# USE OF DIFFERENT SOURCES AND RATES OF FOLIAR POTASSIUM WITH GLYPHOSATE TO OVERCOME ENVIRONMENTAL- AND MANAGEMENT-INDUCED K DEFICIENCY IN SOYBEANS

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By

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled:

USE OF DIFFERENT SOURCES AND RATES OF FOLIAR POTASSIUM WITH GLYPHOSATE TO OVERCOME ENVIRONMENTAL- AND MANAGEMENT-INDUCED K DEFICIENCY IN SOYBEANS

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a candidate for the degree of Master of Science in Soil, Environmental and Atmospheric Sciences

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# USE OF DIFFERENT SOURCES AND RATES OF FOLIAR POTASSIUM WITH GLYPHOSATE TO OVERCOME ENVIRONMENTAL- AND MANAGEMENT-INDUCED K DEFICIENCY IN SOYBEANS

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## ABSTRACT

Some major reasons are the reduced amount of applied K fertilizer to soybean due to low commodity prices, the larger amount of K required by genetically modified crops, and the occurrence of periodic drought and soil compaction in the area. Postemergence application of foliar K fertilizer would have the potential advantage of increased flexibility for growers to respond to K deficiency that may occur during the growing season. In addition, increasing use of postemergence applications of glyphosate for weed control in glyphosate-tolerant soybeans provides the opportunity for applying foliar K fertilizer with glyphosate. Previous research examining the impacts of foliar K fertilization on soybean growth has generally observed inconsistent yield response to foliar application and concluded that the additional cost of the foliar application was not justified. However, few researchers have evaluated the interaction between foliar K fertilizers and glyphosate on soybean growth. The objectives of this research were to determine soybean response to several rates of different foliar K sources mixed with and without glyphosate under different types of soil, soil test K, soil water content, soil compaction and climatic conditions, and to evaluate use of the chlorophyll meter for quickly measuring plant K deficiency in the field. Soybean growth response was initially assessed in the greenhouse due to applications of five foliar K fertilizer sources (i.e., potassium chloride, potassium sulfate, potassium carbonate, potassium thiosulfate, and potassium phosphate) at four applications rates (0, 2.2, 9.0, and 17.9 kg K ha$^{-1}$) mixed with or without glyphosate. In addition, the effects of differences in soil water-filled pore space and soil bulk density on soybean response to foliar K fertilization were also determined in the greenhouse. Two field experiments in Northeastern and Southeastern Missouri were also conducted in 2004 and 2005 to study the effects on soybean growth of several foliar K fertilizer sources (0-0-62 (N-$P_2O_5$-$K_2O$), 3-18-18, 5-0-20 and 0-0-25 fertilizers) applied at the V4 stage of development at four rates (0, 2.2, 8.9, and 17.9 kg K ha$^{-1}$) with or without glyphosate. Visual leaf injury in the field experiments due to foliar K application was less than 10% at 3 days after treatment (DAT) and all plants recovered to foliar treatments by 14 DAT. Soybean grain yield response to applications of foliar K fertilizers in the field experiments was inconsistent and generally not significant. For both years, the level of K content in soybean leaf and in soil was little or not significantly affected by the application of foliar K fertilizers. There was a trend of decreased Mn levels in soybean leaf tissue in the field experiments when glyphosate was foliar-applied along with K fertilizers. The level of other nutrients in soybean leaf tissue including phosphorus, magnesium, calcium, boron, zinc, sulfur, iron, and copper were also little affected. No correlation between SPAD chlorophyll meter readings and total K content in the plant was observed in the greenhouse. Therefore, further research is needed to better assess other soil characteristics and environmental conditions affecting soybean response to foliar K fertilization.

Abbreviations: days after treatment (DAT), diammonium sulfate (DAS), glyphosate-resistant (GR), non-ionic surfactant (NIS), percent water-filled pore space (WFPS).

# CHAPTER 1

# GENERAL INTRODUCTION

## Background to Problem

The incidence of potassium (K) deficiency has increased over the last few years. Among the major causes for this increased K deficiency has been the reduced application of K fertilizer for soybean production due to low commodity prices (Reetz and Murrell, 1998). In cropping systems with a corn-soybean rotation, farmers traditionally apply K fertilizer to the corn crop and not to the soybean part of the rotation. Recently, soybean and corn production has increased significantly due to development of improved genetically-engineered varieties (James, 2004) and the higher K requirements of these new varieties may also have contributed to observed soil K deficiency.

Plant K availability is also influenced by natural and management-induced factors that affect the diffusion of K in soil to plant roots. Kuchenbuch et al. (1986) reported that a decrease in soil water content decreased K diffusion in soil, root growth and K uptake by onion (*Allium cepa* L.) plants. Brown et al. (1960) reported that root and shoot growth and tissue elemental concentration decreased in soybean plants by increasing soil moisture tension from -0.033 to -1.5 MPa. Moreover, soil compaction also influences soil K availability due to its effects on tortuosity and soil water content. Studies by Dolan et al. (1992) found uptake of K and P by corn plants was reduced by up to 22% under compacted and dry conditions.

Postemergence application of foliar K fertilizer would have the potential advantage of increased flexibility for growers to respond to K deficiency due to changing in-season climatic and management conditions. Soybean response to foliar fertilization has been extensively examined and the results of this research vary. Garcia and Hanway (1976) reported significant yield increase when foliar fertilizer was applied at seed development stage, but many subsequent studies found no responses to foliar fertilization (Parker and Boswell, 1980; Vasilas et al., 1980; Poole et al., 1983) Studies by Haq and Mallarino (1998 and 2000) found yield response in soybean when foliar fertilizer was applied to soybean plants at the vegetative stage, but the results were inconsistent. Thus, they suggested that the additional expense for foliar fertilizer application of macronutrients makes this fertilizer application method impractical. However, since glyphosate [*N*-(phosphonomethyl) glycine]-tolerant soybeans have been widely adopted and are planted on the majority of soybean acres in the U.S. (Raymor, 2003), combining and applying K fertilizer with glyphosate would allow for a more economical method of applying foliar K. Nelson et al (2005) reported soybean yield response from plots treated with foliar applications of potassium sulfate. It was suggested the possibility of mixing K fertilizer with glyphosate to reduce the cost of application, thereby, possibly making this practice more cost-effective.

## Factors Affecting K Availability

### *Environmental factors*

Potassium exists in soil as: (a) a structural component of primary and secondary minerals; (b) fixed K in the lattice of clay minerals; (c) an absorbed and exchangeable ion at the surface of soil colloids; and (d) a solute of the soil solution (Mills and Jones, 1996) Equilibrium exists between solution K and exchangeable K, and between exchangeable K and fixed K. Fixation and release is a reversible process that is dependent on the concentration of K ion on the clay surface, which in turn is dependent on the concentration of K ion in the soil solution (Foth, 1984). Total K content ranges between 0.5 to 2.5 % in most soils, which represents approximately 45 Mg ha$^{-1}$. However, only 0.1 to 2% of total soil K is readily available for plant uptake (Troeh and Thompson, 1993). Potassium in solution is the most readily available form of soil K for plant uptake. In comparison, exchangeable K is only available for plant use if the plants root is in close proximity to the K and if exchange of K occurs. Even some of the nonexchangeable K slowly becomes available during the growing season.

Potassium moves in soil through diffusion and mass flow, but diffusion is the most important mechanism involved in the movement of fertilizer K to absorbing roots (Du et al., 2006). Potassium diffusion occurs in soil solution and is affected by several factors, including soil water content and temperature (Barber, 1985). With low soil water content, water films around soil particles are thinner and discontinuous, resulting in a more tortuous path for K movement (Tisdale et al, 1985). Increasing soil water content facilitates movement of K to plant roots and enhances K availability. However, in waterlogged soil, root activity declines due to poor aeration, thereby decreasing K uptake. Therefore, adequate soil aeration is necessary to supply oxygen for root respiration and K uptake. Optimum soil temperature for nutrient uptake is 20 to 30 °C (Tisdale et al, 1985). Low and high soil temperatures can impair root physiological processes involved in K uptake.

Other soil characteristics affecting K availability include bulk density, soil texture, cation exchange capacity (CEC), and clay mineralogy (Bouabid et al., 1991). Soil compaction reduces the rate of K movement as soil pore continuity and water flow are disrupted. Soil macropores, which conduct water at lower tensions, are more susceptible to soil compaction than micropores, which conduct water at higher soil tensions. The increase in the proportion of micropores with compaction modifies water movement and thus potentially reduces nutrient movement and uptake by plants (Ankeny et al. 1990). Clay type is associated with K availability as some clay minerals contain K. For example, soils containing vermiculite or montmorillonite will have more K than soils containing predominately kaolinitic clays, which are more highly weathered and are very low in K (Tisdale et al, 1997). The 2:1-type clay minerals, such as mica, vermiculite and smectite may fix K between clay layers. However, some researchers (Pearson, 1952; Mclean and Simon, 1958a, 1958b) have suggested that K fixation may be beneficial for plant availability since it reduces K losses due to leaching or due to luxury consumption, and maintains a potential available K pool for plant uptake (Bertsch and Thomas, 1995).

### *Management factors*

Application of K is an important practice to increase K availability in soil. The methods of K fertilizer application can be roughly categorized as combinations of two basic methods: 1) banding in high concentrations with a minimum of soil contact (i.e. seed placement, strip application, row/banded placement and, deep placement) and 2) broadcasting (i.e., surface broadcast with or without incorporation, fertigation) (Armstrong et al., 1998). In addition to these conventional methods, K fertilizer can also be directly applied to plant leaves (commonly described as a “foliar” application). In this method, liquid fertilizer is sprayed directly onto plant leaves and absorbed into the plant through the leaf stomates.  This method of fertilizer application avoids possible soil processes that may reduce plant nutrient availability and may shorten the time required to correct nutrient deficiencies. Another advantage of foliar fertilization over traditional methods that apply nutrients to the soil is that it provides a possibility to manage K deficiency that occurs during the growing season. Due to the direct application of the fertilizer on the leaf, the selection of the appropriate type and rate of fertilizer is very important to avoid plant injury.

Because plants at early growth stage require a substantial amount of K for their development, applications of K fertilizer are often done before planting or at planting. Typically, growers will choose to apply K fertilizer in fall because it has lower mobility and chance of leaching compared to N (Hopkins and Ellsworth, 2005). The recommendation for K application is based on the concept of build-up and maintenance (Buchholz, 1992). This program was designed to raise soil test K to an optimum concentration and then to maintain that optimum level based on K losses resulting from cropping. To calculate the amount of fertilizer needed for a build-up application, a measure of soil CEC is needed. Similarly, the rate of K taken up by each crop is critical for calculating the amount of fertilizer to apply as a maintenance application (Buchholz, 1992).

No-tillage crop production has been recommended as a cost-effective way of reducing soil erosion (Amermiya, 1977; Unger and McCalla, 1980). The land area of no-till soybean in North America has increased rapidly since the late 1980’s. However, soils under no-tillage are usually cooler, wetter, and higher in bulk density. Such conditions may influence plant nutrient uptake due to limited root growth and decreased nutrient availability (Buah et al., 2000). Vertical stratification of soil test K has frequently been observed in continuous no-till fields (Crozier et al., 1999; Howard et al. 1999). This K stratification is characterized by significantly higher soil test K concentrations in the surface 0- to 5-cm layer relative to K levels at the 10- to 20- cm depth (Holanda et al., 1998; Yin and Vyn, 1999). Various factors cause the K stratification in no-till systems, including lack of soil mixing, surface application of K fertilizer, high residue concentration at the soil surface, and limited K mobility in soil (Yin and Vyn, 2002).

In order to complement the effect of stratification, new methods of potassium fertilizer application might need to be developed. An application of K in the subsurface soil has been proven to be effective for increasing soybean yields in no-till planting systems. Hairston et al. (1990) showed that deep banding (15-cm depth) of K fertilizer resulted in significantly higher yield of no-till soybean than surface broadcasting of K on soils with low K levels. However, in some other studies, no significant positive grain yield response was detected when P and K fertilizers were applied (Bharati et al., 1986; Rehm, 1986; Mallarino et al., 1991; Buah et al., 2000). The lack of response may possibly be attributed to the initially high levels of soil test P and K in the soils in which the studies were conducted.

## Claypan Soils

The Midwest claypan region covers an area of about 4 million ha within Missouri, Illinois and Kansas (Anderson et al., 1990), and includes large areas of agricultural production cropped to corn and soybeans. Claypan soils are characterized by a relatively high-clay subsoil layer usually occurring 20 to 40 cm below the soil surface. These soils are more susceptible to drought and flooding because of the relatively low water-holding capacity and saturated hydraulic conductivity of the soil in the restrictive clay layer (Blanco-Canqui et al., 2002; Nelson et al., 2005). When wet, the claypan soils are more sensitive to compaction which inhibits plant K uptake (Motavalli et al., 2003). The claypan layer also has shown adverse effects on plant root development (Wang et al., 2002), encouraging high variability in crop productivity (Kitchen et al., 2005).

Topsoil depth in the claypan soils is a vital factor of soil productivity. Reduction of topsoil depth generally reduces the productive capacity of the soil (Thompson et al., 1991) The lower K availability in soils with shallow topsoil depths has been attributed to lower soil fertility, reduced plant-available water capacity, and less air space for root growth in the high-clay subsoil horizon (Kitchen et al., 2001).

### The Role of K in Soybean Nutrition

Potassium is one of the most required nutrients by all living organisms (Evans and Sorger, 1966). Potassium is absorbed as the $K^+$ cation in greater quantities than most other elements except N. While it is immobile in soils, K is very mobile once it has been taken up by the plant (Smith, 1996). The major role of K in plant growth and development is serving as an enzyme activator or cofactor for well over 60 enzymes (Blevins, 1985; Evan and Sorger, 1996).

The role of K in photosynthesis is complex. The activation of enzymes by K and its involvement in adenosine triphosphate (ATP) production is important in regulating the rate of photosynthesis (Blevins, 1985; Troeh and Thompson., 1993). ATP, a high-energy molecule product from photosynthesis, is used as the energy source for many other chemical reactions in plant. When plants are K-deficient, the rate of photosynthesis and ATP production are reduced, and all of the processes dependent on ATP are slowed down. Conversely, plant respiration increases which also contributes to slower growth and development (Blevins, 1985; Troeh and Thompson., 1993).

In carbohydrate metabolism, K deficiency will result in the accumulation of reducing sugars (glucose and fructose) with decreases in complex carbohydrates, such as starch (Huber, 1985). The accumulation of reducing sugars is due to the decreased activity of particular K-activated enzymes, such as starch synthetase, that allow simple sugars to be converted into complex carbohydrates (Murata and Akazawa, 1969). Potassium is also important for all of the major steps involved in protein synthesis in plants (Blevins, 1985). These steps include transport of amino acids to the sites of protein production, enzyme activation, and neutralizing the charge of acidic amino acid residues to establish the proper hydration for optical conformation of enzymatically active forms of protein (Blevins, 1985).

Another major role of potassium is dealing with osmotic potential maintenance, water uptake, and stomatal aperture (Fisher and Hisao, 1968; Troeh and Thompson, 1993). As K moves into the guard cells around the stomates, water is also transferred into the cells, increasing turgor pressure and making cells swell. As a result, stomates become open and allow gases to move freely in and out. When water supply is short, K is pumped out of the guard cells causing the reverse action and the stomates are closed tightly to prevent loss of water. If K supply is inadequate, the stomates become slow to respond and closure is delayed. As a result, plants with an insufficient supply of K are much more susceptible to water stress (Armstrong et al., 1998; Arquero et al., 2006).

Accumulation of K in plant roots produces a gradient of osmotic pressure that draws water into the roots. Therefore, plants deficient in K are less able to absorb water and are more subject to stress when water is in short supply. High K helps increase crop tolerance to drought stress (Armstrong et al., 1998; Arquero et al., 2006; Martinez et al., 2003). More K permits the maintenance of turgor pressure as the plant's environment become drier. With sufficient K, plants can continue to photosynthesize, regulate water loss, and grow through dry periods.

Potassium is necessary for the uptake and translocation of various nutrients. Blevins et al. (1978) concluded that K has an important role as a counter ion for the uptake and translocation of nitrate ($NO_3^-$) within the plant. On the other hand, enriched K soil may cause increased antagonism among nutrient cations competing for uptake and translocation (Ologunde and Sorensen, 1982). Reneau et al. (1983) observed decreased magnesium (Mg) and calcium (Ca) concentrations in sorghum leaf when a high rate of K was applied. Classen and Wilcox (1984) found that increasing K levels decreased the Mg and Ca in the tissue of corn. Very high levels of K can result in Mg deficiency and eventually Ca deficiency (Jones et al., 1991; Senclair, 1993). Potassium and P also interact. Hydroponically-grown wheat seedlings (*Triticum aestivum* L.) absorbed less K when the level of P in nutrient solution was increased (Reinbott and Blevins, 1991). However, P and K together have been found to have a synergistic effect on yield, generating an extra 15% positive yield interaction for soybeans and 50% for Coastal Bermuda-grass (Armstrong, 1998).

Potassium deficiency symptoms, such as thin cell walls, weakened stalks and stems, and accumulation of sugars and unused N in leaves, encourage disease infection (Tisdale et al, 1985; Armstrong et al, 1998). Each of these symptoms reduces plant resistance to infection by fungal, bacteria, and viral disease organisms. A study by Howard et al. (1997) in Tennessee demonstrated the importance of K fertilization in reducing the severity of *Alternaria* leaf spot disease in cotton on a soil testing low in K.

In soybean production, K is essential in every stage of growth. Potassium is needed to maintain favorable plant water status, regulate nutrient uptake, and encourage photosynthesis and plant growth (Reetz and Murrell, 1998). Nitrogen fixation by soybean and other legume plants relies on plant photosynthesis. Substantial amounts of photosynthate are required for N-fixing activity in mature nodules (Fujikake et al. 2003). As K deficiency reduces the rate of photosynthesis, the photosynthate is limited and, thus, root nodule activities are suppressed. In addition, soybean grain yields are affected by K fertilization since a large proportion of K absorbed by the soybean plant is allocated into the seed.

The effects of plant K nutrition on soybean seed quality has been widely studied (Yin and Vyn, 2004; Haq and Mallarino, 2005; Seguin and Zheng, 2006). Appropriate K management also could be an effective approach to increase isoflavone concentrations in the seed (Yin and Vyn, 2004).

### Use of Foliar K Fertilizer

Soybean response to foliar fertilization has been extensively examined by researchers starting in the 1970's (Garcia and Hanway, 1976; Parker and Boswell, 1980; Vasilas et al., 1980; Haq and Mallarino, 1998, 2000). Foliar fertilization with solutions containing macronutrients, such as N, P, K, and S, has shown inconsistent soybean grain yield response (Boote et al., 1978; Parker and Boswell, 1980; Haq and Mallarino, 1998, 2000). Garcia and Hanway (1976) reported large yield increases from foliar application of N-P-K-S fertilizer mixtures during reproductive stages. Some researchers also investigated growth response to foliar fertilization of macronutrients at early vegetative stages (Haq and Mallarino, 1998, 2000; Mallarino et al., 2001). They theorized that foliar application of nutrients to plants when they are rapidly growing would complement the nutrients the plant would be obtaining from the soil and, consequently, increase yield.

Several studies have been conducted on foliar fertilization in soils with initially high soil test levels (Parker and Boswell, 1980; Haq and Mallarino, 1998) and most of soybean yield responses to foliar fertilizer were observed when soil test K and other nutrients were below the optimal level or when plants suffered from water stress. A recent study by Nelson et al. (2005) showed significant soybean yield response to foliar K fertilizer ($K_2SO_4$) applied at the rate of 36 kg K $ha^{-1}$. In the same study there was a higher yield response in the drier year of the two-year study. Many researchers reported that the observed response to foliar fertilizer application did not justify the application expense (Boote et al., 1978; Parker and Boswell, 1980; Haq and Mallarino 1998; Nelson et al., 2005;). However, with the growth in planting of glyphosate-resistant soybean, some researchers have suggested the possibility of tank-mixing K fertilizer with glyphosate and applying them together in order to improve the economics of foliar fertilization practice (Mallarino et al., 2005; Nelson et. al, 2005)

### The Need for Additional Research

Despite some inconsistency in yield response to foliar K fertilization observed in previous research, several recent developments may justify an additional examination of the efficacy and cost-effectiveness of foliar K fertilization. First, the incidence of K deficiency in agronomic crops has increased in recent years in Missouri and other Midwestern states (Nelson et al., 2005). Over 50% of the soil tested by the University of Missouri Soil Testing Laboratory during the fall of 2000 and the spring of 2001 had low to medium levels of soil test K (Fixen, 2000). Second, the genetic compositions of many crops have changed and, therefore, response to applied foliar fertilizers may be different. For example, 83% of soybean varieties produced on over 5 million acres in Missouri were Roundup Ready® or contained another form of transgenic herbicide resistance in 2003 (MASS, 2003).

Widespread use of glyphosate for postemergence weed control in soybeans also provides an opportunity to mix K fertilizer sources with the glyphosate and possibly reduce the cost of foliar K application. This practice would have the potential advantage of increased flexibility for growers to respond to observed K deficiency during the growing season due to the effects of variable soil properties, management practices, or climatic conditions (Nelson et al., 2005). However, few studies have been conducted that examine the possible effects of mixing K fertilizer sources and glyphosate together on either the weed control effectiveness of the glyphosate or on plant K uptake of the foliar-applied K sources. The results of a recent study by Nelson et al. (2007) indicated that many of the fertilizer K sources examined in the study could be mixed with glyphosate and foliar-applied with minimal crop damage and reduction in weed control, but yield response was inconsistent. Further research is needed to understand the factors affecting foliar K response and to develop in-season methods to assess when foliar K fertilization would be most effective.

## Objectives

The objectives of this research were to: 1) determine soybean response to several rates of different foliar K sources mixed with and without glyphosate under different types of soil, soil test K, soil water content, soil compaction and climatic conditions, and

2) evaluate use of the chlorophyll meter for quickly measuring plant K deficiency in the field to assist in management decisions related to application of foliar K fertilizers.

### Hypotheses

The hypotheses were: 1) foliar K fertilizer effectiveness would vary after mixing with glyphosate, 2) differences in soybean growth would occur among several foliar-applied K fertilizers mixed with and without glyphosate, 3) soil water content would influence soybean plant growth and foliar K plant response, and 4) soil compaction would influence soybean plant growth and foliar K plant response.

### Outline of Thesis

Each chapter has been written in a format for submission for publication in a refereed journal. Chapter 2 discusses the result from a greenhouse experiment on the effects of fertilizer sources and rate, soil water content, soil compaction, and glyphosate on production of soybean plants. Chapter 3 evaluates the results from two-year field experiments conducted in Northeast and Southeast Missouri that examined the effects of fertilizer sources and rates, soil test K, soil water content, and glyphosate on soybean grain yield and foliar K. References, tables, and figures are presented at the end of each chapter.

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# CHAPTER 2

# USE OF DIFFERENT SOURCES AND RATES OF FOLIAR POTASSIUM WITH GLYPHOSATE TO OVERCOME ENVIRONMENTAL- AND MANAGEMENT-INDUCED K DEFICIENCY IN SOYBEANS

## ABSTRACT

Potassium (K) deficiency in soybean [*Glycine max* (L.) Merr] has increasingly become a problem in cropping systems in the Midwestern United States with corn-soybean rotations. Many factors, including nematode infestation, drought and soil compaction, contribute to decreased K assimilation thereby reducing plant growth. Because large areas of agricultural land are cropped to glyphosate-resistant (GR) soybean, an opportunity exists for foliar application of K fertilizer sources mixed with glyphosate in order to allow growers to respond to observed K deficiency during the growing season. However, the effects of mixing glyphosate with K fertilizer sources on crop growth and K uptake have not been extensively determined. Three greenhouse experiments were conducted to examine the effects of foliar K fertilizer on leaf injury, K uptake, and plant growth of soybean plants. In experiment #1, five K fertilizer sources (i.e., potassium chloride, potassium sulfate, potassium carbonate, potassium thiosulfate, and potassium phosphate) were applied at four rates (0, 2.2, 9.0, and 17.9 kg K ha$^{-1}$) with or without glyphosate on GR soybean. In experiments #2 and #3, four rates of potassium chloride were applied on soybean planted in soil of either low or high initial soil test K. Three levels of water-filled pore space (WFPS = 20, 40, and 60%) were imposed at the initial vegetative (V1) stage in experiment #2 and three levels of soil bulk density (1.2, 1.4, and 1.6 g cm$^{-3}$) were established in experiment #3. Except for potassium carbonate and the high rate of potassium phosphate, all foliar K fertilizer sources caused less than

10% visual leaf injury 7 days after treatment (DAT) and complete recovery from leaf injury was observed by 14 DAT. A few treatments caused significant increase in plant biomass, plant height and K uptake; however, most of the other treatments did not have any effects on soybean plant growth and K uptake. Increased WFPS and decreased soil compaction promoted plant growth, but these two conditions did not enhance observed response to applied foliar K fertilizer. The use of chlorophyll meter readings to estimate leaf K contents in soybean during vegetative plant growth failed to show a relationship between the chlorophyll readings and measured total K content in the plant.

## INTRODUCTION

Potassium (K) is one of the essential mineral plant nutrient elements and it has several functions in plants, including enzymatic processes, nutrient and water transport, protein synthesis, and regulation of stomatal activity and cell turgor pressure (Tisdale et al., 1985). The multiple functions of K in plants generally have a beneficial effect on a plant's ability to avoid or withstand the negative effects of extreme temperatures, drought, diseases and pests. Potassium deficiency symptoms are often observed when soil test K levels are insufficient or when plants suffer from drought, soil compaction or when K movement to plant roots is restricted. Potassium deficiency can lead to significantly lower yield levels in corn, soybean and other important crops.

Claypan soils in the Midwestern United States cover an area of approximately 4 million ha in Missouri, Illinois, and Kansas (Anderson et al., 1990) and include large agricultural areas where corn and soybeans are grown. Claypan soils are characterized by a relatively high-clay subsoil layer usually occurring 20 to 40 cm below the soil surface. These soils are more susceptible to drought and flooding because of the relatively low hydraulic conductivity of the restrictive clay layer that impedes vertical flow of water and the relatively shallow surface horizon that reduces the total amount of plant-available water (Blanco-Canqui et al., 2002). Under conditions of drought, plant K availability is reduced (Nelson et al., 2005). When wet, the claypan soils are more sensitive to compaction and plant uptake of K is also inhibited (Motavalli et al., 2003). The presence of the claypan layer also has a large effect on plant root development (Wang et al., 2002), encouraging high variability in crop productivity (Kitchen et al., 2005).

Because of the restrictive nature of the claypan, reduction of topsoil depth generally reduces the productive capacity of the soil (Thompson et al., 1991) The lower K availability in soils with shallow topsoil depths has been attributed to lower soil fertility, reduced plant-available water capacity, and less air space for root growth in high-clay subsoil horizon (Kitchen et al., 2001).

Soybean growth response to foliar fertilization has been extensively examined by researchers starting in the 1970's (Garcia and Hanway, 1976; Parker and Boswell, 1980; Vasilas et al., 1980; Haq and Mallarino, 1998, 2000). Garcia and Hanway (1976) reported large yield increases from foliar application of N-P-K-S fertilizer mixtures during reproductive growth stages. Some researchers also investigated the response of foliar application to soybeans at early vegetative growth stages (Haq and Mallarino, 1998, 2000; Mallarino et al., 2001). They theorized that foliar application of nutrients when plants are young and nutrient uptake is limited would complement the nutrient supply from the soil and consequently, increase yield. However, most of the reported growth responses to foliar fertilizer applications have been variable and inconsistent (Boote et al., 1978; Parker and Boswell, 1980; Haq and Mallarino, 1998, 2000). Several studies were conducted under optimal soil test fertility levels (Parker and Boswell, 1980; Haq and Mallarino, 1998) and most of soybean yield responses to foliar fertilizer have been observed when soil test K and other nutrients are below the optimal recommended level or when plants were under water stress. Because of this inconsistent yield response, many researchers have reported that foliar fertilizer application did not justify the application expense (Boote et al., 1978; Parker and Boswell, 1980; Haq and Mallarino 1998).

Despite the previous inconsistent response observed in the research literature, recent developments in soybean management may justify additional research on use of foliar K fertilization (Nelson et al., 2005). First, genetically-modified crops, such as glyphosate-resistant soybeans, have been widely adopted. Over 90% of planted soybean acreage in 2003 in Missouri and in the U.S. as a whole was planted to transgenic soybeans (USDA-NASS, 2003). The widespread use of glyphosate for weed control provides an opportunity to apply foliar K in combination with glyphosate to reduce application costs. Second, K deficiency has been more commonly observed in soybeans in the North Central States, especially under conditions of periodic drought and compaction. Higher corn yields due to use of improved varieties has increased crop K requirements during the corn phase of the corn-soybean rotation and the residual K after corn may not be sufficient for the subsequent soybean crop.

Several challenges exist for recommending use of foliar K fertilization either combined with glyphosate or as a separate fertilizer application. Among these challenges is determining under what conditions plant growth response to foliar K may be expected, developing rapid plant diagnostic methods to identify plant K deficiency, and assessing the appropriate K fertilizer sources and rates and timing of application for foliar application that will not cause excessive plant injury or affect the weed control effectiveness of glyphosate. In addition, the economic costs and benefits of foliar K fertilization when combined with glyphosate also need to be evaluated.

The objectives of this research were to: 1) determine the soybean growth response to foliar application of different rates and sources of K fertilizer when combined with glyphosate; 2) assess the relative effects of soil water content and soil bulk density on plant growth response; and 3) to test the use of a rapid plant diagnostic method to identify plant K deficiency. We hypothesized that use of foliar K application would increase soybean plant growth, especially under conditions of drought and compaction.

## MATERIALS AND METHODS

### Bulk Soil

A greenhouse experiment was conducted at the University of Missouri, near Columbia, MO in a temperature-controlled greenhouse during 2006. A bulk soil sample with low soil test K (see Table 2.1 for initial characteristics of the bulk soil) was collected to a depth of 30 cm at the University of Missouri Delta Research Center Rice Research Farm located approximately 14.5 km west of Malden, Missouri (36.6°N, 90.1°W) in Southeast Missouri, USA. The site had been previously cropped to irrigated rice. Soil collected was classified as a Dewitt silt loam (fine, smectitic, thermic Typic Albaqualfs). The soil was air dried, ground, passed through a 2-mm sieve and stored in plastic containers.

Based on University of Missouri soil fertility recommendations (Buchholz, 1992), an additional amount of $CaHPO_4$ (1.08 g pot$^{-1}$) and $CaOH_2$ (60.0 mg pot$^{-1}$) was added to optimize soil pH and soil test P for soybean growth. The desired soil test K level for optimum soybean growth in this soil was 128 mg K $kg^{-1}$ soil (Buchholz, 1992).

**Experimental Design**

Three experiments were conducted in the greenhouse. Experiment #1 was conducted to determine the soybean growth response to differences in rates (equivalent to 0, 2.2, 9.0, and 17.9 kg K $ha^{-1}$ or 0, 2.4, 9.7, and 19.5 mg K $pot^{-1}$, respectively) of several foliar K fertilizer sources (i.e., potassium chloride (0-0-62 as N-$P_2O_5$-$K_2O$), potassium sulfate (0-0-52-18), potassium carbonate (0-0-30), potassium thiosulfate (0-0-25-17), and potassium phosphate monobasic (0-52-34) from Fisher Chemicals, Fair lawn, NJ) mixed with and without glyphosate (Roundup WeatherMAX®, Monsanto Co, St. Louis, MO applied at an equivalent rate of 0.84 kg ae $ha^{-1}$ or 2.58 µL $pot^{-1}$). The treatments were arranged as a completely randomized factorial design (5x4x2) with four replications.

Experiment #2 and # 3 were designed to study the effects of differences in soil water-filled pore space and soil bulk density on soybean growth response to pre-plant and foliar K fertilization. Both experiments were completely randomized factorial designs (3x2x4) with four replications. Treatments for Experiment #2 were three levels of soil water-filled pore space (WFPS) (20, 40, and 60 % WFPS), two levels of soil test K (30 and 130 mg K $kg^{-1}$) based on University of Missouri soil test interpretations (Buchholz, 1992), and four rates of foliar K application (equivalent to 0, 2.2, 9.0, and 17.9 kg K $ha^{-1}$ as KCl). Treatments for Experiment #3 were three levels of soil bulk density (1.2, 1.4, and 1.6 g $cm^{-3}$, two levels of soil test K (30 and 130 mg K $kg^{-1}$), and four rates of foliar K application (equivalent to 0, 2.2, 9.0, and 17.9 kg K $ha^{-1}$ as KCl).

To establish the different soil bulk density treatments in Experiment #3, the volume of the plastic pot (22 cm in diameter and 30 cm in height) was measured up to 5 cm below the lip of the pot. Then the total soil weighed for each pot, corresponding to a specific bulk density treatment, was divided into four equal portions which were then added and packed to a pre-marked height within the pot. All fertilizer and liming materials were mixed thoroughly with each portion of soil. All plants received adequate supplies of water to maintain field capacity in Experiments #2 and #3. However, in Experiment #2, the soil moisture regime was changed 15 days after growth stage, V1, when three levels of WFPS (20, 40, and 60 % WFPS) were imposed as treatments. Soil water content was maintained throughout the experiment by periodic surface application of distilled water.

For each pot, five seeds of Roundup-Ready® soybean variety 'Thompson 3999RR' were planted in plastic pots (22 cm in diameter and 30 cm in height) to a depth of approximately 1.5 cm and then thinned to one plant after germination. Seeds in some pots that did not germinate or were slow to germinate were removed. The average time for germination was 5 days after planting. Supplemental radiation was provided by 400 watt high pressure sodium lamps to establish an 8 hour lighting regime. As the plant grew, the artificial lights were adjusted to a height of approximately 100 cm above the topmost leaf.

The rate of soybean plant growth was evaluated by periodic measurement of plant height at 14, 21, 28, 35, 49, and 69 (harvest) days after planting. Plant height was measured using a ruler from the ground to the base of the central leaflet on the highest expanded leaf the plant. Vegetative development of soybean was determined according to

Fehr and Caviness (1977). In order to investigate the possible use of leaf color as a rapid method to determine the K status in plants, a Minolta SPAD 502 chlorophyll meter (Konica Minolta, Ramsey, NJ) was used to measure the most recently fully mature leaf at 22, 36, 48 and 68 days after planting. The mean of three readings from the chlorophyll meter were taken at the center and at the edge of the most recent fully mature leaf. The foliar K fertilizer treatments were applied to the plants at 54 days after planting when almost all of the plants had reached the V5-V6 stages of development. Foliar treatments were applied with a modified spray bottle calibrated to deliver a uniform rate of 0.7 $cm^3$ $trigger^{-1}$. After the foliar K fertilizers were imposed, plants were allowed to grow for 15 days before harvest.

Visual soybean leaf injury ratings from 0 to 100% (0 = no effect and 100 = complete plant death) were evaluated at 7 and 14 d after foliar treatment. At the end of 15 days, plants were harvested by cutting the stem of each plant at the first node. Plant tissues were dried at 60 to 70 ºC for 48 hours in a forced-air oven. The dried plant tissue was then weighed, ground in a Wiley Mill and passed through a 1 mm sieve for total K analysis.

### Soil and Plant Analysis

Initial bulk soil properties (Bray-1 P, total N, CEC, pH, organic matter, and exchangeable K, Ca, and Mg) were determined using the soil test procedures described by Brown (1998). Soil test K was extracted with 1 M $NH_4OAc$ at pH 7.0 and analyzed using an atomic absorption spectrophotometer. Total K content in plant tissue was determined by a dry ashing procedure (5 hours of muffling at 500°C followed by digestion of the ash using 6 *M* HCl) and analysis of the digest was conducted using an atomic absorption spectrophotometer. Plant K uptake was calculated by multiplying the total K content in the plant tissue by the aboveground biomass on a dry weight basis.

### Statistical and Data Analysis

The effects of K fertilizer sources, foliar K rate applied, soil bulk density, WFPS, and application of glyphosate on plant height, aboveground yield, K uptake, and leaf injury were assessed using analysis of variance with the PROC GLM procedure of the SAS statistical program (SAS Institute, 1988). Treatment differences were tested using Duncan's multiple range test, DMRT ($P \leq 0.05$). Linear and quadratic regression analysis was performed using best-fit analysis determined with SigmaPlot (Ver. 10.0, SPSS Inc., Chicago, IL).

## RESULTS AND DISCUSSION

### Experiment #1

The objective in selecting foliar K application rates of 0, 2.2, 9.0, and 17.9 kg K ha$^{-1}$ as treatments in greenhouse experiment #1 was to approximate the K rates applied in a companion field experiment conducted at the University of Missouri Delta Research Center Rice Research Farm in Southeast Missouri in 2004 and 2005 (see Chapter 3). Salt injury, primarily necrosis of leaves, was common with all foliar K fertilizer sources. For almost all treatments, foliar crop injury at 7 days after treatment (DAT) was less than 10% and recovery of foliar injury occurred generally occurred by 14 DAT (Table 2.2). However, when potassium carbonate was applied to the plant at the rate of 17.9 kg K ha$^{-1}$ either alone or when combined with glyphosate, severe leaf injury at an average of 25% was observed and persisted until harvest (Table 2.2). Similarly, potassium phosphate also caused leaf damage but only when applied alone at the high rate (Table 2.2). Leaf injury in greenhouse experiment #2 and #3 to which different rates of potassium chloride were applied were not significant and therefore are not shown.

Fig. 2.1 shows the relationship between the SPAD readings and K content in plant tissue. Two sets of SPAD readings, taken at the leaf center and leaf edge, did not show a significant relationship with plant tissue total K concentrations (Fig. 2.1). In general, the visual symptoms of K deficiency in soybean usually begin as yellowing at the edge of older leaves (Tisdale, 1985). Thus, a significant relationship between the chlorophyll reading, especially at the leaf edge, and K concentration in plant tissue should occur. However, the chlorophyll readings in this experiment were obtained from the most recent fully developed leaf at the top of each plant where the K deficiency symptoms may not have yet occurred. Subsequent research may need to examine chlorophyll readings in older leaves or in more mature plants.

The comparison between treatments with and without glyphosate suggested that there was no interaction between glyphosate and K sources since little or no difference in plant height and K content were significantly altered due to added K fertilizers (Table 2.2, 2.3, and 2.4). However, there was a mean increase of 1 g of aboveground biomass over the control when 9.0 kg K ha$^{-1}$ as potassium sulfate was applied (Table 2.2).

The response of soybean plant height as a function of pre-plant and foliar K fertilizers and glyphosate application is shown in Table 2.2. There were generally no significant differences in plant height between the control treatment and all pots applied with different sources of K fertilizers, except for between the control (36.7 cm in height) and middle rate (9.0 kg K ha$^{-1}$) of foliar potassium chloride applied without glyphosate

(45.8 cm in height) (Table 2.2). Pots with the highest rate (17.9 kg K $ha^{-1}$) of foliar potassium carbonate applied with and without glyphosate were visually stunted, but did not statistically differ in plant height compared to the control (Table 2.2). Glyphosate application generally did not also have any significant effect on plant height when applied alone or in combination with foliar K sources, except for when the middle rate of K phosphate was applied (Table 2.2). Under this treatment, plant height was significantly higher with application of glyphosate.

Pre-plant and foliar K applications and glyphosate also had an inconsistent effect on aboveground biomass of soybean (Table 2.2). Highest biomass yields of approximately 3.71 g (dry) $pot^{-1}$ were observed when the middle rate of foliar potassium chloride (- glyphosate), K sulfate (- glyphosate) and K phosphate (+ glyphosate) were applied. Lack of consistent yield response to foliar K application has been observed by other researchers under field conditions (Boote et al., 1978; Parker and Boswell, 1980; Haq and Mallarino, 1998, 2000), but pre-plant K applications are generally effective in raising yield levels when initial soil test K is low (Haq and Mallarino, 2005; Nelson et al., 2005). The lack of increased tissue K with pre-plant K application compared to the control treatment may indicate some other factors (e.g., soil physical conditions in the pot) may have limited K uptake from the soil. A major problem can arise in pot studies when soil is used as the potting media due to compaction caused by repeated watering.

Figure 2.2 A & B shows the changes in K uptake with application of pre-plant or foliar K fertilizer with and without glyphosate. The highest K uptake was observed when the middle rate of K phosphate was applied combined with glyphosate (Fig. 2.2A). Nelson et al. (2005) speculated that higher K uptake may occur when foliar K fertilizer is applied with glyphosate due to the effect of the surfactant improving K absorption in the leaf. However, in this study surfactant was not added with the glyphosate and an increase in K uptake with added glyphosate was only observed when the middle rate of K phosphate was applied with glyphosate. No significant increases in K uptake over the control were observed due to applying pre-plant or foliar-applied K when no glyphosate was applied (Fig. 2.2B). However, significant differences in K uptake did occur among the treatments when glyphosate was applied (Fig. 2.2A). For example, the middle rate of K carbonate had a significantly higher K uptake than the lowest rate of application.

**Experiment #2**

Table 2.3 shows experimental results for the effects of foliar potassium chloride application on plant growth in soils maintained at 20, 40 and 60% WFPS. In general, as WFPS increased, plant height and aboveground biomass also increased in the presence of low or high initial soil test K. However, plant height and aboveground biomass response were significantly higher for the low initial K compared to the high initial K only at 60% WFPS (Table 2.3). No significant increases in plant height and aboveground biomass response were observed among the different rates of foliar K. Differences in tissue K concentration were generally higher when initial soil test K was high compared to the low initial soil test K soil and increasing foliar K application rates did cause a trend in higher tissue K (Table 2.3).

However, these results do not explain the observed differences in growth response between the low and high initial soil test K at the 60% WFPS. In general, low WFPS may limit growth response to applied K (Barber., 1985; Tisdale et al., 1985; Kuchenbuch et al., 1986). Therefore, increasing WFPS would be expected to cause increased response to both the high initial soil test K and increasing rates of applied foliar K. These treatments appeared to have increased levels of tissue K, but not caused the expected differences in growth response.

Plant K uptake results are shown in Fig. 2.3 A&B for Experiment #2. As was observed with plant growth response, plant K uptake generally increased with increasing WFPS. As expected, higher initial soil test K (Fig. 2.3A) resulted in higher K uptake compared to the low initial soil test K treatment (Fig. 2.3B). No significant increases in K uptake were observed with foliar K applications at any of the WFPS treatment levels.

Several researchers have concluded from field trials that growth responses to foliar fertilizer applications have been variable and inconsistent (Boote et al., 1978; Parker and Boswell, 1980; Haq and Mallarino, 1998, 2000). However, drought conditions and subsequent low soil water content are often associated with observed K deficiency, possibly due to the impact of low soil water content on K diffusion to roots (Barber., 1985; Tisdale et al., 1985).

### Experiment #3

Table 2.4 presents results showing the effects of differences in soil bulk density (1.2, 1.4, and 1.6 g $cm^{-3}$) on plant growth with different rates of foliar K application in soils with low or high initial soil test K. In general, as soil bulk density increased, plant height and aboveground biomass decreased, but no responses to foliar K fertilization were observed (Table 2.4). Some increases in plant height and aboveground biomass response were observed with the low initial soil test K treatment compared to the high initial soil test K treatment at bulk densities of 1.2 and 1.4 g $cm^{-3}$, but not at the high bulk density treatment (1.6 g $cm^{-3}$) (Table 2.4). These results confirm the widely observed negative effect of compaction on soybean plant growth (Buttery et al., 1998) but the increased response to low initial soil test K soils is not easily explained. Possible antagonism between $K^+$ uptake and $Ca^{+2}$, $Mg^{+2}$ and $NH_4^+$ uptake have been documented in the literature, but the plant tissue K results do not support this possible mechanism since higher tissue K levels were observed in plants grown in soil with high initial soil test K compared to in soil with low initial soil test K (Table 2.4).

The average plant tissue K concentration over the soil bulk density treatments was 1.34 and 0.38 % K for plants grown in initially high and low soil test K, respectively. Increases in tissue K due to foliar K fertilization compared to the control were only observed when bulk density was 1.2 g $cm^{-3}$ and initial soil test K was high (Table 2.4).

A similar response to the treatments was observed with plant uptake (Fig. 2.4 A&B). As bulk density increased, plant K uptake generally decreased both with initially high (Fig. 2.4A) and low soil test K (Fig. 2.4 B). The low soil test K treatment had the greatest decline in K uptake with increasing soil bulk density (Fig. 2.3 B). Increases in plant K uptake due to foliar K fertilization compared to the control were only observed when bulk density was 1.2 g $cm^{-3}$ and initial soil test K was high (Fig. 2.4A).

## CONCLUSIONS

The results of this greenhouse study suggest that foliar K fertilization does not result in consistent increases in plant growth response under several conditions that may exist in the field that possibly influence early growth soybean K uptake, including initial soil test K, drought and soil compaction. Among the foliar K sources tested, K carbonate either applied alone or mixed with glyphosate before the application caused significant and lasting soybean leaf injury which affected plant growth. Therefore, based on this research, this K fertilizer source is not recommended for foliar application.

As expected, increasing WFPS and decreasing soil bulk density increased K uptake and generally increased plant growth. However, changes in these properties did not generally affect response to foliar K applications compared to the control with the exception of the lowest soil bulk density treatment in which high initial soil test K was present. Therefore, these results do not support our hypothesis that soybeans would have a greater response to foliar K applications at high soil bulk density and low WFPS when plant K uptake from the soil would be possibly reduced. One possible explanation is that foliar K absorption by the leaf may also be reduced under conditions of moisture stress since the leaf stomates might be closed.

Differences between soil physical conditions in pots compared to soil in an agricultural field may explain some of the results of this study. In addition, the soybean plants were only grown over a 69 day period which may not have allowed for sufficient time for K deficiencies to develop or for plant response to the foliar K applications. Additional research that examined soybean K response into reproductive growth stages under controlled conditions may be necessary for foliar K response to occur. However, based on this research no definitive conclusions can be made as to which soil properties have the greatest effect on foliar K response.

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Table 2.1. Selected soil properties of the bulk soil used in the greenhouse experiment. Values presented are averages ± one standard deviation of three subsamples taken of the bulk soil.

|  |  |  |  | Exchangeable (1 *M* $NH_4AOc$) |  |  |
|---|---|---|---|---|---|---|
| Soil organic matter | pH (0.01 *M* $CaCl2$) | CEC | Bray 1 P | K | Ca | Mg |
| % |  | $cmol_{(-)}$ $kg^{-1}$ | ------------------------------- mg $kg^{-1}$ ------------------------- |  |  |  |
| 1.2 ± 0.2 | 6.0 ± 0.1 | 7.4 ± 0.5 | 6 ± 1 | 31 ± 2 | 934 ± 73 | 202 ± 10 |

Table 2.2. The effects of different foliar potassium fertilizer sources that were mixed and applied with and without glyphosate on soybean leaf injury, plant height 69 days after planting, aboveground biomass, and plant tissue K.

| Treatment | Rate | Leaf injury 7 DAT | | | Leaf injury 14 DAT | | | Height | | | Above ground biomass | | | Tissue K | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | + | - | DMRT $_{(0.05)}$ | + | - | DMRT $_{(0.05)}$ | + | - | DMRT[‡] $_{(0.05)}$ | + | - | DMRT $_{(0.05)}$ | + | - | DMRT $_{(0.05)}$ |
| | kg K ha$^{-1}$ | % | | | | | | cm | | | dry g pot$^{-1}$ | | | % | | |
| Control | | | 0 | | | 0 | | 41.2 | 36.7 | | 2.78 | 2.07 | | 0.37 | 0.43 | |
| Preplant | | - | 0 | | - | 0 | | - | 41.1 | | - | 2.78 | | - | 0.40 | |
| K Chloride | 2.2 | 2 | 1 | NS | 1 | 0 | NS | 43.7 | 41.2 | NS | 3.33 | 2.74 | NS | 0.41 | 0.32 | NS |
| (0-0-62-0) | 9.0 | 4 | 1 | NS | 2 | 0 | NS | 42.9 | 45.8 | NS | 3.33 | 3.70 | NS | 0.46 | 0.34 | NS |
| | 17.9 | 2 | 4 | NS | 0 | 2 | NS | 41.1 | 39.0 | NS | 3.04 | 2.48 | NS | 0.39 | 0.40 | NS |
| K Sulfate<br>(0-0-52-18) | 2.2 | 2 | 4 | NS | 1 | 2 | NS | 45.6 | 38.5 | NS | 3.68 | 2.35 | NS | 0.32 | 0.46 | NS |
| | 9.0 | 5 | 7 | NS | 3 | 4 | NS | 40.3 | 45.7 | NS | 2.67 | 3.71 | 1.03 | 0.43 | 0.50 | NS |
| | 17.9 | 8 | 5 | NS | 4 | 3 | NS | 43.5 | 39.8 | NS | 3.34 | 2.69 | NS | 0.53 | 0.48 | NS |
| K Carbonate | 2.2 | 3 | 8 | NS | 1 | 5 | NS | 40.2 | 35.8 | NS | 2.61 | 2.26 | NS | 0.36 | 0.44 | NS |
| (0-0-30-0) | 9.0 | 4 | 5 | NS | 1 | 2 | NS | 40.1 | 41.9 | NS | 3.14 | 2.91 | NS | 0.51 | 0.46 | NS |
| | 17.9 | 26 | 26 | NS | 22 | 19 | NS | 34.5 | 32.6 | NS | 1.79 | 2.38 | NS | 0.60 | 0.59 | NS |
| K Thiosulfate | 2.2 | 0 | 0 | NS | 0 | 0 | NS | 38.7 | 39.4 | NS | 2.41 | 2.48 | NS | 0.50 | 0.38 | NS |
| (0-0-25-17) | 9.0 | 2 | 3 | NS | 0 | 1 | NS | 39.3 | 41.1 | NS | 2.54 | 2.77 | NS | 0.42 | 0.52 | NS |
| | 17.9 | 5 | 3 | NS | 3 | 1 | NS | 41.9 | 38.3 | NS | 3.05 | 2.73 | NS | 0.61 | 0.51 | NS |
| K Phosphate | 2.2 | 2 | 4 | NS | 0 | 3 | NS | 44.0 | 40.5 | NS | 3.41 | 2.70 | NS | 0.44 | 0.38 | NS |
| (0-52-34) | 9.0 | 4 | 9 | NS | 3 | 6 | NS | 46.0 | 39.1 | 4.7 | 3.72 | 2.36 | 0.97 | 0.64 | 0.38 | 0.19 |
| | 17.9 | 15 | 2 | NS | 11 | 1 | NS | 40.8 | 39.7 | NS | 2.78 | 2.44 | NS | 0.51 | 0.48 | NS |
| DMRT $_{(0.05)}$ | | 4 | 5 | | 4 | 3 | | 7.3 | 9.1 | | 1.36 | 1.57 | | 0.20 | 0.19 | |
| Source of variation among all treatments, ANOVA $P > F$ | | | | | | | | | | | | | | | | |
| Replicate | | 0.490 | 0.384 | | 0.579 | 0.084 | | 0.629 | 0.055 | | 0.815 | 0.089 | | 0.298 | 0.308 | |
| K Treatment | | <0.0001 | <0.0001 | | <0.0001 | <0.0001 | | 0.177 | 0.057 | | 0.513 | 0.110 | | 0.113 | 0.007 | |

[†] Indicates whether treatment was combined with (+) or without (-) glyphosate.

[‡] Duncan's Multiple Range Test at $P < 0.05$; NS = not significant.

Table 2.3. The effects of differences in water-filled pore space (WFPS) on soybean growth response to foliar-applied K in soils with low or high initial soil test K

| | | Height | | | Above ground biomass | | | Tissue K | | |
|---|---|---|---|---|---|---|---|---|---|---|
| WFPS | Rate | +[†] | - | DMRT[‡] $_{(0.05)}$ | + | - | DMRT $_{(0.05)}$ | + | - | DMRT $_{(0.05)}$ |
| -- % -- | kg K ha$^{-1}$ | ----------------- cm ------------------ | | | --------------- dry g pot$^{-1}$ ------------- | | | ----------------- % ------------------- | | |
| 20 | 0 | 25.5 | 23.7 | NS | 0.62 | 0.42 | NS | 1.22 | 0.42 | 0.68 |
| | 2.2 | 23.6 | 22.6 | NS | 0.44 | 0.48 | NS | 1.54 | 0.51 | NS |
| | 9.0 | 25.8 | 23.8 | NS | 0.57 | 0.59 | NS | 1.48 | 0.67 | NS |
| | 17.9 | 20.8 | 23.5 | NS | 0.32 | 0.52 | NS | 1.93 | 0.87 | 0.15 |
| 40 | 0 | 30.9 | 31.3 | NS | 1.3 | 1.39 | NS | 1.21 | 0.72 | NS |
| | 2.2 | 30.7 | 30.1 | NS | 1.33 | 1.23 | NS | 0.98 | 0.44 | NS |
| | 9 | 30.2 | 33.1 | NS | 1.22 | 1.58 | NS | 1.37 | 0.63 | 0.28 |
| | 17.9 | 29 | 32.4 | NS | 1.06 | 1.63 | NS | 1.57 | 0.79 | 0.57 |
| 60 | 0 | 38.8 | 41.2 | NS | 2.48 | 2.93 | NS | 0.75 | 0.37 | NS |
| | 2.2 | 37.4 | 43.7 | 4.1 | 2.34 | 3.28 | 0.61 | 1.28 | 0.41 | 0.55 |
| | 9 | 34.0 | 42.9 | 6.3 | 1.69 | 3.29 | 1.12 | 1.28 | 0.46 | 0.57 |
| | 17.9 | 36.4 | 41.1 | NS | 2.18 | 2.94 | NS | 1.15 | 0.39 | 0.55 |
| DMRT $_{(0.05)}$ | | 6.2 | 6.5 | | 0.94 | 0.78 | | 0.79 | 0.61 | |
| Source of variation among all treatments, ANOVA *P*>*F* | | | | | | | | | | |
| Replicate | | 0.276 | 0.211 | | 0.049 | 0.086 | | 0.986 | 0.349 | |
| K treatment | | <0.0001 | <0.0001 | | <0.0001 | <0.0001 | | 0.131 | 0.529 | |

[†] Indicates whether soil was amended with K prior to planting (+) or did not receive additional K (-).

[‡] Duncan's Multiple Range Test at $P < 0.05$; NS = not significant.

Table 2.4. The effects of differences in soil bulk density on soybean growth response to foliar-applied K in soils with low or high initial soil test K.

| | | Height | | | Above ground biomass | | | Tissue K | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Bulk Density | Rate | + | - | DMRT $_{(0.05)}$ | + | - | DMRT $_{(0.05)}$ | + | - | DMRT $_{(0.05)}$ |
| g $cm^{-3}$ | kg K $ha^{-1}$ | -------------------- cm | | ------------------ | ------------ dry g $pot^{-1}$ | | --------------- | --------------- % | | ----------------- |
| 1.2 | 0 | 38.8 | 41.2 | NS | 2.48 | 2.93 | NS | 0.75 | 0.37 | NS |
| | 2.2 | 37.4 | 43.7 | 4.1 | 2.34 | 3.28 | 0.61 | 1.28 | 0.41 | 0.55 |
| | 9.0 | 34.0 | 42.9 | 6.3 | 1.69 | 3.29 | 1.13 | 1.28 | 0.46 | 0.57 |
| | 17.9 | 36.4 | 41.1 | NS | 2.18 | 2.94 | NS | 1.15 | 0.39 | 0.55 |
| 1.4 | 0 | 31.5 | 34.6 | NS | 1.34 | 1.91 | NS | 1.43 | 0.30 | 0.27 |
| | 2.2 | 32.9 | 37.0 | NS | 1.59 | 2.30 | NS | 1.40 | 0.33 | 0.33 |
| | 9.0 | 31.5 | 36.2 | NS | 1.34 | 2.09 | NS | 1.44 | 0.41 | 0.23 |
| | 17.9 | 31.9 | 38.5 | 6.5 | 1.39 | 2.59 | 1.19 | 1.70 | 0.40 | 0.34 |
| 1.6 | 0 | 27.4 | 24.6 | NS | 0.74 | 0.71 | NS | 1.50 | 0.33 | 0.51 |
| | 2.2 | 28.9 | 26.6 | NS | 0.95 | 0.63 | NS | 1.32 | 0.35 | 0.19 |
| | 9.0 | 28.1 | 28.4 | NS | 0.85 | 0.94 | NS | 1.37 | 0.37 | 0.21 |
| | 17.9 | 29.6 | 24.2 | NS | 1.04 | 0.46 | NS | 1.45 | 0.46 | NS |
| DMRT $_{(0.05)}$ | | 4.6 | 6.9 | | 0.72 | 1.02 | | 0.51 | 0.18 | |
| Source of variation among all treatments, ANOVA *P>F* | | | | | | | | | | |
| Replicate | | 0.001 | 0.231 | | 0.001 | 0.330 | | 0.868 | 0.360 | |
| K treatment | | <0.0001 | <0.0001 | | <0.0001 | <0.0001 | | 0.025 | <0.0001 | |

[†] Indicates whether soil was amended with K prior to planting (+) or did not receive additional K (-).

[‡] Duncan's Multiple Range Test at P < 0.05; NS = not significant.

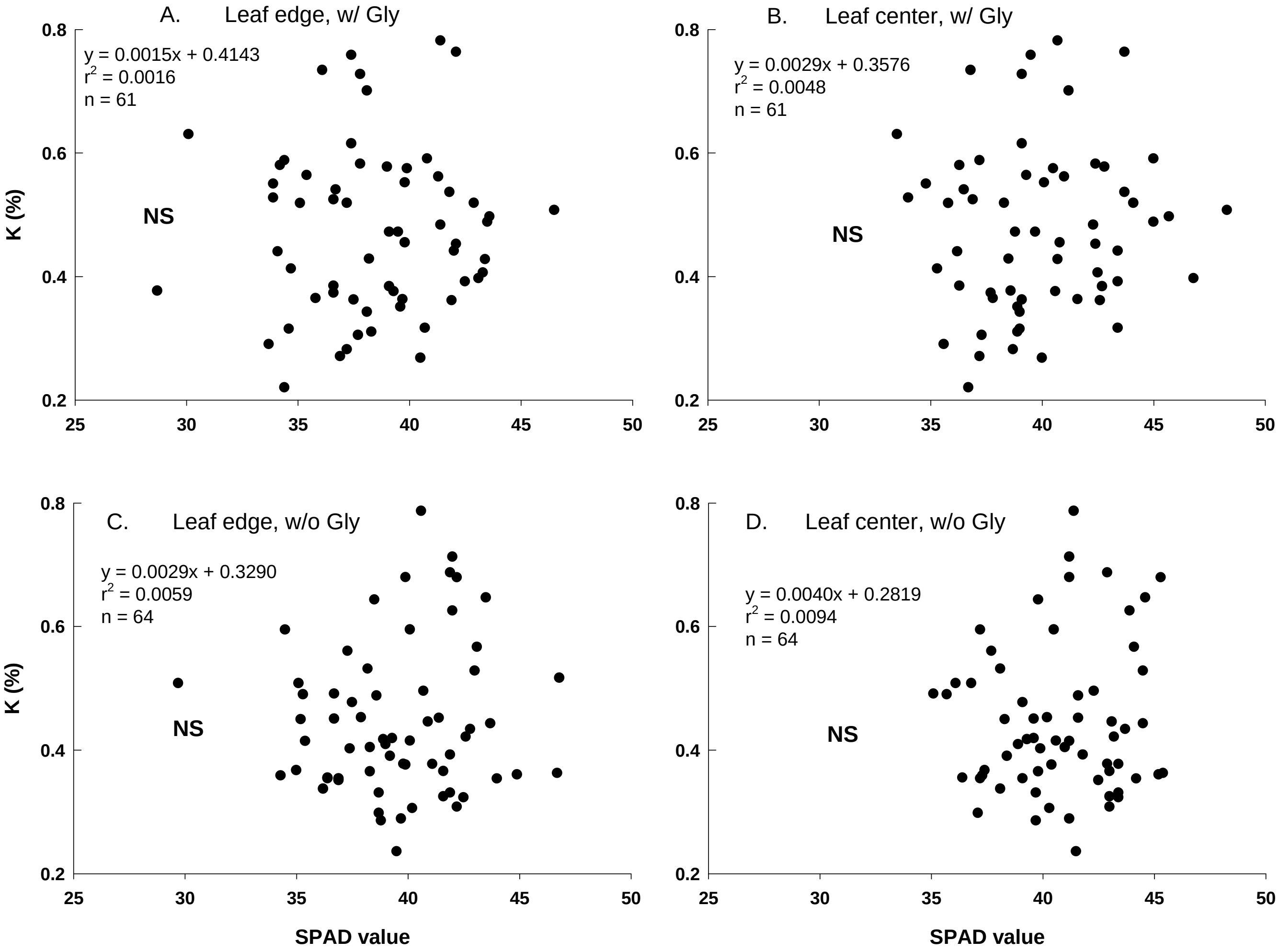

Figure 2.1. Relationship between Chlorophyll meter reading (SPAD) and K concentration in plant from (A.) leaf edge of soybean applied with foliar K fertilizer plus glyphosate, (B.) leaf center of soybean applied with foliar K fertilizer plus glyphosate, (C.) leaf edge of soybean applied with foliar K fertilizer, and (D.) leaf center of soybean applied with foliar K fertilizer; NS = not significant.

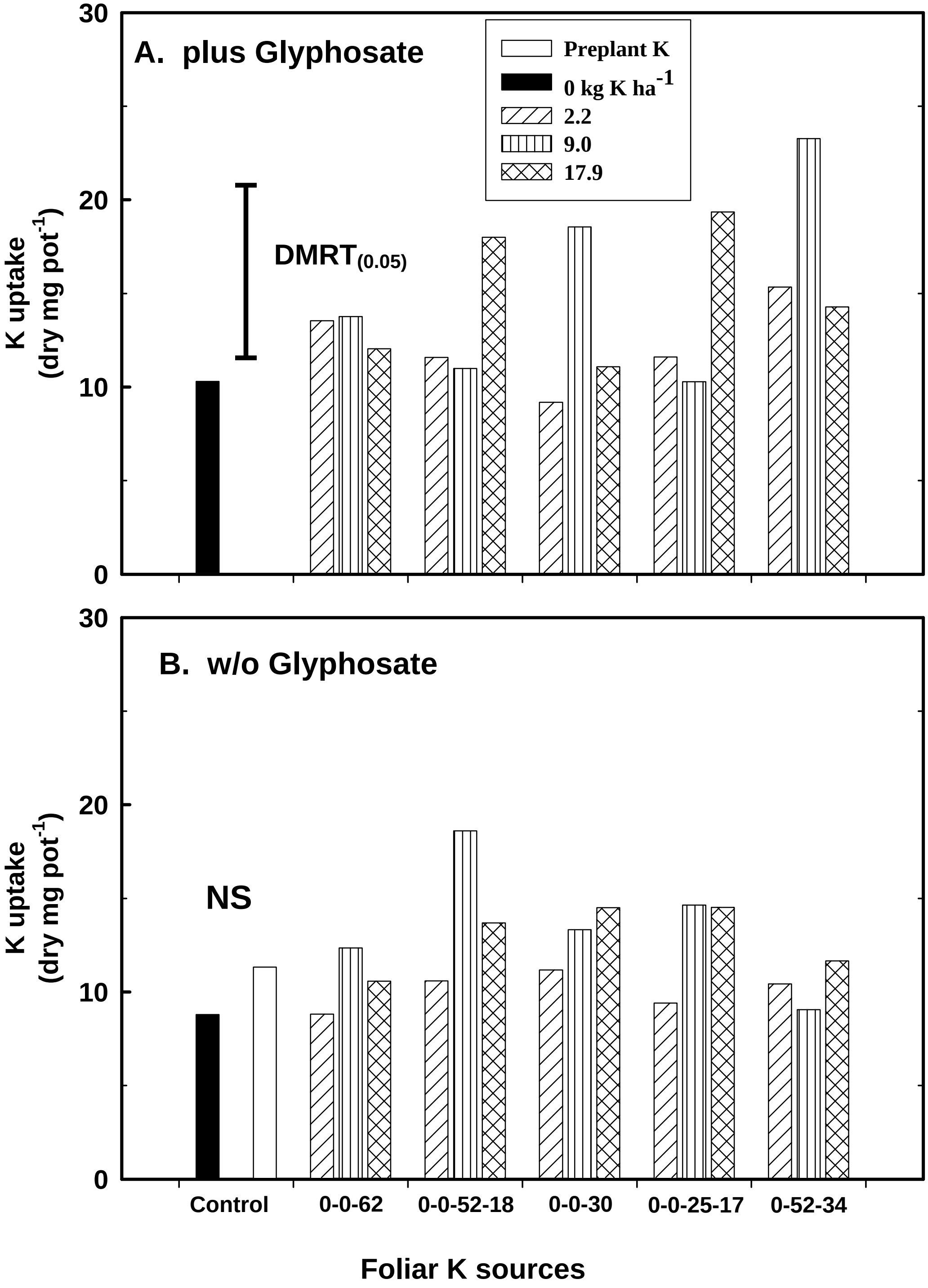

Figure 2.2. Soybean K uptake at 69 days after planting applied with (A.) foliar K fertilizer without glyphosate and (B.) foliar K fertilizer mixed with glyphosate. Vertical bars show DMRT at $\alpha \leq 0.05$; NS = not significant.

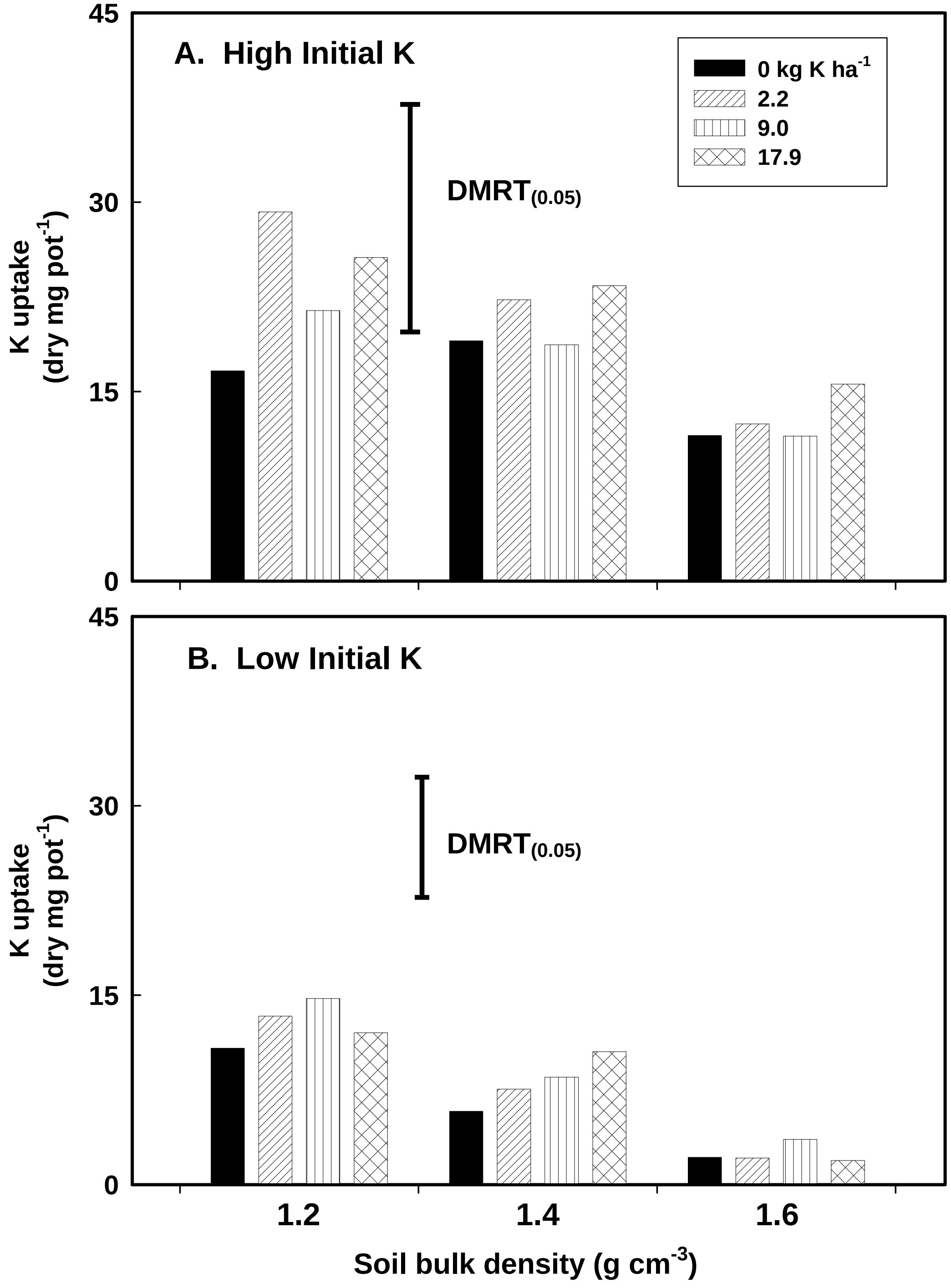

Figure 2.3. Soybean plant K uptake measured at 69 days after planting for three different levels of soil bulk density and applied with different rates of foliar K fertilizer in soils with (A.) high initial soil test K and (B.) low initial soil test K. Vertical bars show DMRT at $\alpha \leq 0.05$

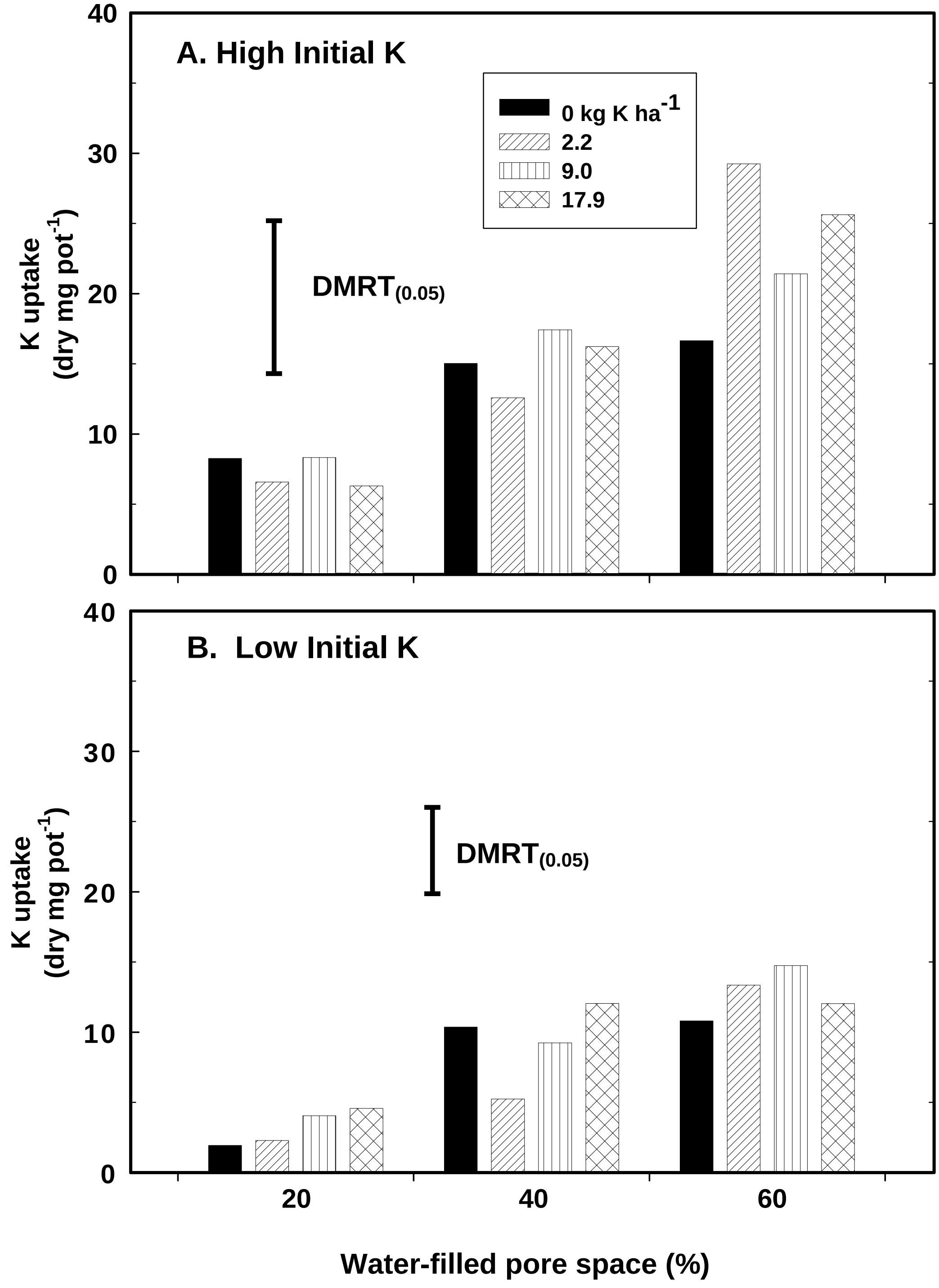

Figure 2.4. Soybean plant K uptake measured at 69 days after planting for three different levels of soil water-filled pore space (WFPS) and applied with foliar K fertilizer with (A.) high initial soil test K and (B.) with low initial soil test K. Vertical bars show DMRT at $\alpha \leq 0.05$.

# CHAPTER 3

# USE OF DIFFERENT SOURCES AND RATES OF FOLIAR POTASSIUM WITH GLYPHOSATE TO OVERCOME ENVIRONMENTAL- AND MANAGEMENT-INDUCED K DEFICIENCY IN SOYBEANS: FIELD EXPERIMENT

## ABSTRACT

Potassium deficiency in soybeans ([*Glycine max* (L.) Merr]) has increasingly become a problem in agronomic crop fields in the Midwestern United States. The major reasons contributing to this increased incidence of crop K deficiency include a lack of adequate K fertilization applied and the occurrence of soil compaction and seasonal water deficits. The use of the combination of glyphosate-resistant (GR) soybean and glyphosate application for postemergence weed control has been widely accepted by soybean growers. To combine K fertilizer with glyphosate before foliar application would allow the grower to supply needed K and possibly correct for any K deficiency found during the growing season. However, the agronomic effects of mixing glyphosate with K fertilizer sources have not been extensively studied. In this research, two-year field experiments were conducted in Northeast and Southeast Missouri to study the effects of 0-0-62 (N-$P_2O_5$-$K_2O$), 3-18-18, 5-0-20 and 0-0-25 fertilizers applied at four rates (0, 2.2, 8.9, and 17.9 kg K $ha^{-1}$) with or without glyphosate on GR soybean at V4 stage of development. Visual leaf injury was less than 10% at 3 days after treatment (DAT) and all plants recovered to foliar treatments by 14 DAT. Foliar K fertilizers did not increase grain yield significantly and sometimes did reduce the yield, but this result did not persist in both years. For both years, the level of K content in soybean leaf and in soil was little or not significantly affected by the application of foliar K fertilizers. There was a trend of decreased Mn levels in soybean leaf tissue when glyphosate was sprayed along with K

fertilizers. However, the treatment of 5-18-18 fertilizer foliar-applied with glyphosate in 2005 at the Northeast Missouri site significantly increased the level of Mn by 17.8 mg $kg^{-1}$. The level of other nutrients in soybean leaf tissue including phosphorus, magnesium, calcium, boron, zinc, sulfur, iron, and copper were also little affected.

## INTRODUCTION

The incidence of potassium (K) deficiency has increased over the last several years. Reetz and Murrell (1998) suggested one of the reasons was the lack of adequate K fertilizer application due to low commodity prices. Traditionally, in cropping systems with a corn-soybean rotation, farmers apply K fertilizer to the corn crop and not the soybean part of the rotation. In addition to the absence of K application, soybean production has increased significantly due to development of improved genetically-engineered varieties (James, 2004) and the higher K requirements of these new varieties may also have contributed to observed soil K deficiency.

Other factors affecting K availability are soil water content and soil compaction, both of which have large effects on K movement in soil. Kuchenbuch et al. (1986) reported that a decrease in soil water content decreased K diffusion in soil and Brown et al. (1960) reported that root and shoot growth of soybean were interrupted when soil moisture tension was increased from -33 to -1500 kPa. Soil compaction impedes soil K availability due to its effect on tortuosity and soil water content. Study results by Dolan et al. (1992) found K and P uptake by corn was reduced by up to 22% under compacted and dry conditions.

Soybean response to foliar fertilization has been extensively examined by researchers starting in the 1970's. In general, nutrient solutions that were used in foliar fertilization studies were mixtures of N, P, K and/or S (Boote et al., 1978; Parker and Boswell, 1980; Haq and Mallarino, 1998, 2000).While some researchers reported positive response on yield when foliar fertilizer mixtures were sprayed during reproductive growth stages (Garcia and Hanway, 1976), a number of other researchers theorized that foliar application of plant nutrients during vegetative growth stages when plants are rapidly growing would increase yield. However, the results from their studies showed infrequent growth responses (Haq and Mallarino, 1998, 2000; Mallarino et al., 2001). These researchers suggested that the unpredictable growth response was due to the initially high soil test K levels in the experiments (Parker and Boswell, 1980; Haq and Mallarino, 1998). Most soybean yield responses to foliar fertilizer were observed when soil test K and other nutrients were below optimal levels for plant growth or when plants suffered from water stress. Nelson et al. (2005) reported positive yield response from an experiment conducted to study the effect of foliar-applied K (as $K_2SO_4$) on soybean growth in a claypan soil. In this research, grain yield increased 727 to 834 kg ha$^{-1}$ when K was foliar-applied at 36 kg K ha$^{-1}$ at the V4 and R1–R2 stage of development. Despite the yield responses observed by some researchers, several studies have concluded that the observed response to foliar fertilizer application did not justify the application expense (Boote et al., 1978; Parker and Boswell, 1980; and Haq and Mallarino 1998).

Glyphosate-resistant soybean accounted for 87% of planted soybean acreage in 2005 (USDA-NASS, 2005). A primary reason why growers choose glyphosate-tolerant soybeans is because of the simplicity and flexibility of weed control when these varieties are grown (Carpenter and Gianessi, 1999).

Widespread use of glyphosate for postemergence weed control in soybeans provides an opportunity to mix K fertilizer sources with the glyphosate and possibly reduce the cost of foliar K application. This possible practice would have the potential advantage of increased flexibility for growers to respond to observed K deficiency during the growing season due to the effects of variable soil properties, management practices, or climatic conditions (Nelson et al., 2005). However, few studies have been conducted that examine the possible effects of mixing K fertilizer sources and glyphosate together on either the weed control effectiveness of the glyphosate or on plant K uptake of the foliar-applied K sources. Mallarino et al. (2005) observed increased yield when glyphosate plus 3-18-18 was foliar-applied to soybean plants at the V5 to V6 growth stage and suggested that the practice could help improve the economics of foliar K application. The results of a recent study by Nelson et al. (2007) indicated that many of the fertilizer K sources examined in the study could be mixed with glyphosate and foliar-applied with minimal crop damage and reduction in weed control, but yield response was inconsistent. Further research is needed to understand the factors affecting foliar K response and to develop in-season methods to assess when foliar K fertilization would be most effective.

The objective of this research was to determine soybean response to several rates of different foliar K sources mixed with and without glyphosate under different soil types and levels of soil test K in Missouri. We hypothesized that soybeans grown on soil of lower K level or lower soil water content due to differences in rainfall would more likely respond to foliar-applied K.

# MATERIALS AND METHODS

## Experimental Design

Field experiments were conducted in 2004 and 2005 at the University of Missouri Greenley Center in Northeast Missouri near Novelty, Missouri on a Putnam silt loam (fine, smectitic, mesic Aeric Vertic Epiaqualfs) with a high soil test K (190 mg K $kg^{-1}$) and at the Delta Center Rice Farm in Southeast Missouri approximately 14.5 km west of Malden, Missouri on a Dewitt silt loam (fine, smectitic, thermic Typic Albaqualfs) in a location with a low soil test K (37 mg K $kg^{-1}$). Glyphosate-tolerant soybean variety 'Thompson 3999RR' was planted at 445,000 seeds $ha^{-1}$ in 38 cm rows at Novelty. Glyphosate-tolerant soybean variety 'Dyna-Grow 3583 NRR' was planted at 443,000 seeds $ha^{-1}$ in 76 cm rows at the Rice Farm site. This research was arranged as a randomized complete block design with four replications. All treatments were no-till planted and applied with a $CO_2$-propelled hand-boom calibrated to deliver 140 L $ha^{-1}$ at 124 kPa, traveling 4.5 km $h^{-1}$, and equipped with 8002 flat-fan nozzles (Spray Systems CO., North Avenue, Wheaton, IL) spaced 38 cm apart and 41 cm above the canopy. Treatments consisted of four rates of foliar K application (0, 2.2, 8.9, and 17.9 kg K $ha^{-1}$) and four K fertilizer sources (K chloride (PCS, Potash Corp. of Saskatchewan, 1101 Skokie Blvd., Suite 400, Northbrook, IL) (0-0-62-0), K phosphate + urea (NA-CHURS/ALPINE Solutions, 421 Leader Street, Marion, OH) (3-18-18-0), K thiosulfate (Tessenderlo Kerley, Inc., 2255 N. 44th Street, Suite 300, Phoenix, AZ) (0-0-25-17), and K thiosulfate + urea-triazone (Tessenderlo Kerley, Inc., 2255 N. 44th Street, Suite 300, Phoenix, AZ) (5-0-20-13) applied at the V4 stage of soybean development (Fehr and Caviness, 1977). A diammonium sulfate (DAS) treatment at a rate of 3 kg $ha^{-1}$ was included since it is commonly used as an additive with glyphosate to reduce the antagonistic effects of hard water on weed control (Nalewaja and Matysiak, 1993). Non-ionic surfactant (NIS) was included in all treatments.

Foliar K treatments were sprayed on plots maintained weed-free or sprayed as a mixture with a glyphosate-based herbicide at 0.84 kg ae $ha^{-1}$ on the high soil test K site with weeds at the Greenley site and at the low soil test K site with low weed pressure at the Rice Farm site. All treatments were applied at a standard postemergence timing for weed control at 140 to 187 L $ha^{-1}$ carrier volume. Soybean injury from 0 (no visual crop injury) to 100% (complete crop death) was evaluated 3 and 14 d after treatment. Reproductive development of soybean was classified according to pod and seed development (Fehr and Caviness, 1977).

### Leaf and Yield Sampling and Analyses

Samples of trifoliolate leaves (including petioles) consisting of 20 uppermost fully expanded leaves were randomly collected at initial bloom (the R2 – R3 growth stage) from each plot. Plant tissues were dried at 60 - 70 ºC for 48 hours in a forced air oven. The dried plant tissue was then weighed, ground in a Wiley Mill and passed through a 1 mm sieve and used to assess crop K status. Additionally, the tissue concentrations of other elements (i.e., total P, Mg, Ca, S, B, Zn, Mn, Fe, and Cu) were determined using inductively-coupled plasma emission spectroscopy.

Soybean grain was harvested from the center rows of the plot using a small plot combine and yields are reported on a dry weight basis.

### Soil Sampling and Analyses

Using a stainless steel soil push probe, soil samples from each treatment were collected from both sites on the same day of leaf sampling. Soil samples were collected to a depth of 15 cm. The samples were transported to the laboratory, air dried, ground, passed through a 2 mm - sieve and stored in plastic bags. For determination of soil K, 2 grams of soil were shaken with 20 mL of 1 *M* $NH_4OAc$ at pH 7.0 for 5 minutes on a shaker before being filtered using Whatman #2 filter paper. The extracts were then analyzed for K using an atomic absorption spectrophotometer.

### Statistical and Data Analysis

The effects of K sources and foliar K rate applied with and without glyphosate on grain yield, tissue K content, and leaf injury were determined using analysis of variance with PROC GLM (SAS Institute, 1988). Treatment differences were tested using Duncan's multiple range test, DMRT ($P \leq 0.05$).

## RESULTS AND DISCUSSION

### Leaf Injury

Foliar fertilization in soybean commonly causes leaf injury and foliage damage can be sometimes so severe that it can lower grain yield (Boote et al., 1978; Parker and Boswell, 1980; Syverud et al., 1980; Poole et al., 1983). Even glyphosate-resistant (GR) soybean is sometimes susceptible to leaf injury from glyphosate under certain conditions and with certain formulations; however, the plant can outgrow the damaging effects of the glyphosate (Reddy and Zablotowicz, 2003; Reddy and Koger, 2004).

In 2004, the average of soybean leaf injury was less than 10% 3 days after foliar fertilizer treatment (DAT) at Novelty (Table 3.1). Commercially-acceptable leaf injury due to the application of foliar fertilizer is 10 % or less. By 14 DAT, all plants with leaf injury were recovered and no visual injury was observed. Compared to the data from 2004, there were only minor differences in leaf injury in 2005. Our results are similar to previous research by Nelson et al. (2007) in which they reported commercially-acceptable leaf injury on GR soybean when foliar K fertilizers was applied alone or applied with glyphosate. The results indicate the possibility of mixing and applying K fertilizer sources with glyphosate with little adverse effect on crop growth.

### Soil Test K

Application of foliar K fertilizer resulted in the increase of soil K levels only at the field site in Southeast Missouri in 2004 (Table 3.2). When compared with the control treatment, the application of 5-0-20 fertilizer alone at the rate of 2.2 kg K ha$^{-1}$ on weed-free soybean significantly increased the level of soil test K (Table3.2).

### Soybean Yield from the Greenley High Soil Test K Site

Precipitation patterns in the 2004 and 2005 growing seasons at the Greenley Center in Northeast Missouri differed considerably (Fig. 3.1 A&B). Cumulative precipitation at the Greenley Center was 539 mm during 2004 whereas in 2005, rainfall totaled less than half of that in the previous year (266 mm). As a result, in 2004 grain yields were generally 57% higher than those observed in 2005 (Fig. 3.2 A&B). Since the diffusion of K in soil to plant root highly depends on soil water content, we would expect the response of foliar fertilization in a drier year. Additionally, the relatively lower water-holding capacity of claypan soils present at this site would also increase the effect of water deficit (Blanco-Canqui et al., 2002; Nelson et al., 2005) possibly increasing any K deficiency that may be caused by the dry conditions.

In 2004, the responses from all foliar K treatments compared to the control were not significantly different. Treatments applied with K foliar fertilizer on weed-free sites indicated that the application of foliar fertilizer had no observed yield advantage (Fig. 3.2 A.). On the other hand, glyphosate combined with foliar application of 0-0-62 at 17.9 kg K ha$^{-1}$ reduced grain yield 356 kg ha$^{-1}$ when compared to 0-0-62 applied in the weed-free check in 2004 (Fig. 3.2 A). The lack of foliar K fertilizer treatment effect might be explained by the high level of soil test K at the site and the abundant rainfall in that year.

In 2005, the results were, however, in contrast to what we expected from a dry year since foliar K fertilization did not show any advantage over the control treatments (Fig. 3.2 B.). Foliar K fertilizer applied alone to weed-free checks had grain yields 396 to 919 kg ha$^{-1}$ greater than a single application of glyphosate plus the fertilizer additive due primarily to the reduced weed stress. In fact, soybean grain yield in some treatments were reduced when compared to the corresponding control treatments. Soybean grain in the amount of 289 kg ha$^{-1}$ was reduced after applied with glyphosate tank-mixed with 5-0-20-13 at 17.9 kg K ha$^{-1}$ when compared to glyphosate plus NIS in 2005 (Fig. 3.2 B). Similarly, 0-0-25-17 at 8.9 and 17.9 kg K ha$^{-1}$ reduced grain yields 393 and 289 kg ha$^{-1}$, respectively. According to former studies of foliar K fertilizer, when soil K concentration was medium to high, no or little grain yield responses were observed (Haq and Mallarino, 1998, 2000). Haq and Mallarino (1998, 2000) reported inconsistent positive soybean yield response to foliar fertilization from field experiments conducted in soil of high K and P level in Iowa. In addition, there were also a few unpredictable decreased yields in the same experiment (Haq and Mallarino; 1998, 2000).

**Soybean Yield from the Rice Farm Low Soil Test K Site**

In 2004, other weed-free treatments had grain yields similar to tank mixtures with glyphosate except for the foliar application of 3-18-18 fertilizer plus glyphosate at a rate of 8.9 kg K ha$^{-1}$ (Fig. 3.3 A). In 2005, the foliar application of 0-0-62 at a rate of 8.9 kg K ha$^{-1}$ significantly increased soybean grain yield. However, other weed-free treatments had grain yields similar to tank mixtures with glyphosate at the Rice Farm site (Fig. 3.3B). Due to the low initial soil test K of this site, greater yield response due to applied foliar K would have been expected compared to the high soil test K site in Northeast Missouri. However, grain yield from all foliar K sources was similar to observed response with glyphosate plus diammonium sulfate. The same yield results to applied foliar K applications were observed by Poole et al. in Minnesota (1982). In their research, the response of soybean yield to various rates and formulas of foliar fertilization from low K site were compared to medium and high soil K sites. In general, foliar fertilization did not improve yield and sometimes yield reductions due to leaf injury were reported (Poole et al, 1982). These results emphasize the possible importance of other factors, such as climate and management practices (e.g., compaction), that may influence plant K response,

**Leaf K Concentration**

In 2004, most levels of K concentration in leaves at the Greenley site in the weed-free treatment were similar to all glyphosate tank mixtures except glyphosate plus 0-0-62 at 17.9 kg K ha$^{-1}$ (Table 3.3). There was also a significantly decreased leaf K level when glyphosate plus 0-0-25-17 fertilizer at 2.2 kg K ha$^{-1}$ was applied compared to glyphosate plus DAS.

Glyphosate plus 5-0-20 and glyphosate plus 0-0-25 at a rate of 8.92 kg K $ha^{-1}$ in 2005 decreased leaf K content compared to the weed-free check (Table 3.5.). Potassium leaf tissue content at the Greenley site was consistently 0.3 % higher compared to the control treatment at the 2.2 kg K $ha^{-1}$ rate of foliar potassium application with glyphosate, except when 0-0-25 fertilizer was applied (Table 3.2). Other than this increase, all leaf K concentration was similar among K treatments at the low soil test K site in Southeast Missouri in both years (Table 3.4 and 3.6). The result is in agreement with the unaltered level of K in soybean leaf after foliar fertilization with 3–8–15 fertilizer at early vegetative growth stages shown by Haq and Mallarino (1998). Boote et al. (1978), and Parker and Boswell (1980) also reported a small or no effect of foliar fertilization at late reproductive stages on plant tissue K concentrations.

### Leaf Mn, Zn, and B Concentrations

Even though a significant increase in leaf Mn was detected when glyphosate was applied with DAS at the site in Northeast Missouri sites in 2005, this difference was not consistent among the different K sources (Tables 3.5). In general, when applied with K fertilizer, glyphosate tended to decrease the level of Mn content in soybean leaf. The result was similar to recent research by Huber et al. (2004) reporting a trend of reduced Mn uptake by glyphosate resistant soybeans. He showed that when Mn fertilizer was applied with glyphosate, Mn uptake by soybean plant was inhibited and he also suggested that applying Mn more than eight days after glyphosate application would reduce the adverse effect. Similarly, Eker et al. (2006) showed reduced levels of Mn uptake in sunflower plant after the application of glyphosate. They believed that the reason for this impairment is probably explained by the formation of glyphosate-cation complexes in plant tissues and/or rhizosphere interactions.

In 2004, at the site in Northeast Missouri, compared to the soybean maintained weed-free and applied with K fertilizer alone, soybean plants had lower levels of leaf Zn content when glyphosate was applied with 0-0-62 and 0-0-25 fertilizer at the rate of 8.9 kg K ha$^{-1}$ and 5-18-18 and 0-0-25 fertilizers at the rate of 2.2, and 8.9 kg K ha$^{-1}$ respectively (Tables 3.3). In 2005, however, the treatments showing reduced leaf Zn content were when glyphosate was sprayed with 0-0-62 at the rate of 8.9 kg K ha$^{-1}$ and with 0-0-25 at the rate of 2.2 and 17.9 kg K ha$^{-1}$(Table 3.6).

In 2005, compared to treatments applied with K fertilizer alone, glyphosate caused decreased B content in soybean leaf when applied with 3-18-18 at the rate of 2.2 kg K ha$^{-1}$ at the site in Northeast Missouri and when applied with 5-0-20 fertilizer at the rate of 17.9 kg K ha$^{-1}$ and 0-0-25 fertilizer at the rate of 8.9 kg K ha$^{-1}$ at the site in Southeast Missouri (Table 3.4 and 3.5). The results for the other nutrients in leaf tissue were inconsistent and, therefore, are not shown.

## CONCLUSIONS

The results from these field experiments suggest that minor leaf injury was common for all foliar-applied K fertilizers at the rates examined in this study. However, the injury had little or no significant effect on soybean grain yield. At both sites, the tank mixture of glyphosate with K fertilizer sources did not increase leaf injury. The effect of foliar fertilization on soybean leaf K content was inconsistent. While some leaf K response to K fertilizer applied alone was observed, glyphosate tank-mixed with K fertilizer sources caused a leaf K decrease in a few treatments. This reduced leaf K level, however, did not apparently affect soybean grain production. Micronutrient content in leaf tissue was not significantly different across the treatments.

The data from the experiment conducted on the high soil test K site showed that some K treatments had an adverse effect on grain production, but most treatments were not affected. On the other hand, we expected to observe more growth response from field sites where soybean was grown in soil with low soil test K or when dry conditions occurred. However, when applied either alone or coupled with glyphosate, foliar K fertilizers tested in this study had little or no significant effects on increasing grain yield, even in the relatively dry year of 2005. These results possibly demonstrate that other factors besides climate and initial soil test K levels may influence soybean response to foliar K application. They also indicate that K sources can be mixed with glyphosate and applied as part of a post-emergence weed control program with little negative agronomic effects. Additional research may be needed to be able to predict when crop response to foliar K fertilization is likely to occur under the different climatic, soil and management conditions that exist in Missouri.

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Table 3.1. The effects of different foliar potassium fertilizer sources that were mixed and applied with and without glyphosate on soybean leaf nutrient content fourteen days after application at the site in Northeast Missouri in 2004.

| | | Leaf injury 3 DAT | | | | | | Leaf injury 14 DAT | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K source | Rate | 2004 | | | 2005 | | | 2004 | | | 2005 | | |
| | | -[†] | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ |
| | kg K ha$^{-1}$ | % | | | | | | | | | | | |
| Control | 0 | 0 | 1 | NS | 0 | 0 | NS | 0 | 2 | NS | 0 | 0 | NS |
| 0-0-62[††] | 2.2 | 0 | 2 | NS | 0 | 0 | NS | 0 | 2 | NS | 0 | 0 | NS |
| | 8.9 | 1 | 5 | NS | 3 | 1 | 1 | 0 | 5 | NS | 0 | 0 | NS |
| | 17.9 | 9 | 6 | NS | 3 | 6 | 2 | 4 | 11 | NS | 0 | 0 | NS |
| 3-18-18 | 2.2 | 1 | 0 | NS | 0 | 0 | NS | 0 | 1 | NS | 0 | 0 | NS |
| | 8.9 | 1 | 3 | NS | 1 | 2 | NS | 0 | 2 | NS | 0 | 5 | NS |
| | 17.9 | 4 | 2 | NS | 5 | 4 | NS | 0 | 2 | NS | 0 | 0 | NS |
| 5-0-20 | 2.2 | 1 | 2 | NS | 0 | 0 | NS | 0 | 2 | NS | 0 | 0 | NS |
| | 8.9 | 5 | 8 | NS | 2 | 5 | NS | 0 | 4 | 3 | 0 | 0 | NS |
| | 17.9 | 5 | 5 | NS | 7 | 4 | 2 | 0 | 3 | NS | 0 | 0 | NS |
| 0-0-25 | 2.2 | 2 | 2 | NS | 0 | 1 | NS | 1 | 3 | NS | 0 | 0 | NS |
| | 8.9 | 4 | 6 | NS | 3 | 4 | NS | 0 | 4 | 2 | 0 | 0 | NS |
| | 17.9 | 4 | 6 | NS | 7 | 7 | NS | 0 | 6 | 2 | 0 | 0 | NS |
| DMRT$_{(0.05)}$ | | 2 | 3 | | 1 | 2 | | 1 | 3 | | NS | 3 | |

[†] Minus sign (-) indicates plots that were maintained weed free and foliar K sources were sprayed without glyphosate. Plus sign (+) indicates when glyphosate was mixed with foliar K source and sprayed on to plots with weeds.

[††] Fertilizer sources included 0-0-62 (potassium (K) chloride), 3-18-18 (K phosphate + urea, NA-CHURS/ALPINE), 5-0-20 (K thiosulfate + urea-triazone, Trisert-K+, Tessenderlo Kerley), and 0-0-25 (K thiosulfate). All tank mixtures with glyphosate included non-ionic surfactant.

Table 3.2. The effects of different foliar potassium fertilizer sources that were mixed and applied with and without glyphosate on soil K level fourteen days after application at both sites in 2004 and 2005.

| | | Northeast Missouri | | | | | | Southeast Missouri | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K source | Rate | 2004 | | | 2005 | | | 2004 | | | 2005 | | |
| | | -[†] | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ |
| | kg K ha$^{-1}$ | ppm | | | | | | | | | | | |
| Control | 0 | 160.4 | 165.8 | NS | 173.3 | 182.8 | NS | 39.8 | 51.0 | NS | 55.1 | 53.6 | NS |
| 0-0-62[††] | 2.2 | 145.5 | 153.7 | NS | 165.8 | 183.3 | NS | 48.9 | 44.9 | 3.9 | 52.0 | 61.4 | NS |
| | 8.9 | 149.2 | 140.4 | NS | 180.8 | 188.3 | NS | 50.0 | 59.3 | NS | 51.7 | 49.8 | NS |
| | 17.9 | 174.1 | 165.3 | NS | 170.5 | 179.0 | NS | 56.7 | 49.1 | NS | 59.7 | 58.3 | NS |
| 3-18-18 | 2.2 | 162.0 | 157.9 | NS | 183.3 | 181.3 | NS | 49.9 | 54.2 | NS | 56.4 | 67.0 | NS |
| | 8.9 | 146.1 | 139.0 | NS | 185.5 | 200.8 | NS | 42.8 | 40.6 | NS | 57.0 | 60.9 | NS |
| | 17.9 | 162.3 | 158.9 | NS | 188.5 | 202.5 | NS | 49.6 | 42.2 | NS | 62.3 | 53.4 | NS |
| 5-0-20 | 2.2 | 150.0 | 162.5 | NS | 185.3 | 195.5 | NS | 65.8 | 53.2 | NS | 54.2 | 57.1 | NS |
| | 8.9 | 173.5 | 160.0 | NS | 177.0 | 175.0 | NS | 55.9 | 57.7 | 3.0 | 65.6 | 54.0 | NS |
| | 17.9 | 166.0 | 145.1 | NS | 207.0 | 187.0 | NS | 61.1 | 55.9 | NS | 58.1 | 56.5 | NS |
| 0-0-25 | 2.2 | 139.0 | 143.2 | NS | 205.5 | 192.0 | NS | 43.4 | 47.1 | NS | 62.3 | 61.3 | NS |
| | 8.9 | 148.2 | 153.1 | NS | 182.0 | 186.8 | NS | 49.3 | 44.5 | 2.0 | 53.8 | 62.6 | NS |
| | 17.9 | 156.2 | 146.8 | NS | 203.5 | 191.5 | NS | 61.3 | 63.4 | 2.0 | 56.2 | 61.3 | NS |
| DMRT$_{(0.05)}$ | | NS | NS | | NS | NS | | 22.4 | 22.1 | | NS | NS | |

[†] Minus sign (-) indicates plots that were maintained weed free and foliar K sources were sprayed without glyphosate. Plus sign (+) indicates when glyphosate was mixed with foliar K source and sprayed on to plots with weeds.

[††] Fertilizer sources included 0-0-62 (potassium (K) chloride), 3-18-18 (K phosphate + urea, NA-CHURS/ALPINE), 5-0-20 (K thiosulfate + urea-triazone, Trisert-K+, Tessenderlo Kerley), and 0-0-25 (K thiosulfate). All tank mixtures with glyphosate included non-ionic surfactant.

Table 3.3. The effects of different foliar potassium fertilizer sources that were mixed and applied with and without glyphosate on soybean leaf nutrient content fourteen days after application at the site in Northeast Missouri in 2004.

| | | K | | | Zn | | | Mn | | | B | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K source | Rate | -[†] | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ |
| | kg K $ha^{-1}$ | --------------%------------- | | | ---------------------------------------------ppm--------------------------------------------------------- | | | | | | | | |
| Control | 0 | 2.4 | 2.4 | NS | 36.4 | 28.2 | NS | 69.0 | 55.7 | 12.7 | 40.2 | 41.4 | NS |
| 0-0-62[††] | 2.2 | 2.4 | 2.4 | NS | 35.4 | 29.2 | NS | 70.4 | 51.5 | 17.3 | 39.9 | 39.1 | NS |
| | 8.9 | 2.4 | 2.3 | NS | 36.0 | 30.5 | 1.2 | 66.1 | 53.8 | 5.3 | 41.4 | 38.7 | NS |
| | 17.9 | 2.5 | 2.4 | 0.1 | 38.3 | 29.4 | NS | 67.6 | 55.4 | NS | 40.6 | 38.9 | NS |
| 3-18-18 | 2.2 | 2.5 | 2.5 | NS | 37.2 | 32.4 | 2.5 | 68.8 | 58.4 | NS | 42.9 | 43.8 | NS |
| | 8.9 | 2.4 | 2.4 | NS | 32.9 | 28.1 | NS | 70.5 | 59.6 | NS | 40.1 | 40.1 | NS |
| | 17.9 | 2.5 | 2.4 | NS | 32.0 | 28.3 | NS | 66.8 | 57.3 | NS | 39.6 | 39.7 | NS |
| 5-0-20 | 2.2 | 2.3 | 2.5 | NS | 30.3 | 31.7 | NS | 65.7 | 58.0 | NS | 38.4 | 40.0 | NS |
| | 8.9 | 2.5 | 2.5 | NS | 38.1 | 30.1 | NS | 71.3 | 55.9 | NS | 41.9 | 40.0 | NS |
| | 17.9 | 2.4 | 2.4 | NS | 35.1 | 28.2 | NS | 62.8 | 56.3 | NS | 40.5 | 36.6 | NS |
| 0-0-25 | 2.2 | 2.5 | 2.2 | NS | 36.2 | 24.9 | 7.0 | 65.4 | 51.6 | 5.9 | 40.9 | 39.0 | NS |
| | 8.9 | 2.5 | 2.3 | NS | 36.9 | 27.2 | 2.2 | 65.8 | 55.4 | NS | 40.0 | 37.8 | NS |
| | 17.9 | 2.4 | 2.5 | NS | 34.5 | 29.2 | NS | 66.7 | 54.6 | 8.9 | 39.0 | 38.4 | NS |
| $DMRT_{(0.05)}$ | | 0.2 | 0.2 | | 6.6 | 6.2 | | NS | NS | | NS | 4.8 | |

[†] Minus sign (-) indicates plots that were maintained weed free and foliar K sources were sprayed without glyphosate. Plus sign (+) indicates when glyphosate was mixed with foliar K source and sprayed on to plots with weeds.

[††] Fertilizer sources included 0-0-62 (potassium (K) chloride), 3-18-18 (K phosphate + urea, NA-CHURS/ALPINE), 5-0-20 (K thiosulfate + urea-triazone, Trisert-K+, Tessenderlo Kerley), and 0-0-25 (K thiosulfate). All tank mixtures with glyphosate included non-ionic surfactant.

Table 3.4. The effects of different foliar potassium fertilizer sources that were mixed and applied with and without glyphosate on soybean leaf nutrient content fourteen days after application at the site in Southeast Missouri in 2004.

| | | K | | | Zn | | | Mn | | | B | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K source | Rate | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ |
| | kg K $ha^{-1}$ | --------------%------------- | | | -------------------------------------------------ppm--------------------------------------------------------- | | | | | | | | |
| Control | 0 | 1.3 | 1.4 | NS | 43.8 | 36.6 | NS | 470.3 | 346.5 | NS | 51.4 | 53.3 | NS |
| 0-0-62 | 2.2 | 1.2 | 1.2 | NS | 33.1 | 38.1 | NS | 530.3 | 452.9 | NS | 53.3 | 53.1 | NS |
| | 8.9 | 1.3 | 1.4 | NS | 38.2 | 39.5 | NS | 487.7 | 406.7 | NS | 49.3 | 43.7 | NS |
| | 17.9 | 1.3 | 1.4 | NS | 41.0 | 37.4 | NS | 363.4 | 342.4 | NS | 46.9 | 46.2 | NS |
| 3-18-18 | 2.2 | 1.3 | 1.4 | NS | 39.8 | 36.6 | NS | 403.8 | 367.1 | NS | 53.3 | 51.9 | NS |
| | 8.9 | 1.3 | 1.4 | NS | 37.8 | 38.5 | NS | 500.4 | 300.5 | NS | 54.0 | 53.7 | NS |
| | 17.9 | 1.4 | 1.4 | NS | 36.4 | 65.5 | NS | 235.4 | 409.0 | NS | 46.5 | 47.1 | NS |
| 5-0-20 | 2.2 | 1.4 | 1.5 | NS | 54.8 | 41.1 | NS | 295.8 | 383.7 | NS | 44.9 | 45.8 | NS |
| | 8.9 | 1.4 | 1.3 | NS | 37.6 | 39.0 | NS | 315.0 | 342.2 | NS | 45.6 | 44.7 | NS |
| | 17.9 | 1.4 | 1.4 | NS | 40.3 | 37.3 | NS | 395.8 | 343.4 | NS | 46.8 | 47.7 | NS |
| 0-0-25 | 2.2 | 1.3 | 1.3 | NS | 41.3 | 40.7 | NS | 416.1 | 396.8 | NS | 47.9 | 49.7 | NS |
| | 8.9 | 1.2 | 1.4 | NS | 38.3 | 36.4 | NS | 586.2 | 475.3 | NS | 51.3 | 47.1 | NS |
| | 17.9 | 1.4 | 1.6 | NS | 43.1 | 39.9 | NS | 363.8 | 329.0 | NS | 48.7 | 46.7 | NS |
| $DMRT_{(0.05)}$ | | NS | 0.3 | | 9.9 | NS | | 249.2 | NS | | NS | 8.2 | |

[†] Minus sign (-) indicates plots that were maintained weed free and foliar K sources were sprayed without glyphosate. Plus sign (+) indicates when glyphosate was mixed with foliar K source and sprayed on to plots with weeds.

[††] Fertilizer sources included 0-0-62 (potassium (K) chloride), 3-18-18 (K phosphate + urea, NA-CHURS/ALPINE), 5-0-20 (K thiosulfate + urea-triazone, Trisert-K+, Tessenderlo Kerley), and 0-0-25 (K thiosulfate). All tank mixtures with glyphosate included non-ionic surfactant.

Table 3.5. The effects of different foliar potassium fertilizer sources that were mixed and applied with and without glyphosate on soybean leaf nutrient content fourteen days after application at the site in Northeast Missouri in 2005.

| | | K | | | Zn | | | Mn | | | B | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K source | Rate | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ |
| | kg K ha$^{-1}$ | --------------%-------------- | | | ---------------------------------------------ppm--------------------------------------------- | | | | | | | | |
| Control | 0 | 3.1 | 2.7 | NS | 37.2 | 36.2 | NS | 67.6 | 85.4 | 16.8 | 27.7 | 23.9 | NS |
| 0-0-62 | 2.2 | 3.0 | 3.0 | NS | 38.6 | 37.0 | NS | 70.9 | 75.8 | NS | 29.6 | 24.8 | NS |
| | 8.9 | 2.9 | 2.8 | NS | 40.4 | 37.1 | 1.3 | 68.9 | 81.1 | NS | 28.2 | 25.4 | NS |
| | 17.9 | 3.1 | 2.8 | NS | 36.1 | 36.5 | NS | 70.6 | 78.9 | NS | 25.1 | 23.5 | NS |
| 3-18-18 | 2.2 | 3.3 | 3.0 | NS | 36.4 | 37.5 | NS | 67.4 | 83.9 | 16.2 | 27.8 | 27.0 | NS |
| | 8.9 | 3.1 | 2.9 | NS | 35.8 | 37.4 | NS | 71.6 | 80.7 | NS | 24.3 | 27.1 | NS |
| | 17.9 | 3.0 | 2.9 | NS | 38.7 | 36.4 | NS | 74.2 | 82.5 | NS | 28.0 | 23.0 | NS |
| 5-0-20 | 2.2 | 3.1 | 3.0 | NS | 37.4 | 36.5 | NS | 65.3 | 78.1 | NS | 29.7 | 26.2 | NS |
| | 8.9 | 3.0 | 2.7 | 0.2 | 37.3 | 36.1 | NS | 71.7 | 77.6 | NS | 26.3 | 24.7 | NS |
| | 17.9 | 3.2 | 2.9 | NS | 38.7 | 35.2 | NS | 69.8 | 77.4 | NS | 29.3 | 23.4 | 4.7 |
| 0-0-25 | 2.2 | 2.8 | 2.8 | NS | 38.6 | 35.2 | 1.1 | 72.6 | 81.7 | NS | 26.3 | 24.0 | NS |
| | 8.9 | 3.0 | 2.7 | 0.2 | 38.9 | 36.3 | NS | 73.4 | 81.1 | NS | 27.1 | 20.6 | 4.2 |
| | 17.9 | 3.0 | 3.0 | NS | 37.9 | 36.0 | 0.8 | 74.5 | 75.1 | NS | 26.7 | 24.1 | NS |
| $DMRT_{(0.05)}$ | | 0.3 | 0.2 | | 2.1 | NS | | 7.3 | NS | | NS | 5.3 | |

[†] Minus sign (-) indicates plots that were maintained weed free and foliar K sources were sprayed without glyphosate. Plus sign (+) indicates when glyphosate was mixed with foliar K source and sprayed on to plots with weeds.

[††] Fertilizer sources included 0-0-62 (potassium (K) chloride), 3-18-18 (K phosphate + urea, NA-CHURS/ALPINE), 5-0-20 (K thiosulfate + urea-triazone, Trisert-K+, Tessenderlo Kerley), and 0-0-25 (K thiosulfate). All tank mixtures with glyphosate included non-ionic surfactant.

Table 3.6. The effects of different foliar potassium fertilizer sources that were mixed and applied with and without glyphosate on soybean leaf nutrient content fourteen days after application at the site in Southeast Missouri in 2005.

| | | K | | | Zn | | | Mn | | | B | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K source | Rate | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ |
| | kg K $ha^{-1}$ | --------------%------------- | | | -----------------------------------------------ppm------------------------------------------------ | | | | | | | | |
| Control | 0 | 2.2 | 2.0 | NS | 40.8 | 40.3 | NS | 130.4 | 138.7 | NS | 37.3 | 39.5 | NS |
| 0-0-62 | 2.2 | 2.0 | 2.2 | NS | 38.3 | 41.3 | NS | 122.1 | 130.1 | NS | 39.4 | 35.2 | NS |
| | 8.9 | 1.9 | 2.1 | NS | 40.3 | 39.0 | NS | 98.9 | 151.2 | NS | 32.1 | 37.8 | NS |
| | 17.9 | 2.2 | 2.2 | NS | 40.8 | 36.7 | NS | 138.1 | 73.2 | 63.8 | 35.5 | 33.1 | NS |
| 3-18-18 | 2.2 | 2.0 | 2.2 | NS | 38.8 | 43.2 | NS | 134.0 | 136.7 | NS | 41.6 | 36.7 | 3.5 |
| | 8.9 | 2.1 | 2.1 | NS | 41.2 | 40.8 | NS | 195.6 | 97.7 | NS | 40.1 | 39.6 | NS |
| | 17.9 | 2.2 | 2.1 | NS | 39.4 | 41.3 | NS | 160.2 | 83.8 | NS | 38.0 | 40.1 | NS |
| 5-0-20 | 2.2 | 2.2 | 2.1 | NS | 39.7 | 39.5 | NS | 110.6 | 131.6 | NS | 38.7 | 37.0 | NS |
| | 8.9 | 2.3 | 2.0 | NS | 39.5 | 37.7 | NS | 148.3 | 126.7 | NS | 37.9 | 36.4 | NS |
| | 17.9 | 2.1 | 1.9 | NS | 41.1 | 40.8 | NS | 140.6 | 93.9 | NS | 40.7 | 37.1 | NS |
| 0-0-25 | 2.2 | 2.3 | 1.9 | 0.3 | 39.6 | 39.3 | NS | 164.0 | 116.4 | NS | 40.7 | 36.4 | NS |
| | 8.9 | 2.0 | 2.3 | NS | 39.2 | 39.8 | NS | 158.6 | 104.7 | NS | 37.1 | 37.3 | NS |
| | 17.9 | 2.0 | 2.1 | NS | 38.5 | 38.5 | NS | 134.3 | 162.6 | NS | 40.6 | 38.4 | NS |
| $DMRT_{(0.05)}$ | | NS | NS | | NS | NS | | NS | 61.2 | | 4.9 | NS | |

[†] Minus sign (-) indicates plots that were maintained weed free and foliar K sources were sprayed without glyphosate. Plus sign (+) indicates when glyphosate was mixed with foliar K source and sprayed on to plots with weeds.

[††] Fertilizer sources included 0-0-62 (potassium (K) chloride), 3-18-18 (K phosphate + urea, NA-CHURS/ALPINE), 5-0-20 (K thiosulfate + urea-triazone, Trisert-K+, Tessenderlo Kerley), and 0-0-25 (K thiosulfate). All tank mixtures with glyphosate included non-ionic surfactant.

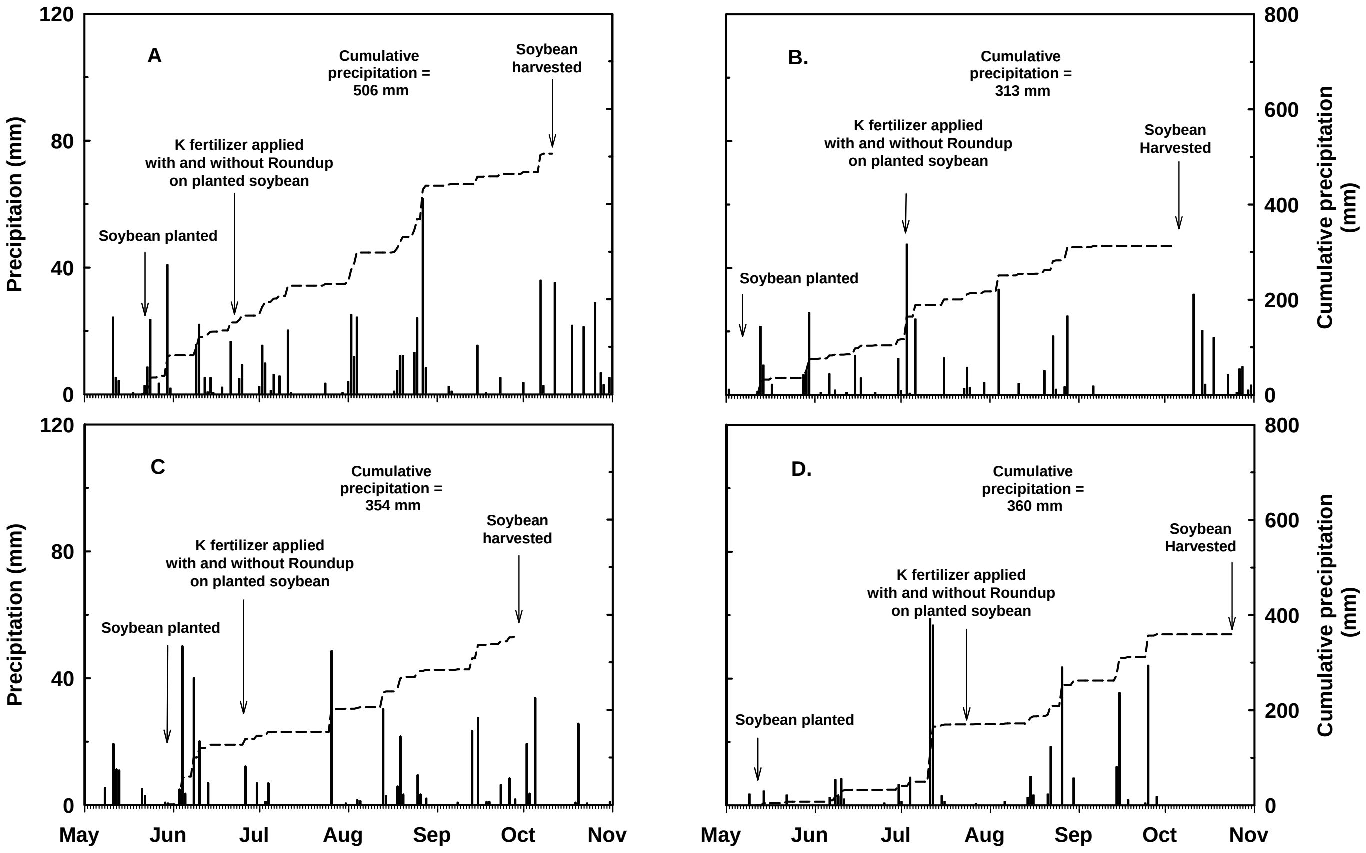

Figure 3.1. Daily precipitation (bars) and cumulative precipitation (line) for the (A.) Northeastern Missouri in 2004, (B.) Southeastern Missouri in 2004, (C.) Northeastern Missouri and in 2005, and (D.) Southeastern Missouri in 2005 growing seasons before and after application of foliar K fertilizer. Arrows indicate time of soybean planting, fertilizer application, and soybean harvesting

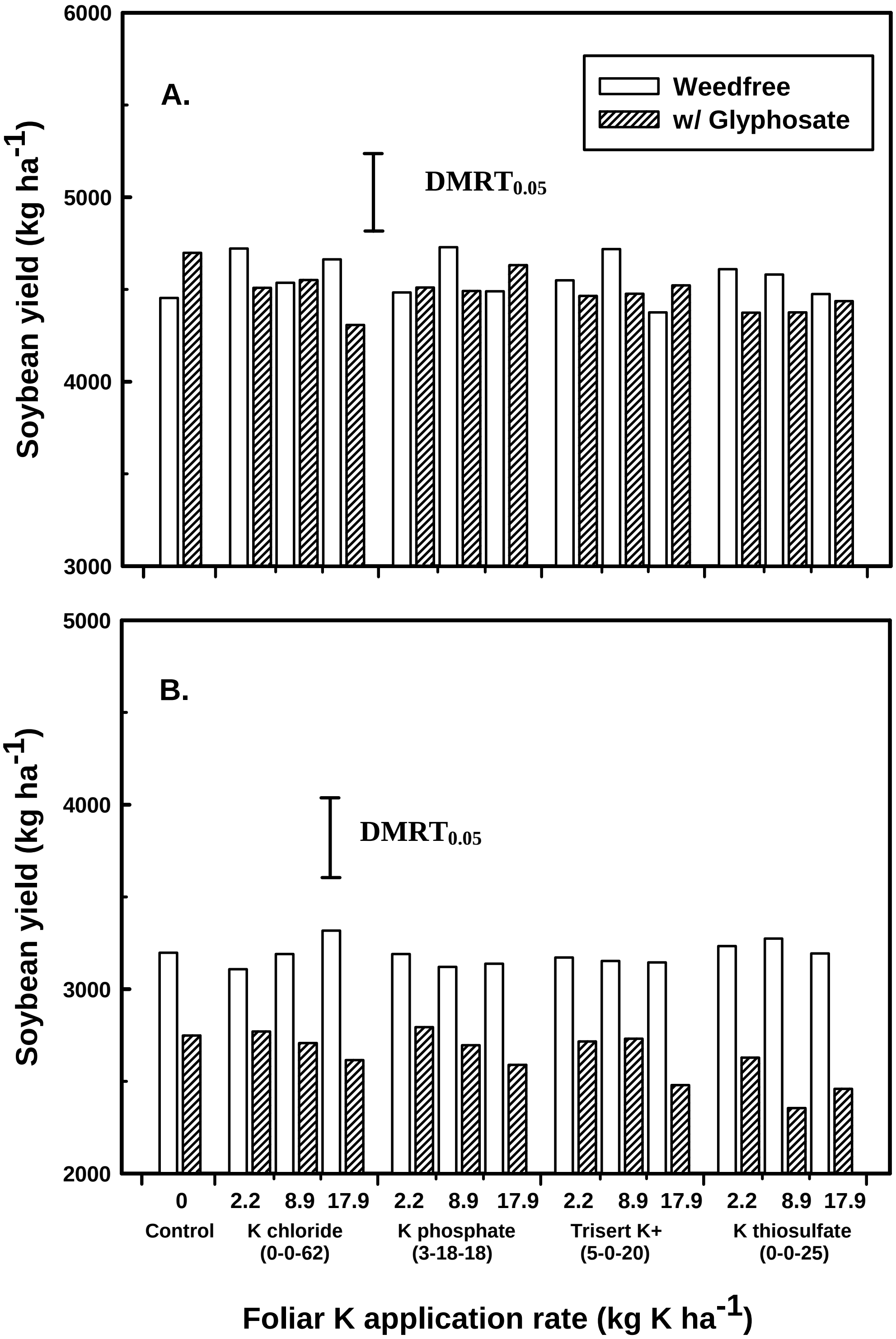

Figure 3.2. Influence of foliar K fertilizers on soybean grain yield at Northeast Missouri (high soil test K site) for A) in 2004, and B) in 2005. Vertical bars show DMRT at α ≤ 0.05. NS denotes not significantly different.

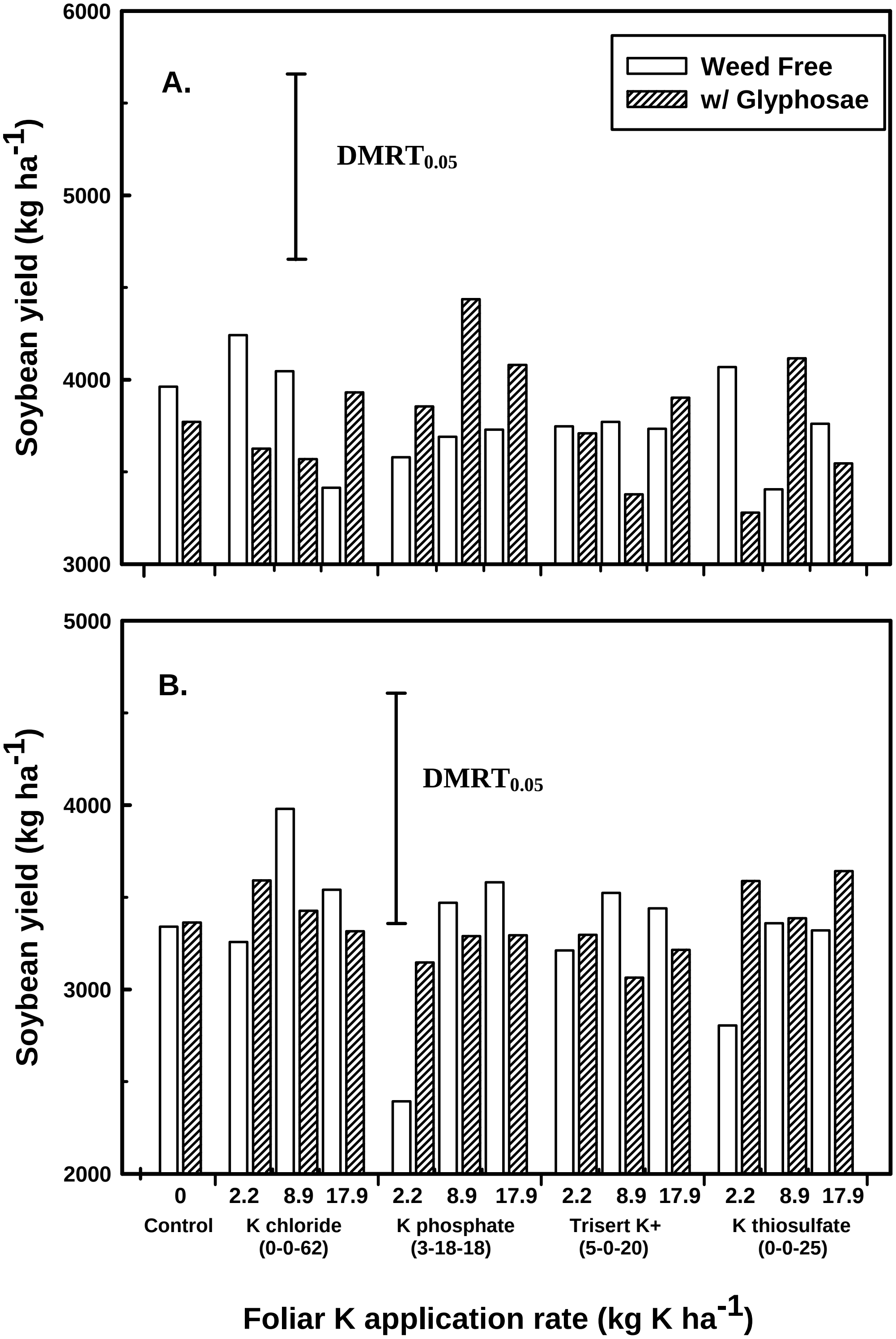

Figure 3.3. Influence of foliar K fertilizers on soybean grain yield at Southeast Missouri (low soil test K site) for A) in 2004, and B) in 2005. Vertical bars show DMRT at $\alpha \leq 0.05$. NS denotes not significantly different.

# CHAPTER 4

# CONCLUSIONS

This thesis has presented results from greenhouse and field studies conducted in Missouri examining the effects of foliar K fertilization added with and without glyphosate, a postemergence herbicide, on soybean plant growth and K uptake. Five sources of K fertilizer (i.e., potassium chloride, potassium sulfate, potassium carbonate, potassium thiosulfate, and potassium phosphate) added at four application rates (2.2, 8.9, and 17.9 kg K ha$^{-1}$) were used in a greenhouse experiment and four sources (i.e., potassium chloride, potassium phosphate + urea, potassium thiosulfate, and K thiosulfate + urea-triazone) were used at equivalent rates in two field studies conducted in different regions of Missouri. The objectives of this research were to determine soybean response to several rates of different foliar K sources mixed with and without glyphosate under different types of soil, soil test K, soil water content, soil compaction and climatic conditions, and also, to evaluate a method to rapidly determine plant K deficiency using leaf color measured by a chlorophyll meter. Among the conclusions that were reached with these studies are:

1. The results from the greenhouse and field studies suggest that minor leaf injury was common for all foliar-applied K fertilizers at the rates examined in this study. However, the injury had no or little significant effect on plant growth. Mixing foliar K sources with glyphosate also did not generally cause increased plant injury compared to the application of foliar K sources without glyphosate. Based on the results of the greenhouse study and prior research (Nelson et al., 2007), growers may wish to avoid use of potassium carbonate

as a foliar K source especially when mixed with glyphosate. Mixing potassium carbonate with glyphosate caused elevated leaf injury and also may reduce the efficacy of the glyphosate for weed control. In general, this research has confirmed that K sources can be mixed with glyphosate and applied as part of a post-emergence weed control program with little negative agronomic effects. In addition, relatively inexpensive and widely available K fertilizer sources, such as potassium chloride, are just as effective as the other possibly more expensive K sources tested in this research,

2. The effect of foliar K fertilizer application mixed with and without glyphosate on plant growth was inconsistent both under controlled conditions in the greenhouse and in the field studies. Conditions that were hypothesized to favor plant K response to foliar K applications (e.g., low initial soil test K, low soil water content and WFPS, and high soil bulk density due to compaction) did not promote increased plant growth response and K uptake as expected. These results possibly demonstrate that other natural and management-induced factors (e.g., nematode infestation, time and weather associated with the foliar K application) may have a greater influence on soybean response to foliar K application. Additional research may be needed to investigate which factors under field conditions have the greatest influence on K deficiency and also which soil, plant physiological and climate factors affect plant K uptake when foliar K is applied.
3. The inhibitory effects of applying glyphosate on soybean Mn concentration were confirmed in the field studies. In addition, inconsistent effects of

applying glyphosate on reducing Zn and B concentrations were also observed. These results suggest that additional research may be needed to develop management practices to overcome the reduction in micronutrient uptake caused by glyphosate.

4. The development of rapid, in-field methods to detect nutrient deficiency during the growing season would assist growers to make timely management decisions related to K fertilizer application. In this research, a method based on changes in leaf color measured with a hand-held chlorophyll meter was tested in the greenhouse. Visual symptoms of K deficiency in soybean usually begins as yellowing at the edge of older leaves and, therefore, chlorophyll readings were compared when taken at the leaf center and leaf margins. Results for this study did not show significant relationships between the chlorophyll reading and K concentration in plant tissue. The failure of this relationship to develop was attributed to taking the chlorophyll readings from the most recent fully developed leaf at the top of each plant where the K deficiency symptoms may not have yet occurred due to the relative immaturity of the plant when readings were taken. Subsequent research may need to examine chlorophyll readings in older leaves or in more mature plants in the field.

The adoption of foliar K fertilization mixed with glyphosate as part of a post-emergence weed control program for soybeans may not depend on consistent annual yield improvement since growers may be willing to add K or other nutrients to glyphosate if some yield advantage occurs periodically and if weed control provided by glyphosate is not reduced by the addition of the K source. Longer term field experiments and in different locations in Missouri in which foliar K is applied with glyphosate may be needed to determine if any long-term yield advantage can occur under a variety of field and environmental conditions. In addition, further research may be needed to identify those conditions which promote response to foliar K applications and to develop rapid in-field and in-season tests that will allow growers to make informed decisions on when response to foliar K is likely to occur.

# APPENDICES

Appendix 1. The effects of different foliar potassium fertilizer sources that were mixed and applied with and without glyphosate on soybean leaf nutrient content fourteen days after application at the site in Northeast Missouri in 2004.

| | | Mg | | | Ca | | | S | | | Fe | | | Cu | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K source | Rate | -[†] | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ |
| | kg K ha$^{-1}$ | ---% | | | | | | | | | ---ppm | | | | | |
| Control | 0 | 0.30 | 0.29 | NS | 1.24 | 1.15 | 0.07 | 0.30 | 0.28 | 0.01 | 101.57 | 87.46 | 12.83 | 11.65 | 9.97 | 1.62 |
| 0-0-62[††] | 2.2 | 0.30 | 0.27 | 0.01 | 1.23 | 1.08 | 0.10 | 0.31 | 0.28 | 0.01 | 101.15 | 84.40 | NS | 11.93 | 10.05 | 1.40 |
| | 8.9 | 0.30 | 0.27 | NS | 1.27 | 1.11 | NS | 0.31 | 0.28 | NS | 104.40 | 98.48 | NS | 12.49 | 11.43 | NS |
| | 17.9 | 0.32 | 0.25 | 0.05 | 1.23 | 1.05 | 0.16 | 0.30 | 0.27 | 0.02 | 106.85 | 102.18 | NS | 12.24 | 10.54 | 1.43 |
| 3-18-18 | 2.2 | 0.31 | 0.28 | NS | 1.26 | 1.14 | NS | 0.31 | 0.30 | NS | 109.74 | 90.23 | 10.47 | 11.74 | 10.41 | 0.81 |
| | 8.9 | 0.32 | 0.28 | NS | 1.26 | 1.14 | NS | 0.30 | 0.29 | NS | 98.30 | 92.62 | NS | 10.27 | 9.70 | NS |
| | 17.9 | 0.31 | 0.27 | NS | 1.24 | 1.11 | NS | 0.30 | 0.28 | NS | 98.81 | 85.61 | 11.25 | 10.85 | 9.56 | NS |
| 5-0-20 | 2.2 | 0.32 | 0.27 | NS | 1.31 | 1.07 | NS | 0.30 | 0.30 | NS | 105.16 | 89.31 | NS | 11.03 | 10.65 | NS |
| | 8.9 | 0.30 | 0.27 | NS | 1.25 | 1.07 | NS | 0.31 | 0.30 | NS | 94.41 | 90.39 | NS | 12.03 | 10.57 | 0.65 |
| | 17.9 | 0.30 | 0.27 | NS | 1.20 | 1.09 | NS | 0.30 | 0.29 | NS | 90.44 | 84.97 | NS | 11.77 | 9.98 | NS |
| 0-0-25 | 2.2 | 0.30 | 0.29 | NS | 1.16 | 1.10 | NS | 0.31 | 0.28 | 0.03 | 96.84 | 84.90 | 10.86 | 12.29 | 9.61 | 2.35 |
| | 8.9 | 0.31 | 0.27 | NS | 1.25 | 1.09 | 0.15 | 0.31 | 0.29 | NS | 96.11 | 89.47 | NS | 12.52 | 10.18 | 1.61 |
| | 17.9 | 0.30 | 0.27 | 0.02 | 1.23 | 1.06 | 0.06 | 0.30 | 0.30 | NS | 96.10 | 88.86 | NS | 11.54 | 10.18 | 0.68 |
| DMRT$_{(0.05)}$ | | NS | 0.03 | | NS | 0.09 | | NS | 0.02 | | 13.25 | NS | | 1.61 | 1.27 | |

[†] Minus sign (-) indicates plots that were maintained weed free and foliar K sources were sprayed without glyphosate. Plus sign (+) indicates when glyphosate was mixed with foliar K source and sprayed on to plots with weeds.

[††] Fertilizer sources included 0-0-62 (potassium (K) chloride), 3-18-18 (K phosphate + urea, NA-CHURS/ALPINE), 5-0-20 (K thiosulfate + urea-triazone, Trisert-K+, Tessenderlo Kerley), and 0-0-25 (K thiosulfate). All tank mixtures with glyphosate included non-ionic surfactant.

Appendix 2. The effects of different foliar potassium fertilizer sources that were mixed and applied with and without glyphosate on soybean leaf nutrient content fourteen days after application at the site in Northeast Missouri in 2005.

| | | Mg | | | Ca | | | S | | | Fe | | | Cu | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K source | Rate | -[†] | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ |
| | kg K $ha^{-1}$ | % | | | | | | | | | ppm | | | | | |
| Control | 0 | 0.27 | 0.29 | NS | 0.99 | 0.98 | NS | 0.26 | 0.28 | NS | 71.52 | 76.34 | NS | 8.66 | 7.60 | 1.03 |
| 0-0-62[††] | 2.2 | 0.29 | 0.30 | NS | 0.98 | 1.07 | NS | 0.27 | 0.28 | NS | 80.86 | 71.82 | NS | 8.81 | 7.55 | NS |
| | 8.9 | 0.30 | 0.31 | NS | 0.95 | 1.01 | 0.06 | 0.28 | 0.28 | 0.02 | 78.95 | 69.91 | NS | 9.41 | 7.65 | 0.76 |
| | 17.9 | 0.30 | 0.31 | NS | 0.99 | 1.02 | NS | 0.26 | 0.27 | NS | 65.67 | 76.25 | NS | 8.61 | 7.93 | 0.64 |
| 3-18-18 | 2.2 | 0.29 | 0.30 | NS | 1.01 | 1.03 | NS | 0.25 | 0.30 | NS | 70.33 | 72.55 | NS | 8.49 | 7.95 | NS |
| | 8.9 | 0.28 | 0.29 | NS | 1.06 | 0.99 | NS | 0.26 | 0.29 | NS | 73.62 | 95.45 | NS | 9.26 | 8.14 | NS |
| | 17.9 | 0.29 | 0.30 | NS | 0.94 | 1.00 | NS | 0.27 | 0.28 | NS | 71.18 | 96.16 | NS | 9.15 | 8.24 | NS |
| 5-0-20 | 2.2 | 0.28 | 0.29 | NS | 0.93 | 1.04 | NS | 0.26 | 0.30 | NS | 61.78 | 66.99 | NS | 8.62 | 7.70 | 0.25 |
| | 8.9 | 0.28 | 0.28 | NS | 0.97 | 1.01 | NS | 0.26 | 0.30 | NS | 83.67 | 78.48 | NS | 8.74 | 7.60 | 0.65 |
| | 17.9 | 0.28 | 0.30 | NS | 0.97 | 1.03 | NS | 0.25 | 0.29 | NS | 69.64 | 70.27 | NS | 8.96 | 7.58 | 0.78 |
| 0-0-25 | 2.2 | 0.28 | 0.30 | NS | 0.90 | 0.99 | NS | 0.28 | 0.28 | 0.02 | 69.61 | 80.01 | NS | 9.14 | 7.59 | 0.29 |
| | 8.9 | 0.29 | 0.30 | NS | 0.94 | 0.99 | NS | 0.28 | 0.29 | NS | 70.63 | 85.28 | NS | 9.09 | 7.90 | NS |
| | 17.9 | 0.30 | 0.28 | NS | 0.94 | 1.04 | NS | 0.28 | 0.30 | 0.02 | 67.04 | 74.04 | NS | 9.15 | 7.70 | 0.53 |
| $DMRT_{(0.05)}$ | | NS | NS | | 0.12 | NS | | 0.02 | NS | | 19.39 | NS | | 0.75 | NS | |

[†] Minus sign (-) indicates plots that were maintained weed free and foliar K sources were sprayed without glyphosate. Plus sign (+) indicates when glyphosate was mixed with foliar K source and sprayed on to plots with weeds.

[††] Fertilizer sources included 0-0-62 (potassium (K) chloride), 3-18-18 (K phosphate + urea, NA-CHURS/ALPINE), 5-0-20 (K thiosulfate + urea-triazone, Trisert-K+, Tessenderlo Kerley), and 0-0-25 (K thiosulfate). All tank mixtures with glyphosate included non-ionic surfactant.

Appendix 3. The effects of different foliar potassium fertilizer sources that were mixed and applied with and without glyphosate on soybean leaf nutrient content fourteen days after application at the site in Southeast Missouri in 2004.

| | | Mg | | | Ca | | | S | | | Fe | | | Cu | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K source | Rate | -[†] | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ | - | + | $DMRT_{(0.05)}$ |
| | kg K $ha^{-1}$ | ---% | | | | | | | | | ---ppm | | | | | |
| Control | 0 | 0.56 | 0.57 | NS | 1.25 | 1.26 | NS | 0.25 | 0.27 | NS | 218.30 | 117.48 | NS | 12.16 | 9.89 | NS |
| 0-0-62[††] | 2.2 | 0.54 | 0.59 | NS | 1.20 | 1.30 | NS | 0.26 | 0.25 | NS | 184.29 | 167.33 | NS | 9.58 | 9.70 | NS |
| | 8.9 | 0.55 | 0.54 | NS | 1.23 | 1.14 | NS | 0.26 | 0.24 | NS | 183.38 | 167.40 | NS | 9.33 | 9.54 | NS |
| | 17.9 | 0.56 | 0.51 | NS | 1.24 | 1.12 | 0.11 | 0.25 | 0.26 | NS | 173.94 | 166.47 | NS | 10.69 | 10.26 | NS |
| 3-18-18 | 2.2 | 0.56 | 0.55 | NS | 1.21 | 1.24 | NS | 0.27 | 0.26 | NS | 146.13 | 126.67 | NS | 10.67 | 10.80 | NS |
| | 8.9 | 0.54 | 0.58 | NS | 1.17 | 1.31 | NS | 0.27 | 0.27 | NS | 156.69 | 124.87 | NS | 10.11 | 11.11 | NS |
| | 17.9 | 0.55 | 0.55 | NS | 1.17 | 1.17 | NS | 0.25 | 0.27 | NS | 187.89 | 159.18 | NS | 10.30 | 10.12 | NS |
| 5-0-20 | 2.2 | 0.50 | 0.54 | NS | 1.10 | 1.15 | NS | 0.26 | 0.25 | NS | 170.45 | 154.97 | NS | 11.17 | 10.14 | NS |
| | 8.9 | 0.52 | 0.57 | 0.04 | 1.14 | 1.21 | NS | 0.27 | 0.25 | NS | 141.02 | 148.42 | NS | 10.20 | 10.39 | NS |
| | 17.9 | 0.58 | 0.56 | NS | 1.24 | 1.15 | NS | 0.26 | 0.26 | NS | 129.42 | 125.62 | NS | 9.93 | 10.98 | NS |
| 0-0-25 | 2.2 | 0.56 | 0.57 | NS | 1.20 | 1.20 | NS | 0.27 | 0.25 | NS | 211.10 | 183.45 | NS | 11.00 | 10.16 | NS |
| | 8.9 | 0.58 | 0.54 | NS | 1.18 | 1.12 | NS | 0.25 | 0.26 | NS | 216.31 | 183.22 | NS | 9.72 | 10.04 | NS |
| | 17.9 | 0.55 | 0.58 | 0.02 | 1.18 | 1.27 | 0.05 | 0.26 | 0.26 | NS | 154.34 | 124.89 | NS | 10.76 | 10.51 | NS |
| $DMRT_{(0.05)}$ | | 0.06 | 0.07 | | NS | 0.19 | | NS | NS | | NS | NS | | NS | NS | |

[†] Minus sign (-) indicates plots that were maintained weed free and foliar K sources were sprayed without glyphosate. Plus sign (+) indicates when glyphosate was mixed with foliar K source and sprayed on to plots with weeds.

[††] Fertilizer sources included 0-0-62 (potassium (K) chloride), 3-18-18 (K phosphate + urea, NA-CHURS/ALPINE), 5-0-20 (K thiosulfate + urea-triazone, Trisert-K+, Tessenderlo Kerley), and 0-0-25 (K thiosulfate). All tank mixtures with glyphosate included non-ionic surfactant.

Appendix 4. The effects of different foliar potassium fertilizer sources that were mixed and applied with and without glyphosate on soybean leaf nutrient content fourteen days after application at the site in Southeast Missouri in 2005.

| | | Mg | | | Ca | | | S | | | Fe | | | Cu | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K source | Rate | -[†] | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ | - | + | DMRT$_{(0.05)}$ |
| | kg K ha$^{-1}$ | % | | | | | | | | | ppm | | | | | |
| Control | 0 | 0.49 | 0.54 | 0.02 | 1.09 | 1.22 | NS | 0.30 | 0.28 | NS | 110.88 | 86.21 | NS | 9.17 | 8.99 | NS |
| 0-0-62[††] | 2.2 | 0.53 | 0.46 | NS | 1.14 | 1.06 | NS | 0.28 | 0.29 | NS | 87.71 | 99.45 | NS | 9.07 | 9.11 | NS |
| | 8.9 | 0.46 | 0.50 | NS | 1.01 | 1.08 | NS | 0.29 | 0.29 | NS | 104.00 | 92.28 | NS | 9.26 | 9.14 | NS |
| | 17.9 | 0.47 | 0.46 | NS | 1.08 | 1.08 | NS | 0.29 | 0.27 | NS | 94.51 | 81.33 | 10.64 | 8.90 | 8.73 | NS |
| 3-18-18 | 2.2 | 0.52 | 0.49 | NS | 1.17 | 1.11 | NS | 0.27 | 0.28 | NS | 84.86 | 91.59 | NS | 8.77 | 9.22 | NS |
| | 8.9 | 0.50 | 0.51 | NS | 1.08 | 1.09 | NS | 0.30 | 0.29 | NS | 92.68 | 84.68 | NS | 9.09 | 9.16 | NS |
| | 17.9 | 0.49 | 0.54 | NS | 1.12 | 1.15 | NS | 0.28 | 0.27 | NS | 86.56 | 81.45 | NS | 8.59 | 9.30 | NS |
| 5-0-20 | 2.2 | 0.52 | 0.51 | NS | 1.14 | 1.15 | NS | 0.29 | 0.28 | NS | 83.00 | 84.28 | NS | 9.19 | 8.99 | NS |
| | 8.9 | 0.48 | 0.51 | NS | 1.08 | 1.16 | NS | 0.30 | 0.28 | NS | 87.03 | 92.76 | NS | 8.96 | 8.51 | NS |
| | 17.9 | 0.54 | 0.53 | NS | 1.18 | 1.20 | NS | 0.31 | 0.29 | NS | 100.75 | 89.75 | NS | 9.86 | 9.13 | NS |
| 0-0-25 | 2.2 | 0.51 | 0.50 | NS | 1.20 | 1.10 | NS | 0.28 | 0.29 | NS | 82.58 | 92.72 | NS | 9.05 | 8.71 | NS |
| | 8.9 | 0.53 | 0.50 | NS | 1.24 | 1.17 | NS | 0.27 | 0.28 | NS | 87.27 | 83.29 | NS | 8.83 | 10.12 | NS |
| | 17.9 | 0.56 | 0.55 | NS | 1.24 | 1.21 | NS | 0.29 | 0.28 | NS | 93.54 | 89.99 | NS | 8.96 | 9.05 | NS |
| DMRT$_{(0.05)}$ | | 0.07 | 0.07 | | 0.17 | NS | | NS | NS | | NS | 17.93 | | 1.08 | NS | |

[†] Minus sign (-) indicates plots that were maintained weed free and foliar K sources were sprayed without glyphosate. Plus sign (+) indicates when glyphosate was mixed with foliar K source and sprayed on to plots with weeds.

[††] Fertilizer sources included 0-0-62 (potassium (K) chloride), 3-18-18 (K phosphate + urea, NA-CHURS/ALPINE), 5-0-20 (K thiosulfate + urea-triazone, Trisert-K+, Tessenderlo Kerley), and 0-0-25 (K thiosulfate). All tank mixtures with glyphosate included non-ionic surfactant.

# VITA

Sutham Phurahong was born in Bangkok, Thailand. He received his B.S. degree in Environmental Science from Kasetsart University in 1997. After graduation, he plans to return to Thailand to work in mushroom production in Changmai in Northern Thailand.