IMPROVING CORN AND SOYBEAN YIELD THROUGH FERTILITY AND WEED MANAGEMENT PRACTICES

by

NATHAN D. MUELLER

B.S., University of Nebraska-Lincoln, 2005
M.S., University of Nebraska-Lincoln, 2007

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agronomy
College of Agriculture

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Manhattan, Kansas

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Abstract

Winter annual weeds (WAW) could affect nitrogen supply for corn production. The objectives of first study were to determine the diversity and abundance of WAW and to evaluate the effect of delaying herbicide applications on nitrogen supply and no-till corn response. Research was conducted in 2010 and 2011 at 14 sites in eastern Kansas. A factorial arrangement of three herbicide application dates (Nov.-Mar., April, and May) and five N rates were used. The three most abundant WAW across sites were henbit, purslane speedwell, and horseweed. Delaying herbicide application until April significantly reduced early corn N uptake by 52 mg N plant^{-1}, chlorophyll meter readings at silking by 3.4%, and grain yield by 0.48 Mg ha^{-1} across sites. An additional 16 to 17 kg N ha^{-1} was needed to maintain yield if herbicide application was delayed until April. Starter and foliar micronutrient fertilization can potentially increase corn and soybean yield. The objectives of the second study were to evaluate crop response from combinations of starter and foliar fertilizers that contain N-P-K mixtures with and without a blend of micronutrients at four sites for each crop under irrigated conditions. No early corn growth or yield increase was attributed to application of micronutrients (Fe, Mn, Zn, Cu, and B) beyond what was achieved with N-P-K starter fertilization. There was an increase in soybean height (8 cm) and yield (293 kg ha^{-1}) with starter fertilizer containing N-P-K plus micronutrients over the control. No increase in corn or soybean yield was obtained with foliar fertilization. The objective of the third study was to compare soil mobility and changes in soybean nutrient concentration in the leaf and seed from Mn and Zn sources (EDTA and oxysulfate) at two sites. Zinc sources were more mobile in the soil. Both Zn sources increased seed Zn concentration. Manganese oxysulfate increased seed Mn concentration. However, soybean trifoliolate leaf and

seed Mn concentration decreased with soil-applied Na_2EDTA and MnEDTA. This response was attributed to formation of FeEDTA and increased Fe supply that reduced root Mn absorption. Manganese EDTA is not recommended for soil application.

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Chapter 1 - Introduction

Corn and soybean growth and yield can be regulated by numerous factors, including competition with weeds. Weeds have remained a significant problem in row-crop production agriculture despite changes in crop rotations, tillage systems, and weed control measures due to the change in weed communities and biotypes. In Kansas, there is a shift towards planting more corn and soybean and less wheat and sorghum along with increasing adoption of no-till. Winter annual weeds (WAW) are well-adapted in the no-till corn-soybean rotation and are considered indicator species of this tillage and cropping system. More winter fallow periods exist without winter wheat in rotation, less soil disturbance, use of herbicides like glyphosate that have no residual soil activity, and late spring weed control in April and May are selection pressures on weed communities that likely explain the increasing abundance of WAW in eastern Kansas. The abundance of WAW may have negative impacts such as less suitable seedbed conditions for no-till planting, increased damage from insects and soybean cyst nematodes (SCN), and decreased yields. However, little is known about how significant WAW N use can be on corn yields when additional N fertilizer is not applied above the optimum rate. Further, WAW community composition and characterization has not been assessed in the western Corn Belt and Great Plains. This has implications since some weed species serve as an alternative host for SCN, which is considered the most damaging soybean pathogen in the United States. Therefore, a survey was performed to measure the diversity and abundance of WAW (Chapter 2), and field trials and to quantify the affect WAW can have on the N supply for no-till corn in eastern Kansas (Chapter 3). Results of the survey and trials will provide practical information for extension staff in making weed management recommendations and will aid producers in making decisions that have a positive impact on their farm.

In efforts to maximize net profits, producers try to minimize factors that limit yield. However, maximizing yield may not lead to maximizing profits. It is this point of contention that producers must deal with when making management decisions not only for the entire farm, but individual fields and even locations within a field. High commodity prices can create interest in practices that have potential for generating small yield increases while still returning a profit. The uses of various fertilizer application strategies, fertilizer sources, and plant essential nutrients to achieve maximum yields and enhance nutrient use efficiency have been proposed. Micronutrient (Fe, Mn, Zn, Cu, B, Cl, and Mo) fertilization has been receiving renewed attention. Micronutrients are needed by plants in relative small amounts that could feasibly be applied with N-P or N-P-K starter fertilizers or applied as a foliar fertilizer. Based on our current knowledge of nutrient deficiencies and frequency of occurrence in Kansas, the likelihood of increasing corn yield with micronutrient fertilizer is higher for Zn, Cl, and Fe and lower for B, Mn, Cu, Mo, and Ni. For soybean, it is higher for Fe and Zn and lower for Mo, Mn, B, Cu, and Cl. There are many sources or forms of micronutrients available commercially. Previous research has shown that the form of nutrient, like $MnSO_4$ versus MnEDTA, can impact soybean yield response. As a result of renewed interest in micronutrients and need for continued assessment of soil fertility practices, a study (Chapter 4) was designed to evaluate corn and soybean response to combinations of starter and foliar fertilization that contain N-P-K with and without a blend of micronutrients (Fe, Mn, Zn, Cu, and B) under irrigated conditions in Kansas. A second study (Chapter 5) was implemented to compare the effects of two fertilizer sources (oxysulfate and EDTA) for each Mn and Zn have on soil mobility and soybean nutrient concentration in field small-plot trials. Results of these studies will provide new local data on the potential yield response in corn and soybean from micronutrient fertilization.

Chapter 2 - Winter Annual Weed Community Composition and Characterization of No-Till Fields in Kansas

ABSTRACT

The prevalence of winter annual weeds (WAW) particularly in a no-till corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation may lead to negative impacts such as less suitable seedbed conditions at planting, increased damage from insects and soybean cyst nematodes (SCN) (*Heterodera glycines*), and decreased yields. The objective of this survey was to determine the WAW community composition and density and species richness, evenness, and Shannon-Weiner Index of diversity at each site and to determine the abundance of species. Fourteen sites with naturally-occurring populations of WAW in eastern Kansas were surveyed in March through early April in 2010 and 2011. A total of 25 of the 29 weed species indentified were dicots and the largest represented family was Brassicaceae with eight species. The mean density of all weeds across 14 sites was 214 plants m^{-2} while the dicot density was 201 plants m^{-2}. The median species richness per site was seven and species evenness was less than 0.50 at all but three sites. The five most abundant WAW species were henbit (*Lamium amplexicaule* L.), purslane speedwell (*Veronica peregrina* L.), horseweed [*Conyza canadensis* (L.) Cronq], field pennycress (*Thlaspi arvense* L.), and common chickweed [*Stellaria media* (L.) Vill.] with abundance index values of 360.0, 104.7, 88.8, 87.6, and 58.8, respectively. This survey provided data which were not previously available and can be used to track future changes in WAW communities found in no-till corn-soybean rotations in Kansas.

Abbreviations: AMF, arbuscular mycorrhizae fungi; H′ Shannon-Weiner Index of diversity; RA, relative abundance; SCN, soybean cyst nematode; WAW, winter annual weed(s).

INTRODUCTION

Winter annual weeds are well-adapted in the no-till corn-soybean rotation. *Lamium* spp. and *Veronica* spp. are considered indicator species of no-till systems (Sosnoskie et al., 2009). This cropping system creates a niche that favors winter annual broadleaf species (Derksen et al., 2002; Creech and Johnson, 2006). Winter fallow, use of herbicides without residual soil activity, and late spring weed control are some of the selection pressures on weed species in the no-till system. Winter annuals weeds can be obligate (fall germination only) or facultative (fall or early spring germination) species. For example, horseweed (Davis and Johnson, 2008), henbit (Baskin and Baskin, 1981), and field pennycress (Venkatesh et al., 2000) are facultative species while purple deadnettle (*Lamium purpureum* L.) (Baskin et al., 1986) is an obligate WAW. However, some perennials, biennials, and early emerging summer annuals can behave like winter annuals in this cropping and tillage system. For this reason, this group of weeds is sometimes referred to as early spring weeds in no-till production (Fishel et al., 2000).

The presence or absence of WAW can affect both biotic and abiotic factors in the field. Assessment of WAW community composition and characterization is important since some WAW serve as an alternative host for SCN, which is considered the most damaging soybean pathogen in the United States (Wrather and Koenning, 2006). Soybean cyst nematodes are primarily distributed in eastern and south central Kansas (Jardine and Todd, 2001). Winter annual weeds can also be utilized by black cutworm moths [*Agrotis ipsilon* (Hufnagel)] as sites of ovipostion, thus increasing potential for seedling corn damage from larvae (Monnig et al., 2007). Additionally, WAW slow the warming of soil at planting time (Monnig et al., 2007) and reduces yield (Mannam et al., 2008). However, the positive ecological role that WAW can play in a cropping system that lacks crop diversity cannot be ignored. Some benefits of WAW compared to a winter fallow can be increased residue cover, reduced erosion, and increased arbuscular mycorrhizae fungi (AMF) root colonization on corn and soybean. Overwintering survival of AMF is favored by attachment to living roots (Kabir et al., 1997). Therefore, WAW can benefit corn and soybean production by serving as host species for AMF during the winter fallow period and thus maintain the diversity and abundance of beneficial AMF. The positive effects of increased AMF on growth and yield can be attributed to improved nutrient uptake (Feldmann and Boyle, 1999; Kabir and Koide, 2000), tolerance to water stress (Sylvia et al., 1993), and overall plant health. Winter annuals belonging to the Brassicaceae family, however are non-hosts of AMF due to the production of antifungal compounds in the roots (Schreiner and Koide, 1993).

Surveys that determine community composition and characterization of WAW in the western Corn Belt and the Great Plains of the United States are lacking. The prevalence of broadleaf WAW is known in the eastern Corn Belt through a survey by Creech and Johnson (2006). Weeds have remained a significant problem in production agriculture despite changes in crop rotations, tillage systems, and weed control measures which is attributed to the change in weed communities (Sosnoskie et al., 2006). From 2001 to 2012, a shift towards planting more corn and soybean and less wheat and grain sorghum has been occurring in Kansas (USDA-NASS, 2011; USDA-NASS, 2012). Surveys are useful tools to track changes in the prevalence of weed species over time (Webster and Nichols, 2012). The relative abundance (RA) method by Thomas (1985) is widely used to calculate the abundance of a weed based on calculations of its relative frequency, relative uniformity, and mean density (Creech and Johnson, 2006; Moeini et al., 2008; Uddin et al., 2010). Another method, the abundance index by Moeini et al. (2008) places more emphasis on the absolute frequency and uniformity of a species, with less weight on mean density. Species richness, evenness, and Shannon-Weiner Index of diversity can be additional measures to characterize a community of species (Creech and Johnson, 2006; Sosnoskie et al., 2006).

The objective of the study was to determine the WAW community composition and density and calculate measures for description and characterization.This study provides data for tracking future changes in fields dedicated to the no-till corn-soybean rotation in Kansas. Additionally, these data will be used to assess future research needs in the area of WAW management and extension activities.

MATERIALS AND METHODS

Sites Surveyed and Sampling Scheme

Fourteen sites with naturally-occurring populations of WAW were surveyed in eastern and south-central Kansas during March and April of 2010 and 2011 (Table 2-1). This survey was conducted late in the spring following soybean harvest prior to corn planting to capture WAW with facultative germination. All sites were under rainfed conditions where producers were using no-till practices. At each site, 45 plots (dimensions were 3 by 15 plots or 5 by 9 plots for a total area of 3146 m^2) were established where plot size was 4.6 by 15.2 m, except Site 8 where it was 3.0 by 15.2 m. Fifteen out of 45 plots were randomly selected *a priori*. A 1 m by 1 m frame was placed in two predetermined locations within each plot. The square frame was divided into nine small 0.11 m^2 grids and two grids in each frame were utilized to determine weed density (plants

m^{-2}) and species composition. Therefore, four subsamples were collected from each plot. Total area used to assess density and composition was 6.7 m^2 at each site.

Data Analysis

Weed density and species composition data from 14 sites were used to calculate additional quantitative measurements in order to determine importance of individual species in eastern Kansas. Equations from Thomas (1985) were used to calculate frequency, uniformity, mean density, and RA. The frequency of a particular species was the number of sites in which a species occurred divided by the total number of surveyed sites (n=14) expressed as a percentage. The uniformity of a particular species was the number of total plots (maximum of 15 plots by 14 sites = 210 plots) in which a species occurred divided by the total plots surveyed expressed as a percentage. The mean density of a particular species was determined by summing the density of a species from each site divided by the total number of sites surveyed. The RA of a particular species was determined by summing relative frequency, relative uniformity, and relative mean density together to generate a single value. These relative values were determined by using the frequency, uniformity, or mean density of a particular species divided by the summation of all species frequency, uniformity, or mean density. The abundance index method proposed by Moeini et al. (2008) was also calculated. The abundance index of each species was determined by adding frequency, uniformity, and mean density together. Therefore, the abundance index is not in relative terms as proposed by Thomas (1985).

The species richness, species evenness, and Shannon-Weiner Index of diversity (H′) were determined to help characterize the weed community at each site. Species richness is the total number of species at each site. The Shannon-Weiner Index of diversity (Shannon, 1948) was estimated by:

$$H' = -\Sigma P_i(\mathrm{Ln}\ P_i) \quad [1]$$

and

$$P_i = N_i/N_{total} \quad [2]$$

where N_i = number of individuals of species *i* and the N_{total} = total number of individuals (of all species) per site. P_i is the probability of state *i*. Evenness for each site is H′ divided by the natural log of species richness. The weed density and species evenness were not transformed prior to these calculations.

RESULTS AND DISCUSSION

Weed Species and Diversity

A total of 29 weed species and one volunteer crop species were identified during the survey in 2010 and 2011 (Table 2-2). Of the 29 weed species, four were monocots all in the Poaceae family and 25 were dicots in 14 families. Volunteer winter wheat was one of the winter annuals identified at three sites. Site 1 was the only surveyed site where a corn-wheat-double crop soybean rotation was being used and where winter wheat densities were high, likely from harvest losses (Table 2-1). The largest represented family was Brassicaceae with eight species, followed by four in Poaceae, three in Asteraceae, three in Carophyllaceae, two in Scrophulariaceae, and one in nine other families.

The mean density across the 14 sites was 214 plants m^{-2} and a broadleaf density of 201 plant m^{-2}. Grasses did not make up a large percentage of the weed density except at Sites 1 (volunteer wheat), 8, and 10. The average broadleaf WAW density across 55 sites in Indiana was

120 plants m^{-2} in a survey by Creech and Johnson (2006). Some sites in that study were surveyed after tillage and herbicide treatment that may have resulted in lower broadleaf WAW density.

The density and composition of the WAW community at each site was used to determine diversity, which takes into account both species richness and species evenness. Species richness varied from one to 14 across surveyed sites (Table 2-3) with a mean of 7.2 and median of 7. Creech and Johnson (2006) found the broadleaf WAW species richness varied from one to 14 per site with most sites containing four to nine species as was found in our survey. Species evenness can range from 0 to 1, with 1 representing a weed community where all species are equally abundant. All but three sites had an evenness value below 0.50, which suggest most sites were dominated by two to three species, with the remaining species being found at low densities. This is typical of agricultural weed communities (Clements et al., 1994).

Thymeleaf sandwort (*Arenaria serpyllifolia* L.), common whitlow-grass (*Draba reptans* (Lam.) Fernald), yellow woodsorrel (*Oxalis stricta* L.), and annual bluegrass (*Poa annua* L.) were only found at Site 7. Site 7 had a coarser soil texture than other sites in the survey (Table 2-1). The significant variation in soil and environmental conditions at Site 7 from other sites may explain its increased richness, evenness, and diversity.

Winter Annual Weed Abundance

In 1898, henbit was not considered a problem weed in Kansas (Hitchcock and Clothier, 1898). In this current survey however, henbit was the only species that occurred at 100% of the surveyed sites and was determined to be the most abundant species in the survey by both the RA and abundance index methods (Table 2-4). Mean density across 14 sites was 165 henbit plants m^{-2}, with up to 373 plants m^{-2} at Site 2 (Table 2-3). Very high henbit densities have been reported before in fields (Creech et al., 2007). Henbit has been viewed as a problem weed by producers of corn and soybean (Gibson et al., 2005). No main dispersal method has been identified for henbit. Defelice (2005) determined in his review that henbit seed can remain viable for greater than 25 years and that seed production can be 200 to 2,000 per plant, which is relatively low compared to other weed species. However, the high density of henbit plants at surveyed sites would lead to significant annual contributions to the seed bank. Henbit has been and still is considered a troublesome weed in wheat production (Webster and Nichols, 2012), suggesting that henbit may have been relatively abundant prior to increased production areas dedicated to corn and soybean (USDA-NASS, 2011; USDA-NASS 2012). In Kansas, henbit was observed to germinate in standing corn in early September. Henbit can flower in Kansas as early as December in some years (Gates, 1931). It was observed during this survey that henbit flowered and produced seed by early April in Kansas. Baskin and Baskin (1984) have observed henbit producing seed prior to winter in Kentucky.

Purslane speedwell was the second most abundant species in the survey largely due to its high frequency and uniformity (Table 2-4). The two most abundant species (henbit and purslane speedwell) identified in this study have been considered indicator species of no-till systems in previous studies (Sosnoskie et al., 2009). However, speedwells (*Veronica* spp.) are considered to be less troublesome weeds than henbit (Webster and Nichols, 2012). Purslane speedwell is a facultative winter annual having both a fall and early spring germination pattern (Baskin and Baskin, 1983). Flowering and seed production occurs during spring. Previous surveys and studies have reported the prevalence of speedwells as a genus, not as individual species (Creech and Johnson, 2006; Sosnoskie et al., 2009; Webster and Nichols, 2012). If speedwells were grouped in this survey, the rank would be unchanged by both the RA and abundance index methods.

Horseweed and field pennycress changed in rank of abundance based on the index used. Field pennycress had a higher RA than horseweed, but not a higher abundance index (Table 2-4). Moeini et al. (2008) determined that the RA determined by Thomas (1985) was more affected by the mean density, while the frequency and uniformity were less influential, frequency and uniformity have a more significant role in determining the abundance index value. The frequency of occurrence was higher for horseweed than field pennycress, but field pennycress had higher uniformity and mean density. This supports interpretations of the RA and abundance index methods by Moeini et al. (2008). Field pennycress is facultative WAW as is henbit and purslane speedwell. Horseweed is a facultative WAW though a significant portion of horseweed densities in can be composed of spring-emerging plants (Davis and Johnson, 2008). Horseweed's life cycle extends into early summer in corn. However, the life-cycle of horseweed is very plastic and may not mature and produce seed until late summer in soybean fields (Davis and Johnson, 2008). Therefore, horseweeds can behave as a early emerging summer annual.

A WAW broadleaf survey in Indiana ranked common chickweed, henbit, and speedwells as the three most abundant weeds by the RA method (Creech and Johnson, 2006). These same three weeds ranked in the top six in abundance in our survey. Common chickweed ranked as the sixth most abundant weed by the RA method in our survey which suggests common chickweed is less abundant in eastern Kansas than it is in Indiana where it ranked first. The similarity in the most abundant species between the two surveys supports claims by Clements et al. (1994) who concluded that the number of weed species in an agricultural geographic region with temperate climates is relatively low and a few species tend to dominate.

Implications for Weed Management

Henbit has the ability to produce seed early in the spring before spring herbicide applications occur on fields being planted to corn and soybean. This may be contributing to its abundance over other species which take longer to complete their life cycles. Fall herbicide applications have been effective at controlling henbit (Krausz et al., 2003), which could help reduce seed production and abundance over time. In a 4–yr study, Harrison et al. (2008) found that absence of WAW that serve as hosts for SCN reduced SCN populations. Of the five most abundant WAW, henbit, field pennycress, and common chickweed have been confirmed as alternative hosts for SCN (Venkatesh et al., 2000). Henbit has been implicated to be the strongest host for the SCN Race 3 (Venkatesh et al., 2000), which is the most common race in Kansas (Jardine and Todd, 2001). Studies suggest that early fall or summer herbicide applications with residual activity lasting into the early fall to control WAW that serve as host for SCN are likely to be the most effective practices at reducing SCN populations (Harrison et al., 2008; Mock et al., 2010).

Horseweed has been considered an emerging troublesome weed especially in soybean production (Webster and Nichols, 2012) with biotypes possessing herbicide resistance to glycines (found in Kansas), photosystem II inhibitors, bipyridiliums, ureas and amides, and acetolactate synthase inhibitors (Heap, 2012) and potential resistance to 2,4-D (Kruger et al., 2010). Horseweed plants are prolific seed producers with long-distance wind seed dispersal capabilities and that germinate best at shallow depths in the soil (Nandula et al., 2006; Dauer et al., 2007; Davis and Johnson, 2008). These traits suggest the frequency of occurrence could be high in no-till fields and there is a potential for increasing abundance. Horseweed was the thirteenth most abundant weed species in 2004 in Indiana and was found to the fourth most relatively abundant species in our survey in 2010 and 2011. Populations of horseweed in Kansas have shown a facultative (fall or spring) germination pattern similar to other studies in the Corn Belt high life-cycle plasticity allowing it to behave as a summer annual (Davis and Johnson, 2008). Selection of herbicides for fall application should contain active ingredients that can provide residual activity to control spring emerging horseweed. Conducting spring herbicide applications earlier prior to bolting should help to improve control of horseweed (Loux et al., 2006).

CONCLUSION

The five most abundant WAW species in order from first to fifth were henbit, purslane speedwell, horseweed, field pennycress, and common chickweed when the abundance index method was used. However, the RA of horseweed was less than field pennycress. The abundance index method placed more emphasis on frequency and uniformity than did the RA method. The abundance of henbit and horseweed particularly appear to be problem. Henbit, which occurred at all survey sites, serves as a strong host for SCN Race 3, which is the most common race in eastern Kansas, suggesting it may be the most important alternative host in the cropping system. Horseweed is a problem due to its resistance to several herbicide modes of action in a no-till system reliant on herbicides. Further, horseweed does not complete its life cycle until summer, which increases its presence and competitiveness with corn and soybean compared to other WAW. Early fall herbicide applications with residual activity that last through early spring may help to reduce the potential negative effects that henbit, horseweed, and other WAW could have in the no-till corn-soybean rotation.

This study provided data for tracking future changes in WAW communities in fields dedicated to no-till corn-soybean rotation in Kansas. Future research needs in the area of WAW management should focus on henbit control timing effects on SCN populations and effectiveness of fall herbicide applications at providing residual control for spring emerging horseweeds. Extension activities should focus on species identification to facilitate improved management of problem WAW.

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TABLES

Table 2-1. Site information, predominant soil, crop rotation, and rainfall.

		Predominant soil			
Site	County	Series	Subgroup	Crop rotation†	Annual precipitation‡
					mm
			2010		
1	Franklin	Woodsen	Abruptic Argiaquolls	C-W-S	996
2	Jackson	Wymore	Aquertic Argiudolls	C-S	955
3	Jefferson	Grundy	Aquertic Argiudolls	C-S	972
4	Marshall	Wymore	Aquertic Argiudolls	C-S	835
5	Osage	Woodsen	Abruptic Argiaquolls	C-S (W)	949
6	Reno	Ost	Udic Argiustolls	C-S (W)	770
7	Riley	Belvue	Typic Udifluvents	C-S (W)	884
			2011		
8	Atchison	Grundy	Aquertic Argiudolls	C-S	924
9	Franklin	Woodsen	Abruptic Argiaquolls	C-S	996
10	Jefferson	Grundy	Aquertic Argiudolls	C-S	924
11	Jefferson	Grundy	Aquertic Argiudolls	C-S	924
12	Osage	Woodsen	Abruptic Argiaquolls	C-S (W)	949
13	Reno	Ost	Udic Argiustolls	C-S (W)	770
14	Riley	Smolan	Pachic Argiustolls	C-S (W)	884

† Crop Rotation: C-S-W, Corn-Wheat-Soybean (double-crop); C-S, Corn-Soybean; C-S (W); Corn-Soybean with a recent history (< 5 yrs) of wheat in rotation.

‡ Mean annual precipitation (30-yr norm, 1981-2010) from weather station within 20 km of each survey site.

Table 2-2. Scientific and common names of winter annual weeds from surveys in eastern Kansas of no-till corn fields following soybean in 2010 and 2011.

Scientific name	Common name	D/M†
annual bluegrass	*Poa annua* L.	M
bushy wallflower	*Erysimum repandum* L.	D
Carolina foxtail	*Alopecurus carolinianus* Walt.	M
Carolina geranium	*Geranium carolinianum* L.	D
catchweed bedstraw	*Galium aparine* L.	D
common chickweed	*Stellaria media* (L.) Vill.	D
common whitlow-grass	*Draba reptans* (Lam.) Fernald	D
corn gromwell	*Buglossoides arvensis* (L.) I.M. Johnston	D
corn speedwell	*Veronica arvensis* L.	D
cutleaf evening-primrose	*Oenothera laciniata* Hill	D
dandelion‡	*Taraxacum officinale* G.H. Weber ex Wiggers	D
downy brome	*Bromus tectorum* L.	M
field pansy	*Viola bicolor* Pursh	D
field pennycress	*Thlaspi arvense* L.	D
fleabanes	*Erigeron* spp.	D
flixweed	*Descurainia sophia* (L.) Webb. ex Prantl	D
henbit	*Lamium amplexicaule* L.	D
horseweed	*Conyza canadensis* (L.) Cronq	D
jagged chickweed	*Holosteum umbellatum* L.	D
little barley	*Hordeum pusillum* Nutt.	M
mousetail	*Myosurus minimus* L.	D
purslane speedwell	*Veronica peregrina* L.	D
shepherd's-purse	*Capsella bursa-pastoris* (L.) Medik.	D
smallflowered bittercress	*Cardamine parviflora* L.	D
tansy mustard	*Descurainia pinnata* (Walt.) Britt.	D
thymeleaf sandwort	*Arenaria serpyllifolia* L.	D
veiny pepperweed	*Lepidium oblongum* Small	D
western rock-jasmine	*Androsace occidentalis* Pursh	D
wheat§	*Triticum aestivum* L.	M
yellow woodsorrel	*Oxalis stricta* L.	D

† D, dicot (broadleaf); M, monocot (grass)

‡ Dandelion is a perennial but behaves as a winter annual under no-till corn-soybean rotations.

§ Volunteer wheat

Table 2-3. Density, occurrence, specie richness, species evenness, and Shannon-Weiner index of diversityfor winter annual weed communities at 14 sites from no-till corn fields following soybeans in eastern Kansas in 2010 and 2011.

	Site													
Common name	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	plants m^{-2}													
annual bluegrass							0.5							
bushy wallflower								3.2		0.9	0.3			
carolina foxtail	7.4													
carolina geranium							0.3			1.4			0.5	
catchweed bedstraw										0.6				
common chickweed							0.2	16.5	0.2	0.5	3.6	29.3		
common whitlow-grass							1.2							
corn gromwell								3.6		2.0				
corn speedwell							12.6	7.4				0.2		
cutleaf evening-primrose							2.3						1.1	0.3
dandelion	0.9					0.8	0.2		0.6		0.2			
downy brome												1.7		
field pansy								2.3		6.0				
field pennycress		23.0	1.2		52.0			10.2	0.6	4.8	0.3	1.5		
fleabanes	2.3													
flixweed/tansy mustard						8.4				0.5	6.0		0.5	0.2
henbit	1.2	373.1	233.4	216.9	170.7	77.6	57.0	12.5	128.6	141.0	300.0	161.9	199.8	239.0
horseweed	0.8					26.6	8.0	3.5	1.4		0.6	0.9	0.5	0.5
jagged chickweed							6.8							12.3
little barley								109.5		37.0	0.2			
mousetail	7.1													
purslane speedwell	89.0	18.0	0.5		2.3	1.5	5.9	1.8		8.3	3.5	1.5		
shepherd's-purse						0.2		0.3		3.9			5.9	0.5
smallflowered bittercress	14.4					30.5			2.6					
thymeleaf sandwort							20.4							
veiny pepperweed						0.6								
western rock-jasmine	1.1						5.3							
wheat	28.4				0.6				0.3					
yellow woodsorrel							5.1							
	Species richness, evenness, and diversity													
Species richness (S)	10.0	3.0	3.0	1.0	4.0	8.0	14.0	11.0	7.0	12.0	9.0	7.0	6.0	6.0
Species evenness (J)	0.58	0.36	0.04	-	0.44	0.6	0.68	0.57	0.12	0.45	0.12	0.3	0.12	0.13
Shannon-Weiner (H′)	1.33	0.39	0.05	0	0.61	1.24	1.8	1.36	0.24	1.11	0.26	0.59	0.21	0.24

Table 2-4. The frequency, uniformity, mean density, relative abundance, and abundance index of winter annual weeds from surveys in eastern Kansas from no-till corn fields following soybean.

Common name†	Frequency	Uniformity	Mean Density	Relative abundance	Abundance index
	——— % ———		plants m^{-2}		
henbit	100.0	94.8	165.2	122.3	360.0
purslane speedwell	71.4	23.8	9.5	22.2	104.7
field pennycress	57.1	23.8	6.7	18.9	87.6
horseweed	64.3	21.4	3.1	17.4	88.8
little barley	21.4	13.8	10.5	12.4	45.7
common chickweed	42.9	12.4	3.6	11.7	58.8
smallflowered bittercress	21.4	14.3	3.4	9.3	39.1
shepherd's-purse	35.7	8.1	0.8	8.0	44.6
tansy mustard/flixweed	35.7	6.7	1.1	7.7	43.5
dandelion	35.7	7.1	0.2	7.4	43.1
wheat	21.4	10.0	2.1	7.3	33.5
corn speedwell	21.4	8.6	1.4	6.5	31.4
jagged chickweed	14.3	9.0	1.4	5.6	24.7
cutleaf evening-primrose	21.4	6.2	0.3	5.1	27.9
carolina geranium	21.4	4.3	0.2	4.5	25.9
bushy wallflower	21.4	3.3	0.3	4.2	25.1
thymeleaf sandwort	7.1	7.1	1.5	4.0	15.7
field pansy	14.3	3.8	0.6	3.5	18.7
western rock-jasmine	14.3	2.9	0.5	3.1	17.6
corn gromwell	14.3	1.9	0.4	2.8	16.6
mousetail	7.1	4.3	0.5	2.6	11.9
carolina foxtail	7.1	2.9	0.5	2.2	10.5
fleabanes	7.1	2.9	0.2	2.0	10.2
yellow woodsorrel	7.1	2.4	0.4	1.9	9.9
common whitlow-grass	7.1	2.4	0.1	1.8	9.6
veiny pepperweed	7.1	1.9	<0.1	1.6	9.1
downy brome	7.1	1.4	0.1	1.5	8.7
catchweed bedstraw	7.1	0.5	<0.1	1.2	7.7
annual bluegrass	7.1	0.5	<0.1	1.2	7.7

† Species are ordered by relative abundance.

Chapter 3 - Winter Annual Weed Management Effects on Corn Nitrogen Supply and Yield

ABSTRACT

Management of winter annual weeds (WAW) can affect soil N supply and corn (*Zea mays* L.) production under no-till systems. The objective of this study was to evaluate the effect of delaying WAW herbicide applications on nitrogen availability and grain yield for no-till corn following soybean [*Glycine max* (L.) Merr.]. Field research was conducted in 2010 and 2011 at 14 sites with naturally-occurring populations of WAW in eastern Kansas. A factorial arrangement of three herbicide application dates (November–March, April, and May) and five N rates (0, 17, 34, 67, and 135 kg N ha^{-1}) was used to evaluate the interaction between weed management on N response. Corn plant population, soil nitrate-N, early corn N uptake, chlorophyll meter (CM) readings at silking, and grain yield were measured. There was no significant interaction between herbicide application date and N rate for all variables measured across site-years. Delaying herbicide application until April significantly reduced early corn N uptake by 52 mg N plant^{-1}, CM readings at silking by 3.4%, and grain yield by 0.48 Mg ha^{-1} across site-years. Using the N fertilizer equivalence values (based on CM readings and grain yield), an estimated additional 16 to 17 kg N ha^{-1} was needed if herbicide application were delayed until April. Producers can increase corn N uptake and grain yield for rainfed no-till corn following soybeans in eastern Kansas by applying herbicides on WAW prior to April.

Abbreviations: CM, chlorophyll meter; C/N ratio, carbon to nitrogen ratio; OM, organic matter; WAW, winter annual weed(s).

INTRODUCTION

Long-term research has shown that the no-till corn and soybean rotation in the U.S. Midwest is one of the most profitable cropping systems (Stanger et al., 2008). Tillage practices, crop rotations, and herbicides can influence the composition and abundance of weed species (Cardina et al., 2002). Winter annual weeds (WAW) such as henbit (*Lamium amplexicaule* L.) have been more associated with no-till systems (Cardina et al., 2002). The increasing prevalence of WAW may be due to the management practices used in the no-till corn-soybean rotation (Nice and Johnson, 2005). Reduced tillage practices such as no-till, lack of winter crops in the rotation, use of herbicides without residual soil activity, and late spring weed control can create a niche that can favor some winter annual broadleaf species (Derksen et al., 2002). Winter annual weeds can have either obligate (fall) or facultative (fall or early spring) germination, but they typically complete their life cycle by spring. The life cycle of most WAW overlap with the early development stages of corn.

Many producers perceive WAW as an agronomic concern and addressing the management of WAW prior to planting corn in no-till systems is particularly important (Gibson et al., 2005). Studies suggest that dense stands of WAW can slow the warming of soil at planting time, cause allelopathic effects, increase damages from lepidopteron, and reduce corn yield (Vaughn et al., 2006; Monnig et al., 2007; Mannam et al., 2008). Several studies (Krausz et al., 2003; Nelson et al., 2006; Creech et al., 2008) have shown no yield reduction when herbicide application is delayed, but the single N rate used in these studies was either high (220 kg N ha^{-1}) or not stated; therefore, evaluating the effect of WAW on soil N supply and corn response is difficult. The uptake of N by WAW is a factor that may negatively affect corn yields when more N fertilizer is not added to reach the optimum rate. Improving our understanding of the relationship between WAW and N supply in no-till corn production may provide practical information for producers and industry professionals.

No studies have assessed the use of N by WAW and their ensuing effects on N supply for no-till corn in a corn-soybean rotation. Related no-till research in Georgia found that a WAW community composed primarily of henbit and cut-leaf evening primrose (*Oenothera laciniata* Hill.) can take up 17 to 36 kg N ha^{-1} (Sainju and Singh, 2001). The carbon to nitrogen (C/N) ratio in the aboveground biomass of a WAW community of henbit and cut-leaf evening primrose is 20 to 24 (Sainju et al., 2007). Ranells and Wagger (1997) determined that the C/N ratio of a henbit and chickweed (*Stellaria media* L.) mixture is 15, 22, and 24–37 during December, March, and April, respectively. When C/N ratios are below 25, the release of N occurs early in the decomposition process (Ranells and Wagger, 1997; Sainju and Singh, 2001). Sainju et al. (2007) found that WAW (predominately henbit and cut-leaf evening primrose) cause similar reductions in soil nitrate-N as a cereal rye (*Secale cereale* L.) winter cover crop. Most WAW are grasses and non-leguminous forbs. Winter annual weeds fill a similar seasonal niche as small grain winter cover crops in the corn-soybean rotation. Corn following small grain winter cover crops often requires more fertilizer N to achieve N uptake (Wagger, 1989; Clark et al., 2007a) and grain yield (Reinbott et al., 2004) comparable to corn grown with no cover crop. Ranells and Wagger (1997) found that WAWs had lower C/N ratios than cereal rye. The lower C/N ratio of WAW compared with cereal rye may allow for more rapid N mineralization from WAW residue and better synchrony of N release with corn N demand. Termination date of winter cover crops, and thus WAW, can have varied effects on soil moisture depending on climatic conditions (Stipesevic and Kladivko, 2005), which may affect processes related to the N supply (N mineralization, immobilization, leaching, and denitrification). Furthermore, direct immobilization of fertilizer N from cover crops may also occur (Wagger and Mengel, 1988).

Producers may delay the first herbicide application until near the date of corn planting to limit the number passes across the field and additional application cost. Winter annual weeds complete most of their vegetative growth and N uptake in the spring. Delaying herbicide applications for WAW control may lead to additional N use and higher C/N ratios of weed biomass. The objective of this study was to determine if delayed herbicide application on WAW affects N availability and grain yield for no-till corn following soybean.

MATERIALS AND METHODS

Field research was conducted in cooperation with producers and Kansas State University staff at 14 sites in the eastern half of Kansas in 2010 and 2011 (Table 3-1). All sites were rainfed no-till corn following soybeans. Sites were selected with naturally-occurring populations of WAW that were found in no-till fields. At each site, the experimental design was a two-factor (herbicide application date and N rate) factorial arrangement in a randomized complete block design with three replications. There were three different herbicide application dates at each site, including November through March (1), April (2), and May (3). The date of herbicide application for each treatment across sites ranged from 7 Nov. to 31 Mar., 1 April to 13 April, and 3 May to 26 May. For the Nov.–Mar. herbicide application date, herbicide was applied in March for Sites 1, 3, 5, 6, and 7, and to the remaining sites in Nov. and Dec. Within each site, more than 14 days separated herbicide application treatments. May herbicide applications were conducted after corn emergence prior to the V2 growth stage (Abendroth et al., 2011). Five N rates of 0, 17, 34, 67, and 135 kg N ha^{-1} were applied as broadcast urea immediately after the

May herbicide application date. Plot size was 4.5 by 15 m at all sites except at Site 8, where it was 3.0 by 15 m.

Herbicide for WAW control was applied with a CO_2 pressurized backpack sprayer adjusted to 0.1 MPa and diluted into 140 L ha^{-1} of water. The boom width was 2.3 m with 76-cm nozzle spacing and XR11003 Teejet flat fan nozzle tips (Spraying Systems Co., Wheaton, IL) were used. Ammonium sulfate was used as an adjuvant at 20 g L^{-1} water spray solution. In 2010, herbicide(s) used to control WAW consisted of glyphosate (*N*-(phosphonomethyl)glycine) at 0.86 kg a.i. ha^{-1} with or without 2,4-D ((2,4-dichlorophenoxy)acetic acid) at 0.53 kg a.i. ha^{-1} in accordance with the label recommendations depending on planting and emergence date of corn. In 2011, acetochlor (2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6-methylphenyl)acetamide) at 1.05 kg a.i. ha^{-1}, flumetsulam (*N*-(2,6-difluorophenyl)-5-methyl[1,2,4]triazolo[1,5-a]pyrimidine-2-sulfonamide) at 0.03 kg a.i. ha^{-1}, and clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) at 0.11 kg a.i. ha^{-1} were added to the tank mixture (glyphosate and 2,4-D).

Soil samples were collected before planting at the 0- to 15-cm depth from each block. Samples were analyzed for soil test P by Mehlich-3 colorimetric method (Frank et al., 1998) and K by ammonium acetate (Warncke and Brown, 1998). Soil organic matter (OM) was measured by the Walkley-Black Method (Combs and Nathan, 1998). Soil samples for nitrate-N were collected from each plot at the 0- to 60-cm depth when corn was at the V5–V7 growth stage in June and were measured with a 1 M KCl extraction (Gelderman and Beegle, 1998) using a Rapid Flow Analyzer (Alpkem, College Station, TX). Fertilizer P and K were applied based on soil test results using triple superphosphate and potassium chloride, respectively, following guidelines by Leikam et al. (2003).

Aboveground weed biomass was determined prior to the May herbicide application date outside the grain yield harvest area. A square 1-m^2 frame was placed in two predetermined areas within each plot (2 m from the front and 2 m from the back). The frame was divided into nine 0.11 m^2 grids and weed biomass samples were removed (cut at the soil surface) from two grids in the frame and placed in paper bags. Weed biomass samples were oven-dried at 60°C, weighed, and ground to pass through a 2-mm screen. Total C and N concentration of weed biomass was determined with an automated Dumas instrument (LECO Co., St Joseph, MI) (McGeehan and Naylor, 1988). Total N uptake in aboveground weed biomass was determined by multiplying dry matter weight by N concentration and was expressed in kg N ha^{-1}.

Corn plant population was determined from a 7.6-m length from the middle two rows at the V5–V7 growth stage in June. Aboveground biomass of corn was evaluated at the V5–V7 growth stage. Ten whole-plant corn samples were collected and oven-dried at 60°C, weighed, and ground to pass through a 2 mm-screen. Total N concentration in corn biomass was determined with an automated Dumas instrument (LECO Co., St Joseph, MI) in 2010. In 2011, N concentration was measured by wet-digesting samples with H_2SO_4 and H_2O_2 (Linder and Harley, 1942; Thomas et al., 1967), and the total N in the digest was analyzed by a colorimetric procedure (nitroprusside-sodium hypochlorite) using an RFA autoanalyzer (Alpkem Co., Clackamas, OR). Nitrogen uptake per plant was determined by multiplying aboveground dry matter weight by the N concentration and dividing by the number of plants collected. Chlorophyll meter (CM) readings were collected at R1 corn growth stage from the ear leaf of 20 corn plants in the middle two rows using a Minolta SPAD 502 CM (Minolta, Ramsey, NJ). Final corn yield was determined by hand-harvesting 7.6-m length from the middle two rows of each plot. Grain yield was adjusted to a moisture content of 155 g kg^{-1}.

Data were analyzed both by site-year and across site-years with the MIXED procedure in SAS 9.2 (SAS Institute, 2010) with blocks as a random factor. For analysis across sites, both site-year and block within site-year were considered as random factors. When the herbicide application date × N rate interaction was significant, main effect tests were ignored and simple effect tests were tested between herbicide application dates within each N rate. When the herbicide application date × N rate interaction was not significant, main effect tests were tested and pairwise comparisons, using the LSD method, were used to interpret those significant main effects. Statistical significance was determined at $\alpha = 0.05$.

The N fertilizer equivalence method using CM readings and grain yield was used to determine differences in corn N availability between herbicide application dates and N rates (Varvel and Wilhelm, 2003; Ruiz Diaz et al., 2011). The method assumes that CM readings and grain yield are suitable indicators of N availability and that N uptake efficiency is the same between herbicide application dates. Non-responsive sites for CM and grain yield as determined by the mixed model analysis of variance were not included in this analysis. Chlorophyll meter readings and grain yield were analyzed using data from all small plots (all herbicide application date and N rate combinations). No herbicide application date by N rate interaction occurred for CM readings and grain yield from the mixed model analysis above, so a common slope could be used for further analysis of covariance models with fertilizer N rate as the covariate and herbicide application date as the fixed-effect treatment. As previously, site-year and block within site-year were treated as random effects. The MIXED procedure was also used for this analysis (SAS Institute, 2010). The response of N rate was evaluated and the simple linear regression was significant at $\alpha = 0.05$. This resulted in a regression line for each herbicide application date with a common slope and the difference in intercepts was evaluated to determine the N fertilizer equivalent value. The N fertilizer rate needed by the April and May herbicide application dates to produce the same CM reading and grain yield as the Nov.–Mar. herbicide application at the 0 N rate determined the N fertilizer equivalent value.

RESULTS AND DISCUSSION

Winter Annual Weed Biomass, Nitrogen Uptake, and C/N Ratio

The most frequently occurring and highest density WAW species across sites-years was henbit (data not shown). Winter annual weed control with herbicide was greater than 92% at all sites and herbicide application dates (data not shown). The WAW aboveground dry biomass ranged from 475 to 1727 kg ha^{-1} across sites prior to May herbicide application date (Table 3-1). The N uptake from WAW near weed maturity in May ranged from 7 to 32 kg N ha^{-1} across 14 sites, with a mean of 18 kg N ha^{-1}. The C/N ratio ranged from 16 to 32 across sites. These findings on N uptake and C/N ratios for WAW are similar to previous studies done in the southeast United States (Ranells and Wagger, 1997; Sainju and Singh, 2001). A recent study conducted in Nebraska found that WAW N uptake by mid-April was 4 to 15 kg N ha^{-1}; by mid-May, uptake was 24 to 37 kg N ha^{-1} (Bernards and Sandell, 2011). These findings highlight the rapid vegetative growth and N uptake that occurs in WAWs in the spring. Even though the weed composition may have differed, accumulation of N in WAW biomass by mid-May in our study was similar to the accumulation in Nebraska. Delaying herbicide application until May after corn emergence allowed most WAW to complete maturity, maximize N uptake, and achieve higher C/N ratios, which should have caused the greatest possible reduction in N supply for corn.

Corn Plant Population

For corn plant population, the herbicide application date by N rate interaction was significant only at Site 7 (Table 3-2). This result may be an artifact of planter equipment issues experienced at this site because this effect was not consistent at other sites or across site-years. Nitrogen rate did not affect plant population at 13 of 14 sites or across site-years; however, herbicide application date showed a significant effect on plant population at sites 5, 11, 13, and 14 (Table 3-2) and across site-years. At sites responsive to herbicide application date, April or May herbicide application dates, which did not eliminate WAW as early, resulted in the lowest plant population (Table 3-3). Across all site-years, delays in herbicide application tended to decrease final plant population. April herbicide applications decreased final plant populations by 1300 plants ha^{-1} over earlier herbicide application dates, which killed WAW sooner (Table 3-3).

The effect of herbicide application date on corn plant population across site-years suggests that seedbed conditions for planting operations, germination, and plant establishment were likely improved with fall and early spring herbicide application dates before April. Stipesevic and Kladivko (2005) found that delaying cover crop termination increases soil volumetric water content at the 0 to 10-cm depth except during spring drought periods, when the early termination increased soil moisture over no cover crop and late termination. Herbicide application dates had a significant effect on corn plant population at Site 13 due to an extended drought period from the previous year into the 2011 crop year. Corn emerged soon after planting in plots that received fall herbicide applications, but emergence was delayed with the two spring herbicide application dates until a rainfall event occurred. The interaction between climatic conditions, soils, and herbicide application dates for control of WAW obviously affects soil water content and affects planting operations and early crop establishment.

Soil Nitrate-Nitrogen and Early Corn Nitrogen Uptake

Significant differences in soil nitrate-N levels occurred between treatments (Tables 3-2 and 3-4). Only one site (Site 11) exhibited a significant herbicide application date × N rate interaction. At Site 11, the later herbicide application date only lowered soil nitrate-N levels at higher fertilizer rates of 67 and 135 kg N ha^{-1} (data not shown). Soil nitrate-N decreased at the two higher N rates when herbicide application was delayed from Nov.–Mar. to May (data not shown). As expected, soil nitrate-N tended to increase with increasing fertilizer N rates. Across site-years, soil nitrate-N was increased by all N rates compared with the 0 N rate, except with 17 kg N ha^{-1} (Table 3-4). The lack of a significant increase in soil nitrate-N at low rates of N fertilizer suggests that measuring a decrease in soil nitrate-N as a result of a WAW N uptake of 7.0 to 32.0 kg N ha^{-1} across site-years is difficult to confirm statistically at individual sites. Six of the 14 sites showed a significant change in soil nitrate-N due to delayed herbicide application. Across site-years, soil nitrate-N to a depth of 60 cm was significantly reduced by 13 kg N ha^{-1} when herbicide application was delayed to May (Table 3-4). Herbicide application dates in May represent the timing when the maximum amount of soil inorganic N depletion was expected to occur, because most WAW have reached maturity.

In general, early corn N uptake was affected by herbicide application dates and N rates (Table 3-2). Similar to soil nitrate-N results, Site 11 was the only site where a significant date × N rate interaction occurred. At Site 11, early corn N uptake was decreased with May herbicide application date at all N rates over Nov.-Mar., except at the 34 kg N ha^{-1} rate (data not shown).

Early corn N uptake at the V5–V7 stage was affected at all sites by the different rates of nitrogen fertilizer (Tables 3-2 and 3-5), except Site 13. Site 13 was located in Reno County, where corn emergence and early growth were negatively affected by drought (Table 3-1). Nitrogen fertilizer rates of 135 kg N ha^{-1} maximized early corn N uptake across site-years (Table 3-5).

Early uptake of N was affected at 10 sites by the date of herbicide application. Corn N uptake was unresponsive to different herbicide application dates at Sites 1, 3, 4, and 5 (Table 3-2). The earliest date of herbicide application (Nov.–Mar.) maximized corn N uptake at the V5–V7 growth stage at seven of the 10 responsive sites and across site-years (Tables 3-2 and 3-5). Sites with changes in early corn N uptake were not related to soil nitrate-N levels at all sites. This result suggests that corn N uptake at the V5–V7 growth stage integrates the net effect (soil temperature, soil moisture, etc.) of different herbicide application dates more than soil nitrate-N alone. Monnig et al. (2007) found that soil temperature was increased with earlier herbicide application dates to control WAWs, which may affect corn early growth. In our study, we did observe slightly earlier emergence and a slight increase in the crop growth stage with earlier herbicide application dates as some sites which can be explained by higher soil temperatures (Al-Darby and Lowery, 1987).

Chlorophyll Meter Readings

Chlorophyll meter readings are highly correlated with the N concentration in corn leaves (Zhu et al., 2011) and were utilized in this study to determine the relative N status of corn plants at R1 growth stage. No interaction effects were found between herbicide application date and N rate at any site or across site-years for CM readings (Table 3-2). The CM reading increased with higher rates of N fertilizer at all sites, except Site 1 (Table 3-6). Site 1 was under an extended period of saturated soil conditions that led to visible symptoms of N deficiency across N rates prior to the R1 growth stage. Across site-years, CM readings increased with each additional increase in the N rate (Table 3-6).

The CM readings were significantly affected by the date of herbicide application at seven sites (Table 3-2). In general, chlorophyll meter readings were lower when herbicide application occurred during May than in Nov.–Mar. (Table 3-6). Across sites-years, delaying herbicide application after Nov.–Mar. resulted in significantly lower CM readings (Table 3-6). The effect of herbicide application date on soil nitrate-N early in the season likely persisted prior to the R1 growth stage in July. Miguez and Bollero (2006) found that CM readings were lower in corn ear leaves around the R1 growth stage with a cereal rye winter cover crop (no-till corn soybean rotation) compared with the no cover crop treatment at lower N rates (0 and 90 kg N ha^{-1}), although no differences were found at the higher N rates (180 and 270 kg N ha^{-1}).

A linear regression model described the CM reading response to N rate across responsive site-years (Figure 3-1). The intercept values (±standard error) were 39.0 (±0.4), 37.3 (±0.4), and 35.9 (±0.4) for the Nov.–Mar., April, and May herbicide application dates, respectively, with a common slope of 0.111 (±0.004) CM reading per kg N ha^{-1}. To achieve a CM reading similar to the Nov.–Mar. herbicide application date at the 0 N rate, the N fertilizer equivalent value indicated that an additional 16 kg N ha^{-1} for April and 28 kg N ha^{-1} for May herbicide application dates were needed.

Grain Yield

A significant interaction between herbicide application date and N rate occurred at sites 4, 11, 12, and 14 (Table 3-2). At Site 4, there was no difference between herbicide application date at the 0, 17, and 135 kg N ha^{-1} rate (Table 3-7). At the 34 kg N ha^{-1}, herbicide application in May yielded significantly less than the two earlier application dates; however, at 67 kg N ha^{-1}, delaying WAW control increased yield at Site 4, which was contrary to the trend found in the CM readings at this site and to yield data from other sites. Corn yield response to N fertilization was significant ($p < 0.001$) for all three herbicide application dates at Site 4. At Site 14, a lower yield was obtained with the April herbicide application at the 0 kg N ha^{-1} rate than with the Nov.–Mar. and May herbicide application dates (Table 3-7). Also, yield was lower at the 0 kg N ha^{-1} rate than with higher N rates ($p < 0.001$), but only for herbicide applications in April, not in Mar.–Nov. ($p = 0.449$) and May ($p = 0.580$). Yields at Site 14 were low due to low rainfall (Table 3-1), and the highest yield was at 17 kg N ha^{-1} with Nov.–Mar. herbicide application. At Sites 11 and 12, a significant decrease in grain yield occurred when herbicide application was delayed at lower N rates, but not at highest N rate (Table 3-7). Site 11 and 12 had high soil nitrate-N (Table 3-4) and CM readings (Table 3-6) compared with other sites at high fertilizer N rates, suggesting that N was less limiting. Corn yield response to N fertilization was significant ($p < 0.001$) for all three herbicide application dates at Site 11 and Site 12 for April and May herbicide application dates, and was close to significance ($p = 0.080$) for the Nov.–Mar. We hypothesized that herbicide application dates at the high N rate (135 kg N ha^{-1}) would affect grain yield less than lower N rates. This trend may be expected for most sites with higher N rates (greater than 135 kg N ha^{-1}) when additional fertilizer N could compensate for the N used by WAW, but this tendency was not observed for most sites with the N rates applied in this study. This result also may suggest that N uptake by WAW was not the only factor affecting corn growth and yield.

Corn yield response to N fertilizer was significant at 11 sites (Table 3-2). Similar to CM reading results, the lack of N fertilizer response at Site 1 may have been due to excessive N losses after fertilizer application. Site 7 was unresponsive to N fertilization. Grain yield responses to herbicide application dates occurred at five sites across N rates and at specific N rates at Sites 4, 11, 12, and 14 as formally discussed (Tables 3-2, 3-7, and 3-8). Across site-years, corn yield decreased by 0.48 and 0.70 Mg ha^{-1} with April and May herbicide application dates, respectively, compared with earlier application (Nov.–Mar.) (Table 3-8). These results differ from Krausz et al. (2003) in Illinois, who found no yield differences between atrazine applied in Nov. and herbicide application at planting in May for two site-years; however, the single rate of N used in the study was not given, and corn yields were much higher than yields in our study. Nelson et al. (2006) found no difference in corn yield between an untreated check, spring-applied herbicide, or fall-applied herbicide at four site-years for WAW, but the single rate of N used in their study was not stated. Creech et al. (2008) found no yield differences between spring-applied, fall-applied, or a fall plus spring-applied herbicide application at two site-years; they stated that WAW densities were relatively low compared to recent surveys conducted in the region. The N rate in their study was 220 kg N ha^{-1}, which was much higher than the maximum rate of 135 kg N ha^{-1} used in our study. The N rate used in their study may have eliminated any N stress on the corn imposed by different herbicide application dates. A study in Nebraska found delaying herbicide applications to kill WAW until mid-May reduced corn yield at both of the study sites (Mannam et al., 2008). Studies on the effects of herbicide application dates and N rates were limited, but non-leguminous winter cover crops with similar life cycles may be comparable. Clark et al. (2007b) determined the economically optimum N rate to be 149 kg N ha^{-1} for no cover crop, 192 kg N ha^{-1} for early-killed cereal rye, and 203 kg N ha^{-1} for late-killed cereal rye. Reinbott et al. (2004) found that a fall-seeded oat (*Avena sativa* L.) cover crop needed an additional 28 kg N ha^{-1} to achieve comparable yield in a no-till corn-soybean rotation in Missouri compared to the no cover crop control. Likewise, Wagger (1989) found that fall-seeded cereal rye needed an additional 25 kg ha^{-1} fertilizer N than a plot with no cover crop. A linear regression model described the grain yield response to N rate across responsive site-years (Figure 3-2). The intercept values (±SE) were 4.15 (±0.117), 3.78 (±0.117), and 3.38 (±0.117) Mg ha^{-1} for the Nov.–Mar., April, and May herbicide application dates, respectively, with a common slope of 0.022 (±0.001) Mg ha^{-1} per kg N ha^{-1}. The N fertilizer equivalent value needed to achieve a grain yield similar to the Nov.–Mar. herbicide application dates at the 0 N rate were 17 and 35 kg N ha^{-1} for April and May, respectively (Figure 3-2). These N fertilizer equivalent values are similar to those estimated using CM readings.

CONCLUSION

Delaying herbicide applications through spring when WAW are actively growing and taking up N can reduce available N for the subsequent corn crop. Delaying herbicide application after the Nov.–Mar. period caused reductions in corn plant population, soil nitrate-N, early corn N uptake at the V5–V7 growth stage, CM at R1 growth stage, and grain yield across N fertilizer rates. Our results suggest that producers can avoid reduction in corn plant population and increase grain yield by applying herbicides before April. Estimated additional N fertilizer rates of 17 and 35 kg N ha^{-1} for April and May, respectively, would be required to achieve comparable yield response to the earlier herbicide application date. The expected trend of reduced differences in early corn growth, CM readings, and grain yield at the highest N rates was not observed and may suggest that N supply was not the only factor creating differences among herbicide application dates. We recommend targeting no-till fields with heavy WAW pressure to receive fall herbicide applications to decrease the probability of corn yield reduction.

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FIGURES AND TABLES

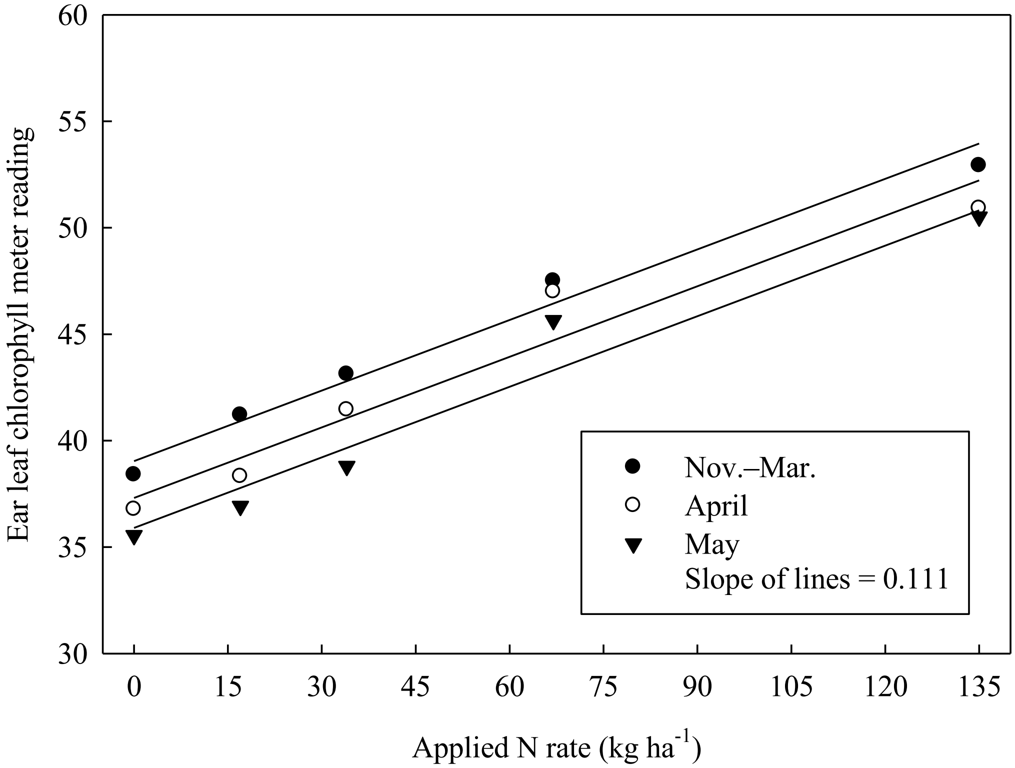

Figure 3-1. The mean corn ear leaf chlorophyll meter reading (R1 growth stage) response to fertilizer N application rates for each winter annual weed herbicide application date (n=540).

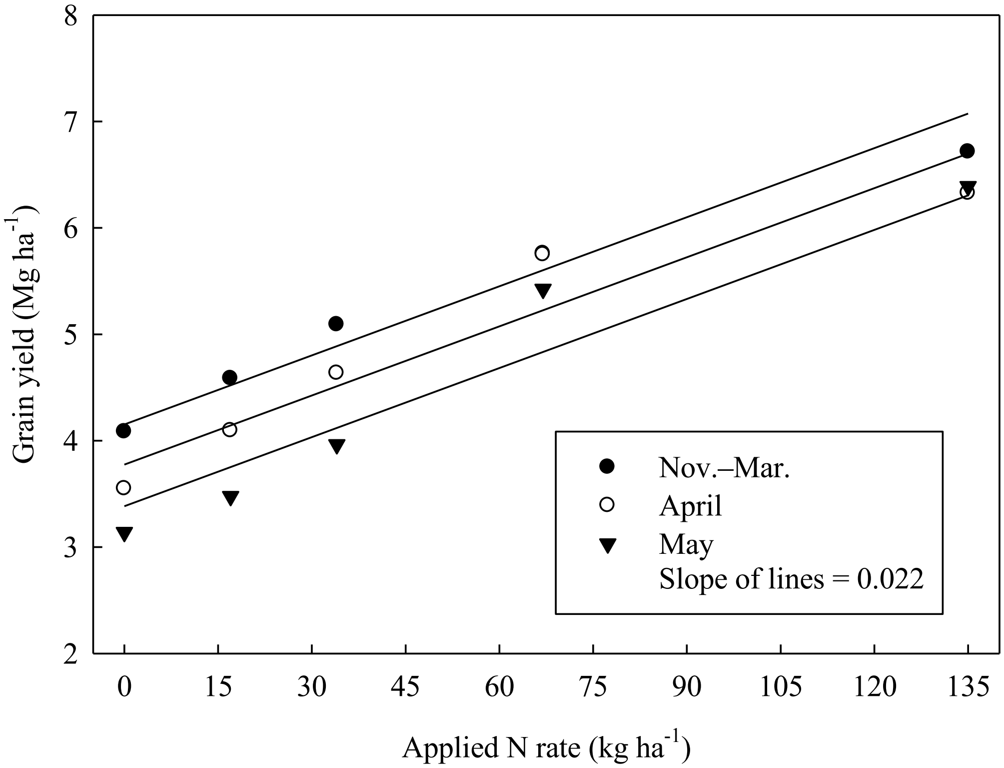

Figure 3-2. The mean corn grain yield response to fertilizer N application rates for each winter annual weed herbicide application date (n=495).

Table 3-1. Site information, predominant soil, planting date, rainfall, soil chemical analysis, and aboveground winter annual weed biomass characteristics.

		Predominant soil				Soil chemical analysis†				Weed		
Site	County	Series	Subgroup	Planting date	Rainfall‡	OM§	pH	STP¶	STK¶	Dry biomass	N uptake	C/N ratio
					mm	g kg^{-1}		– mg kg^{-1} –		—— kg ha^{-1} ——		
					2010							
1	Franklin	Woodsen	Abruptic Argiaquolls	1 June	778 (+52)	29	6.3	9	111	739	14.7	28
2	Jackson	Wymore	Aquertic Argiudolls	12 Apr.	824 (+100)	32	6.5	10	216	663	11.5	21
3	Jefferson	Grundy	Aquertic Argiudolls	14 Apr.	883 (+147)	40	7.1	78	374	475	8.9	20
4	Marshall	Wymore	Aquertic Argiudolls	20 Apr.	838 (+175)	28	5.5	43	165	476	7.0	26
5	Osage	Woodsen	Abruptic Argiaquolls	20 Apr.	936 (+233)	35	7.1	49	315	908	17.3	19
6	Reno	Ost	Udic Argiustolls	14 Apr.	656 (+58)	23	5.4	67	276	1028	21.9	16
7	Riley	Belvue	Typic Udifluvents	25 May	654 (-33)	14	7.6	58	237	1714	27.6	24
					2011							
8	Atchison	Grundy	Aquertic Argiudolls	6 May	799 (+99)	30	5.8	16	174	1087	32.0	32
9	Franklin	Woodsen	Abruptic Argiaquolls	20 Apr.	482 (-244)	29	6.4	11	192	948	18.4	19
10	Jefferson	Grundy	Aquertic Argiudolls	1 May	799 (+99)	35	5.5	20	189	1727	24.9	29
11	Jefferson	Grundy	Aquertic Argiudolls	4 May	799 (+99)	35	7.1	56	229	1068	17.4	25
12	Osage	Woodsen	Abruptic Argiaquolls	19 Apr.	482 (-221)	33	6.0	43	259	1320	17.9	29
13	Reno	Ost	Udic Argiustolls	14 Apr.	123 (-475)	22	6.2	53	317	931	13.2	29
14	Riley	Smolan	Pachic Argiustolls	29 Apr.	476 (-210)	27	6.5	23	469	882	14.4	24

† Mean values collected from each block at the 0- to 15-cm soil sampling depth.

‡ Measured rainfall (deviation from 30-yr norm, 1981-2010) for March through September from weather station within 20 km of each study site.

§ OM, organic matter.

¶ STP, soil test phosphorus; STK, soil test potassium.

Table 3-2. Significance of F values for the fixed effects of herbicide application date (D) and nitrogen rate (N) on plant population, soil nitrate-N, early corn N uptake, chlorophyll meter (CM) readings, and grain yield for each site and across site-years.

	Plant population			Soil nitrate-N			Early corn N uptake			CM readings			Grain yield		
Site	D	N	D × N	D	N	D × N	D	N	D × N	D	N	D × N	D	N	D × N
								P > *F*							
1	0.359	0.364	0.896	0.034	0.004	0.823	0.618	<0.001	0.309	0.104	0.577	0.283	0.938	0.166	0.353
2	0.309	0.952	0.252	0.050	<0.001	0.252	0.002	<0.001	0.922	0.009	<0.001	0.203	0.038	<0.001	0.508
3	0.824	0.983	0.727	0.260	0.001	0.087	0.742	<0.001	0.976	0.627	0.003	0.213	0.750	0.043	0.498
4	0.446	0.361	0.270	0.472	<0.001	0.490	0.930	<0.001	0.544	0.393	<0.001	0.144	0.235	<0.001	<0.001
5	0.026	0.487	0.290	0.040	0.002	0.206	0.146	<0.001	0.065	0.001	<0.001	0.089	0.001	<0.001	0.115
6	0.254	0.062	0.338	0.687	0.004	0.923	<0.001	<0.001	0.246	0.776	<0.001	0.540	0.271	<0.001	0.771
7	0.473	0.653	0.012	0.162	0.035	0.348	<0.001	0.006	0.372	0.181	0.008	0.239	0.010	0.123	0.469
8	0.225	0.273	0.657	0.160	<0.001	0.869	<0.001	<0.001	0.855	<0.001	<0.001	0.682	<0.001	<0.001	0.527
9	0.578	0.504	0.412	0.262	<0.001	0.323	<0.001	0.050	0.816	0.062	<0.001	0.088	0.152	<0.001	0.118
10	0.971	0.599	0.656	0.845	<0.001	0.143	<0.001	<0.001	0.752	0.002	<0.001	0.211	<0.001	<0.001	0.230
11	0.039	0.930	0.215	0.004	<0.001	<0.001	<0.001	<0.001	0.048	<0.001	<0.001	0.183	<0.001	<0.001	<0.001
12	0.469	0.778	0.533	0.010	<0.001	0.748	<0.001	<0.001	0.211	<0.001	<0.001	0.267	0.001	<0.001	0.041
13	0.004	0.712	0.281	0.152	0.003	0.541	<0.001	0.361	0.735	--†	--	--	--	--	--
14	<0.001	0.308	0.058	<0.001	<0.001	0.138	<0.001	<0.001	0.111	<0.001	<0.001	0.061	0.013	0.005	0.019
								<u>Across sites and years</u>							
	0.003	0.826	0.908	0.027	<0.001	0.449	<0.001	<0.001	0.250	<0.001	<0.001	0.529	<0.001	<0.001	0.408

† Data not available due to crop death from extreme drought.

Table 3-3. Main effect means of N rate (kg N ha^{-1}) and herbicide application date on corn plant population by site and across site-years.

	Corn plant population							
	N rate					Herbicide application date		
Site	0	17	34	67	135	Nov.–Mar.	Apr.	May
	thousands of plants ha^{-1}							
1	61.7	60.5	63.0	63.5	58.9	61.8	60.0	62.9
2	58.6	58.1	58.8	59.7	58.9	60.0	57.6	58.8
3	70.4	70.1	69.5	70.0	70.4	69.7	70.0	70.5
4	59.0	59.0	57.2	58.8	58.3	58.5	58.0	59.0
5	54.7	56.2	54.9	56.5	54.7	55.0ab†	54.1b	57.0a
6	54.9	54.9	54.6	59.3	57.2	57.1	54.9	56.7
7	67.4	66.8	65.3	65.8	65.4	65.4	67.0	66.1
8	74.9	73.1	76.9	72.6	72.3	75.8	73.0	73.1
9	52.4	53.9	51.5	50.3	53.0	52.9	52.5	51.3
10	65.7	65.5	67.5	65.2	66.4	65.9	66.1	66.2
11	53.1	54.0	53.6	53.5	52.9	53.9ab	51.9b	54.4a
12	47.1	46.2	46.5	45.5	45.9	45.6	46.7	46.4
13	51.2	52.0	52.1	50.6	49.5	53.8a	51.6a	47.8b
14	61.7	62.8	62.4	64.2	63.6	66.0a	59.9c	62.9b
	Across sites and years‡							
	59.5	59.5	59.6	59.7	59.1	60.1a	58.8b	59.5ab

† Numbers within each row and main effect followed by different letters are statistically different at the 0.05 probability level.

‡ Standard error of the means across sites and years for N rate was ±0.5 thousands of plants ha^{-1} and herbicide application date ±0.4 thousands of plants ha^{-1}.

Table 3-4. Main effect means of N rate (kg N ha^{-1}) and herbicide application date on soil nitrate-N by site and across site-years.

	Soil nitrate-N							
	N rate					Herbicide application date		
Site	0	17	34	67	135	Nov.-Mar.	April	May
	kg ha^{-1}							
1	15b†	17b	16b	21b	30a	18ab	24a	16b
2	47c	39c	55bc	65ab	62a	65a	59ab	48b
3	39b	44b	40b	50b	69a	49	44	53
4	26c	30bc	36bc	51b	83a	44	51	41
5	42b	43b	40b	55b	73a	46b	61a	45b
6	31b	37b	43b	56ab	81a	45	51	53
7	37bc	40bc	34c	56a	50ab	45	38	49
8	33c	30c	38c	81b	192a	84	82	58
9	52c	64c	78bc	106b	179a	90	109	89
10	42c	44c	75bc	107b	228a	100	104	94
11	40	89	86	206	329	194	149	108
12	49c	62c	86c	142b	220a	139a	92b	106b
13	67b	76b	108ab	134a	150a	108	90	124
14	40d	60c	71c	100b	150a	106a	75b	72b
	Across sites and years‡							
	40d	48cd	57c	88b	137a	81a	73ab	68b

† Numbers within each row and main effect followed by different letters are statistically different at the 0.05 probability level.

‡ Standard error of the means across sites and years for N rate was ±6 kg ha^{-1} and herbicide application date was ±5 kg ha^{-1}.

Table 3-5. Main effect means of N rate (kg N ha^{-1}) and herbicide application date on early corn N uptake by site and across site-years.

	Early corn N uptake							
	N rate					Herbicide application date		
Site	0	17	34	67	135	Nov.–Mar.	April	May
	mg N plant^{-1}							
1	93c†	100c	115bc	130b	164a	121	126	115
2	83cd	74d	101bc	136a	124ab	115a	115a	81b
3	99c	115c	142bc	176b	246a	151	164	152
4	104c	132bc	152b	170b	211a	151	155	156
5	284c	379b	387b	472a	527a	438	404	389
6	208d	322c	411b	424b	508a	455a	356b	313b
7	286c	316bc	325bc	486a	423ab	457a	242b	403a
8	43b	47b	50b	69a	74a	69a	57b	43c
9	61c	66bc	81abc	90ab	97a	99a	82a	55b
10	98d	132cd	149bc	170b	215a	207a	138b	114b
11	85	123	131	194	207	185	148	111
12	81d	121c	148b	194a	208a	208a	157b	85c
13	54	67	86	86	93	191a	20b	20b
14	100d	135c	163b	192a	206a	199a	152b	126c
	Across sites and years‡							
	122e	154d	172c	214b	233a	217a	165b	155b

† Numbers within each row and main effect followed by different letters are statistically different at the 0.05 probability level.

‡ Standard error of the means across sites and years for N rate was ±9 mg N plant^{-1} and herbicide application date was ±7 mg N plant^{-1}.

Table 3-6. Main effect means of N rate (kg N ha^{-1}) and herbicide application date on chlorophyll meter (CM) readings by site and across site-years.

	Chlorophyll meter readings							
	N rate					Herbicide application date		
Site	0	17	34	67	135	Nov.–Mar.	April	May
	SPAD†							
1	34.4	34.1	33.2	33.2	34.3	33.3	34.8	33.4
2	39.4c‡	37.1c	38.7c	42.9b	47.1a	41.9a	42.0a	39.2b
3	33.8b	32.1b	33.0b	34.2b	36.7a	33.7	33.7	34.4
4	33.6e	39.5d	42.6c	50.0b	55.8a	44.4	44.9	43.6
5	36.8c	37.4c	39.4c	45.1b	49.6a	43.2a	42.9a	39.0b
6	39.6c	41.9c	46.4b	54.3a	56.0a	47.9	47.9	47.2
7	36.6c	38.4c	37.5bc	43.3ab	45.0a	42.1	38.3	40.1
8	29.4d	32.9c	31.6cd	37.1b	44.9a	37.9a	36.1a	31.5b
9	36.2e	38.8d	42.0c	47.0b	52.5a	44.0	43.9	42.0
10	41.4d	44.9cd	46.5c	54.7b	59.7a	52.4a	49.3b	46.6b
11	40.6d	41.6d	46.7c	52.1b	59.2a	49.8a	48.3b	45.9c
12	42.7d	45.1d	49.3d	55.2b	61.8a	55.3a	47.6b	49.5b
13§	--	--	--	--	--	--	--	--
14	32.9e	36.1d	39.8c	44.7b	49.2a	42.9a	39.9b	38.8b
	Across sites and years¶							
	36.7e	38.4d	40.5c	45.7b	50.1a	43.8a	42.3b	40.9c

† Units of SPAD chlorophyll meter readings.

‡ Numbers within each row and main effect followed by different letters are statistically different at the 0.05 probability level.

§ CM readings were not collected at site 13 due to extreme drought.

¶ Standard error of the means across sites and years for N rate was ±0.5 SPAD units and herbicide application date was ±0.4 SPAD units.

Table 3-7. Mean grain yield in response to herbicide application date × N rate (kg N ha^{-1}) interaction at four sites.

	N rate				
Date	0	17	34	67	135
	---------------------- Mg ha^{-1} ---------------------				
			Site 4		
Nov-Mar.	2.99	3.62	4.83a†	4.88c	7.76
April	3.34	3.87	4.54a	6.05b	7.63
May	2.94	3.73	3.73b	7.18a	7.64
			Site 11		
Nov-Mar.	5.90a	6.77a	7.04a	7.89a	8.80
April	4.82b	5.75b	6.48b	7.84a	8.68
May	4.28c	4.84c	6.19b	7.26b	9.04
			Site 12		
Nov-Mar.	4.41a	5.38a	6.01a	5.87	6.03
April	2.43b	3.61b	4.41b	5.56	6.32
May	2.93b	2.74b	4.16b	5.99	6.25
			Site 14		
Nov-Mar.	3.23a	3.64	3.54	3.13	3.06
April	1.46b	3.14	3.07	3.39	3.07
May	2.74a	2.88	3.15	3.11	2.64

† Numbers within each N rate (simple effects) followed by different letters are statistically different at the 0.05 probability level.

Table 3-8. Main effect means of N rate (kg N ha^{-1}) and herbicide application date on grain yield by site and across site-years.

	Grain yield							
	N rate					Herbicide application date		
Site	0	17	34	67	135	Nov.–Mar.	April	May
	Mg ha^{-1}							
1	1.44	1.35	1.34	1.18	1.59	1.40	1.36	1.38
2	4.41c†	4.06c	4.55c	5.67b	6.97a	5.51a	5.12ab	4.77b
3	4.13bc	3.86c	4.42abc	4.67ab	4.80a	4.30	4.48	4.34
4	3.09	3.74	4.37	6.04	7.68	4.82	5.09	5.04
5	3.60d	4.23c	4.33c	5.43b	6.64a	5.10a	5.16a	4.28b
6	5.00c	5.62c	7.05b	9.25a	9.91a	7.72	7.23	7.15
7	4.80	5.20	4.45	6.27	6.27	6.32a	4.21b	5.67a
8	3.01c	3.56c	3.26c	4.81b	6.50a	5.12a	4.41a	3.14b
9	1.23b	1.33b	1.57a	1.63a	1.77a	1.56	1.55	1.41
10	4.29d	5.26c	5.95c	7.76b	9.16a	7.43a	6.53b	5.49c
11	5.00	5.78	6.57	7.66	8.84	7.28	6.71	6.32
12	3.25	3.91	4.86	5.80	6.20	5.54	4.47	4.41
13‡	--	--	--	--	--	--	--	--
14	2.48	3.22	3.25	3.21	2.92	3.32	2.82	2.90
	Across sites and years§							
	3.52e	3.93d	4.31c	5.35b	6.09a	5.03a	4.55b	4.33b

† Numbers within each row and main effect followed by different letters are statistically different at the 0.05 probability level.

‡ Grain yield was not collected at site 13 due to extreme drought.

§ Standard error of the means across sites and years for N rate was ±0.15 Mg ha^{-1} and herbicide application date was ±0.12 Mg ha^{-1}.

Chapter 4 - Corn and Soybean Response to Starter and Foliar Fertilization with Micronutrients

ABSTRACT

Micronutrient fertilizer blends are being applied to fields without a history of deficiencies during planting with N-P-K starter fertilizers or during foliar applications on corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. Four sites for each crop were established to evaluate combinations (factorial arrangement) of liquid starter and foliar fertilizers that contain N-P-K with and without a blend of micronutrients (Fe, Mn, Zn, Cu, and B) under irrigated conditions. Starter fertilizer treatments included: control; N-P-K fertilizer at 4–15, 5, and 9 kg ha^{-1} of N, P, and K; and N-P-K plus 0.56 kg ha^{-1} of each micronutrient. Foliar fertilizer treatments included: control; N-P-K fertilizer at 2, 1, and 2 kg ha^{-1} of N, P, and K; and N-P-K plus 0.22 kg ha^{-1} of each micronutrient. Foliar applications were made at the R2 and V6–V8 growth stages in soybean and corn, respectively. No early growth or yield increases were attributed to the micronutrient blend in corn. Across four site-years, there was an increase over the control in soybean height (8 cm) and yield (293 kg ha^{-1}) with starter N-P-K plus micronutrients. Starter N-P-K plus micronutrients decreased soybean trifoliolate leaf Mn concentration at all site-years. This response was attributed to the formation of FeEDTA and increased Fe supply that reduced root Mn absorption and translocation to leaves. Foliar fertilization did not increase yield in corn or soybean. Starter fertilizers showed more tendencies to increase yield than did foliar fertilization in corn and soybean.

Abbreviations: DTPA, diethylene triamine pentaacetic acid; EDTA, ethylenediamine tetraacetic acid; HEDTA, N-hydroxyethyl-ethylenediamine triacetic acid; NSRs, nutrient sufficiency ranges; STK, soil-test K; STP, soil-test P.

INTRODUCTION

A relatively small increase in yield may be sufficient to return a profit with micronutrient fertilization, especially when commodity prices are high. As a result, there in an increasing interest in applying micronutrients in geographic regions without a history of micronutrient deficiencies. Starter and foliar fertilization of macronutrients (N, P, and K) and secondary nutrients such as S are usually a supplement to higher rates of nutrient applications made during a separate field pass. However, micronutrients are needed by plants in relative small amounts that could be exclusively applied during planting with N-P or N-P-K starter fertilizers or during foliar applications, which minimizes any additional application cost.

Starter and foliar fertilization of corn and soybean have been evaluated with varying levels of success in increasing yield. Starter fertilization with N and P often increases corn early growth and early N and P uptake more frequently than is does grain yield (Kaiser et al., 2005; Wortmann et al., 2006; Mallarino et al., 2011). Probability of a yield response with N-P-K starter fertilizer is higher when soil test P (STP) or K (STK) is low (Kaiser et al., 2005; Wortmann et al., 2006, Mallarino et al., 2011). Starter fertilizers often include N-P or N-P-K mixtures making it difficult to attribute the response to a single nutrient (Bermudez and Mallarino, 2003). Based on our current knowledge of nutrient deficiencies and frequency of occurrence in the Great Plains region of the USA, the likelihood of increasing corn yield with micronutrient fertilizer is higher for Zn, Cl, and Fe and lower for B, Mn, Cu, Mo, and Ni. Soil DTPA (diethylene triamine pentaacetic acid)-Zn at less than 1 mg kg^{-1} has been used as indicator of potential corn yield response (Liekam et al, 2003).

An increase in early growth and yield from starter N fertilization of soybean has been successful in the northern Great Plains (Osborne and Riedell, 2006). Research on soybean response to starter fertilization including P has been shown to increase plant height (Ham et al., 1973) and yields (Ham et al., 1973; Bauh et al., 2000) when STP is low. Preplant and foliar K applications can be effective at increasing soybean height and yield on low STK soils (Nelson et al., 2005). Further, leaf area index can be increased with P and K fertilization as early at the V2 growth stage (Farmaha et al., 2012). Foliar N-P-K fertilization of soybean had led to only small and inconsistent yield increases where STP and STK are optimum to very high (Haq and Mallarino, 2000; Mallarino et al., 2001). Mallarino et al. (2001) found no additional yield increase with micronutrients (B, Fe, and Zn) added to an N-P-K foliar fertilization. However, a positive yield response of 93 kg ha^{-1} from the use 1.2-3.1-5.9 kg ha^{-1} of N-P-K foliar fertilizer was measured over 18 site-years by Mallarino et al. (2001). Further, foliar B application has increased soybean yield where rice (*Oryza sativa* L.) is produced in the rotation (Ross et al., 2006).

Iron and Zn applications may result in more frequent soybean yield response in the Great Plains region. Soil DTPA-Zn has been proven to be a useful indicator of potential soybean yield response, but soil DTPA-Fe has been less effective. Plant nutrient analysis in combination with soil analysis has been used to diagnose and monitor plant nutrient status to correct or prevent deficiencies. There is an increasing interest in using plant analysis as a monitoring and quality assurance tool. For monitoring plant nutrient status, specific plant parts at particular growth stages are needed to compare to established nutrient sufficiency ranges (NSRs). Jones (1967) determined the soybean NSRs based on the youngest uppermost mature trifoliolate leaf without the petiole during blooming prior to pod set (R1 to R2 growth stage). Mills and Jones (1996) published a set of NSRs that included only small changes since the 1960s set was available. Those changes were adding the NSR for S and adjusting the lower end of the NSR for N from 45.1 to 40.0 g N kg^{-1}. Given the growing interest and use of plant analysis to make fertilizer recommendations, ongoing research is needed to confirm that the corn and soybean NSRs are robust across time, environments, and genetics (soybean varieties and corn hybrids).

The overall purpose of this study was to evaluate corn and soybean response (growth, plant nutrition, and yield) to combinations of starter and foliar fertilization that contain N-P-K with and without a blend of micronutrients (Fe, Mn, Zn, Cu, and B) and to determine which combination of starter and foliar fertilization increases yield under irrigated conditions in Kansas.

MATERIALS AND METHODS

Four irrigated locations were selected in 2010 to 2011 for each corn and soybean (Table 4-1). Sites had no history of visible micronutrient deficiency symptoms. All sites were irrigated with pivot sprinkler irrigation systems in corn-soybean rotations. Irrigation was applied as needed during the growing season. The corn N fertilizer rates were 202, 252, 169, and 225 kg N ha^{-1} at Sites 1, 2, 3 and 4, respectively. A fertilizer application of 29 kg P ha^{-1} and 20 kg S ha^{-1} occurred at Site 1 for corn during the same pass with anhydrous ammonia. Plot size was 11 or 15 m in length and 3.0 or 4.6 m in width with row-spacing of 76 cm, except for soybean row spacing was 38 cm at Site 1.

Treatment Design, Experiment Design, and Implementation

The experimental design was a factorial arrangement in a randomized complete block design with three replications. The starter fertilizer factor consisted of three treatments: control, N-P-K, and N-P-K plus a micronutrient blend of Fe, Mn, Zn, Cu, and B (referred hereafter as N-P-K-M). The rates were 4.5, 4.9, and 9.4 kg ha^{-1} of N, P, and K in 2010 using a 4-4-8 (4-10-10, N-P_2O_5-K_20) starter fertilizer formulation. In 2011, the starter N rate was changed to 15.0 kg ha^{-1} by adding urea ammonium nitrate to the 4-4-8 starter fertilizer formulation. The micronutrient mix contained B derived from boric acid, CuEDTA (ethylenediamine tetraacetic acid), MnEDTA, ZnEDTA, and FeHEDTA (N-hydroxyethyl-ethylenediamine triacetic acid) at rates of 0.56 kg ha^{-1} for each micronutrient. Starter fertilizer was surface dribbled over the row.

The foliar fertilizer factor consisted of same three treatments: control, N-P-K, and N-P-K-M. The factorial arrangement resulted in nine treatment combinations between starter and foliar. The foliar fertilizer was applied at the V6–V8 corn growth stage (Abendroth et al., 2011) and at the R2 soybean growth stage (Ritchie et al., 1997). The rates were 2.0, 0.9, and 1.7 kg ha^{-1}of N, P, and K in 2010 and 2011 using a 10-4-8 (10-10-10, N-P_2O_5-K_20) fertilizer formulation. The foliar micronutrient blend contained the same products utilized for starter at rates of 0.22 kg ha^{-1} for each micronutrient in 2010 and 2011 for corn and 2010 for soybean. For soybean in 2011, CuEDTA was removed from the foliar micronutrient blend. Foliar application of micronutrients on soybeans was reduced to 0.11 kg ha^{-1} for micronutrients (Fe, Mn, Zn, and B) at Site 4. Foliar fertilizer was applied using a CO^2 pressurized backpack sprayer adjusted to 0.14 MPa and diluted into 187 L ha^{-1} of water (boom width of 2.3 m at 76 cm nozzle spacing with 80° flat fan nozzles).

Field Measurements

Composite soil samples (10 to 12 cores, 1.9 cm in diameter) were collected from each small plot from the 0- to 15-cm depth prior to planting (Table 4-2). Soils were oven dried at 40°C, crushed to pass through a 2 mm sieve. Soil samples were analyzed for pH (1:1 soil:water), P by Mehlich-3 colorimetric method (Frank et al., 1998), K by ammonium acetate (Warncke and Brown, 1998), organic matter (OM) by weight loss-on ignition or Walkley-Black method (Combs and Nathan, 1998), cation exchange capacity (CEC) by summation (Warncke and Brown, 1998), Fe, Mn, Zn, and Cu by DTPA (Whitney, 1998), and B by hot water (Watson, 1998) in 2010 and Mehlich-3 (Mehlich, 1984) in 2011.

Corn samples consisted of five or ten aboveground whole corn plants collected at the V6–V8 growth stage from each small plot prior to foliar application. Plant samples for soybeans consisted of 30 of the uppermost fully-expanded trifoliolate leaves without petioles at the R2 growth stage from each small plot prior to the foliar fertilizer treatment application. Post foliar fertilization plant analysis was conducted on 15 corn ear leaves at the R1 growth stage and 30 soybean trifoliolates at the R3 growth stage in 2011. Plant samples were oven-dried at 65°C for 3–5 days, weighed, and ground to pass a 2 mm screen. After digesting with HNO_3 and 30% H_20_2, the concentration in plant samples for P, K, Ca, Mg, S, Cu, Fe, Mn, Zn, and B were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Total N for plant samples was determined by dry combustion using a LECO FP-528 Nitrogen Analyzer (LECO Co., St Joseph, MI). Soybean plant height was recorded at full maturity (R8 growth stage). Grain yield was determined from the center two rows for 76 cm row spacing and the middle 4 rows for 38 cm row spacing of each small plot and adjusted to 130 and 155 g kg^{-1} H_2O for soybean and corn, respectively.

Statistical Analysis

Data were analyzed both by site-year and across site-years with the MIXED procedure in SAS 9.2 (SAS Institute, 2010) with blocks as a random factor. For analysis across sites, both site-year and block within site-year were considered as random factors. When the starter by foliar interaction was significant for yield and soybean height at maturity, main effect tests were ignored and all pairwise comparisons were tested using the least significant difference (LSD) method to assess differences between combinations of starter and foliar fertilization. This was done because our objective was to determine the best combination of starter and foliar fertilization. When the starter by foliar interaction was not significant, main effect tests were tested and pairwise comparisons, using the LSD method, were used to interpret those significant main effects. Statistical significance was determined at $\alpha = 0.10$.

Starter fertilizer effects were analyzed as a one-way treatment structure for corn early growth, early corn nutrient uptake, and soybean trifoliolate nutrient concentrations because foliar applications were imposed after collection of these parameters. In 2011, the effect of foliar N-P-K-M without starter on plant nutrient concentrations compared to the control (no starter or foliar) were analyzed in the same manner.

RESULTS AND DISCUSSION

Corn Grain Yield and Early Growth

The analysis of variance showed no interaction effect between starter and foliar fertilization on corn grain yield (Table 4-3). Starter N-P-K fertilizer increased corn grain yield at Site 4 by 0.95 Mg ha^{-1} where STP was the lowest and overall yield was the highest compared to other sites (Tables 4-2 and 4-4). Soil test P was considered low at Site 2, 3, and 4 (Leikam et al., 2003). Across site-years, yield was significantly increased with starter N-P-K fertilizer over both the control and N-P-K-M starter fertilizer treatments. The average grain yield for the N-P-K-M starter treatment was higher than the control but not statistically significant (Table 4-4). Foliar fertilization did not significantly affect grain yield at any site. Site 3, where soil test Zn was less low (Liekam et al., 2003), was the only site where grain yield was numerically higher (not statistically significant) with starter and foliar micronutrient fertilization (Table 4-4). Leaf burn from foliar application on corn was uncommon. Leaf burn only occurred at Site 3 with an N-P-K-M foliar application. Therefore, it is unlikely that the lack of a yield response to foliar applications can be attributed to leaf burn. Foliar N-P-K applications during the V6–V8 growth stages at Site 4 did not substitute for the yield response achieved with N-P-K starter fertilization.

Early corn growth (V6–V8) was significantly increased by the addition of starter fertilizers at Site 3, Site 4, and across site-years (Tables 4-3 and 4-5). Soil-test K (Table 4-2) was very high at all four site-years and K seldom has a starter or yield effect in this situation (Mallarino et al., 2011). Nitrogen or P are likely responsible for the increased early growth at Site 3 and 4 and the grain yield response at Site 4. Increased early corn growth and grain yield did occur at site-years with very low to low STP (Table 4-2), suggesting starter P was the major contributor. Mallarino et al. (1999) did find corn early growth response to P fertilization without N where STP $\leq$ 35 mg kg^{-1}. No increase in early corn growth response occurred with starter fertilizer at Site 1 that had very high STP (114 mg kg^{-1}) and a fall P fertilizer application.

No additional increase in early growth or grain yield was achieved by adding micronutrients (Fe, Mn, Zn, Cu, and B) to the N-P-K starter (Tables 4-3, 4-4, and 4-5). Soil DPTA-Zn less than 1.0 mg kg^{-1} is considered low and Zn fertilizer application is recommended

(Liekam et al., 2003). Corn biomass increases from zinc fertilization have been achieved when soil DPTA-Zn values were less than 0.8 mg kg^{-1} (Lindsay and Norvell, 1978), less than 0.45 mg kg^{-1} (Havlin and Soltanpour, 1981), are less than 0.4 mg kg^{-1} (Hergert et al., 1984). Lindsay and Norvell (1978) found no increase in corn biomass in a greenhouse study using Mn and Cu fertilization. In their study, soil DTPA-Mn and Cu were greater than 1.0 and 0.2 mg kg^{-1}, respectively, similar to those in our study. Soil DPTA-Fe values less than 4.5 ppm can elicit vegetative growth response in sorghum (Lindsay and Norvell, 1978), though sorghum is a relatively more Fe-sensitive plant than corn (Lytle and Jolley, 1991; Martens and Westermann, 1991; Havlin et al., 2005). Soil DPTA-Fe in our study was greater than 19 mg kg^{-1} and pH $\leq$ 7.4 (Table 4-1), suggesting Fe was not limiting early growth or yield. Boron deficiency in corn is symptomatic during reproductive stages and has not been shown to significantly affect vegetative growth (Lordkaew et al., 2011).

Corn Nutrient Concentration and Uptake

The N-P-K starter fertilization decreased N concentration while P concentration remained unchanged in the aboveground corn biomass (V6–V8 growth stage) at Site 3 and 4 (Table 4-6). However, both N and P uptake were increased at Site 3 and 4 due to an increase in early growth from starter fertilization (Tables 4-5 and 4-7). Also, the addition of starter fertilizer did increase plant P concentration and uptake at Site 2 (Tables 4-6 and 4-7). Early P uptake is a better reflection of starter P response than is corn plant P concentration because of the dilution effect (Kaiser et al., 2005). Interpretation of plant nutrient concentrations can be complicated by this dilution effect when vegetative growth is stimulated by fertilizer addition (Mills and Jones, 1996). In general, when P is not limiting early corn growth, P concentration decreases due to the dilution effect as higher N fertilizer rates stimulate early growth (Ziadi et al., 2007). This was different from the situation observed at Site 3 and 4 where early growth was stimulated by the N-P-K starter fertilization, N concentration decreased, and P concentration remained unchanged (Tables 4-5 and 4-6). Corn plant P concentrations at Site 2, 3 and 4 were not greater than 3.4 g P kg^{-1}, which is considered sufficient for corn at the V6 growth stage (Mallarino, 1996). Soil test P was less than 13 mg kg^{-1} (low) at these sites supporting our plant analysis interpretations and suggesting an increased probability of a yield response to P fertilization which occurred at Site 4 and across site-years. In spite of extremely high K concentrations in young corn plant (> 53.1 g kg^{-1}), starter N-P-K increased K concentration at Site 2. Young corn plants have a large capacity for luxury K uptake (Mallarino et al., 1999; Kaiser et al., 2005). Similar to N and P uptake results, K uptake was increased at Site 2, 3 and 4. Even though secondary nutrients (S, Ca, and Mg) were not included in the fertilizer treatments, a more reliable interpretation of plant analysis values are achieved when all plant essential nutrients are evaluated (Bergmann, 1992). Secondary nutrient (S, Ca, and Mg) uptake was also increased by N-P-K starter at Site 2, 3, and 4 (Table 4-7), though increases in concentration were less consistent (Table 4-6). The increase in secondary nutrient uptake is likely attributed to early growth stimulation from P or N-P and concurrent increase in uptake.

Starter N-P-K did not increase or decrease the concentration of micronutrients in corn plants, except at Site 3 (Table 4-6). Zinc concentration decreased and Zn uptake was unchanged with N-P-K starter fertilizer application at Site 3 where soil DTPA-Zn was low at 0.6 mg kg^{-1} (Tables 4-2, 4-6, and 4-7). These finding could be attributed to dilution by the biomass stimulation from the N-P-K starter (Table 4-4); though no other nutrients measured at Site 3 decreased in concentration with N-P-K starter fertilization (Table 4-5). Phosphorus-induced zinc deficiencies are thought to occur when high fertilizer P rates are applied (or high soil labile P concentrations) on soils with marginal or low Zn concentrations (Nichols et al., 2012). However, soil test P and Zn were both relatively low at Site 3 and the P-Zn interaction has been frequently studied and poorly understood, with antagonistic (P-induced Zn deficiency) effects being very inconsistent or not measured at all (Hernandez and Killorn, 2009; Nichols et al., 2012). Nitrogen-P-K starter fertilization increased plant uptake of micronutrients only occurred where early growth was increased (Site 3 and 4) and at Site 2 where the early growth approached significance from the (Tables 4-2 and 4-7). An increase in Fe and Cu uptake occurred at Site 2, 3, 4, and across site-years. An increase in B uptake only occurred where early growth was stimulated by N-P-K starter fertilization. However, no increase in Mn and Zn uptake occurred with N-P-K starter across site-years.

Starter N-P-K-M did not increase the concentration or the uptake of N, P, K, S, Ca, or Mg over N-P-K alone (Tables 4-6 and 4-7). The addition of micronutrient blend (Fe, Mn, Zn, Cu, and B) to the N-P-K starter did not affect Fe and Mn whole-plant (V6–V8) concentrations or uptake over N-P-K alone at any site or across site-years (Tables 4-6 and 4-7). Manganese EDTA is highly unstable in soils and has little or no advantage over inorganic Mn salts at keeping Mn in a soluble form (Norvell and Lindsay, 1969). The stability of FeHEDTA that was used in this study is reduced above pH 7 (Norvell, 1991) and suggests FeHEDTA would be less able to keep Fe complexed and increase Fe solubility in soil at Site 1 where pH was 7.4. However, corn is a strategy II plant where release of phytosiderophores and a high affinity uptake system for Fe^{3+} phytosiderophores helps improve Fe uptake (Guerinot and Yi, 1994). Iron uptake from Fe^{3+} phytosiderophores can be 100 to 1000 times more rapid than synthetic chelates in monocots (Römheld and Marschner, 1991). Zinc concentration at Site 2 and across site-years increased with N-P-K-M over N-P-K alone. Corn research has shown that ZnEDTA is a very effective fertilizer source in slightly acidic to calcareous soils (Hergert et al., 1984; Norvell, 1991; Goos et al., 2000). Corn plant Cu concentration at Site 1 and 2 and across site-years was increased with the micronutrient blend (Table 4-6). Copper uptake was also increased across site-years. The literature provides very little direct evidence on the effectiveness of CuEDTA to increase Cu concentration in young corn plants. Results of this study suggest that low rates of CuEDTA in a micronutrient blend applied with an N-P-K starter fertilizer can be effective at increasing concentration and total uptake in young corn plants (Tables 4-6 and 4-7). The inconsistent effect of the starter micronutrient blend on B concentration at each site resulted in no differences between starter treatments across site-years (Table 4-6). Numerous studies have documented more consistent increases in B concentration in corn ear leaves (Peterson and MacGregor, 1966; Touchton and Boswell, 1975; Woodruf et al., 1987; Grove and Schwab, 2010). However, young plant concentrations were not assessed in those studies. During the second year of the study, nutrient analysis of corn ear leaves at the R1 growth stage following the foliar application at V6–V8 growth stage revealed no consistent or significant changes in nutrient concentrations except an increase in B concentration (Table 4-8). In this study, the N-P-K-M foliar fertilization at V6–V8 was effective at increasing ear leaf B concentrations at the R1 growth stage similar to other studies (Peterson and MacGregor, 1966; Touchton and Boswell, 1975). A foliar application at the V6–V8 growth stage does result in non-target soil application making it difficult to determine the mechanism of plant uptake.

Micronutrient concentrations (Fe, Mn, Zn, Cu, and B) in controls plots all fell within established nutrient sufficiency ranges (Mills and Jones, 1996) and no early growth or corn grain yield increases were attributed to application of micronutrients (Tables 4-4, 4-5, and 4-6). Soil and plant analysis from three sites (Site 2, 3, and 4) suggested that P was the potential limiting factor in achieving higher yield. Increases in both early growth and grain yield across site-years were achieved with surface banded N-P-K starter fertilizer. Foliar fertilization did not increase corn yield.

Soybean Seed Yield and Height at Maturity

There was a significant interaction effect between starter and foliar fertilization at Site 1 (Table 4-9) in soybean seed yield. Pairwise comparisons revealed a yield increase was only achieved with N-P-K-M starter without foliar fertilization over the control (Table 4-10). An N-P-K-M foliar application decreased yield except when used in combination with an N-P-K starter (Table 4-10). No yield difference was measured between foliar applications when an N-P-K starter was applied. Some minor leaf burn or necrosis was observed with N-P-K-M foliar applications, but none with N-P-K foliar applications in this study. Leaf damage from foliar fertilizers in soybean is not uncommon and sometimes is attributed to the lack of a measured yield response (Haq and Mallarino, 2000; Mallarino et al. 2001). A separate study (data not shown) concluded that leaf necrosis was mostly attributed CuEDTA in the foliar micronutrient blend. Removal of CuEDTA in the foliar micronutrient blend at Site 3 and 4 did reduce the severity of the leaf burn, though leaf burn was not completely eliminated.

Across site-years, the interaction between starter and foliar fertilization for seed yield were similar to those found at Site 1 (Table 4-9). Across site-years, pairwise comparison (Table 4-10) again revealed seed yield was only increased by an N-P-K-M starter without foliar fertilization, with an average yield increase of 293 kg ha^{-1} over the control (Table 4-10). Although not statistically significant, average soybean yield increased 120 kg ha^{-1} with the starter micronutrient blend compared to N-P-K starter fertilizer. Soybean yield was not increased by foliar fertilization with either N-P-K or N-P-K-M treatments at any site (Tables 4-10 and 4-11). Yield response to N-P-K foliar fertilization have been inconsistent and small (Haq and Mallarino, 2000; Mallarino et al., 2001). No significant yield response with the addition of foliar micronutrients B, Fe, and Zn to an N-P-K foliar fertilization was found by Mallarino et al. (2001) either. Foliar Fe fertilization has not been an effective at increasing yield in Western Kansas (Liesch et al., 2011).

At Site 4, soybean seed yield increased 425 and 485 kg ha^{-1} over the control with N-P-K and N-P-K-M starter fertilization, respectively (Table 4-11). With low STP at this site, most of this yield increase can be attributed to the addition of starter P. Though a large increase in yield of 425 kg ha^{-1} was achieved with N-P-K starter, a foliar application of N-P-K at the R2 growth stage only increased yield by 48 kg ha^{-1} (Table 4-11). Where STP was less than optimum (Site 2, 3, and 4), foliar fertilization with N-P-K decreased the mean yield by 66 kg ha^{-1} (Table 4-11). Haq and Mallarino (2000) only found yield responses to soybean foliar fertilization at one of six sites where STP was low. However, at the responsive site, the N-K foliar fertilization increased yield comparable to N-P-K treatments suggesting that foliar P fertilization was not significantly contributing to the yield response.

Soybean height at full maturity (R8 growth stage) was significantly affected by fertilization at two of four sites and across site-years (Table 4-9). A starter × foliar interaction effect occurred for soybean height at Site 3. No height difference was measured between foliar applications when an N-P-K starter was applied at Site 3 (Table 4-10). However, height was increased with foliar fertilization (N-P-K and N-P-K-M) when no starter was applied. Foliar fertilization when used in combination with N-P-K-M starter fertilization decreased height. A significant height increase over the control was observed with all treatments except a starter N-P-K-M plus foliar N-P-K-M. Soil test K was in the responsive range and may explain some of the increase in soybean height with starter and foliar K applications as has been found by Nelson et al. (2005). However, starter and foliar fertilization effects on height did not translate into measurable yield differences at Site 3.

Across site-years, the starter × foliar interaction effect was significant. Similar to Site 3, no height difference was measured between foliar applications when an N-P-K starter was applied (Table 4-10). Soybean height at maturity was maximized by an N-P-K-M starter without foliar fertilization, with an increase in height of 8 cm over the control (Table 4-10). However, soybean height response due to addition of micronutrients to the N-P-K starter fertilizer was only 2 cm and was not statistically different across site-years.

At Site 4, where yield was significantly increased with starter fertilizer, height was increased over the control by 3 and 6 cm with N-P-K and N-P-K-M starter fertilization, respectively (Table 4-11). The addition of the micronutrient blend increased soybean height by an additional 3 cm over N-P-K alone at Site 4, but not seed yield.

Soybean Trifoliolate Leaf Nutrient Concentrations

Trifoliolate leaf N, K, and secondary nutrient concentrations at all sites were near or within the established nutrient sufficiency range (Table 4-12) (Mills and Jones, 1996). Trifoliolate leaf N concentration increased at Site 4 and N and P concentration increased across site-years with the N-P-K starter fertilization (Table 4-12). Parker and Harris (1977) also showed that trifoliolate leaf N concentrations were increased by preplant N applications. Potassium concentration in trifoliolate leaves was decreased at Site 4 with starter N-P-K fertilizer application, but this effect was not consistent at other sites or across site-years (Table 4-12). At

Site 3, no increase in trifoliolate leaf K concentration or yield was measured from N-P-K starter at low STK. A trifoliolate leaf K concentration of 18.3 mg kg^{-1} in control plots fell near or within a majority of published sufficiency ranges (Bell et al., 1995; Mills and Jones, 1996; Sabbe et al., 2000; Slaton et al., 2010) suggesting that K supply was probably adequate. At Site 4, where yield and height at maturity increased with N-P-K starter fertilization, mean leaf P and STP in control plots were 3.2 g kg^{-1} and 7 mg kg^{-1} (very low), respectively. The lower end of the P sufficiency range in trifoliolate leaves is somewhere between 2.5 and 4.0 g kg^{-1} (Rehm, 1986; Bergmann, 1992; Bell et al., 1995; Mills and Jones, 1996; Sabbe et al., 2000; Malvolta, 2006). Bell et al. (1995) showed yield increased at one in ten observations to phosphorus fertilizer application when trifoliolate leaf P was between 3.1 and 3.9 g kg^{-1}. A concentration of 3.9 g P kg^{-1} eliminated all but one observation (336 total observations) where a yield response to phosphorus fertilization occurred. However, a concentration of 3.9 g P kg^{-1} generates too many false positives or sufficient cases diagnosed deficient (Bell et al., 1995). We suggest that additional research is needed to improve the value and understand the limitations of soybean trifoliolate P analysis for diagnostic and monitoring purposes. No secondary or micronutrient concentration changes occurred with N-P-K starter fertilization except a decrease in Zn concentration at Site 3 and increase in Fe at Site 1.

The nutrient blend used in this study makes is difficult to attribute the yield responses over the control measured with starter N-P-K-M at Site 1 and across site-years to an individual nutrient. No change in trifoliolate leaf N, P, K, S, Ca, Mg, Fe, or Cu concentration occurred when the micronutrient blend was added compared to N-P-K alone (Table 4-12). Manganese, Zn, and B concentrations changes were measured in some instances with starter N-P-K-M; though trifoliolate leaf concentrations at all sites were within or slightly above the established NSR

(Table 4-12) (Mills and Jones, 1996). No increase in trifoliolate leaf Cu concentration occurred with the starter N-P-K-M even though concentrations were considered low or deficient at Site 1, 2 and 3 (Table 4-12) (Mills and Jones, 1996). Site 1 and 3 soil DTPA-Cu was 0.2 to 0.3 mg Cu kg^{-}1, respectively, which is near the critical soil DTPA-Cu concentration value of 0.12– 0.25 mg kg^{-1} (Table 4-2) (Sims and Johnson, 1991). However, soybeans are considered relatively insensitive to Cu deficiency (Martens & Westermann, 1991). A trifoliolate leaf concentration of 10 mg Cu kg^{-1} for the lower end of the sufficiency ranges used by Mills and Jones (1996) may be too high. The lower end of the Cu sufficiency range in trifoliolate leaves is more likely near 4–6 mg Cu kg^{-1} (Melsted, 1969; Makarim and Cox, 1983; Sabbe et al., 2000; Embrapa-Soja, 2006; Hitsuda et al., 2010). Therefore, yield responses to the micronutrient blend that included Cu would not be expected based on Cu leaf analysis. Payne et al. (1986) found no yield increase with Cu fertilization of 11 kg Cu ha^{-1} even though trifoliolate leaf Cu increased 2.1 mg Cu kg^{-1} from an average of 4.7 to 6.8 mg Cu kg^{-1}.

The addition of the micronutrients (N-P-K-M) increased trifoliolate leaf Zn concentration at Site 2, though this effect was not consistent at other sites or across site-years. An increase in leaf B concentration was quantified at three sites and across site-years with N-P-K-M starter fertilizer (Table 4-12). Boron concentration exceeded the sufficiency range at Site 3 with starter N-P-K-M fertilization, though concentrations are not considered excessive until 80 mg B kg^{-1} (Jones, 1967). However, the concentration of Mn decreased at all sites when the micronutrient blend was applied (Table 4-12). Across site-years, concentration decreased by 7 mg Mn kg^{-1} with the addition of the micronutrient blend to the N-P-K starter. Soil-applied MnEDTA is considered unstable in aerobic soils and the loss of chelated Mn can be very rapid (Aboulroos, 1981; Ryan and Hariq, 1983; Norvell, 1991) making the Mn no more soluble in soil than with Mn inorganic salts (Norvell and Lindsay, 1969). Unlike Mn inorganic salts, the application of MnEDTA can lead to formation of FeEDTA, thus increasing the solubility of Fe in soil (Norvell and Lindsay, 1969). It is this increase in soil Fe solubility that would explain lower trifoliate Mn concentrations. This is because an increase in Fe uptake by soybean leads to a reduction in Mn root adsorption and translocation from root to the shoot (Ghasemi-Fasaei et al., 2003; Moosavi and Ronaghi, 2011). The dilution effect and changes in root/shoot ratio are not responsible for the decrease in plant manganese concentration (Heenan and Campbell, 1983; Roomizadeh and Karimian, 1996; Ghasemi-Fasaei et al., 2003; Moosavi and Ronaghi, 2011).Small increases in Fe concentration can lead to larger corresponding decreases in Mn concentration (Ghasemi-Fasaei et al., 2003; Moosavi and Ronaghi, 2011). The lack of change in trifoliolate leaf Fe concentration measured in this study may have been hidden by only small increases in trifoliolate leaf Fe concentrations. Based on other studies looking at shoot concentrations (Ghasemi-Fasaei et al., 2003; Moosavi and Ronaghi, 2011), only a 1 to 2 mg Fe kg^{-1} increase would be expected with a 7 mg Mn kg^{-1} decrease. Randall et al. (1975) found that row-applied MnEDTA decreased biomass, trifoliolate leaf Mn concentration (14 mg Mn kg^{-1} in control plots), and yields when soybeans were displaying Mn deficiency. The row-applied micronutrient blend which contained MnEDTA in our study decreased trifoliolate leaf Mn concentration, though still within the NSR. However, there was no decrease in yield with the starter micronutrient blend, rather an increase over the control.

The N-P-K-M foliar treatment during the R2 growth stages did not increase nutrient concentrations in the trifoliolate leaves at the R3 growth stage, except B concentration at Site 3 (Table 4-8). A decrease in trifoliolate leaf Mn concentration was measured after N-P-K-M foliar application over the control across site-years (Table 4-8). Moosavi and Ronaghi (2011) measured a decrease in shoot Mn concentration and uptake with foliar Fe applications, but lower than reductions caused by soil Fe applications.

CONCLUSION

No increase in early growth or grain yield was attributed to the application of starter micronutrients (Zn, Cu, Mn, Fe, and B) in corn. Zinc and Cu concentration increased in young corn plants (V6–V8 growth stage) with N-P-K-M compared to N-P-K starter. Micronutrient concentrations in young corn plants of control plots were within currently established sufficiency ranges. Soil and plant analysis suggested that P was the potential limiting factor in achieving higher yield in three of four sites-years. An increase in early corn growth and grain yield across site-years was achieved with a surface banded N-P-K starter fertilizer over-the-row. Corn yield was not increased with foliar fertilization. Corn producers are most likely to gain an economic benefit from the use of an N-P-K starter fertilizer application.

Soybean height at maturity and seed yield was increased over the control with the starter N-P-K-M treatment across site-years. Nutrient analysis of the uppermost fully-expanded trifoliolate leaves at the R2 growth stage did not provide a clear explanation for which nutrient(s) may have provided the small increase height and yield associated with starter N-P-K-M treatment. However, the lack of a significant increase in height or yield with the addition of the micronutrients to the N-P-K starter suggests the benefit to adding micronutrients is small. The largest increase in soybean yield was obtained at Site 4 with starter N-P-K fertilizer where STP was very low. A starter fertilizer application did increase trifoliolate leaf N and P concentration across site-years. Soybean trifoliolate leaf Mn concentration was decreased at all four site-years by N-P-K-M starter fertilization, with an average decrease of 7 mg Mn kg^{-1}. This response was attributed to the formation of FeEDTA and increased Fe supply that reduced root Mn absorption. Manganese EDTA is not recommended for soil application to help alleviate manganese deficiency in soybean. No increase in soybean yield was obtained with foliar fertilization even where a yield response was measured with starter fertilization. We highlighted in this study that the current soybean trifoliolate leaf P and Cu sufficiency ranges are not well defined. A growing interesting in using corn and soybean plant nutrient analysis as a monitoring tool justifies additional research to verify that established NSRs are robust.

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TABLES

Table 4-1. Study sites, corn hybrids, soybean varieties, planting date and population.

Site	County	Tillage†	Hybrid/ Variety‡	Planting date	Plant population
					plants ha^{-1} ×1000
			Corn		
2010					
1	Clay	nt	P 33D49	27 Apr.	70.9
2	Republic	rt	G 83X61	28 Apr.	98.8
2011					
3	Shawnee	ft	D 64-69	4 May	69.3
4	Republic	rt	P 33D49	28 Apr.	90.6
			Soybean		
2010					
1	Clay	nt	NK 39A3	28 May	198.8
2	Republic	rt	NK 33N5	24 May	304.0
2011					
3	Shawnee	ft	LG C3616	16 May	376.6
4	Republic	rt	NK 31L7	17 May	336.1

† Tillage; ft, field cultivate spring and fall; nt, no-till; rt, ridge-till.

‡ Hybrid/Variety; D, Dekalb; G, Garst; LG, LG seeds; NK, Northup King; P, Pioneer.

Table 4-2. Mean soil-test values (0- to 15-cm depth) for each site-year.

							Micronutrients¶				
Site	Soil series†	CEC	pH	OM	P‡	K§	Zn	Fe	Mn	Cu	B
		cmolc kg-1		g kg-1	———	———	mg kg-1	———	———	———	
					Corn						
1	Muir sil	9.7	7.4	18	114	389	2.5	19.6	4.9	0.4	0.3
2	Crete sil	14.4	6.7	29	11	462	1.4	31.2	28.3	0.9	0.5
3	Bismarckgrove sil	17.8	6.4	18	13	244	0.6	34.7	36.5	0.9	0.5
4	Crete sil	19.3	6.3	24	10	563	1.7	43.5	45.7	1.0	0.9
					Soybean						
1	Cass fsl	7.1	7.1	16	34	252	4.1	16.2	8.5	0.3	0.3
2	Crete sil	15.4	7.0	28	11	482	1.1	26.3	16.9	0.9	0.7
3	Eudora fsl	8.4	6.4	9	17	96	0.6	18.2	16.1	0.2	0.3
4	Crete sil	19.0	6.5	22	7	455	1.1	41.8	37.8	1.0	1.0

† Soil Series: fsl, fine sandy loam; sil, silt loam.

‡ P, Mehlich-3 test.

§ K, Ammonium-acetate.

¶ Zn, Fe, Mn, and Cu DTPA; B by hot-water in 2010 and Mehlich-3 in 2011

Table 4-3. Significance of F values for the fixed effects of starter for early corn growth and starter and foliar for grain yield for each site. Sites and blocks within site considered random effects for analysis across all site-years.

	Fixed effects			
	Early corn growth	Grain yield		
Site	Starter(S)	Starter(S)	Foliar (S)	S x F
	P > F			
1	0.935	0.334	0.972	0.625
2	0.134	0.841	0.698	0.215
3	0.004	0.595	0.836	0.801
4	<0.001	0.087	0.691	0.603
	All site-years			
	0.053	0.050	0.694	0.235

Table 4-4. Mean corn grain yield response to starter and foliar fertilizations.

	Starter			Foliar		
Site	Control	N-P-K‡	N-P-K-M‡	Control	N-P-K	N-P-K-M
			Mg ha^{-1}			
1	14.32	14.80	14.17	14.42	14.48	14.38
2	13.27	13.31	13.11	13.33	13.29	13.05
3	14.05	14.37	14.40	14.15	14.31	14.37
4	14.37b†	15.32a	14.84ab	14.85	15.01	14.66
			All site-years			
	14.00b	14.45a	14.13b	14.19	14.27	14.11

† Starter treatment means within a row followed by a different letter are statistically different at the 0.10 probability level.

‡ Fertilizer containing N, P, and K; M, micronutrient blend of Fe, Mn, Zn, Cu, and B.

Table 4-5. Mean response of early corn growth (V6–V8 growth stage) to starter fertilization.

Site	Control	N-P-K‡	N-P-K-M‡
		g plant^{-1}	
1	21.6	22.2	21.8
2	17.0	18.7	18.5
3	4.7b†	5.5a	5.5a
4	4.3b	5.4a	5.3a
	All site-years		
	11.9b	13.0a	12.8a

† Treatment means within site followed by a different letter are significantly different at the 0.10 probability level.

‡ Fertilizer containing N, P, and K; M, micronutrient blend of Fe, Mn, Zn, Cu, and B.

Table 4-6. Mean response of nutrient concentration in aboveground corn plants at the V6–V8 growth stage to starter fertilizers.

	Nutrients										
Starter	N	P	K	S	Ca	Mg	Fe	Mn	Zn	Cu	B
	g kg^{-1}						mg kg^{-1}				
						Site 1					
Control	40.2	5.4	55.0	2.3	4.9	2.2	99	61	33	5.5ab	10
N-P-K‡	39.6	5.1	55.9	2.3	4.9	2.3	99	60	34	5.2b	10
N-P-K-M‡	40.7	5.1	54.5	2.3	4.8	2.2	93	59	37	6.2a	11
						Site 2					
Control	37.1	2.3b†	53.1b	2.1b	3.6b	2.1b	134	64	37b	8.6b	15b
N-P-K	37.6	2.5a	55.8a	2.2a	3.8a	2.1ab	152	70	38b	8.8b	14b
N-P-K-M	37.6	2.6a	56.5a	2.2a	3.9a	2.2a	144	68	43a	9.4a	13a
						Site 3					
Control	40.3a	3.0	47.5	2.3	6.8	2.1	203	105	28a	9.4	24
N-P-K	39.1b	3.1	48.3	2.3	6.9	2.2	198	92	26b	9.8	28
N-P-K-M	38.9b	3.0	47.7	2.3	7.0	2.2	202	96	26b	9.3	24
						Site 4					
Control	41.4a	3.3	51.6	2.9ab	4.7	2.4	149	54	35	11.9	23b
N-P-K	40.2b	3.3	50.8	2.8b	4.9	2.4	147	58	31	11.9	24b
N-P-K-M	40.5b	3.3	53.0	3.0a	4.9	2.4	147	55	33	12.1	28a
						All site-years					
Control	3.97a	3.5	5.18	2.4	5.0	2.18b	146	71	33ab	8.9b	18
N-P-K	3.91b	3.5	5.27	2.4	5.1	2.24a	149	70	32b	8.9b	19
N-P-K-M	3.94ab	3.5	5.29	2.5	5.1	2.26a	146	69	35a	9.3a	19
						Significance of treatment *P* > F					
Site 1	0.273	0.292	0.708	0.702	0.885	0.548	0.333	0.909	0.111	0.097	0.185
Site 2	0.540	0.007	0.011	0.016	0.013	0.068	0.199	0.397	0.066	0.003	0.043
Site 3	0.007	0.869	0.804	0.851	0.548	0.426	0.890	0.195	0.070	0.524	0.292
Site 4	0.016	0.799	0.369	0.041	0.668	0.619	0.969	0.544	0.127	0.429	0.078
All	0.083	0.981	0.255	0.572	0.250	0.057	0.788	0.817	0.045	0.038	0.445

† Treatment means within site for each nutrient followed by a different letter are statistically different at the 0.10 probability level.

‡ Fertilizer containing N, P, and K; M, micronutrient blend of Fe, Mn, Zn, Cu, and B.

Table 4-7. Mean response of nutrient uptake in aboveground corn plants at the V6–V8 growth stage to starter fertilizers.

	Nutrient										
Starter	N	P	K	S	Ca	Mg	Fe	Mn	Zn	Cu	B
	mg plant^{-1}						µg plant^{-1}				
Site 1											
Control	867.9	118.0	1194.6	50.8	105.2	47.0	2148	1313	719	119	222
N-P-K‡	867.9	113.4	1242.4	51.3	108.6	50.3	2202	1311	755	114	221
N-P-K-M‡	886.2	112.2	1193.8	49.9	105.5	48.1	2040	1247	811	133	242
Site 2											
Control	632.9	39.6b†	904.2b	36.3b	61.3b	35.1b	2292b	1093b	631b	146b	249
N-P-K	703.6	47.5a	1044.7a	41.4a	70.5a	40.1a	2839a	1316a	719ab	164a	270
N-P-K-M	698.5	48.6a	1044.6a	41.4a	71.9a	40.5a	2684ab	1258a	792a	175a	244
Site 3											
Control	189.6b	14.2b	224.3b	10.9b	32.0b	9.9b	947b	494	133	44b	112b
N-P-K	214.8a	16.8a	265.5a	12.8a	37.6a	11.8a	1091a	500	141	53a	148a
N-P-K-M	215.7a	16.7a	266.2a	12.9a	38.7a	12.1a	1118a	540	146	52a	133a
Site 4											
Control	178.6b	14.2b	223.3b	12.7b	20.4b	10.2b	645b	234b	151	51b	101b
N-P-K	218.6a	17.9a	276.1a	15.4a	27.0a	13.0a	800a	317a	171	64a	132a
N-P-K-M	215.4a	17.7a	281.5a	15.9a	25.9a	12.9a	744a	289a	177	64a	149a
All site-years											
Control	467b	46.5	636.6b	27.7b	54.7b	25.6b	1508b	783	409b	90c	171b
N-P-K	503a	48.9	707.2a	30.2a	60.9a	28.8a	1733a	861	447ab	99b	193a
N-P-K-M	504a	48.8	696.5a	30.0a	60.5a	28.4a	1654a	833	481a	106a	192a
Significance of treatment *P* > F											
Site 1	0.956	0.809	0.860	0.957	0.920	0.700	0.724	0.896	0.486	0.271	0.659
Site 2	0.133	0.012	0.006	0.048	0.009	0.005	0.085	0.089	0.027	0.026	0.149
Site 3	0.018	0.024	0.008	0.003	0.007	0.002	0.045	0.616	0.362	0.023	0.018
Site 4	<0.001	<0.001	<0.001	<0.001	0.004	<0.001	0.022	0.008	0.011	<0.001	0.002
All	0.068	0.544	0.027	0.100	0.024	0.006	0.027	0.278	0.011	0.001	0.019

† Treatment means within site for each nutrient followed by a different letter are statistically different at the 0.10 probability level.

‡ Fluid fertilizer containing N, P, and K; M, micronutrient blend of Fe, Mn, Zn, Cu, and B.

Table 4-8. Mean response of nutrient concentrations at R1 growth stage in corn and R3 growth stage in soybean to N-P-K-M foliar fertilizer.

	Nutrient										
Foliar	N	P	K	S	Ca	Mg	Fe	Mn	Zn	Cu	B
	g kg^{-1}						mg kg^{-1}				
					Corn, Site 3						
Control	3.07	2.6	20.8	2.1	5.6	1.7	91	83	26	10.4a†	49b
N-P-K-M‡	3.07	2.5	21.0	2.1	5.4	1.7	88	81	24	9.9b	71a
					Corn, Site 4						
Control	27.4	2.1	26.8	1.9	3.8	1.6	86	52	19	9.3	32b
N-P-K-M	28.0	2.2	27.3	2.0	3.9	1.7	90	51	20	9.5	38a
					Across corn sites						
Control	29.0	2.3	23.8	2.0b	4.7	1.7	89	67	23	9.9	40b
N-P-K-M	29.4	2.4	24.1	2.0a	4.7	1.7	89	66	22	9.7	55a
					Soybean, Site 3						
Control	52.5	3.4	18.5	3.0	10.8	3.7	79	74	37	6.9	59b
N-P-K-M	53.6	3.3	17.8	3.1	10.0	3.7	85	65	37	7.1	66a
					Soybean, Site 4						
Control	58.3	2.9b	21.0	3.5	10.5	2.9	99	73	40	10.5	53
N-P-K-M	57.1	2.7a	20.6	3.3	10.4	2.8	97	66	40	10.1	51
					Across soybean sites						
Control	55.4	3.2a	19.8	3.2	10.7	3.3	89	74a	39	8.7	56
N-P-K-M	55.3	3.0b	19.2	3.2	10.2	3.3	91	65b	39	8.6	58
					Significance of treatments *P* > F						
Corn, Site 3	0.899	0.423	0.844	1.000	0.183	0.529	0.224	0.679	0.140	0.085	0.003
Corn, Site 4	0.248	0.270	0.598	1.000	0.333	0.184	0.197	0.987	0.261	0.336	0.028
Across corn Sites	0.308	0.415	0.571	0.076	0.603	1.000	1.000	0.636	0.397	0.564	0.013
Soybean, Site 3	0.336	0.478	0.299	0.225	0.340	0.717	0.244	0.223	1.000	0.727	0.095
Soybean, Site 4	0.533	0.020	0.778	0.553	0.894	0.870	0.782	0.173	0.910	0.145	0.448
Across soybean Sites	0.948	0.042	0.426	0.878	0.341	0.678	0.509	0.034	0.932	0.722	0.307

† Treatment means within site for each nutrient followed by a different letter are statistically different at the 0.10 probability level.

‡ Fluid fertilizer containing N, P, and K; M, micronutrient blend of Fe, Mn, Zn, Cu, and B.

Table 4-9. Significance of F values for the fixed effects of starter and foliar fertilization on soybean plant height at maturity and seed yield for each site. Sites and blocks within site considered random effects for analysis across all site-years.

	Fixed effects		
Site	Starter(S)	Foliar (S)	S x F
	——————— *P* > F ———————		
	Seed yield		
1	0.394	0.175	0.017
2	0.910	0.552	0.746
3	0.295	0.409	0.687
4	0.006	0.904	0.337
All site-years	0.119	0.182	0.088
	Plant height		
1	0.972	0.838	0.305
2	0.563	0.162	0.591
3	0.155	0.372	0.002
4	0.002	0.253	0.693
All site-years	0.020	0.189	0.026

Table 4-10. Mean response of soybean height at maturity (R8 growth stage) and seed yield to combinations of starter and foliar fertilization.

	No starter			N-P-K starter			N-P-K-M starter		
Site	No foliar	N-P-K‡	N-P-K-M‡	No foliar	N-P-K	N-P-K-M	No foliar	N-P-K	N-P-K-M
	seed yield, kg ha^{-1}								
1	3931bc†	3905bc	3345d	3702bcd	3915bc	4173ab	4359a	3559cd	3620cd
2	4293	4271	4230	4311	4047	4398	4354	4265	4292
3	2858	2983	2681	2994	2672	2698	2711	2545	2610
4	4069	4466	4312	4746	4792	4584	4904	4605	4790
All site-years	3788cb	3906bc	3642c	3961ab	3857b	3963ab	4081a	3765cb	3828bc
	plant height, cm								
1	110	116	112	117	110	111	111	115	114
2	110	111	107	110	111	111	111	111	109
3	70e	79bcd	82bc	85ab	78cd	79bcd	90a	82bc	73de
4	99	100	97	102	103	100	107	103	104
All site-years	97e	101bcd	100de	103ab	100bcd	100bcd	105a	103abc	100cde

† Numbers in the same row followed by different letters are statistically different at the 0.10 probability level

‡ Fertilizer containing N, P, and K; M, micronutrient blend of Fe, Mn, Zn, Cu, and B.

Table 4-11. Mean response of soybean height at maturity to starter and foliar fertilization.

Site	Starter			Foliar		
	Control	N-P-K‡	N-P-K-M‡	Control	N-P-K	N-P-K-M
	seed yield, kg ha^{-1}					
1	3727	3930	3846	3997	3793	3713
2	4265	4252	4304	4319	4195	4307
3	2840	2788	2622	2854	2733	2663
4	4282b†	4707a	4767a	4573	4621	4562
All site-years	3779	3928	3892	3944	3843	3811
	plant height, cm					
1	112	113	113	112	114	112
2	110	111	111	110	111	109
3	77	81	81	82	79	78
4	99c	102b	105a	103	102	100
All site-years	99	101	102	102	102	100

† Numbers in the same row followed by different letters are statistically different at the 0.10 probability level

‡ Fertilizer containing N, P, and K; M, micronutrient blend of Fe, Mn, Zn, Cu, and B.

Table 4-12. Mean response of nutrient concentration in the uppermost fully-expanded soybean trifoliolate leaves at the R1 to R2 growth stage to starter fertilizers.

	Nutrient										
Starter	N	P	K	S	Ca	Mg	Fe	Mn	Zn	Cu	B
	g kg^{-1}						mg kg^{-1}				
						Site 1					
Control	46.0	4.0	23.1	1.9	8.9	3.5	78b	64a	34	5.0	45b†
N-P-K‡	47.4	4.0	23.0	1.9	8.8	3.5	91a	62a	33	5.0	44b
N-P-K-M‡	47.4	4.0	22.8	1.9	8.8	3.5	86a	53b	31	5.0	47a
						Site 2					
Control	50.4	3.4b	21.7	2.4	8.5	3.4	90	50a	31b	8.7	38
N-P-K	51.2	3.6ab	21.6	2.5	8.2	3.5	92	49a	31b	8.4	37
N-P-K-M	51.6	3.7a	22.2	2.4	8.3	3.5	90	44b	33a	8.7	39
						Site 3					
Control	52.9	3.2	18.3	2.9	10.8	3.9	157	68a	34a	6.0	41b
N-P-K	53.4	3.3	18.3	3.0	10.8	3.8	156	65a	32b	5.7	42b
N-P-K-M	53.3	3.3	17.6	2.9	11.5	3.9	158	61b	32b	5.8	60a
						Site 4					
Control	54.3b	3.2	27.0a	3.1	11.5	3.8	116	73a	40	11.2	47b
N-P-K	56.0a	3.4	26.4b	3.2	11.3	3.7	117	73a	39	11.4	48b
N-P-K-M	56.1a	3.4	26.3b	3.2	11.4	3.7	119	63b	39	11.3	50a
						All site-years					
Control	50.9b	3.4b	22.5	2.6	9.9	3.6	110	64b	35	7.6	43b
N-P-K	52.0a	3.6a	22.3	2.6	9.8	3.6	114	62b	34	7.7	43b
N-P-K-M	52.1a	3.6a	22.2	2.6	10.0	3.7	113	55a	34	7.7	49a
						Significance of treatments *P* > F					
Site 1	0.230	0.906	0.890	0.717	0.799	0.955	0.014	0.001	0.199	1.000	0.010
Site 2	0.537	0.097	0.420	0.556	0.431	0.230	0.823	0.001	0.059	0.689	0.233
Site 3	0.781	0.495	0.150	0.857	0.108	0.230	0.986	0.011	0.026	0.591	<0.001
Site 4	0.050	0.196	0.064	0.316	0.551	0.107	0.769	<0.001	0.521	0.799	0.033
All	0.014	0.021	0.451	0.366	0.282	0.823	0.323	<0.001	0.179	0.845	<0.001

† Treatment means within site for each nutrient followed by a different letter are significantly different at the 0.10 probability level.

‡ Fertilizer containing N, P, and K; M, micronutrient blend of Fe, Mn, Zn, Cu, and B.

Chapter 5 - Manganese and Zinc Fertilizer Source Affects Soil Mobility and Soybean Leaf and Seed Nutrient Concentration

ABSTRACT

The selection and use of the various Mn and Zn fertilizer sources can impact soybean [*Glycine max* (L.) Merr.] response. The objective of this study was to evaluate the effect of two fertilizer sources (oxysulfate and EDTA) for Mn and Zn on soil mobility and soybean nutrient concentration in the leaf and seed. Two small-plot trials were carried out under rainfed and irrigated condition. Fertilizer was banded over the row after planting and included a control, Na_2EDTA (an equivalent rate of EDTA applied with Mn and ZnEDTA), MnEDTA, ZnEDTA, Mn oxysulfate, and Zn oxysulfate. Zinc and Mn were applied at 4.5 kg ha^{-1} with EDTA and 22.5 kg ha^{-1} with oxysulfates. Soil samples from the 0- to 7.5-cm, 7.5- to 15-cm, and 15- to 30-cm depth were collected to assess fertilizer mobility. Soil test Mn (STMn) and Zn (STZn) were increased with fertilization. Zinc sources were more mobile in the soil than Mn sources. Both Zn fertilizer sources increased seed Zn concentration ([Zn]). Manganese oxysulfate increased seed Mn concentration ([Mn]). Soybean trifoliolate leaf and seed [Mn] were decreased with soil-applied EDTA fertilizers across site-years. This response can be attributed to the formation of FeEDTA and increased Fe absorption that reduced root Mn absorption. The Mehlich-3 and DTPA Zn soil tests were strongly correlated (R^2=0.93), and a simple transformation exist that may allow for regional interpretations. Producers should not use EDTA chelated micronutrient fertilizers if soybean manganese deficiency is a concern.

Abbreviations: CEC, cation exchange capacity; [Mn], manganese concentration; [Zn], zinc concentration; EDTA, ethylenediamine tetracetic acid; NSR(s), nutrient sufficiency range(s); OM, organic matter; [S], sulfur concentration; STMn, soil test Mn ;STZn, soil test Zn.

INTRODUCTION

The likelihood of increasing soybean yield with micronutrient fertilization is higher with Fe (Liesch et al., 2011), Zn (Whitney, 1997), and Mn (Loecker et al., 2010) and lower for Mo, B, Cu, Cl, and Ni in the Great Plains region. Iron deficiency is widespread in the Great Plains and North Central U.S. (Goos and Johnson, 2000; Hansen et al., 2003; Liesch et al., 2011). Manganese deficiency is more common in the Great Lakes region and the Atlantic Coastal Plains of the U. S. (Voth and Christenson, 1980; Gettier et al., 1985); however increased interest in Mn has occurred in other regions related to information suggesting glyphosate use and glyphosate-resistant soybean varieties creates a higher need for Mn fertilization (Huber 2007; Gordon 2007). However, Loecker et al. (2010) measured yield increases with manganese fertilization at three locations, though response was linked to differences in genotype and not to the glyphosate resistant trait. It is well-known that soybean is less sensitive than corn to Zn deficiency (Rashid and Fox, 1992; Martens and Westermann, 1991), However, soybean Zn deficiency can still occur especially where topsoil have been removed from either erosion or leveling (Whitney, 1997).

There are numerous Zn and Mn fertilizer sources available on the market which can create uncertainty for producers when selecting a source. The source and water solubility of the fertilizer is often a concern in the year of application, but less important in the long-term (Goos et al., 2000). Numerous inorganic (sulfates, oxysulfate, oxides, carbonates, and phosphates) and organic (EDTA, lignosulfonate, citric acid, etc.) compounds of both Zn and Mn exist. Zinc and

Mn sulfates and chelates are highly water soluble (Amrani et al., 1999) whereas water solubility of oxysulfates (mix of metal sulfate and metal oxide) can vary greatly (Amrani et al., 1999) depending on the amount of sulfuric acid used, while metal oxides are almost completely insoluble at high soil pH. The different soil-applied Zn and Mn fertilizer sources can affect crop response (Randall et al., 1975; Hergert et al., 1984; Goos et al., 2000).

Studies have shown that ZnEDTA is a very effective fertilizer source for slightly acidic to calcareous soils (Hergert et al., 1984; Norvell, 1991; Goos et al., 2000). Zinc-EDTA is more mobile in the soil than other Zn sources and potential for leaching does exist (Hergert et al., 1984; Obrador et al., 2003). In calcareous soils, ZnEDTA appears to be more plant available during the first year of application than other sources (Goos et al., 2000; Obrador et al., 2003). However, ZnEDTA, $ZnSO_4$, and Zn humate-lignosulfonate all perform equally well during the second cropping cycle at raising STZn (Goos et al., 2000).

Band-applied $MnSO_4$ is more effective than broadcast applications at alleviating manganese deficiency (Randall et al., 1975; Mascagni and Cox, 1985a). However, residual effects from $MnSO_4$ are generally low which can require applications each time soybeans are grown (Shuman et al., 1979; Parker et al., 1981; Wilson et al., 1982). Contrary to $MnSO_4$, MnEDTA is not an effective soil-applied fertilizer source to correct manganese deficiency in soybean (Randall et al, 1975; Shuman et al., 1979; Voth and Christenson, 1980). Soil-applied MnEDTA is unstable in aerobic soils and the loss of chelated Mn is very rapid due to displacement (Aboulroos, 1981; Ryan and Hariq, 1983; Norvell, 1991). Row-applied MnEDTA in field trials can decrease biomass, trifoliolate leaf [Mn], and yields when soybeans are displaying Mn deficiency (Randall et al., 1975). The Fe/Mn antagonism effect in soybean is stronger than it is in other crops like wheat (Ghasemi-Fasaei et al., 2003; Ghasemi-Fasaei and

Ronaghi, 2008). The application of soil-applied chelated Fe can decrease Mn uptake and [Mn] in the root, stems, and leaves due to a reduction in Mn root absorption and some reduction in Mn translocation from roots to the shoot (Heenan and Campbell, 1983; Roomizadeh and Karimian,1996; Ghasemi-Fasaei et al., 2003; Moosavi and Ronaghi, 2011).

A comprehensive set of nutrient sufficiency ranges (NSRs) for soybean was put together by J.B. Jones at the Ohio Agricultural Experimental Station in the 1960s (Jones, 1967). The youngest uppermost mature trifoliolate leaf without the petiole during the R1-R2 growth stage (Ritchie, 1997) prior to pod set is an index of soybean plant nutrient sufficiency (Jones, 1967; Ohki et al., 1977). Therefore, the inclusion of the petiole (Ohki, 1976) and sampling at earlier and later growth stages (Ohki, 1976; Ohki et al., 1977) can lead to poor interpretations. Soybean seed nutrient analysis has been proposed as an additional tool to index soybean plant nutrient sufficiency (Rashid and Fox, 1992; Moraghan and Helms, 2005; Hitsuda et al., 2010). The advantage of mature seed over trifoliolate leaf analysis is the reduced chance for error and ease of sampling. Errors associated with leaf analysis can occur when different genotypes (different flowering dates and growth habits, i.e. determinate and indeterminate) are included in the same study (Moraghan and Helms, 2005). Hitsuda et al. (2010) suggest seed micronutrient analysis could help determine the need for micronutrient fertilization of the next soybean crop. Critical levels for Zn in the soybean seed were found to be 43 mg Zn kg^{-1} (Rashid and Fox, 1992), 33 mg Zn kg^{-1} (Moraghan and Helms, 2005), and 42 mg Zn kg^{-1} (Hitsuda et al., 2010). The determination of the critical seed [Mn] based on yield response curves is near 15 to 20 mg Mn kg^{-1} (Cox, 1968; Boswell et al., 1981; Wilson et al., 1982; Gettier et al., 1985).

The concentration of Mn and Zn in the seed can be important when soybeans are used for human consumption. Manganese deficiency worldwide is generally not a significant problem

(Van Campen, 1991). However, Zn deficiency is listed as a major risk factor for human health across the world (WHO, 2002). Soybeans can serve as good alternative source of Zn (Van Campen, 1991). Zinc concentration is higher in soybean than most legume seeds (USDA, 2003). Further, Zn fertilization of soybean can increase [Zn] in seed when STZn is low (Moraghan and Helms, 2005). An increase in soybean seed [Zn] can increase dietary Zn intake without having an effect on bioavailability (Welch et al., 1982). Agronomic biofortification with Zn is viewed as an attractive and useful strategy to resolve Zn deficiency in the human population (Cakmak, 2008).

More field trials are needed to verify that Fe/Mn antagonism in soybean can be a legitimate concern beyond greenhouse conditions (Heenan and Campbell, 1983; Roomizadeh and Karimian, 1996; Ghasemi-Fasaei et al., 2003; Moosavi and Ronaghi, 2011). Producers often consider higher rates of relatively cheaper oxysulfate fertilizers as an alternative to more expensive chelated micronutrients. The lower solubility of metal oxysulfates can be a concern during the year of application. The objective of this study was to compare the effects of two fertilizer sources (oxysulfate and EDTA) for each Mn and Zn on soil mobility and soybean leaf and seed nutrient concentrations in field conditions.

MATERIALS AND METHODS

Site Information, Experimental and Treatment Design, and Implementation

Studies were conducted at two sites in Kansas during 2011 (Table 5-1). Plot size was one 3 m long row with row-spacing of 76 cm with one untreated row located between each plot. The experimental design was a one-way treatment structure in a randomized complete block design with four replications. The six fertilizer treatments consisted of a control, Na_2EDTA, MnEDTA, ZnEDTA, Mn oxysulfate, and Zn oxysulfate. An EDTA rate of 22.5 kg ha^{-1} was applied with liquid Na_2EDTA to supply an equivalent amount of EDTA as applied with MnEDTA and ZnEDTA. Zinc was applied at 22.5 and 4.5 kg ha^{-1} through dry Zn oxysulfate (20% Zn, minimum of 70% is water soluble) and liquid ZnEDTA (6% Zn), respectively. Manganese was applied at 22.5 and 4.5 kg ha^{-1} through dry Mn oxysulfate (20% Mn, minimum of 50% is water soluble) and liquid MnEDTA (6% Mn), respectively. All treatments were banded over the row on the surface immediately after planting. Zinc-EDTA, MnEDTA, and Na_2EDTA were diluted in water and applied at 132, 132, and 526 L ha^{-1}, respectively.

Field Measurements

For each treatment, composite soil samples (10 cores) were collected from the 0- to 7.5-cm, 7.5- to 15-cm, and 15- to 30-cm depth (Table 5-2) in the soybean row at the R2 growth stage (Ritchie et al., 1997). Soils were oven dried at 40°C, crushed to pass through a 2 mm sieve, and analyzed to for soil pH (1:1 soil:water), Mehlich-3 extractable P, K, Ca, Mg, S-SO_4, Fe, Mn, Zn, Cu, and B (Mehlich, 1984), organic matter by weight loss-on ignition (Combs and Nathan, 1998), and cation exchange capacity (CEC) by summation (Warncke and Brown, 1998). Mehlich-3 extractants were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES).

Plant samples for soybeans consisted of collecting 20 of the youngest uppermost fully expanded trifoliolates (without petioles) at the R2 growth stage (Ritchie et al., 1997) from each plot. Trifoliolate leaf samples were oven-dried at 65°C for 3–5 days, weighed, and ground to pass a 2 mm screen. Seed samples were oven-dried at 65°C for 7 days, weighed, and ground to pass a 2 mm screen. After digesting with HNO_3 and 30% H_20_2, the concentration in trifoliolate leaf samples for P, K, Ca, Mg, S, Cu, Fe, Mn, Zn, and B and seed for S, Fe, Mn, and Zn were determined by ICP-AES. Total N for trifoliolate leaf samples was determined by dry combustion using a LECO FP-528 Nitrogen Analyzer (LECO Co., St Joseph, MI).

In another study to assess the relationship between Mehlich-3 and DTPA extractable Zn and Mn, composite soil samples (n=119) from the 0- to 15-cm depth from four locations in Kansas were collected (Table 5-3). Soils were oven dried at 40°C, crushed to pass through a 2 mm sieve, and analyzed to for soil pH (1:1 soil:water), Mehlich-3 (Mehlich, 1984) and DTPA (Whitney, 1997) extractable Mn and Zn, organic matter (OM) by weight loss-on ignition (Combs and Nathan, 1998), and cation exchange capacity (CEC) by summation (Warncke and Brown, 1998). Mehlich-3 extractants were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES) and DTPA extractants by atomic absorption (AA) spectrometry.

Statistical Analysis

Analysis of variance for each site was analyzed using the MIXED procedure in SAS 9.2 (SAS Institute, 2010) and considering block as a random factor in the model. For analysis across sites, site and block within site were considered as random factors. Mean separation was determined by Fisher's protected least significant difference procedure at $\alpha = 0.10$. The fertilizer treatment effects were compared within each soil sampling depth (0- to 7.5-cm, 7.5- to 15-cm, and 15- to 30-cm), not between sampling depths. Regression analysis was performed using PROC REG in SAS to determine the relationship between soil test Mehlich-3 and DTPA for both Zn and Mn.

RESULTS AND DISCUSSION

Soil Test Interpretations

The mean Mehlich-3 Zn value for the 0- to 15-cm depth in control plots were 3.9 and 1.5 mg kg^{-1} at site 1 and 2, respectively (Table 5-2). Mehlich-3 soil extractable zinc is considered deficient at concentrations less than 1.0 mg Zn kg^{-1} for soybean in the Northeast U. S. (Heckman, 2009). In the Great Plains, soils are considered to be deficient in zinc for soybean production when DTPA extractable Zn is less than 0.4 mg kg^{-1} (Ferguson et al., 2006). However, because soybeans are often grown in rotation with corn, a critical level of 1.0 mg kg^{-1} is often used for soybean production (Liekam et al., 2003). Moraghan and Helms (2005) suggested that soybeans are sufficient in Zn when soil DTPA-Zn was greater than 0.6 mg kg^{-1}.

Similar to results found by Wang et al. (2004), regression analysis suggested a good linear relationship ($R^2 = 0.93$) between Mehlich-3 Zn by ICP and DTPA Zn by AA (Figure 5-1). The lower and upper limits (L, U) of the 95% confidence interval for the intercept and slope were (0.58, 0.71) and (1.08, 1.19), respectively. Therefore, our relationship between the two soil tests differed from those determined with Louisiana soils with an intercept of 0.17 and a slope of 1.69 (Wang et al., 2004). More similar to our results, the relationship between Mehlich-3 Zn by ICP and DTPA Zn by AA in Missouri soils generated an intercept of 0.7, but a slope of 1.5 (Nathan et al., 2005). Based on our data, critical values (0.4 mg kg^{-1} DTPA-Zn and 1.0 mg Zn kg^{-1} Mehlich-3) arrived at by Ferguson et al. (2006) and Heckman (2009) are in agreement and a simple transformation exist that may allow for regional interpretations of Mehlich-3 Zn (Figure 5-1). Using the transformation shown in Figure 5-1, soil Zn availability was sufficient at both sites.

The mean Mehlich-3 Mn value for the 0- to 15-cm depth in control plots were 47.6 and 76.2 mg kg^{-1} at site 1 and 2, respectively (Table 5-2). In the Great Plains region, no soil test manganese interpretations currently exist for soybean. On the U.S. Atlantic Coastal Plain, critical levels of Mehlich-3 Mn were determined for soybean at 3.9 and 8.0 mg Mn kg^{-1} at a pH of 6.0 and 7.0, respectively (Mascagni and Cox, 1985b). The Mehlich-3 and DTPA Mn soil tests were more weakly correlated (R^2=0.65) than Zn soil tests, which is in agreement with previous findings (Wang et al., 2004; Nathan et al., 2005) (Figure 5-2). Additional predictors would need to be considered to possibly improve the relationship.

Soil Mobility

The measured rainfall from nearby weather stations from planting until the date of soil sample collection was 234 mm and 235 mm for site 1 and 2, respectively (Table 5-1). Irrigation events at Site 2 did not occur until after soil samples were collected. The use of Zn and Mn oxysulfate allowed us to compare the movement of SO_4-S in the soil relative to the movement of Mn and Zn. Sulfate-S is considered to be mobile in soils near a pH near 7.0 with 2:1 clay mineralogy where adsorption capacity is low (Bohn et al., 1986). An increase in SO_4-S concentration was measured at Site 1 at all three sampling depths (Table 5-4). At Site 2, however, no increase in SO_4-S was measured at the 0- to 7.5-cm depth suggesting SO_4-S was leached out of the 0- to 7.5-cm depth. Additionally, there was a larger relative increase in SO_4-S at the 15- to 30-cm depth than at the 7.5- to 15-cm depth compared to the control.

Mehlich-3 soil test Zn (STZn) was increased by the band applied Zn oxysulfate and ZnEDTA at all soil depths. Zinc EDTA fertilization only increased STZn at the 7.5- to 15-cm depth at Site 1 and across site-years. At Site 2, only STZn at 7.5- to 30-cm depth was increased, which is similar to results found with SO_4-S (Table 5-4). The movement of Zn into the soil profile with ZnEDTA may explain lack of an increase in the 0- to 7.5-cm depth. Chelated zinc fertilizer has been shown to be very mobile in the soil profile (Obrador et al., 2003).

Mehlich-3 soil test Mn (STMn) was increased with both MnEDTA and Mn oxysulfate at the 0- to 7.5-cm depth at each site. Even though Mn is displaced from EDTA quickly (Aboulroos, 1981; Ryan and Hariq, 1983; Norvell, 1991), Mn may have been chelated long enough for MnEDTA to move further into the soil profile based on the increase in STMn measured in the 7.5- to 15-cm depth and not with Mn oxysulfate across site-years (Table 5-4). However, no increase in STMn was measured at the 15- to 30-cm depth for either fertilizer source. Wilson et al. (1981) found that broadcast applications of Mn sulfate at 168 kg Mn ha^{-1} applied over 3 years to sandy soils resulted in higher extractable Mn in the top 0- to 30-cm depth with no significant increase at lower depths.

The relative concentration increase in STMn was less than STZn with the oxysulfate fertilizers. This is in agreement with previous findings that show Zn has a much higher soil residual availability than Mn which undergoes rapid oxidation and formation of insoluble manganese hydroxides and oxides of low plant availability (Martens and Westermann, 1991). This may also result in low soil test extractability with the methods used in our study.

Trifoliolate Leaf Concentration

The trifoliolate leaf concentration of all nutrients measured in control plots were sufficient or high based on NSRs by Jones (1967) and Mills and Jones (1996). Zinc and Mn fertilizer treatments did not affect N, K, Ca, Mg, or Cu concentration in the soybean trifoliolate leaf (Table 5-5). No differences between the control and fertilizer treatments were found in S and

P trifoliolate leaf concentration at either site and the increase in trifoliolate leaf B concentration at Site 2 with the MnEDTA treatment was not consistent across site-years. Further, no increase in trifoliolate [S] was measured with sulfur containing fertilizers (oxysulfates).

Mn oxysulfate did not increase trifoliolate leaf [Mn] at either site. However, a significant increase in trifoliolate leaf [Fe] and decrease in [Mn] occurred at Site 1 with all treatments containing EDTA (Table 5-5). At Site 1, trifoliolate leaf [Mn] decreased 51–53% with the addition of soil-applied EDTA containing fertilizers. At Site 2, a 22% decrease in trifoliolate leaf [Mn] was measured with Na_2EDTA. Application of ZnEDTA and MnEDTA did not affect trifoliolate leaf [Fe] and [Mn] at Site 2. Less EDTA should be available to complex with other elements with the use of ZnEDTA compared to Na_2EDTA and MnEDTA (Norvell and Lindsay, 1969). In general, the application of EDTA chelates had less affect on leaf [Fe] and [Mn] concentrations at Site 2 compared to Site 1. The difference may be attributed to known differences in variety sensitivity to Fe/Mn antagonism (Ghasemi-Fasaei et al., 2003). Additionally, soil adsorption of EDTA or Ca^{2+} competition for EDTA may have been higher at Site 2 resulting in reduced FeEDTA formation and lower Fe solubility (Norvell and Lindsay, 1969). It is likely that the loss of Mn from the EDTA lead to the formation of FeEDTA and increased soil Fe solubility, greater Fe uptake (Norvell and Lindsay, 1969), increased trifoliolate leaf [Fe], and decreased trifoliolate leaf [Mn] even though STMn was increased with MnEDTA applications (Table 5-5). Previous studies have found that application of soil-applied chelated Fe can decrease Mn uptake and [Mn] in the root, stems, and leaves (Heenan and Campbell, 1983; Ghasemi-Fasaei et al., 2003; Moosavi and Ronaghi, 2011) without decreasing concentrations of other metals like Cu and Zn (Roomizadeh and Karimian, 1996; Ghasemi-Fasaei et al., 2003). The dilution effect, changes in root/shoot ratio, and toxic effects of Fe are not responsible for the decrease in plant [Mn] (Heenan and Campbell, 1983; Roomizadeh and Karimian, 1996; Ghasemi-Fasaei et al., 2003; Moosavi and Ronaghi, 2011). High solubility of Fe in soil can lead to a reduction in Mn root absorption as determined by lower root [Mn] and a possible reduction in Mn translocation from roots to the shoot (Heenan and Campbell, 1983; Roomizadeh and Karimian, 1996; Ghasemi-Fasaei et al., 2003; Moosavi and Ronaghi, 2011). Small increases in plant [Fe] can lead to larger corresponding decreases in [Mn] (Ghasemi-Fasaei et al., 2003; Moosavi and Ronaghi, 2011) when synthetic Fe chelates are soil-applied. The lack of change in trifoliolate leaf [Fe] measured at Site 2 with the EDTA treatment may have been hidden by only small increases in whole-plant [Fe] not measured in this study. Based on other studies (Ghasemi-Fasaei et al., 2003; Moosavi and Ronaghi, 2011), only a 1 to 2 mg Fe kg^{-1} increase would be expected with a 7 mg Mn kg^{-1} decrease in whole-plants.

At Site 1, the trifoliolate leaf [Mn] was reduced by fertilizer EDTA, MnEDTA, and ZnEDTA to 20 to 21 mg kg^{-1}, which is near the critical level (Cox, 1968; Ohki, 1976; Ohki et al., 1977; Wilson et al., 1982; Bell et al. 1995) (Table 5-5). The use of soil-applied EDTA chelated micronutrients could potentially induce manganese deficiency based our results. Randall et al. (1975) found that row-applied MnEDTA (0.56 and 1.12 kg Mn ha^{-1}) can decrease biomass, trifoliolate leaf [Mn], and yield slightly when soybeans are displaying Mn deficiency. Voth and Christenson (1980) found no increase in trifoliolate leaf [Mn] with application of MnEDTA (1.4 kg Mn ha^{-1}) or Mn oxysulfate (9 kg Mn ha^{-1}), however $MnSO_4$ at 9 kg Mn ha^{-1} showed an increase in Mn leaf concentration. Shuman et al. (1979) observed no increase in trifoliolate leaf [Mn] with any broadcast rate of MnEDTA (0.56, 1.12 and 2.24 kg Mn ha^{-1}), though increases were observed with $MnSO_4$ and MnO at 11.2 kg Mn ha^{-1}. Other studies have increased trifoliate leaf [Mn] and yield with applications of $MnSO_4$ at sites with a history of manganese-deficiency soybean (Randall et al., 1975; Ohki et al., 1977; Boswell et al., 1981; Mascagni and Cox, 1985a; Gettier et al., 1985).

Trifoliolate leaf [Zn] was increased with both ZnEDTA (10%) and Zn oxysulfate (23%) at Site 2 (Table 5). No response to Zn was observed at Site 1 where STZn and trifoliolate leaf [Zn] were higher. Trifoliolate leaf [Zn] at both sites were above the lower end of the NSR of 17 to 22 mg Zn kg^{-1} (Jones, 1967; Gettier et al., 1985; Rashid and Fox, 1992; Bell et al., 1995) and above the critical level of 34 mg Z kg^{-1} determined by Hitsuda et al. (2010).

Seed Concentration

Band-applied oxysulfate fertilizers did not increase seed [S] (Table 5-6). Mean concentration of seed was 3.4 and 3.9 mg S kg^{-1} at Site 1 and 2, respectively. A seed S concentration greater than 2.3 g kg^{-1} is considered an indicator of S sufficiency in the plant and the critical level to achieve standard protein quality (Hitsuda et al., 2004). Hitsuda et al. (2004) found that seed [S] explained more of the variation in yield than did the uppermost fully expanded trifoliolate at flowering. Seed and leaf [S] both suggest that S was sufficient in soybean plants (Hitsuda et al, 2004).

Fertilizer treatments did not affect seed [Fe] at any site (Table 5-6). Mean seed [Fe] was 82 and 65 mg kg^{-1} at Site 1 and 2, respectively. Wiersma (2005) showed than seed [Fe] is affected by the environment and the differences between varietal seed [Fe] are conserved within and across environments. Therefore, no clear conclusions can be drawn from the difference in [Fe] between the two sites. The concentrations found in this study are comparable to those found in other studies (Ohki et al., 1980; Parker et al., 1981; Wiersma, 2005;Wiersma, 2007; Wiersma, 2012). No defined critical seed [Fe] has been determined (Wiersma, 2005). This is largely due to the fact that seed [Fe] is genetically controlled and large applications (11.2 kg ha-1) of FeEDDHA lead to small increases in seed [Fe], but large yield increases (Wiersma, 2005). Large difference in seed [Fe] between resistant and susceptible varieties occurs regardless of relative yield changes with Fe fertilization (Wiersma, 2005).

Seed [Mn] was decreased at Site 1 by fertilizer treatments containing EDTA similar to trifoliolate leaf concentrations (Tables 5-5 and 5-6). There was slight trend at both sites for Na_2EDTA and MnEDTA to cause more of a decrease than ZnEDTA. An increase in seed [Mn] was only measured with application of Mn oxysulfate at both sites, which was not observed in the leaf analysis. Previous studies have shown increases in seed [Mn] with $MnSO_4$ fertilization (Parker et al., 1981; Boswell et al., 1981; Wilson et al., 1982; Gettier et al., 1985). The critical seed [Mn] based on yield response curves is near 15 to 20 mg kg^{-1} for soybeans grown in the field (Cox, 1968; Boswell et al., 1981; Wilson et al., 1982; Gettier et al., 1985). Hitsuda et al. (2010) calculated the critical [Mn] in seed to be 55 mg kg^{-1} in their greenhouse study, which is much higher than any previous field studies. However, no yield responses were measured above approximately 32 to 36 mg Mn kg^{-1} (Hitsuda et al., 2010). The lowest concentrations in our study were 33 and 34 mg Mn kg^{-1} at Site 1 and Site 2, respectively, with the Na_2EDTA and MnEDTA treatments. Trifoliolate leaf and seed analysis both suggest that manganese deficiency was not induced. However, in environments were manganese-deficient soybeans occur more regularly (Great Lakes region and Atlantic Coastal Plain), application of MnEDTA and EDTA based micronutrient mixes could induce deficiency and decrease yield as observed by Randall et al. (1975). The similar response observed between Na_2EDTA and MnEDTA in our study confirm that MnEDTA is not an effective soil-applied Mn fertilizer source for soybean.

Zinc-EDTA and Zn oxysulfate treatments increased seed [Zn] at both sites. It was interesting to find that Mn oxysulfate increased seed [Zn], which may be supported by the slight trend for increased STZn in the 0- to 7.5-cm depth at both sites as well (Table 5-2). An increase in soil test Cu also occurred in the 0- to 7.5-cm depth with Mn oxysulfate application but not with Zn oxysulfate (data no shown), which may suggest that small amounts various metals (Zn, Cu, etc.) are found in the Mn oxysulfate fertilizer or that it somehow increases Mehlich-3 extractable Cu and Zn as a result of some reactions after application.

Similar seed [Zn] were reached with both ZnEDTA and Zn oxysulfate (Table 5-6). It has been found that lower rates of ZnEDTA can be applied compared to other sources with similar crop responses (Martens and Westermann, 1991). Across all treatments, seed [Zn] was higher at Site 1 than Site 2 as was found with STZn and trifoliolate leaf concentrations. High rates of band-applied Zn fertilizer at Site 2 were not enough to increase seed [Zn] to concentrations measured at Site 1. Hartwig et al. (1991) did find that some soybean varieties differ in efficiency of Zn absorption and this may explain the lack of a large increase in seed [Zn]. However, other studies observed relatively small difference in seed [Zn] between varieties (Moraghan and Helms, 2005; Wiersma, 2012). Seed ranged from 39 to 65 mg Zn kg^{-1} in this study and in others it ranged from 22 to 82 mg Zn kg^{-1} (Ohki et al., 1980; Park et al., 1981; Rashid and Fox, 1992; Moraghan and Helms, 2005; Hitsuda et al., 2010; Wiersma, 2012). Critical seed concentration levels derived from grain yield response have been 43 mg Zn kg^{-1} (Rashid and Fox, 1992) in Hawaii and 42 mg Zn kg^{-1} with soils from Brazil (Hitsuda et al., 2010). Moraghan and Helms (2005) suggested that only values less than 31 to 33 mg Zn kg^{-1} were indicative of zinc deficiency with genotypes adapted to the northern Great Plains. Based on interpretation of sufficiency for STZn and trifoliolate leaf Zn, we conclude that seed [Zn] greater than 39 mg kg^{-1} as sufficient.

The [Zn] in the soybean seed can be important when soybeans are used for human consumption (Van Campen, 1991). This study found that zinc fertilization of soybean did increase [Zn] in seed even when STZn was considered adequate to maximize yield. Agronomic biofortification of soybean with zinc was successful as has been found with cereal grains crops (Cakmak, 2008). However, soybean breeding or genetic biofortification for higher seed [Zn] appears to be an alternative (Hartwig et al., 1991).

CONCLUSION

Oxysulfate and EDTA sources of Mn and Zn can be effective at increasing STZn and STMn in the year of application. The Mehlich-3 Zn soil test was strongly correlated to DTPA-Zn and simple transformation exist (Figure 5-1) that may allow for regional interpretations to be made. Zinc fertilizer sources were more mobile in the soil than Mn sources (EDTA and oxysulfate). An increase in trifoliolate leaf and seed [Zn] were measured with both ZnEDTA and Zn oxysulfate when STZn was considered adequate to maximize yield.

Similar to previous findings, band-applied Mn oxysulfate can be effective source to improve soybean Mn nutrition. However, trifoliolate leaf and seed [Mn] were decreased with EDTA fertilizer sources. With the inclusion of Na_2EDTA, this study confirms findings of previous studies that MnEDTA is not an effective soil-applied fertilizer source for soybean production. This study demonstrated that leaf [F] can be increased and leaf and seed [Mn] decreased in soybean with soil-applied EDTA fertilizers (Na_2EDTA, MnEDTA, and ZnEDTA).

Producers should not soil apply micronutrients chelated with EDTA if their goal is to increase Mn uptake in soybean.

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FIGURES AND TABLES

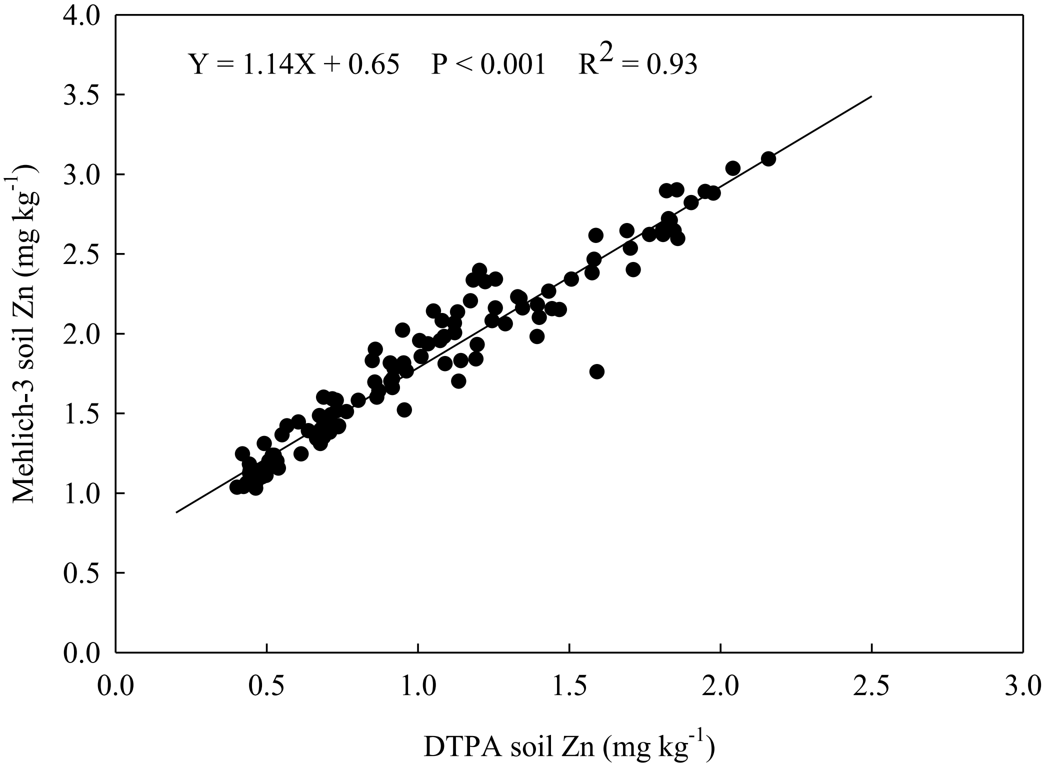

Figure 5-1. Linear relationship between DTPA Zn by atomic absorption spectrometry and Mehlich-3 Zn by inductively coupled plasma (n=119). Standard error of the intercept is ± 0.03 and the slope is ± 0.03.

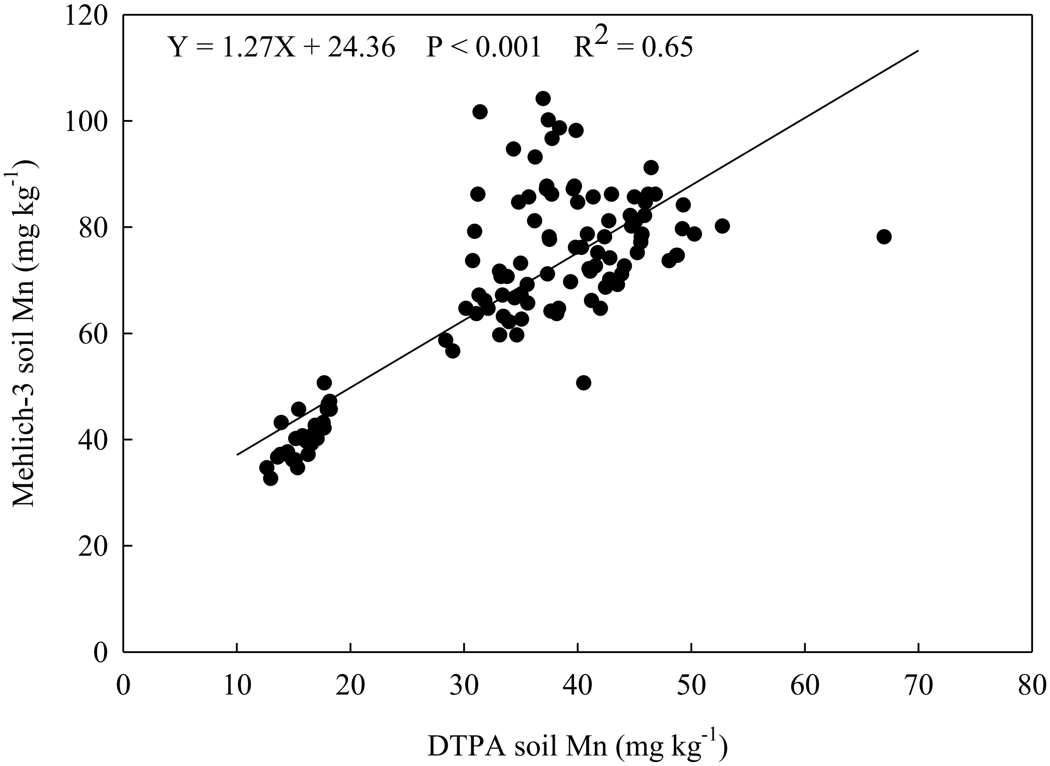

Figure 5-2. Linear relationship between DTPA Mn by atomic absorption spectrometry and Mehlich-3 Mn by inductively coupled plasma (n=119). Standard error of the intercept is ± 3.07 and the slope is ± 0.86.

Table 5-1. Summarized information about conditions at sites

								Soybean		
Site	County	Soil series†	Tillage‡	Previous Crop	Rainfall§	Planting Date	Plant Population	Variety¶	Iron Chlorosis Tolerance#	Soil and plant sampling date
					mm		plants ha^{-1}			
1	Riley	Rossville sil	nt	soybean	234	17 May	191,593	KS 3406	S	29 June
2	Republic	Crete sil	rt	corn	235	17 May	337,979	NK S31L7	MR	13 July

† Soil Series: sil = silt loam.

‡ Tillage: nt = no-till, rt = ridge-till.

§ Rainfall: rainfall/irrigation from planting to soil sampling date from weather station within 10 km

¶ Variety: KS = Kansas State, NK = Northup King.

Iron Chlorosis Tolerance: MR=moderately resistant, S=susceptible.

Table 5-2. Mean soil-test values (0- to 15-cm depth) for each site from control plots.

Depth	CEC	pH	OM†	P‡	K	Ca	Mg	SO_4-S	Zn	Fe	Mn	Cu	B
cm	$cmol_c\ kg^{-1}$		$g\ kg^{-1}$	$mg\ kg^{-1}$									
Site 1													
0-7.5	15.1	6.6	20	31	393	2053	216	9	4.2	92.6	47.1	2.4	0.6
7.5-15	15.4	6.4	17	21	328	2094	211	8	3.6	98.4	48.1	2.6	0.5
15-30	15.9	6.4	15	19	325	2155	240	9	2.0	82.3	28.0	1.9	0.5
Site 2													
0-7.5	15.8	6.8	20	12	609	1958	305	8	2.0	75.8	93.9	1.5	0.7
7.5-15	18.5	5.9	17	9	392	2257	366	10	0.9	104.4	58.4	1.4	0.6
15-30	21.0	5.6	17	9	358	2567	433	11	0.6	99.5	40.8	1.4	0.6

† OM, organic matter determination through loss of weight by ignition

‡ P, K, Ca, Mg, SO_4-S, Zn, Fe, Mn, Cu, and B by Mehlich-3 ICP

Table 5-3. Mean soil-test values (0- to 15-cm depth) for four locations in Kansas.

						Zn		Mn	
Site	County	Soil series†	CEC	pH	OM	DTPA	M-3	DTPA	M-3
			$\text{cmol}_c\ \text{kg}^{-1}$		g kg^{-1}	——— mg kg^{-1} ———			
1	Shawnee	Bismarckgrove sil	17.8	6.4	18	0.6	1.3	36.5	67.1
2	Republic	Crete sil	19.3	6.3	24	1.7	2.5	45.7	77.5
3	Shawnee	Eudora fsl	8.4	6.4	9	0.6	1.4	16.1	41.7
4	Republic	Crete sil	19.0	6.5	22	1.1	2.0	37.8	84.7

† Soil Series: fsl = fine sandy loam, sil = silt loam.

Table 5-4. Soil test sulfate-sulfur (SO_4-S), Zn, and Mn by depth and site for each fertilizer treatment.†

	SO_4-S			Zn			Mn		
Treatment	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30	0-7.5	7.5-15	15-30
	mg kg^{-1}								
	Site 1								
Control	8.8c‡	8.5c	8.8b	4.2b	3.6c	2.0b	47.5cd	48.3c	28.3
EDTA	9.5bc	9.5c	9.8b	3.3b	3.4c	1.8b	55.5bc	51.0bc	27.5
MnEDTA	9.5bc	9.0c	9.0b	3.5b	3.6c	2.0b	65.8b	58.8a	31.0
ZnEDTA	9.3c	8.8c	8.8b	8.3b	7.7b	3.6b	52.5bcd	50.5bc	29.3
Mn oxysulfate	15.5a	17.3a	16.5a	7.1b	3.5c	1.9b	108.8a	53.8b	33.5
Zn oxysulfate	12.0b	13.8b	17.0a	292.5a	17.8a	15.8a	36.8d	48.0c	26.8
	Site 2								
Control	7.8	9.8c	11.3b	2.0b	0.9b	0.6c	94.0c	58.8b	40.8
EDTA	8.3	10.0bc	11.0b	2.0b	1.0b	0.5c	92.8c	67.0ab	46.8
MnEDTA	8.0	9.3c	12.0b	2.0b	1.3b	0.6c	111.0b	82.5a	58.5
ZnEDTA	8.3	10.0bc	10.8b	5.8b	4.9a	1.3b	94.3c	51.0b	43.3
Mn oxysulfate	8.5	13.3a	18.3a	6.4b	1.2b	0.6c	161.2a	62.3b	48.0
Zn oxysulfate	8.5	12.0ab	15.3a	129.9a	5.3a	2.0a	79.3d	54.8b	48.0
	Across Sites								
Control	8.3c	9.1c	10.0b	3.1b	2.2c	1.3b	70.8c	53.5b	34.5
EDTA	8.9bc	9.8c	10.4b	2.7b	2.2c	1.2b	74.1c	59.0b	37.1
MnEDTA	8.8bc	9.1c	10.5b	2.8b	2.5c	1.3b	88.4b	70.6a	44.8
ZnEDTA	8.8bc	9.4c	9.8b	7.0b	6.3b	2.5b	73.4c	50.8b	36.3
Mn oxysulfate	12.0a	15.3a	17.4a	6.8b	2.3c	1.2b	135.0a	58.0b	40.8
Zn oxysulfate	10.3b	12.9b	16.1a	211.2a	11.5a	8.9a	58.0d	51.4b	37.4
	Significance of treatments (*P* > F)								
Site 1	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.486
Site 2	0.297	0.032	0.024	0.002	<0.001	<0.005	<0.001	0.050	0.238
Across Sites	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.003	0.147

† Mehlich-3 ICP.

‡ Treatment means within column for each site followed by a different letter are significantly different at the 0.10 probability level.

§ ns, no significant at the 0.10 probability level

Table 5-5. Nutrient concentration in the uppermost fully expanded soybean trifoliolate leaves at R1-R2 growth stage response to fertilizer sources.

Treatment	N	P	K	S	Ca	Mg	Fe	Mn	Zn	Cu	B
	g kg^{-1}						mg kg^{-1}				
					Site 1						
Control	47.0	4.3ab†	25.8	3.2ab	11.7	3.5	116c	43b	62	15	73
EDTA	47.4	4.5a	26.6	3.5a	12.3	3.7	137a	21c	63	16	69
MnEDTA	47.6	4.5a	26.5	3.4a	12.2	3.6	136a	20c	62	15	69
ZnEDTA	46.3	4.1b	25.3	3.1b	12.0	3.4	129ab	21c	64	15	79
Mn oxysulfate	48.5	4.5a	26.8	3.5a	11.7	3.6	121bc	43b	63	15	61
Zn oxysulfate	47.7	4.4a	26.5	3.3ab	11.9	3.6	118c	49a	70	15	66
					Site 2						
Control	52.2	3.0	26.7	3.2	12.4	4.1	108	70a	40c	10	53b
EDTA	51.5	3.1	27.0	3.2	12.2	3.9	109	54b	40bc	11	52b
MnEDTA	51.6	3.2	27.8	3.3	13.2	4.2	108	71a	41bc	11	57a
ZnEDTA	52.4	3.2	28.0	3.2	12.8	4.0	106	67a	44b	11	53b
Mn oxysulfate	51.5	3.1	27.2	3.2	12.5	4.0	110	78a	41bc	11	53b
Zn oxysulfate	51.8	3.2	27.8	3.2	12.6	4.0	105	75a	49a	11	52b
					Across Sites						
Control	49.6	3.7	26.3	3.2bc	12.0	3.8	112b	56a	51b	13	63
EDTA	49.5	3.8	26.8	3.3ab	12.2	3.8	123a	38c	52b	13	60
MnEDTA	49.6	3.9	27.1	3.4a	12.7	3.9	122a	45b	52b	13	63
ZnEDTA	49.3	3.6	26.6	3.1c	12.4	3.7	118ab	44bc	54b	13	66
Mn oxysulfate	50.0	3.8	27.0	3.3ab	12.1	3.8	115b	60a	52b	13	60
Zn oxysulfate	49.7	3.8	27.1	3.3ab	12.2	3.8	112b	62a	60a	13	59
					Significance of treatments (P > F)						
Site 1	0.321	0.096	0.278	0.096	0.839	0.395	0.004	<0.001	0.273	0.508	0.548
Site 2	0.967	0.539	0.519	0.549	0.151	0.399	0.559	0.060	0.004	0.556	0.022
Across Sites	0.966	0.178	0.541	0.070	0.437	0.441	0.011	<0.001	<0.001	0.261	0.469

† Treatment means within column for each site followed by a different letter are significantly different at the 0.10 probability level.

Table 5-6. Soybean seed nutrient concentration response to fertilizer treatments.

Treatment	S	Fe	Mn	Zn
	– g kg^{-1} –	mg kg^{-1}		
		Site 1		
Control	3.4	83	38b†	61c
EDTA	3.3	82	33c	62bc
MnEDTA	3.3	84	33c	62bc
ZnEDTA	3.4	80	35c	63ab
Mn oxysulfate	3.3	83	42a	64ab
Zn oxysulfate	3.4	79	37b	65a
		Site 2		
Control	3.9	67	36bc	40d
EDTA	3.9	64	34c	39d
MnEDTA	4.0	67	34c	41cd
ZnEDTA	3.9	64	35bc	45a
Mn oxysulfate	3.9	64	38a	42bc
Zn oxysulfate	3.9	64	36b	44ab
		Across Sites		
Control	3.6	75	37b	50d
EDTA	3.6	73	34c	50cd
MnEDTA	3.7	75	34c	51bcd
ZnEDTA	3.7	72	35bc	54ab
Mn oxysulfate	3.6	73	40a	53abc
Zn oxysulfate	3.7	72	37b	54a
		Significance of treatments (*P* > F)		
Site 1	0.702	0.800	<0.001	0.046
Site 2	0.566	0.715	0.004	0.003
Across Sites	0.759	0.514	<0.001	<0.001

† Treatment means within column for each site followed by a different letter are significantly different at the 0.10 probability level.

Chapter 6 - Conclusions

A survey of winter annual weeds (WAW) was conducted prior to no-till corn planting following soybeans in the spring of 2010 and 2011 at 14 fields spread across northeast, east central, and south central Kansas. The five most abundant WAW were henbit (*Lamium amplexicaule* L.), purslane speedwell (*Veronica peregrina* L.), horseweed [*Conyza canadensis* (L.) Cronq], field pennycress (*Thlaspi arvense* L.), and common chickweed [*Stellaria media* (L.) Vill.]. This survey provided data which was not previously available and will be used for tracking future changes in WAW communities found in no-till corn-soybean rotations in Kansas. The abundance of henbit and horseweed particularly pose to be problematic. Henbit serves as a strong host for SCN Race 3 which is common in eastern Kansas and the abundance of henbit may help maintain higher SCN populations. Horseweed is problematic due to its resistance to several modes of action in commonly used herbicides. The potential negative effects that henbit, horseweed, and other WAW have in corn and soybean production could be reduced by early fall herbicide applications with residual activity that last through early spring.

Producers often delay the first herbicide application until near the date of corn planting in April to eliminate passes across the field and application cost. Delaying herbicide applications through spring when WAWs are actively growing and taking up N can reduce the N available for the subsequent corn crop. Delaying herbicide application until April significantly reduced early corn N uptake by 52 mg N plant^{-1}, CM readings at silking by 3.4%, and grain yield by 0.48 Mg ha^{-1} across site-years. Using the N fertilizer equivalence values (based on CM readings and grain yield), an estimated additional 16 to 17 kg N ha^{-1} was needed if herbicide application was delayed until April. Producers can increase corn N uptake and grain yield for rainfed no-till corn following soybeans in eastern Kansas by applying herbicides on WAWs prior to April.

In efforts to maximize net profits, producers are applying micronutrient mixes to eliminate any yield limitations in corn and soybean. These micronutrient mixtures are often being applied to fields where there is no history of micronutrient deficiencies. Our study found no stimulation in early growth or increase in grain yield from application of a micronutrient mixture (Fe, Mn, Zn, Cu, and B) in corn. Micronutrient concentrations in young corn plants were within currently established sufficiency ranges without micronutrient fertilization. Soil and plant analysis suggested that P was the potential limiting factor in achieving higher yield at three of four site-years. An increase in early corn growth and grain yield across site-years was achieved with a surface banded N-P-K starter fertilizer over-the-row. No additional corn yield benefits from foliar fertilization were measured. Corn producers are more likely to gain an economic benefit from the use of an N-P-K starter fertilizer without micronutrients.

Soybean height at maturity and seed yield was increased over the control with the starter N-P-K plus the micronutrient mix across site-years. Nutrient analysis of the uppermost fully-expanded trifoliolate leaves (w/o petioles) at the R2 growth stage did not provide a clear explanation for which nutrient(s) may have provided the small increase height and yield associated with starter N-P-K-M treatment. However, the lack of a significant increase in height or yield over N-P-K without micronutrients suggests the benefit to adding micronutrients was small. Starter N-P-K fertilizer increased soybean yield the most at a site where soil test P was very low. No increase in soybean yield was obtained with foliar fertilization even where a yield response was measured with starter fertilization. Current soybean trifoliolate leaf P and Cu sufficiency ranges are not well defined. A growing interesting from industry and producers in using corn and soybean plant nutrient analysis as a monitoring tool justifies additional research to verify that established NSRs are still robust. Micronutrient mixtures chelated with EDTA used in this study decreased trifoliolate leaf Mn concentration at every site. As a result of these findings, a second study was conducted to assess how the selection of various Mn and Zn starter fertilizer sources (EDTA or oxysulfate) can impact soybean response. Soybean micronutrient fertilizers containing MnEDTA are currently labeled for soil application even though research in the 1970s found it to be ineffective. Trifoliolate leaf and seed Mn concentration were decreased with Na_2EDTA and MnEDTA starter fertilizer applications. The inclusion of Na_2EDTA in this study confirms hypotheses or conclusions made by previous studies that MnEDTA is not an effective soil-applied Mn fertilizer source due to displacement of Mn from the chelate and replacement by Fe. An increase in soil Fe supply near soybean roots can cause Fe/Mn antagonism during root absorption leading to decreased Mn uptake. It would be possible to induce Mn with soil application of MnEDTA. Soil application of MnEDTA is not recommended and extension activities should be increased to inform producers about this issue.