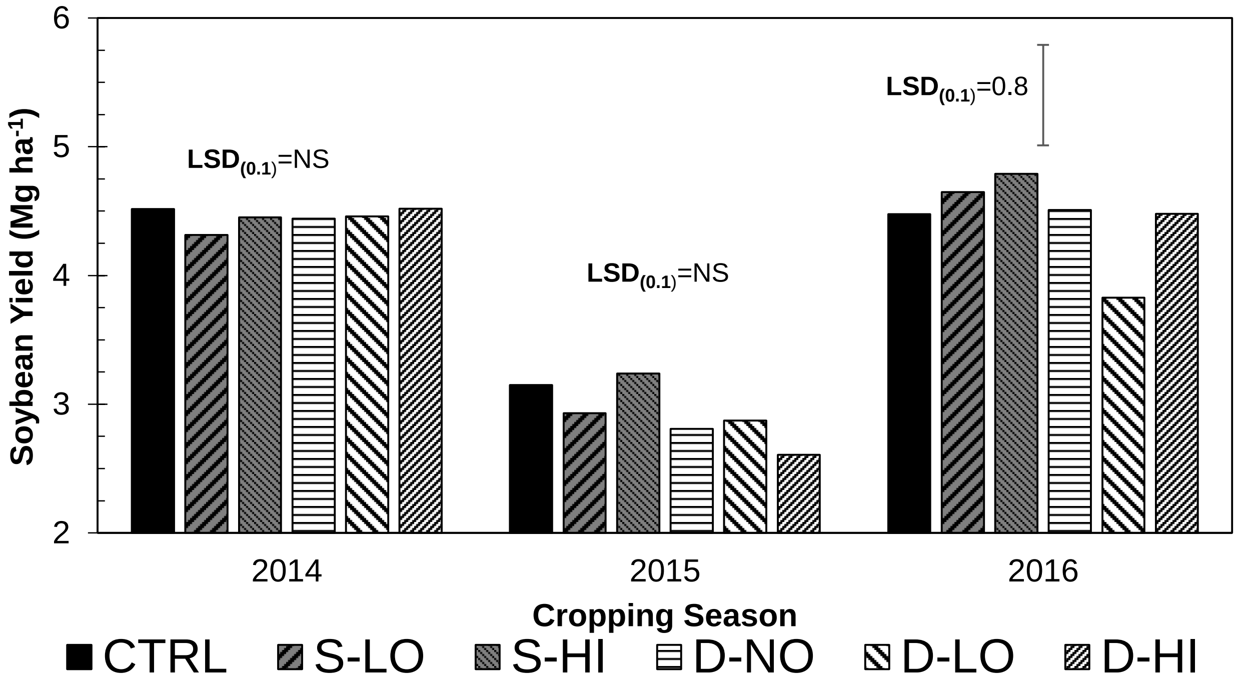

Figure 3.10. Trial #3 soybean yields (Mg $ha^{-1}$) for lime treatments from 2014 to 2016 cropping season. $LSD_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: CTRL, Control; S-LO, Surface 3.4 Mg $ha^{-1}$; S-HI, Surface 6.7 Mg $ha^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg $ha^{-1}$; D-HI, Deep placement 6.7 Mg $ha^{-1}$)

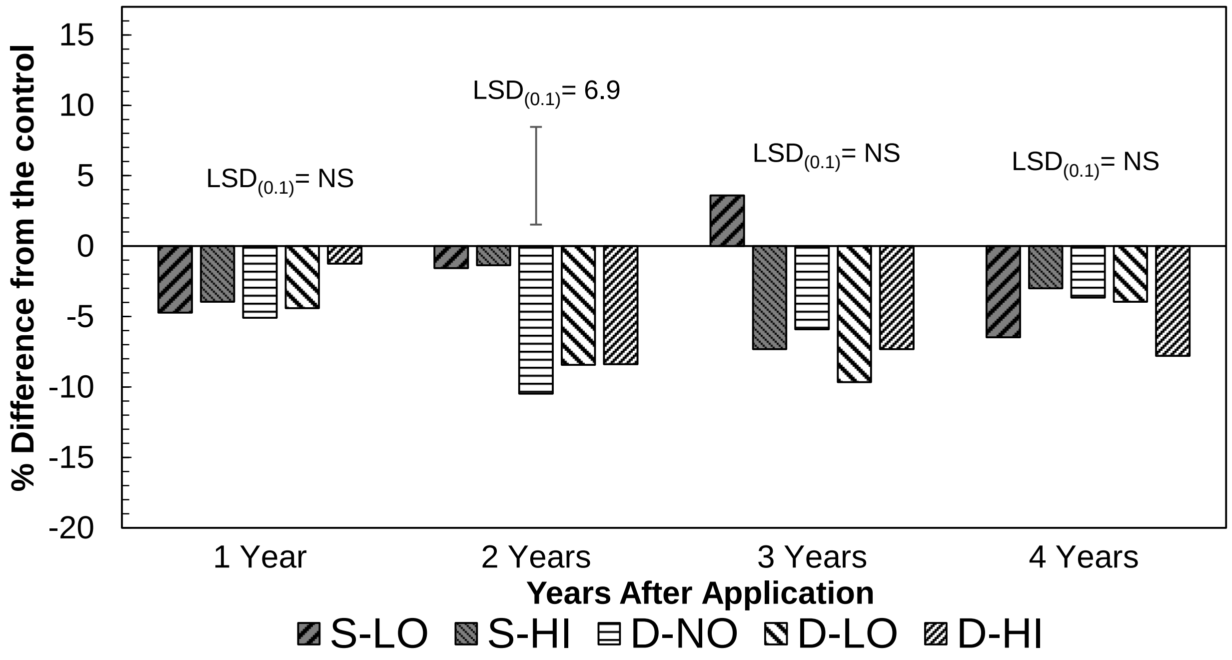

Figure 3.11. Soybean yield difference from control plots (%) for all trials 1 – 4 years after lime treatments. $LSD_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: S-LO, Surface 3.4 Mg $ha^{-1}$; S-HI, Surface 6.7 Mg $ha^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 3.4 Mg $ha^{-1}$; D-HI, Deep placement 6.7 Mg $ha^{-1}$).

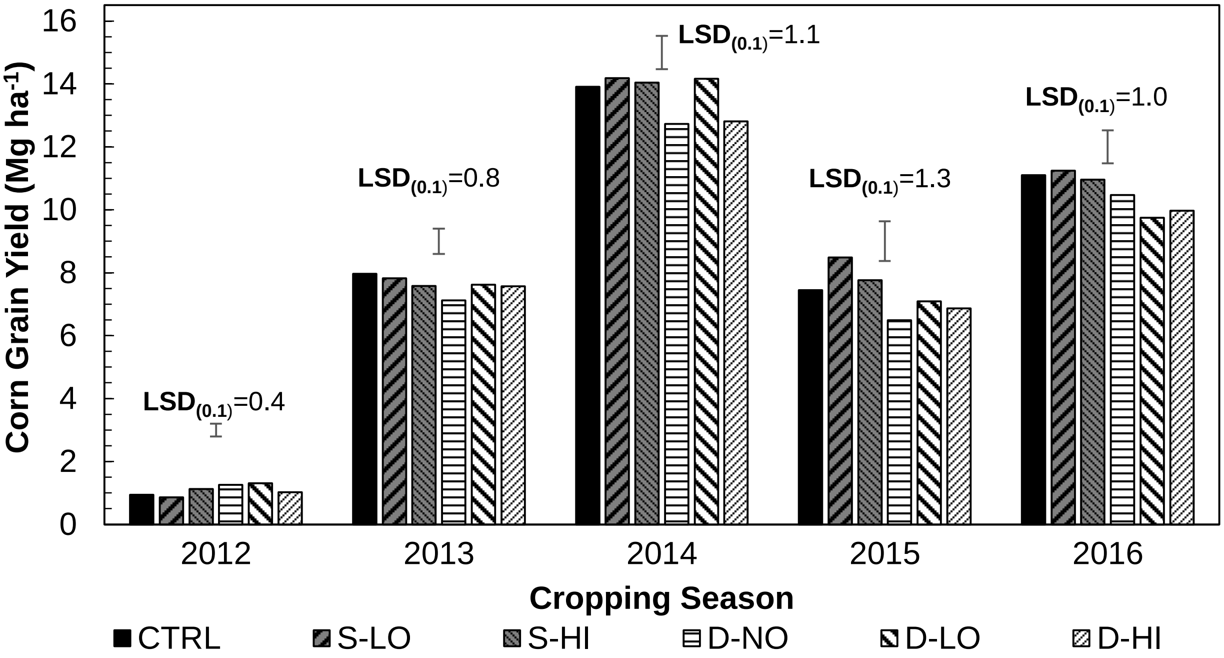

Figure 3.12. Trial #1 corn grain yields (Mg ha$^{-1}$) for gypsum treatments in 2012 to 2016 cropping season. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: CTRL, Control; S-LO, Surface 2.9 Mg ha$^{-1}$; S-HI, Surface 5.2 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 2.9 Mg ha$^{-1}$; D-HI, Deep placement 5.2 Mg ha$^{-1}$).

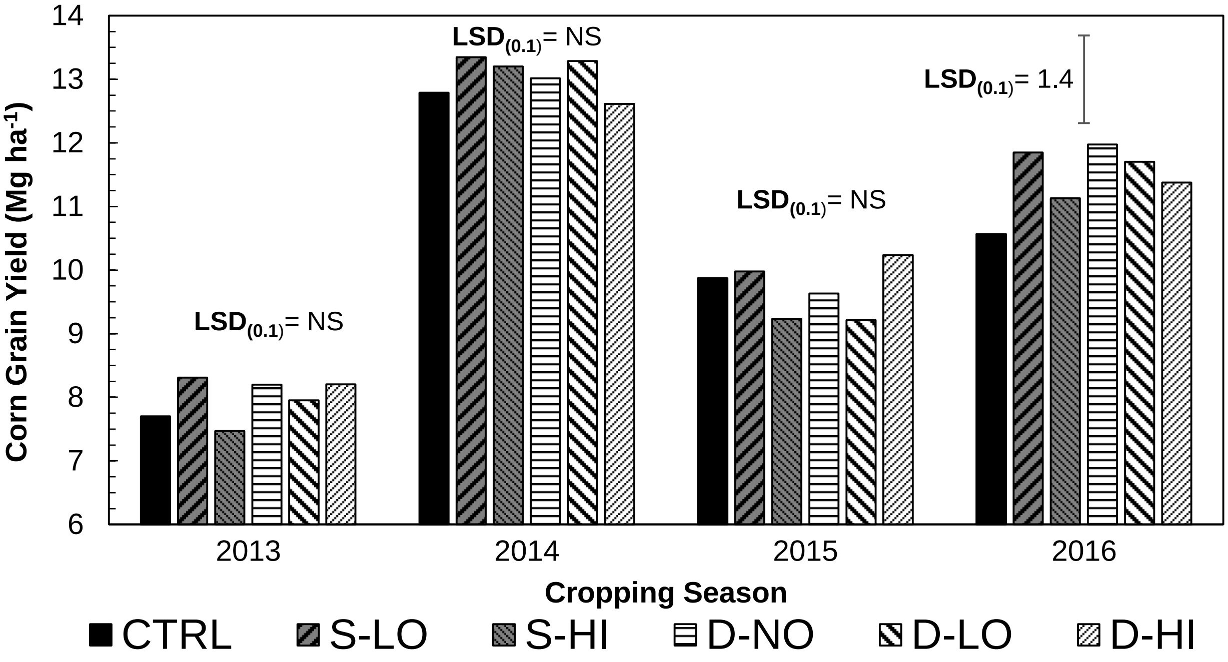

Figure 3.13. Trial #2 corn grain yields (Mg ha$^{-1}$) for gypsum treatments in 2013 to 2016 cropping season. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: CTRL, Control; S-LO, Surface 2.9 Mg ha$^{-1}$; S-HI, Surface 5.2 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 2.9 Mg ha$^{-1}$; D-HI, Deep placement 5.2 Mg ha$^{-1}$).

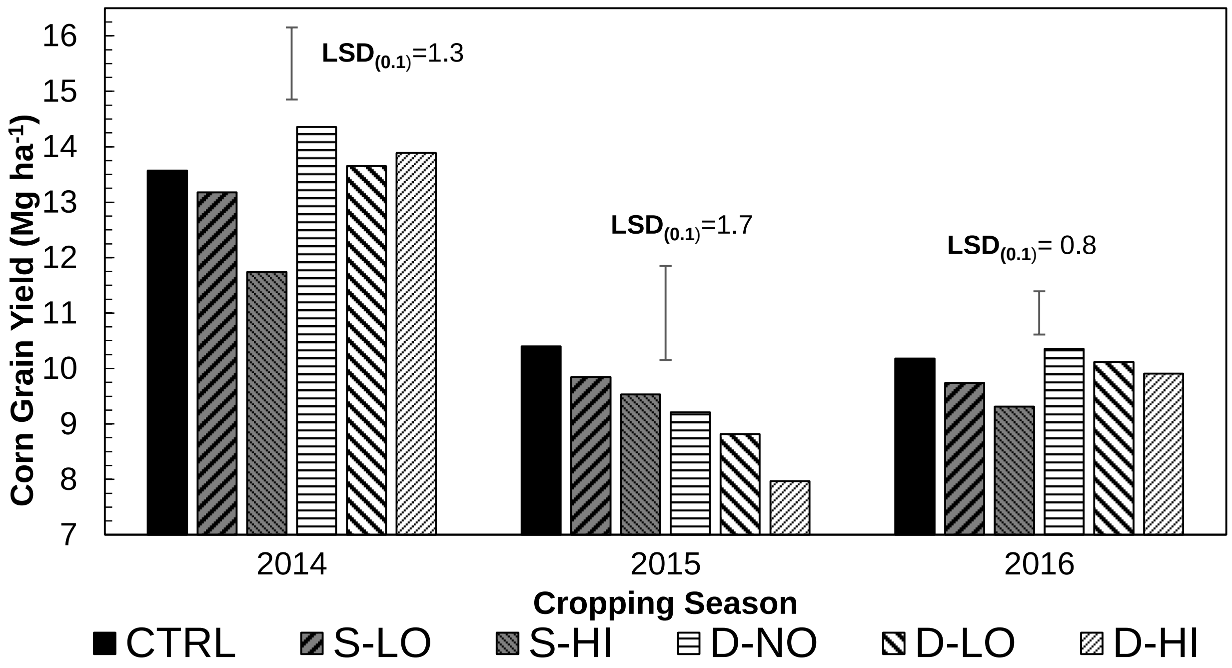

Figure 3.14. Trial #3 corn grain yields (Mg ha$^{-1}$) for gypsum treatments in 2013 to 2016 cropping season. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: CTRL, Control; S-LO, Surface 2.9 Mg ha$^{-1}$; S-HI, Surface 5.2 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 2.9 Mg ha$^{-1}$; D-HI, Deep placement 5.2 Mg ha$^{-1}$)

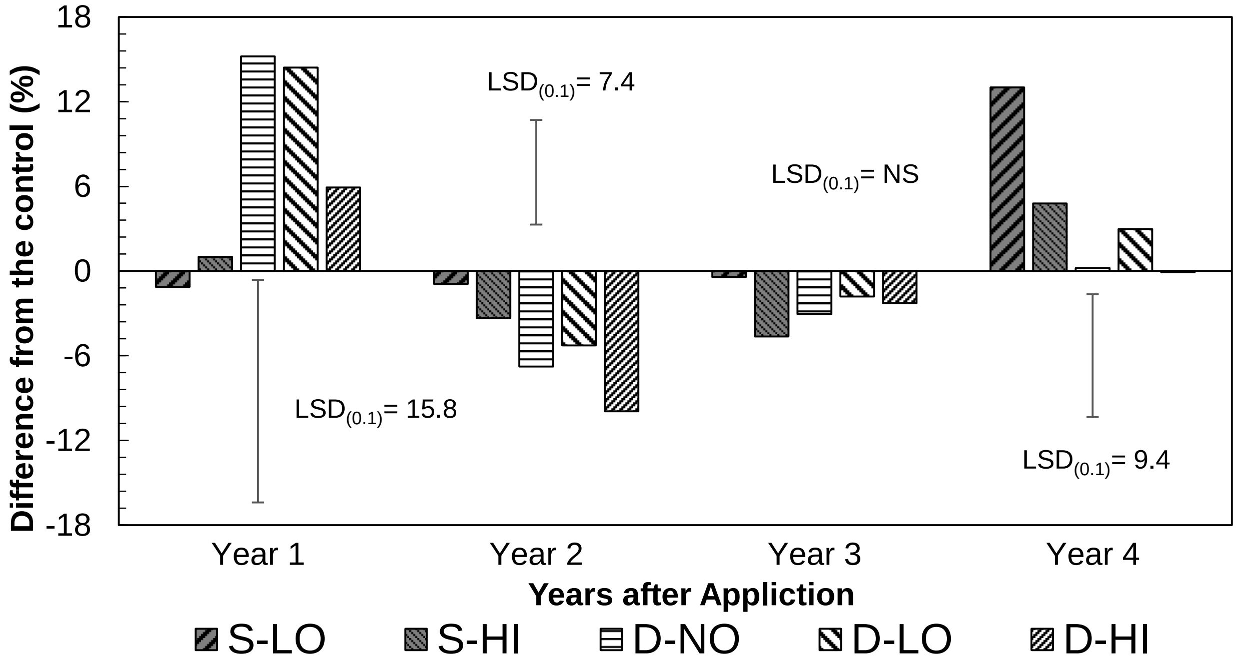

Figure 3.15. Corn grain yield difference from control plots (%) of gypsum treatments for all trials 1 to 4 years after treatments. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: S-LO, Surface 2.9 Mg ha$^{-1}$; S-HI, Surface 5.2 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 2.9 Mg ha$^{-1}$; D-HI, Deep placement 5.2 Mg ha$^{-1}$).

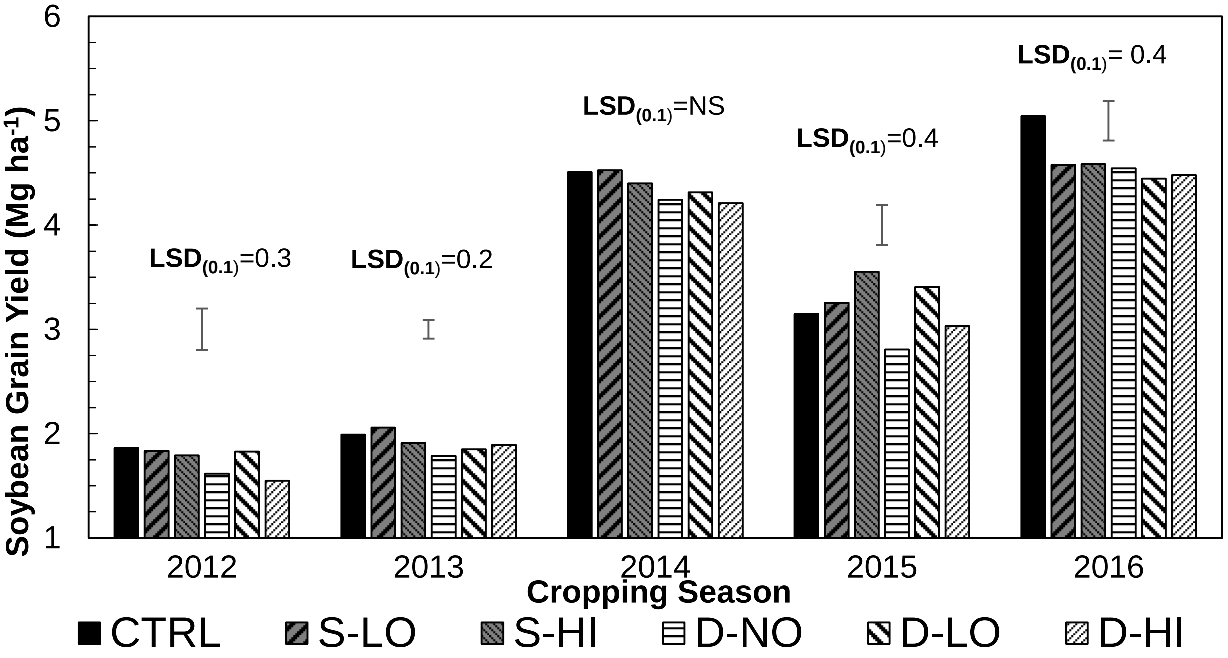

Figure 3.16. Trial #1 soybean yields (Mg ha$^{-1}$) for gypsum treatments in 2012 to 2016 cropping season. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: CTRL, Control; S-LO, Surface 2.9 Mg ha$^{-1}$; S-HI, Surface 5.2 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 2.9 Mg ha$^{-1}$; D-HI, Deep placement 5.2 Mg ha$^{-1}$).

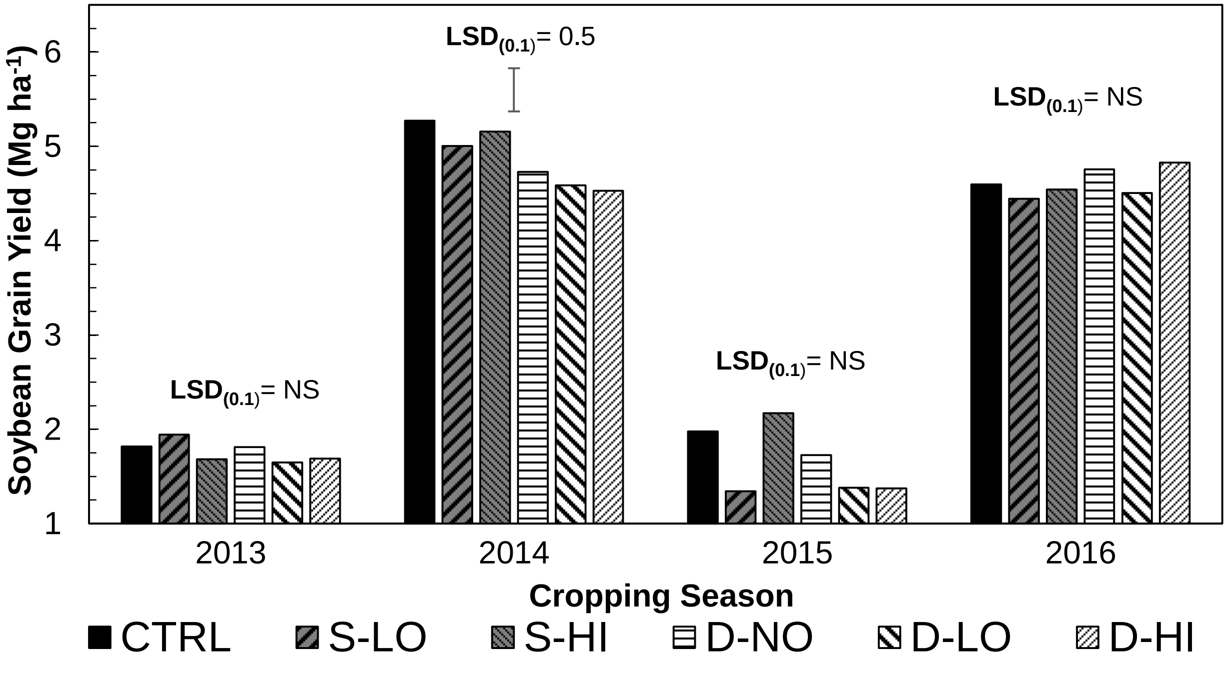

Figure 3.17. Trial #2 soybean yields (Mg ha$^{-1}$) for gypsum treatments in 2013 to 2016 cropping season. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: CTRL, Control; S-LO, Surface 2.9 Mg ha$^{-1}$; S-HI, Surface 5.2 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 2.9 Mg ha$^{-1}$; D-HI, Deep placement 5.2 Mg ha$^{-1}$).

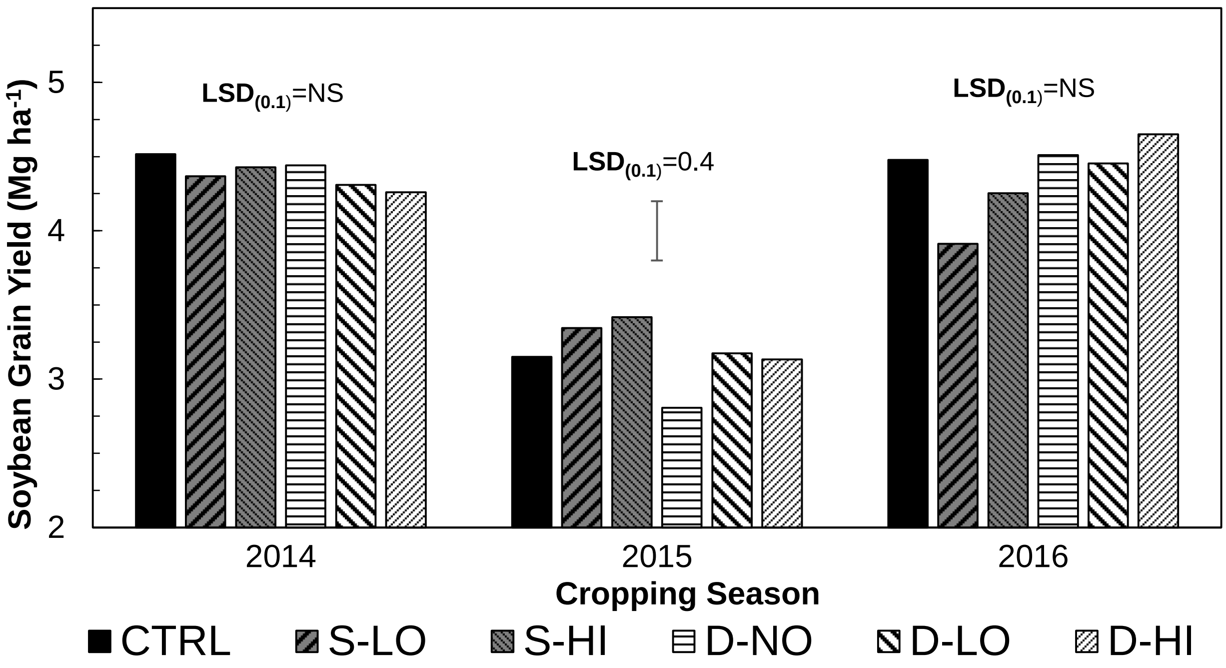

Figure 3.18. Trial #3 soybean yields (Mg ha$^{-1}$) for gypsum treatments in 2014 to 2016 cropping season. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: CTRL, Control; S-LO, Surface 2.9 Mg ha$^{-1}$; S-HI, Surface 5.2 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 2.9 Mg ha$^{-1}$; D-HI, Deep placement 5.2 Mg ha$^{-1}$).

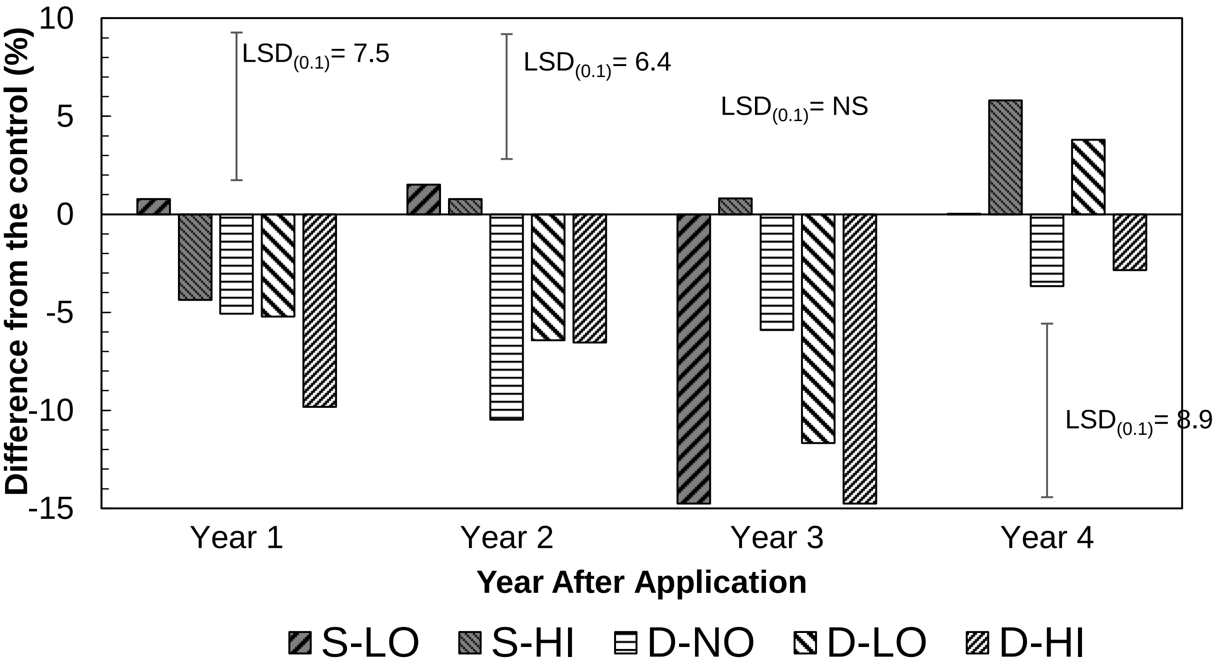

Figure 3.19. Soybean yield difference from control plots (%) for all trials 1 to 4 years after gypsum treatments. LSD$_{(0.1)}$ is least significant differences at $p \leq 0.1$. (Abbreviations: S-LO, Surface 2.9 Mg ha$^{-1}$; S-HI, Surface 5.2 Mg ha$^{-1}$; D-NO, Deep tillage no lime; D-LO, Deep placement 2.9 Mg ha$^{-1}$; D-HI, Deep placement 5.2 Mg ha$^{-1}$).

# CHAPTER 4

# OVERALL CONCLUSIONS

Stratification of soil pH is common in the Central Claypan Region of the United States. Soil acidity can result in decreasing nutrient availability and reduced root growth, which can decrease grain yields of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. Additionally, intensive agronomic production can further increase soil acidity requiring more attention to this issue as demands for food and fiber production become higher around the world. Gypsum amendments may increase grain yields through reductions in aluminum (Al) toxicity and addition of Ca in the highly weathered soils of the tropics. However, they may be less effective on lesser weathered soils of more temperate climates. Lime amendments have shown to be effective in increasing soil pH and reducing Al toxicity. However, alterations to subsoil pH becomes increasingly difficult under no-till management practices due to the slow solubility of calcium carbonate ($CaCO_3$) and the limited effects of surface lime applications on the subsoil. Studies on strip placement of lime and gypsum using conservation tillage methods indicate beneficial short- and long-term effects to both grain yields and soil chemical properties for tropical soils; however, research on temperate climate soils was lacking.

Research addressed methods to alter subsoil chemical properties for Midwest soils, more specifically Missouri claypan soils, under no-till or conservation-tillage may be crucial to sustain future production requirements. The deep vertical placement treatments in this research were selected to evaluate the ability of zone-tillage, paired with lime or gypsum amendments, to address subsoil acidity and increase grain yields of corn and soybean.

The custom built attachment successfully delivered appropriate amounts of lime and gypsum into the subsoil; however, spatial analysis of lime treatments along with soil probe samples indicated a limited affected zone caused by this amendment over the seven months of evaluation. A trench excavated along the deep vertical placement band revealed a lack of soil disturbance past the 38 cm depth. Additionally, the largest soil chemical effects observed for deep vertical placement treatments occurred at the 13 to 38 cm depth range, indicating a pooling of amendment at that depth. The area of influence from the deep vertical placement of lime ranged about 20 cm laterally away from the band with some greater spreading occurring seven months after application. Furthermore, little to no downward neutralization of soil was observed below the area of placement. Lateral movement of lime throughout the soil profile can be attributed to the poor drainage of Northeastern Missouri claypan soils and could be greater over time.

Climatic conditions varied greatly from year to year which had an impact on overall grain yields. This provided an opportunity to evaluate responses in drought and high yield environments. Overall, grain yields of corn and soybean appeared to be negatively affected by deep vertical placement treatments of both lime and gypsum. However, tillage effects from deep vertical placement treatments did appear to increase corn yields in the first year after treatment. In contrast, soybean yields were reduced with deep vertical placement treatments. This may be attributed the difference in rooting characteristics of corn and soybean. Furthermore, deep vertical placement of lime increased corn grain yields 0.4 to 1.5 Mg ha$^{-1}$ in Trial #1 and #3, in drier years (2012 and 2016); however, yield increases may be attributed to deep tillage effects. Nevertheless, this may indicate an increase in drought tolerance with deep vertical placement of lime for deeper rooting corn plants.

In the early years of this study, deep vertical placement treatments of lime and gypsum did not have a consistent effect on grain yields of corn and soybean. Overall effects on both soil and plant characteristics appeared to be influenced by variability in both climatic and environmental conditions. Differences in soil acidity parameters in the soil profiles between Trials #1 and #3 and Trial #2, combined with differing treatment dates made early comparisons between trials challenging. A longer evaluation period could improve the evaluation of the long-term effects of the lime and gypsum treatments.

Greater success of lime placement in other studies could be an indication that soil acidity is a larger limiting factor for those soils and management conditions compared to this research. A smaller limiting effect can result in greater opportunity for variability due to environmental conditions. Furthermore, past research on deep placement of lime and gypsum indicated that long-term studies were essential in understanding the effects of lime treatments. Additionally, most studies on lime placement were carried out in tropical regions where rainfall is much greater. As lime reactivity is dependent on soil water content, it would suggest that greater timespan could be required to have similar level of reactivity of previous studies conducted on tropical soils.

Grain reductions observed from deep vertical placement treatments may be explained by various unintended factors affecting the experiment. For example, with the first level of amendment placement being 13 cm below the soil surface, deep vertical placement treatments had smaller levels of lime at the soil surface. As initial soil samples indicated, the fields had very low surface $pH_s$, especially in the case of Trial #2. Surface acidity in deep vertical placement plots may have led to poorer initial growth of seedlings and young plants, resulting in decreased yields later in the season. However, yields should have been similar to the non-treated controls. Similarly, differences in rooting depths between corn and soybean may also have resulted in the greater response of corn yield over soybean to deep vertical placement treatments due to unamended surface horizons. Furthermore, past research suggests that pelletized lime injected into the soil does not behave like a fine powder, but more as a granule the size of the pellet and could affect reactivity of the material. This observation is supported by the results of the spatial analysis of deep vertical placement treatments, which indicated little movement of lime treatments within the subsoil zero to seven months after application. Additionally, visual observation of soil probe samples and excavated pits found lime prills maintaining their structure up to a year after application.

Suggestions for future research may include an additional surface application to deep vertical placement plots along with possible reapplication of deep vertical banding between existing bands to expand treated regions. Additionally, a fourth trial could be established on soils similar to that of Field Trial #2 to allow better comparison among different soils. Lastly, an examination of rooting systems of corn and soybean plants may be beneficial to further understand the effects treatments have on plant properties.