FIELD INVESTIGATIONS OF FOILAR FERTILIZER STRATEGIES OF SOYBEAN MN DEFICIENCY IN MICHIGAN AND PHOSPHORUS AND POTASSIUM FERTILIZER APPLICATION STRATEGIES IN CORN-SOYBEAN ROTATIONS IN THE UNITED STATES

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ABSTRACT

FIELD INVESTIGATIONS OF FOLIAR FERTILIZER STRATEGIES OF SOYBEAN MN DEFICIENCY IN MICHIGAN AND PHOSPHORUS AND POTASSIUM FERTILIZER APPLICATION STRATAGIES IN CORN-SOYBEAN ROTATIONS IN THE UNITED STATES

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Manganese deficiency in soybeans is an annual management issue on high pH, high organic matter soils in Michigan. Soil characteristics render soil Mn unavailable for plant uptake, necessitating in-season foliar fertilizer applications to meet plant Mn requirements. In 2009, research studies were established at two central Michigan muck soil locations. Fertilizers were applied either as tank-mixes with glyphosate when possible or separated by at least three days before or seven days after glyphosate. Three Mn fertilizers were evaluated: $MnSO_4$, a sugar alcohol Mannitol, and $MnSO_4$ chelated with EDTA. All fertilizers alleviated Mn deficiency in the field, but $MnSO_4$ application was most effective at increasing tissue Mn concentrations. Manganese fertilizers influenced soybean leaf Mn levels similarly when tank-mixed with glyphosate or applied separately. Manganese deficiencies reduced yield at three of the six sites years. At one responsive site, all fertilizer treatments increased yield above the control. At the two other responsive sites, $MnSO_4$ and Mannitol applied separately from glyphosate resulted in the greatest yield.

A second project to evaluate additional Mn fertilizers was initiated in 2010 at the same two muck soil sites. Fertilizers were applied at a low and high rate as suggested on product labels. At both

sites in 2010 and 2011, two fertilizer applications were required to treat Mn deficiency symptoms. $MnSO_4$ tended to increase tissue Mn concentrations compared to other products. Manni-plex, Citraplex, and Max-In applied at the high rate generally resulted in higher leaf Mn level compared to other products. Products with EDTA chelates often did not increase tissue Mn levels above that of the untreated control. Applications of $MnSO_4$ at both high and low rates and Citraplex, Manni-plex and Max-In at high rates consistently resulted in higher yields. The use of unchelated or low molecular weight fertilizer products increase foliar fertilizer uptake and result in higher yields than products with higher molecular weight EDTA formulations.

As part of a broad six-state project to address agronomic limitations of soybean yield and quality, trials were initiated in Arkansas, Iowa, Kentucky, Louisiana, Michigan, and Minnesota to examine the impact of P and K fertilizer strategies on corn and soybean grain yield. Fertilizer rates were determined by local state recommendations for a two year corn-soybean rotation and applied at 1x and 2x rates for each crop annually in the spring before crop establishment or biannually as one application both crops prior to corn in the first year. Corn grain yield was increased by fertilizer application at five of twelve sites with initial soil test P and K values in the medium range or higher. At sites with either P or K soil test values below the medium soil test range, increases in corn grain yield with fertilizer application were noted at five of eighteen sites. Yield responses were variable, with increasing fertilizer rates associated with decreasing corn yield at some locations. Soybean grain yield was increased at three site years, all at locations with soil test P in the medium or lower range. No clear trend was observed at these three sites indicating a difference in annual and biannual fertilizer applications. These results uphold current university P and K fertilizer recommendations.

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CHAPTER 1. FOLIAR APPLICATION STRATEGIES TO TREAT MANGANESE DEFICIENCY IN GLYPHOSATE-RESISTANT SOYBEAN

Abstract

Manganese deficiency in soybeans is an annual management issue on high pH, high organic matter soils in Michigan. Soil characteristics render soil Mn unavailable for plant uptake, necessitating in-season foliar fertilizer applications to meet plant Mn requirements. Multiple fertilizer applications are typically needed to correct deficiencies and to minimize total application costs, producers seek to combine Mn fertilizer with glyphosate herbicide. This research investigated the feasibility of employing Mn-glyphosate tank-mixtures compared to separating applications of these products. Manganese fertilizer and glyphosate herbicide application timing and frequency was based on observed soybean chlorosis and weed heights. Three Mn fertilizers; $MnSO_4$, a sugar alcohol Mannitol, and $MnSO_4$ chelated with EDTA, all alleviated Mn deficiency in the field, but $MnSO_4$ application was most effective at increasing tissue Mn concentrations. Manganese fertilizers influenced soybean leaf Mn levels similarly when tank-mixed with glyphosate or applied separately. Manganese deficiencies reduced yield at three of the six sites years. At one responsive site, all fertilizer treatments increased yield above the control. At the two other responsive sites, $MnSO_4$ and Mannitol applied separately from glyphosate resulted in the greatest yield. At sites with low to moderate Mn deficiency, tank-mixing Mn fertilizer with glyphosate was effective at treating Mn deficiency while reducing total application events. At sites with severe Mn deficiency, separating fertilizer and herbicide applications increased soybean grain yield.

Introduction

Soybean manganese deficiencies are common production challenges on organic soils in Michigan. Manganese is absorbed by plants primarily as the free Mn^{2+} ion. In purely inorganic conditions, the principle solution species is Mn^{2+} (Lindsay, 1979) In agricultural soils with soil organic matter, complexed Mn^{2+} comprises upwards of 90% of the solution Mn^{2+} (Tisdale et al., 1993). Manganese cycling in the soil is governed by pH, redox potential, organic matter concentration, microbial activity, and soil moisture. Of these factors, Christenson et al. (1951) noted that pH and organic matter concentration impact cycling to the greatest extent. Under low soil pH or reducing conditions, Mn exists primarily in the divalent Mn^{2+} form. As pH and redox potential increase, the Mn valance state increases to Mn^{3+} and Mn^{4+}; shifting Mn to MnOOH and MnO_2 forms (Lindsay, 1979). Organic matter can complex with Mn^{2+} to decrease its solubility through the formation of chelate compounds, some of which may inhibit plant uptake of Mn (Tisdale et al., 1993). Organic matter complexing is pH dependent, as the bonding of Mn^{2+} with organic solids strengthens as pH increases (McBride, 1982). Page (1962) found increases in soil pH enhance Mn complexation with soil organic matter. Lucas and Davis (1961) have noted that as pH levels rise above 5.5 on organic soils, Mn availability decreases and deficiencies can appear in 6.5-7.5 pH soils.

Foliar applications of Mn fertilizer are recommended for treatment of Mn deficiencies on high pH, high OM soils in Michigan (Brouder et al., 2003, Vitosh et al., 1995). These applications are timed with the emergence of visual deficiency symptoms. Applications of Mn in the absence of foliar deficiency symptoms have not been found to increase yield (Nelson et al., 2009). Manganese is relatively immobile in the plant, frequently necessitating multiple foliar Mn applications which are often necessary to maintain maximum yield potential. Mascagni and Cox (1985a) increased yield 202% above the control with one application of $MnSO_4$ and 249% when two applications were made. While a number of Mn fertilizer products are available to growers for the treatment of Mn deficiency, few research studies have compared formulations. Randall et at. (1975) found $MnSO_4$ increased trifoliate Mn concentrations compared to Mn-EDTA, though yield was not affected by either product.

In many production systems, glyphosate has become the preeminent herbicide used for weed control. Glyphosate has a broad spectrum of weed control, a wide window of application, low crop injury potential, and a low price relative to other herbicides. In 2011, genetically engineered herbicide resistant soybeans comprised 94% of all US soybean production (USDA Natl. Agric. Stat. Serv., 2011). Glyphosate affects aromatic amino acid biosynthesis, inhibiting 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) of the shikimate pathway (Amrhein et al., 1980; Rubin et al., 1982). The shikimate pathway is one of several major biosynthetic pathways in higher plants, located in plastids of all plant tissues. Glyphosate is structurally similar to the amino acid glycine, so that it binds to the active site of the EPSPS enzyme. This enzyme catalyzes the reaction of shikimate-3-phosphate (S-3-P) to 5-enolpyruvylshikimate-3-phosphate (EPSP). When applied to a plant, glyphosate binds with EPSPS enzymes, preventing the conversion to S-3-P to EPSP. This pathway is a precursor to the production of auxins, folic acid, lignin, plastoquinone, flavonoids, phenolics, and alkaloids (Monaco et al., 2002).

Glyphosate tolerant soybeans contain an EPSP synthase that was originally isolated from *Agrobacterium* sp. (Padgette et al., 1995). Glyphosate resistance in soybeans occurs through the incorporation of CP4-EPSP synthase, a glyphosate-insensitive EPSP sythase. CP4-EPSP is used to bypass native glyphosate-inhibited EPSP sythase that is susceptible to amino acid starvation and metabolic process deregulation when exposed to glyphosate. Through the presence of this alternative EPSP pathway, soybeans are resistant to glyphosate. Whereas glyphosate applications to non-GR plants interfere with the pathway, GR plants have EPSP inserted genes, allowing the pathway to function with these outside genes. Glyphosate-resistant plants do not metabolize glyphosate, they simply can live with its effects.

Glyphosate was originally developed as a chelate and like many other phosphoric acids, forms stable complexes with divalent and trivalent metal cations (Glass, 1984; Subramaniam and Hoggard, 1988). The presence of these cations, such as Ca^{2+}, Mg^{2+}, and Fe^{3+}, in spray solutions decreases glyphosate efficacy by complexing with glyphosate to form salts that are not readily absorbed by plants (Thelen et al., 1995). Hall et al. (2000) demonstrated that glyphosate efficacy can be decreased not only by cations on the plant, but also those found in the plant. Current Michigan State University recommendations call for the inclusion of 17 lbs of ammonium sulfate per 100 gallons of water with glyphosate when applied to combat these antagonism issues (Everman and Sprague, 2009). Ammonium sulfate in spray solutions effectively binds with free cations to increase glyphosate activity in plants and addresses efficacy problems of the herbicide.

On high organic matter soils, Mn deficiencies are generally observed early in the season, often around the soybean V2 growth stage. Applying foliar Mn fertilizers to correct these deficiencies frequenytly corresponds with the optimal timing of post-emergent glyphosate applications, and producers view tank-mixes of Mn fertilizer and glyphosate herbicides as a means to reduce application costs and increase convenience. Because of cation antagonism, chelated Mn forms are typically recommended when applying Mn with glyphosate (Mullen et al., 2011, Camberato et al., 2010). Johnson et al. (2010) noted decreased glyphosate activity on velvetleaf and waterhemp when applied with $MnSO_4$ or Mn-EDTA, though Mn-EDTA was found to be less antagonistic to glyphosate than $MnSO_4$. Bernards et al. (2005a) attributed decreased weed control with glyphosate when applied with $MnSO_4$ compared to EDTA to the greater strength EDTA binds with Mn, which in turn decreases the formation of Mn-glyphosate complexes that reduce glyphosate activity.

Diedrick (2010) investigated effects of Mn application timing with glyphosate at six site years in Ohio and found in the one instance where Mn deficiency limited yield, tank-mixes of Mn and glyphosate increased yield compared to applying Mn eight days after glyphosate. Yield for the untreated control at this site yielded 88% of the maximum, suggesting deficiency pressure lower than that which can be observed in moderate to severe cases on high OM soils in Michigan.

Applying Mn to correct Mn deficiency symptoms can be an effective approach at minimizing yield losses (Nelson et al., 2009), but the appearance of deficiency symptoms in relation to optimum post-emergent weed control timing varies from year to year. The objective of this study was to examine glyphosate and Mn tank-mix or separated application strategies using $MnSO_4$, Mannitol and EDTA formulations on high OM soils where Mn deficiencies are commonly encountered.

Materials and Methods

Field experiments were established on two organic soil sites in central Michigan in 2009, 2010, and 2011 (Table 1.1). Plots measured 3.0 by 15.2 m in 2009 and 2010 and 3.0 by 12.2 m in 2011 and were arranged in a randomized complete block design with four replications. Soybeans were seeded at 400,000 plants ha^{-1} at Stockbridge, 450,000 plants ha^{-1} at Owosso, and 494,000 plants ha^{-1} at Bath. Row width was 25 cm at Stockbridge and Owosso and 76 cm at Bath. Corn preceded soybeans at Stockbridge and Owosso and carrots at Bath. Soybeans were no-tilled at Stockbridge and established with conventional tillage at Owosso and Bath.

Fifteen 2.5 cm diameter cores (0-15 cm) were randomly collected and composited for each plot area. Samples were dried at 38°C, ground to pass through a 2 mm sieve, and analyzed for soil organic matter, pH, Bray P1, exchangeable K, and Mn by the Michigan State University Soil and Plant Nutrient Laboratory (East Lansing, MI). Soil organic matter was determined from loss-on-ignition at 500° C, pH by pH meter, Bray P1 extraction using 0.03 N NH_4F – 0.025 N HCl extraction and colorimeter analysis, exchangeable K by 1 N NH_4OAc extraction and photocolorimeter analysis, and Mn with 0.1 N HCl extraction and atomic adsorption spectrometer analysis (Brown, 1998).

Two application approaches were employed in this study. Tank-mix treatments were designed to minimize total application events, combining Mn and glyphosate applications when appropriate. Separate application treatments isolated Mn from glyphosate applications, applying Mn at least three days before or seven days after glyphosate as recommended (Camberato et al., 2010). In

Table 1.1. Site descriptions including soil type, selected soil chemical characteristics (0-15 cm), variety, and planting and harvest dates at Bath, Owosso and Stockbridge sites in 2009, 2010 and 2011.

Site	**Soil series**†	**SOM**‡	**pH**	**P**	**K**	**Mn**	**Variety**§	**Planting date**	**Harvest date**
		g kg^{-1}		**—— mg kg^{-1} ——**					
2009									
Owosso	Linwood muck	23.3	7.4	139	238	21.4	DF 5191	29 May	11 Oct.
Stockbridge	Adrian muck	59.3	6.4	59	40	9.9	DF 8225 RR	15 June	29 Oct.
2010									
Owosso	Linwood muck	24.0	7.5	172	248	6.0	DF 9161LL	4 May	4 Oct.
Stockbridge	Adrian muck	72.5	5.9	51	315	8.9	DF 5191	10 May	1 Oct.
2011									
Bath	Houghton muck	77.0	6.9	118	272	14.7	DG 36RY19	29 June	1 Nov.
Stockbridge	Adrian muck	60.5	6.8	34	155	12.4	DF 5211	30 May	30 Oct.

†Linwood, a loamy, mixed, euic, mesic Terric Haplosaprists; Adrian, a sandy or sandy-skeletal, mixed, euic, mesic Terric Haplosaprists; Tawas, a sandy or sandy-skeletal, mixed, euic, frigid Terric Haplosaprists; Houghton, a euic, mesic Typic Haplosaprists
‡Soil organic matter content
§DF, D.F.Seeds, Dansville, MI; DG, Dyna-Gro, MCIA, Michigan Crop Improvement Association, Lansing, MI

each of these scenarios, manganese sulfate monohydrate[1] ($MnSO_4$); Mannitol[2], a sugar alcohol derived from $MnSO_4$; and EDTA[3], a ethylenediaminetetraacetate (EDTA) chelate were applied. Products were applied at 1.12 kg Mn ha^{-1}. Glyphosate [N-(phosphonomethyl)glycine] was formulated as Roundup WeatherMax (Monsanto Co., St. Louis, MO) and applied at 1.6 L ha^{-1} with 20 g L^{-1} ammonium sulfate [$(NH_4)_2SO_4$]. All fertilizer and herbicide treatments were applied with a backpack sprayer at 240 kPa and 140 L water ha^{-1} using 8002 flat fan nozzles (TeeJet, Spraying Systems Co., Wheaton, IL). When combining Mn and glyphosate, ammonium sulfate was added to the spray tank, followed by Mn, then glyphosate. These treatments were compared to a control treatment receiving glyphosate for weed control, but no Mn fertilizer.

Fertilizers were applied with a backpack sprayer at 240 kPa and 140 L water ha^{-1} using 8002 flat fan nozzles (TeeJet, Spraying Systems Co., Wheaton, IL). The timing and frequency of Mn fertilizer and glyphosate herbicide applications were based on visual observation of soybean chlorosis and weed height. Herbicide applications were applied according to label recommendations when weeds were between 2.5 and 10.0 cm in height. Visual ratings were used to time Mn applications and conducted on a 0 to 10 scale, with 0 corresponding to no visual

[1] $MnSO_4$ (32% Mn), The Pestell Group, 141 Hamilton Rd, New Hamburg, ON N3A2H1, Canada
[2] Manni-plex Mn (5% Mn), Brandt Consolidated, Inc., 2935 S Koke Mill Rd, Springfield IL, 92711
[3] Mn-EDTA (6% Mn), Nachurs Alpine Solutions, 421 Leader St., Marion, OH, 43302

Mn deficiency symptoms and 10 corresponding to severe necrosis and stunting. Ratings were recorded for each plot and averaged across replications.

At all sites prior to early season Mn and glyphosate applications, uniform Mn deficiency and weed populations were observed.

Manganese applications were made when deficiency symptoms exceeded a visual rating of 4.0 across treatments within a management system (Table 1.2). For initial applications each season, this timing corresponded to the V2 growth stage and was typically 3-6 days after initial Mn deficiency symptoms were observed. Visual Mn deficiency ratings were recorded following early season Mn fertilizer and glyphosate herbicide applications. Subsequent Mn and glyphosate applications were made when Mn deficiency exceeded a 4.0 rating on a 0 to 10 scale and when weed pressure exceeded a 4.0 rating on a 0 to 10 scale.

Twenty of the uppermost fully expanded trifoliates not present at the time of application were sampled from four to seven days after application, depending on plant growth conditions. Leaves were washed with a 1.0 g kg^{-1} soap solution and triple rinsed in deionized water, dried at 66°C, and ground to pass through a 1 mm sieve. Manganese concentrations were determined with a hot acid extract open vessel procedure where 0.2 g of plant tissue was combined with 2.0 ml of Nitric acid and heated by microwave oven to 90° C and held for 90 seconds. Following cooling to 50° C, 1.0 of peroxide was combined with the sample and heated by microwave oven to 105° C and held for 10 minutes. Samples were cooled and brought to a final volume of 25 ml

Table 1.2. Manganese fertilizer and glyphosate herbicide applications at Bath, Owosso and Stockbridge sites in 2009, 2010, and 2011.

Site	Tank-mix		Separate Applications		Control
	Herbicide	**Fertilizer**	**Herbicide**	**Fertilizer**	**Herbicide**
2009					
Owosso	29 June, 4 Aug.	29 June, 9 July	29 June	24 June, 4 Aug.	29 June
Stockbridge	9 July	9 July, 5 Aug.	9 July	5 July, 26 July, 18 Aug.	9 July
2010					
Owosso	3 June, 24 June	3 June	3 June	17 June	3 June
Stockbridge	14 June	14 June	14 June	21 June	14 June
2011					
Bath	25 July	25 July	17 July	1 Aug.	17 July
Stockbridge	6 July	6 July, 25 July	8 July	30 June, 25 July	8 July

with deionized water, for a 1:125 dilution factor. Samples were then analyzed with an inductively coupled plasma emission spectrometer.

Grain yield was determined from a 1.5 m swath in the plot center with an Almaco (Almaco, Nevada, IA) research combine in 2009 and a Massey 8XP (Kincade Manufacturing, Haven, KS) research combine in 2010 and 2011. Seed moisture and yield was recorded and yield was adjusted to 130 g kg^{-1} moisture.

Data were analyzed with SAS statistical software (SAS Institute, Cary, NC). Analysis of variance was performed using PROC MIXED. Both site and year effects were significant; data are presented separately for each year and site. Treatment means were considered significant at the $P \leq 0.10$ level.

Results

Season growing degree day numbers were below 30 year averages at both sites in 2009 (Table 1.3). Temperatures were particularly below average in July. While total rainfall amounts from March to October was near average at Stockbridge, below average rainfall was recorded during July, August, and September. Temperatures were near average for both sites in 2010. August rainfall at Stockbridge was significantly below the 30-year average. Soybeans at Owosso demonstrated severe drought symptoms in late June and July of 2010 at Owosso, though precipitation records fail to show marked deviations from averages. In 2011, wet early season conditions delayed soybean establishment at both sites. May, June and July growing degree day unit accumulation was near average at both sites, though August and September were slightly below average.

In 2009 at both Owosso and Stockbridge, Mn deficiencies began to appear when soybeans were at the V2 growth stage and weeds were less than 5cm in height. At Owosso, Mn fertilizer was applied on 24 June and glyphosate herbicide on 29 June for separate application treatments (Table 1.2). Glyphosate and Mn were applied together for tank-mix treatments on 29 June. Glyphosate was also applied on 29 June for the control treatment. Manganese was reapplied to treat deficiency symptoms on 9 July in tank-mix treatments and 4 August in separate application treatments. Glyphosate was applied on 4 August in tank-mix treatments to control weed escapes. At Stockbridge, Mn was applied on 5 July in separate application treatments and 9 July in tank-mix treatments. Glyphosate was applied on 9 July to all treatments. In separate application treatments, Mn deficiencies were seen in late July and mid-August and Mn fertilizer applications

Table 1.3. Growing degree day and precipitation data for Owosso, Bath, and Stockbridge sites in 2009, 2010, and 2011.

Site	Growing Degree Days†				Precipitation			
	2009	2010	2011	30-yr	2009	2010	2011	30-yr
	C°				mm			
Owosso/Bath								
March	9	7	1	12	71	19	68	54
April	47	62	25	38	126	64	125	73
May	118	175	155	151	78	106	126	72
June	248	289	267	281	146	80	59	83
July	245	377	399	364	143	58	107	69
August	292	356	310	326	133	6	77	90
September	177	164	151	197	28	98	49	93
October	19	51	58	64	87	59	63	62
Season	1155	1481	1365	1433	810	490	674	596
Stockbridge								
March	0	4	3	13	95	22	68	46
April	49	67	26	52	113	40	134	67
May	108	175	163	151	82	114	146	84
June	232	285	275	296	83	153	51	83
July	231	358	386	370	57	102	253	91
August	270	336	286	342	78	42	63	88
September	166	161	145	206	34	60	77	88
October	22	55	9	66	102	33	77	67
Season	1077	1440	1293	1496	644	567	866	615

†Growing Degree Days (C°, base 10°C)
Owosso and Bath weather observations recorded at Michigan State University's Enviro-weather station near Bath, MI
Stockbridge weather observations recorded at Michigan State University's Enviro-weather station near Leslie, MI

were made on 26 July and 18 August. Manganese was applied on 5 August in tank-mix treatments to control deficiency symptoms.

In early 2010 at both sites, weed pressure was significant while Mn deficiencies were minimal, so herbicide applications took precedent to fertilizer applications. At Owosso, glyphosate was applied to all treatments on 3 June. Manganese fertilizer was applied with glyphosate in tank-mix treatments.   Manganese was applied on 17 June in separate application treatments in response to visual Mn deficiency symptoms. Glyphosate was applied on 24 June in tank-mix treatments to control weed escapes. At Stockbridge, glyphosate was applied to all treatments on 14 June. Manganese was included with glyphosate in tank-mix treatments. Manganese was applied on 21 June in separate application treatments.

Wet planting conditions in 2011 delayed soybean establishment at Bath and Stockbridge. At Bath, glyphosate was applied 17 July in separate application and control treatments. Glyphosate and Mn were applied together in tank-mix treatments on 25 July. Glyphosate was applied on 17 July in separate application treatments. At Stockbridge, Mn was applied in separate application treatments on 30 June. Glyphosate and Mn were applied together on 6 July in tank-mix treatments. Glyphosate was applied on 8 July in separate application and control treatments. Manganese deficiency symptoms were uniform across treatments in late July and fertilizer was applied to all treatments on 25 July.

Visual Mn ratings were recorded at Owosso in 2009 on 3 July and 4 August (Table 1.4). On 3 July, Mn deficiency ratings were highest for the untreated control compared to other treatments.

Table 1.4. Soybean Mn deficiency visual ratings at Owosso and Stockbridge sites in 2009.

Treatment	**Owosso**		**Stockbridge**			
	3 July	**4 Aug.**	**13 July**	**24 July**	**5 Aug.**	**18 Aug.**
Control	8.5a†	5.3a	7.0c	10.0a	9.8a	8.3a
Tank-Mix						
$MnSO_4$	5.5c	0.0c	1.0a	3.5c	5.5b	0.0d
Mannitol	6.8b	0.5c	0.8a	3.0c	5.8b	0.3d
EDTA	5.5bc	0.8c	1.0a	3.3c	6.8b	0.3d
Separate Application						
$MnSO_4$	3.3d	2.5b	1.5ab	5.5b	0.0c	1.8c
Mannitol	3.8d	4.3a	2.5b	6.3b	1.3c	3.3b
EDTA	4.8cd	5.0a	2.8b	6.3b	1.0c	3.3b
$P > F$	0.0005	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

†Means within a column followed by the same letter are not significantly different at $P > 0.10$

In separate application treatments, where Mn had been applied nine days previously, no differences were observed between products. In tank-mix treatments, applications were made four days previously and Mn deficiency ratings were lower with $MnSO_4$ application compared to Mannitol. Manganese deficiency ratings were lower when $MnSO_4$ and Mannitol were applied in separate application treatments compared to tank-mix application, despite the fact tank-mix treatments had been applied four days sooner. No differences were observed in Mn deficiency ratings when EDTA was applied in separate application or tank-mix treatments. The greater relative Mn deficiency ratings for tank-mix treatments compared to separate application treatments triggered Mn fertilizer applications for tank-mix treatments on 9 July. Ratings recorded on 4 August indicated higher Mn deficiencies in separate application treatments compared to tank-mix treatments. Manganese deficiencies were greater in separate application treatments where Mannitol or EDTA had been applied compared to $MnSO_4$. Following Mn applications in separate application treatments on 4 August, no further Mn deficiencies were observed during the season other than the control.

Manganese deficiency ratings recorded at Stockbridge in 2009 on 13 July were lower when Mn was applied as Mannitol or EDTA in tank-mix treatments compared to separate application treatments (Table 1.4). No differences were observed between tank-mix and separate application treatments when $MnSO_4$ was applied. On 24 July, Mn deficiency ratings were greater for separate application treatments compared to tank-mix treatments, though no differences were observed between products. Average ratings exceeding 4.0 for separate application treatments dictated additional Mn applications. On 5 August, Mn deficiency ratings were greater for tank-mix treatment compared to separate application treatments. No differences were observed between products. On 18 August, Mn deficiency ratings were greater for separate application treatments compared to tank-mix treatments, regardless of product.

At Owosso, application of $MnSO_4$ increased Mn concentrations compared to Mannitol and EDTA when fertilizers were applied four days previous to glyphosate, but Mn concentrations were similar between the three fertilizers when applied with glyphosate (Table 1.5). While trifoliate samples on 3 July in tank-mix treatments indicated that all fertilizers had been effective at increasing Mn content, visible Mn deficiency symptoms remained in the field. Trifoliate samples on 13 July indicated that $MnSO_4$ application increased Mn levels compared to Mannitol and EDTA. While Mn applications on August 4 were observed to eliminate deficiency symptoms, tissue samples on 14 August did not indicate a difference between products, other untreated treatments, or the control.

Soybean trifoliates sampled on 13 July at Stockbridge showed that all fertilizer applications increased Mn concentrations compared to the control. Manganese fertilizers had been applied eight days previously and glyphosate five days previously in separate application treatments while Mn and glyphosate had been applied together five days previously in tank-mix treatments. Tissue Mn concentrations were significantly lower for separate application treatments compared to tank-mix treatments, presumably a factor of the three day difference between application and sampling. For both separate application and tank-mix treatments, application of $MnSO_4$

Table 1.5. Soybean trifoliate Mn concentration following foliar fertilizer application at Owosso and Stockbridge sites in 2009.

Treatment	**Owosso**			**Stockbridge**	
	3 July	**13 July**	**14 Aug.**	**13 July**	**3 Aug.**
	mg Mn kg^{-1}			**mg Mn kg^{-1}**	
Control	15d[†]	15e	13	22f	8c
Tank-Mix					
$MnSO_4$	119ab	178a	18	394a	8c
Mannitol	102abc	137b	17	271b	9c
EDTA	89bc	115c	14	187c	6c
Separate Application					
$MnSO_4$	122a	35d	47	149d	72a
Mannitol	94bc	29d	27	114de	48b
EDTA	83c	25d	32	79e	42b
$P > F$	0.0003	<0.0001	0.3246	<0.0001	<0.0001

[†]Means within a column followed by the same letter are not significantly different at $P > 0.10$

increased Mn concentrations compared to EDTA. On 3 August, following fertilizer application to separate application treatments, $MnSO_4$ increased Mn levels compared to Mannitol and EDTA.

Visual Mn deficiency ratings were recorded at Owosso in 2010 on 16 June, thirteen days following tank-mix treatment fertilizer applications (Table 1.6). Manganese deficiency was decreased when EDTA was applied as a tank-mix treatment with glyphosate compared to Mannitol. Ratings on 22 June, five days after Mn fertilizers were applied in separate application treatments were greater when Mannitol was applied compared to $MnSO_4$ or EDTA. This effect remained visible on 24 June, when fertilizer was applied in tank-mix treatments. On 30 June, six days following tank-mix treatment fertilizer applications, Mn deficiencies were lower when treated with $MnSO_4$ compared to Mannitol or EDTA.

At Stockbridge in 2010, no Mn deficiencies were visible besides slight uniform symptoms across the trial before initial applications of fertilizer. No deficiencies were evident at any point following Mn applications.

Trifoliate Mn concentrations on 23 June at Owosso in 2010 were increased by all separate application fertilizer treatments applied six days earlier (Table 1.7). $MnSO_4$ and Mannitol treatments resulted in higher Mn concentrations compared to EDTA. While fertilizer products applied in tank-mix treatments lowered visible Mn deficiency ratings compared to the control on

Table 1.6. Soybean Mn deficiency visual ratings at Owosso and Stockbridge sites in 2010.

Treatment	**Owosso**				**Stockbridge**
	16 June	**22 June**	**24 June**	**30 June**	**3 Aug.**
Control	6.8a†	6.0a	5.5b	6.0a	0
Tank-Mix					
$MnSO_4$	2.0de	3.8bc	7.0a	2.3b	0
Mannitol	2.5d	3.3c	6.0ab	1.3c	0
EDTA	1.3e	3.3c	6.3ab	1.0c	0
Separate Application					
$MnSO_4$	3.5c	2.8c	3.0c	1.3c	0
Mannitol	4.5b	5.0ab	5.3b	2.8b	0
EDTA	3.8bc	3.0c	3.3c	2.8b	0
$P > F$	<0.0001	0.0192	0.0024	<0.0001	*n/a*

†Means within a column followed by the same letter are not significantly different at $P > 0.10$

Table 1.7. Soybean trifoliate Mn concentration following foliar fertilizer application at Owosso and Stockbridge sites in 2010.

Treatment	**Owosso**		**Stockbridge**
	23 June	**30 June**	**28 June**
	mg Mn kg^{-1}		**mg Mn kg^{-1}**
Control	11c[†]	11d	22
Tank-Mix			
$MnSO_4$	11c	196b	32
Mannitol	10c	293a	12
EDTA	11c	107c	18
Separate Application			
$MnSO_4$	44a	23d	43
Mannitol	42a	24d	32
EDTA	26b	20d	29
$P > F$	<0.0001	<0.0001	0.8465

[†]Means within a column followed by the same letter are not significantly different at $P > 0.10$

6 June and 22 June, tissue Mn concentrated assessed on 23 June did not differ between tank-mix treatments and the untreated control. Trifoliate Mn concentrations measured on 30 June, six days following tank-mix fertilizer applications, were higher when Mannitol was applied compared to $MnSO_4$ or EDTA. Application of $MnSO_4$ resulted in higher Mn concentrations compared to EDTA. All fertilizer treatments applied on 23 June resulted in increases of Mn concentrations compared to the control. At Stockbridge, no differences in Mn concentrations were observed between any treatment on 28 June.

At Bath in 2011, no differences in visual Mn deficiency symptoms were noted on 29 July, following fertilizer applications in tank-mix treatments, or 10 August, following fertilizer applications in separate application treatments (Table 1.8). At Stockbridge, no deficiency symptoms were recorded on 10 July following fertilizer applications ten days earlier in separate application treatments or seven days earlier in tank-mix treatments. On 25 July, all treatments displayed a greater level of Mn deficiency compared to the control and fertilizer applications made in in all treatments. Trifoliate Mn concentrations measured on 29 July at Bath did not indicate any difference between the control and products applied in separate application treatments (Table 1.9). In tank-mix treatments, Mn concentrations were greater with EDTA compared to other products. At Stockbridge, no differences in Mn concentrations were seen between the control and tank-mix treatments on 10 July. In separate application treatments, Mn concentrations were greatest for Mannitol, followed by $MnSO_4$, then by EDTA. On 31 July, Mannitol application in both separate application and tank-mix treatments had greater Mn concentrations than EDTA applications in either separate or tank-mix treatments. Mn

Table 1.8. Soybean Mn deficiency visual ratings at Bath and Stockbridge sites in 2011.

Treatment	**Bath**		**Stockbridge**	
	29 July	**10 Aug.**	**10 July**	**25 July**
	mg Mn kg^{-1}		**mg Mn kg^{-1}**	
Control	3.0	0	0	7.3a†
Tank-Mix				
$MnSO_4$	2.0	0	0	5.5bc
Mannitol	1.8	0	0	4.0d
EDTA	‡	0	0	4.3cd
Separate Application				
$MnSO_4$	3.0	0	0	4.5bcd
Mannitol	2.5	0	0	5.3bcd
EDTA	2.3	0	0	5.8b
P > F	0.1708	*n/a*	*n/a*	0.0062

†Means within a column followed by the same letter are not significantly different at $P > 0.10$

‡Foliar necrosis associated with EDTA application resulted in complications assessing visual Mn deficiency

Table 1.9. Soybean trifoliate Mn concentration following foliar fertilizer application at Bath and Stockbridge sites in 2011.

Treatment	**Bath**	**Stockbridge**	
	29 July	**10 July**	**31 July**
	mg Mn kg^{-1}	**—— mg Mn kg^{-1} ——**	
Control	19c[†]	28d	12d
Tank-Mix			
$MnSO_4$	119b	14d	117abc
Mannitol	133b	17d	169a
EDTA	237a	18d	62cd
Separate Application			
$MnSO_4$	22c	212b	118b
Mannitol	21c	242a	156ab
EDTA	22c	180c	54d
P > *F*	<0.0001	<0.0001	<0.0001

[†]Means within a column followed by the same letter are not significantly different at *P* > 0.10

concentrations were less in the control treatment compared to all other treatments except EDTA in separate application.

Weed control visual ratings in 2009 at Owosso did not differ between the control treatment and any product in separate application treatments (Table 1.10). In tank-mix treatments, weed control was less in EDTA treatments compared to other products. At Stockbridge in 2009, application of EDTA in tank-mix treatments was the only treatment to reduced weed control. In 2010 at Owosso, no significant differences were measured between treatments. At Stockbridge in 2010 and 2011, no weed pressure was observed. In 2011 at Bath, no differences were seen between treatments.

Yields at Owosso in 2009 were increased with applications of $MnSO_4$ or Mannitol when applied separately from glyphosate and with $MnSO_4$ when tank-mixed with glyphosate (Table 1.11). Regardless of timing with glyphosate, $MnSO_4$ increased yield compared to EDTA. Yields tended to be greater when Mn was applied separately from glyphosate rather than tank-mixed. This effect is likely a factor of both decreased Mn efficacy, as evidenced by fertilizer reapplications on 9 July, and decreased glyphosate efficacy, as evidenced by a second herbicide application on 4 August, compared to separate application treatments.

At Stockbridge in 2009, applications of $MnSO_4$ and Mannitol applied separately from glyphosate resulted in greater yields compared to tank-mixed glyphosate and EDTA. All treatments increased yield compared to the untreated control. The control treatment yielded 29%

Table 1.10. Weed control visual rating at Owosso, Bath and Stockbridge sites in 2009, 2010 and 2011.

Treatment	Owosso		Bath	Stockbridge		
	2009	2010	2011	2009	2010	2011
	4 Aug.	**3 Aug.**	**29 July**	**9 Aug.**	**4 Aug.**	**30 July**
Control	0.0c[†]	1.8	1.8	0.0b	0	0
Tank-Mix						
$MnSO_4$	4.3b	0.5	1.3	0.0b	0	0
Mannitol	4.3b	2.5	2.0	0.0b	0	0
EDTA	6.8a	0.5	1.9	0.5a	0	0
Separate Application						
$MnSO_4$	0.3c	2.5	2.3	0.0b	0	0
Mannitol	1.3c	1.5	2.0	0.0b	0	0
EDTA	0.0c	0.5	1.8	0.0b	0	0
$P > F$	<0.0001	0.2367	0.7073	0.0327	*n/a*	*n/a*

[†]Means within a column followed by the same letter are not significantly different at $P > 0.10$

Table 1.11. Soybean grain yield at Bath, Owosso and Stockbridge sites in 2009, 2010 and 2011.

Treatment	**Owosso**		**Bath**	**Stockbridge**		
	2009	**2010**	**2011**	**2009**	**2010**	**2011**
	Mg ha^{-1}					
Control	1.98c†	1.25	1.10	0.70c	3.01	1.71b
Tank-Mix						
$MnSO_4$	2.28b	1.42	1.14	2.02ab	3.26	2.66a
Mannitol	2.08bc	1.49	1.13	2.13ab	3.26	2.70a
EDTA	1.94c	1.50	0.94	1.84b	3.21	2.37a
Separate Application						
$MnSO_4$	2.55a	1.25	1.04	2.45a	3.14	2.68a
Mannitol	2.58a	1.48	1.21	2.35a	3.29	2.68a
EDTA	2.17bc	1.66	1.14	2.17ab	3.16	2.34a
$P > F$	0.0009	0.9194	0.1142	<0.0001	0.8180	0.0047

†Means within a column followed by the same letter are not statistically different at $P > 0.10$

of the maximum yield, suggesting this site was subjected to the greatest Mn deficiency of the six site years.

Significant treatment effects were seen at four of the six site years. At Stockbridge in 2010, deficiency symptoms were apparent early in the season, but soybeans quickly regained a healthy, green appearance. These early season deficiencies proved to not be yield limiting. At Owosso, deficiency symptoms were much more evident through June and necessitated a second Mn application in TM treatments on 24 June. Drought conditions, however, stunted plants in July and August and dramatically reduced yields compared to the other sites.

The late planting of soybeans at Bath in 2011 resulted in frost damage prior to physiological maturity and subsequent yield reduction. Leaf burn from applications of EDTA with glyphosate was observed on July 29. This was the only occurrence of leaf necrosis observed from EDTA application in the six site years of the study. Numerically lower yield for tank-mixed EDTA may be attributable to this fertilizer injury.

At Stockbridge, all treatments increased yield above the control. A numerical trend can be observed, while not statistically significant, of greater yield with $MnSO_4$ or Mannitol applications compared to EDTA in both separate application and tank-mix treatments.

Discussion

Soybean grain yield in 2009 was consistent with treatment effects observed during the growing season. However, while Owosso in 2010 demonstrated similar in-season visual differences between treatments, no yield response was recorded. Drought conditions through August dramatically reduced soybean yield potential and masked the effect these early season differences in Mn deficiency were expected to have on yield.

Sites at Stockbridge in 2010 and 2011 illustrated expected responses at low to medium Mn deficiency pressure. While soybeans in 2010 demonstrated Mn deficiency in mid-June, the untreated control did not differ in yield from treatments receiving Mn fertilizers. Tissue samples on June 28 did not indicate differences between fertilizer products. The untreated control Mn content of 21.5 mg kg^{-1} was greater than the 17-20 mg kg^{-1} range considered deficient. The lack of yield response suggests that decreased glyphosate efficacy with Mn tank-mixes did not lead to yield reductions.

Tank-mixing Mn fertilizer with glyphosate herbicide was not a consistent method to minimize the total number of applications. At Stockbridge in 2010 and Bath in 2011, sites where deficiency pressure was low, one application of Mn applied either with glyphosate or at least seven days later was sufficient to eliminate visual deficiency symptoms. At Stockbridge in 2011 where deficiency pressure was greater, redevelopment of Mn deficiency symptoms in late July was uniform across tank-mix and separate application treatments, suggesting Mn applied either with glyphosate or following several days later was equally effective at treating deficiencies. Similar yields between all treatments confirm this observation. These three sites support the approach of tank-mixing Mn fertilizer with glyphosate herbicides.

At the other three sites, however, results from tank-mixing were more variable. When Mn was tank-mixed with glyphosate at Owosso in 2010, a second application of Mn was required while one application of Mn separated from glyphosate was sufficient to eliminate deficiency symptoms. Thus, Mn fertilizer costs were doubled for tank-mix treatments. A similar effect was observed at Owosso in 2009 where tank-mix treatments required reapplication of both Mn and glyphosate while separate application treatments still required three total applications, but half the herbicide costs. At Stockbridge in 2009, separating Mn from glyphosate early in the season led to two applications of Mn later in the season compared to only one additional application when Mn and glyphosate were tank-mixed. Despite Mn deficiencies apparent in the field three times in SA treatments, these treatments yielded higher than tank-mix treatments, covering costs of four application events compared to two.

Soybean Mn tissue concentration critical levels have been cited as 17 mg kg^{-1} by Gettier et al. (1985a), 15-20 mg kg^{-1} by Randall et al. (1975), 12 mg kg^{-1} by Ohki et al. (1979) and 20 mg kg^{-1} by Melsted et al. (1969). Cox (1968) found yield responses when untreated control plot trifoliate Mn concentrations were below 20 mg kg^{-1}. In this study, trifoliate Mn concentrations were observed to test as low as 7.8 mg kg^{-1} in treatments with yields that did not differ significantly from the maximum. Manganese concentrations generally dropped to levels similar to the untreated control by ten days after fertilizer application. Low Mn content was not always associated with visual deficiency symptoms, particularly late in the season. The trifoliate Mn levels in this study suggest that in environments with low soil Mn availability, critical Mn levels may be lower than those listed by other researchers.

Trifoliates sampled within ten days of Mn application generally demonstrated differences between fertilizer products. The exception to this was Stockbridge in 2010 where seven days after application, no treatment differed from the untreated control. Given the lack of yield response to Mn fertilizers at this site, a lack of response between Mn fertilizer products is not unexpected. Fertilizer effects on tissue Mn concentrations were similar regardless of timing with glyphosate. Tissue Mn content was consistently increased by applications of $MnSO_4$ compared to EDTA.

Mannitol effects on trifoliate Mn concentrations were variable and did not appear to be correlated with glyphosate timing. When differences between fertilizer effects on Mn levels were observed, Mn levels tended to be greater with Mannitol application compared to EDTA, although Mn levels were similar between Mannitol and EDTA for SA treatments in 2009.

Related research examining a wider range of Mn fertilizers observed similar differences between products and is addressed in more detail in the following chapter. $MnSO_4$ consistently increased tissue Mn concentrations compared to Mannitol. Both products increased tissue Mn levels compared to EDTA. Differences in grain yields were less pronounced. At one of the four site years, $MnSO_4$ increased yield compared to EDTA, while Mannitol was statistically equivalent to each. At other sites, yield increases from $MnSO_4$ or Manntiol application compared to EDTA were seen only when EDTA was applied at the low end of the labeled rate. A higher application rate of EDTA increased soybean grain yield to statistically similar levels as $MnSO_4$ and Mannitol, though a trend on numerically lower yield at the three sites was apparent.

The larger molecular mass of the EDTA ($C_{10}H_{16}N_2O_8$) chelate may have served as a barrier to cell entry compared to the relatively smaller molecular weights of the Mannitol ($C_6H_8(OH)_6$) chelate and elemental $MnSO_4$. Low permeability of cell membranes to compounds with high molecular weight has been suggested as an explanation for reduced foliar uptake of compounds such as EDTA (Marschner, 1986). Haile-Mariam (1965) observed decreased penetration of Mn though coffee leaves when applied as EDTA compared to $MnSO_4$. Stacey and Oosterhuis (2005) recorded reduced sorption of Zn by 96% and Fe by 83% when chelated with EDTA compared to when applied as sulfate forms in Valencia orange leaves. Reduced absorption of foliar applied Mn when chelated with large molecular mass compounds such as EDTA may be an impediment to the use of these compounds to treat Mn deficiencies.

Glyphosate antagonism has been reported with divalent cations found in hard water such as Ca^{2+}, reducing glyphosate absorption and phototoxicity (Thelen et al., 1995). As Mn fertilizers disassociate in the spray tank, Mn^{2+} can complex with glyphosate much like Ca^{2+}. Bernards et al. (2005a) noted decreased weed control when glyphosate was applied with $MnSO_4$ compared to EDTA. Results of that study and other have led to the recommendation of Mn-EDTA as a Mn fertilizer source when applying tank-mixes of glyphosate and Mn in order to maximize weed control. In our study, however, at only one site, 2010 Owosso, was weed control compromised by the addition of Mn with glyphosate. However, this effect was observed to be consistent for all three Mn fertilizer treatments, suggesting that EDTA did not minimize glyphosate antagonism.

Tissue Mn concentrations were observed to be greater for $MnSO_4$ and Mannitol compared to EDTA, even when these products were applied with glyphosate. Manganese complexation with glyphosate would be expected to occur with unchelated Mn tank-mixes, but tissue test results indicate that Mn uptake was greater with $MnSO_4$ and Mannitol compared to EDTA. These effects are similar to those observed by Diedrick (2010), who recorded increased tissue Mn concentrations when Mn was applied as $MnSO_4$ compared to Mn-EDTA at two Ohio locations in 2009. This effect was observed when Mn products were tank-mixed with glyphosate or applied seven days following glyphosate. At both sites, Mn-EDTA application did not increase Mn levels compared to an untreated control. At Owosso in 2009 and Bath in 2011, $MnSO_4$ was observed to increase yield compared to EDTA in TM treatments, indicating Mn source is a larger yield driver than timing with glyphosate.

Recommendations

Separating glyphosate herbicide applications from Mn fertilizer application remains the most effective means to maximize weed control and alleviate Mn deficiency symptoms, but tank-mixes of these two products remain an attractive option for producers to minimize application costs. The effects of tank-mixing Mn fertilizer with glyphosate have been previously addressed in Michigan. Bernards et al. (2005b) noted that glyphosate applied with $MnSO_4$ resulted in reduced glyphosate absorption, translocation, and efficacy compared to when glyphosate was applied with EDTA. Bernards et al. (2005a) developed regression equations from visual ratings of velvetleaf 14 days after treatment, finding that while Mn-EDTA did not affect glyphosate control, increasing quantities of unchelated Mn fertilizers reduced weed control.

Recommendations for applications of Mn fertilizer and glyphosate herbicide can be categorized by relative severity of Mn deficiency and weed pressure (Figure 1.1). Weed pressure is defined here by not only the number of weeds present, but also the size and species of weeds. Taller, more difficult to control weed species would qualify as a condition of greater weed pressure. In conditions of low weed pressure and low Mn deficiency, tank-mixes of glyphosate with $MnSO_4$ or Mannitol may be recommended. Low levels of glyphosate antagonism may be tolerated in a low weed pressure situation, as will be flexibility of Mn fertilizer formulation. In this study, $MnSO_4$ and Mannitol consistently increased tissue Mn levels compared to EDTA, but grain yield was similar between all products in situations of low Mn deficiency. Applications of Mn formulated as Mannitol cost less than EDTA and avoided glyphosate weed antagonism challenges associated with $MnSO_4$.

Figure 1.1. Manganese fertilizer and glyphosate herbicide application recommendations.

	Low Mn deficiency	High Mn deficiency
High weed pressure	**Tank-mix glyphosate with Mn-EDTA** Differences between Mn fertilizers are negligible in low deficiency situations, but EDTA forms reduce glyphosate antagonism and ensure better weed control.	**Separate glyphosate and $MnSO_4$ applications** Separate applications to ensure best weed control and treatment of Mn deficiency.
Low weed pressure	**Tank-mix glyphosate with any Mn fertilizer** Slight antagonism of Mn and glyphosate will still allow for adequate weed control. Differences between Mn fertilizers are negligible in low deficiency situations. Mannitol is cheaper than EDTA and doesn't have difficulty mixing in spray solutions like $MnSO_4$.	**Tank-mix glyphosate with $MnSO_4$** Some antagonism between glyphosate and $MnSO_4$ may be expected. Low weed pressure allows for a reduction in glyphosate efficacy. $MnSO_4$ should be used in high Mn deficiency conditions.

In situations of low weed pressure and high Mn deficiency, tank-mixing glyphosate with $MnSO_4$ is possible. Glyphosate antagonism may be expected to occur, but weed control was observed to remain adequate in our study. Frequently, tank-mixing glyphosate and Mn allows for each product to be applied at optimal timings. Even when applied with glyphosate, $MnSO_4$ consistently increased tissue Mn concentrations compared to EDTA and resulted in greater yields in high Mn deficiency situations.

In conditions with high weed pressure and low Mn deficiency, tank-mixes of glyphosate with EDTA may be expected to result in uncompromised weed control while adequately treating Mn deficiency. High weed pressure and high Mn deficiency situation are best approached with separate herbicide and fertilizer applications. Treatment of Mn deficiencies with $MnSO_4$ has resulted in consistently higher tissue Mn concentrations and grain yield compared to other products. Documented antagonism with $MnSO_4$ requires separate applications of glyphosate herbicide to control weeds in high pressure conditions.

Conclusion

The form of Mn used to correct soybean Mn deficiencies had a greater effect on tissue Mn concentrations and grain yield than whether or not the Mn product was tank-mixed with glyphosate. $MnSO_4$ consistently increased tissue Mn concentrations relative to EDTA and while Mannitol effects were more variable, Mannitol tended to increase tissue Mn levels compared to EDTA as well. These increases in tissue Mn concentrations were consistent regardless of tank-mixing with glyphosate or separated from glyphosate by at least three days prior or seven days following. All sites demonstrated visible deficiency symptoms and trifoliate Mn levels below critical levels, though untreated control treatments did not differ from fertilizer treatments at three of six sites years. At the three sites with a significant Mn yield response, one site responded positively to any fertilizer treatment, while separating $MnSO_4$ or Mannitol from glyphosate applications was the optimum deficiency management strategy at the other two. At sites with low to moderate Mn deficiency pressure, one application of Mn applied either separately or in combination with glyphosate effectively alleviated Mn deficiency symptoms. At sites with high Mn deficiency pressure, tank-mixing Mn with glyphosate did not consistently reduce total application events required during the season, but tended to decrease yield compared to separating fertilizer and herbicide applications.

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CHAPTER 2. EVALUATION OF FOLIAR MANGANESE FERTILZIERS FOR TREATMENT OF SOYBEAN MN DEFICIENCY

Abstract

Soybeans produced on high organic matter soils in Michigan frequently develop Mn deficiencies as inherent soil characteristics render soil Mn unavailable for plant uptake. Foliar applications in response to visual deficiency symptoms are effective for correcting Mn deficiencies, but producers lack recommendations for optimal product and application rate. Field trials were conducted at two high organic matter sites in central Michigan in 2010 and 2011. Manganese fertilizer was applied in response to visible Mn deficiency symptoms, coinciding with the V2 and R1-R2 growth stages. Fertilizer products represented commercially available products and were applied at the low and high range of labeled rates. $MnSO_4$ tended to increase tissue Mn concentrations compared to other products, with high rates of $MnSO_4$ resulting in higher Mn tissue levels than low rates. Manni-plex, Citraplex, and Max-In applied at the high rate generally resulted in greater leaf Mn levels compared to other products at either low or high application rates. Application of products containing EDTA chelates tended to result in tissue Mn levels similar to that of the untreated control. Application of $MnSO_4$ at both high and low rates and Citraplex, Manni-plex and Max-In applied at the high rate resulted in consistently greater grain yield compared to other treatments. The use of unchelated or low molecular weight fertilizer products increase foliar fertilizer uptake and result in higher yields than products with higher molecular weight EDTA formulations.

Introduction

Successful production of soybeans often requires specific management techniques tailored to unique conditions. In Michigan, cationic micronutrient availability can be significantly reduced in high pH or organic matter level soils common to the region. Soybeans are particularly sensitive to manganese deficiencies encountered in these conditions. Traditionally, producers have applied foliar fertilizers in response to visual deficiency symptoms, with varying degrees of success. Manganese deficiency in soybean is characterized in early stages by interveinal chlorosis (Hoth and Boyd, 1997), followed by progressive yellowing of the plant. In young plants, deficiency symptoms may be observed in both young and old leaves. In more mature plants, the immobile nature of Mn in the plants results in deficiency symptoms more prominent in young leaves. Deficiencies commonly redevelop with time during the growing season, necessitating multiple Mn applications.

Manganese is absorbed by soybean roots as the free Mn^{2+} ion. The carboxylic group (RCOO-) functions as a cation exchanger in the free space of roots, accumulating cations in a non-metabolic step (Mukhopadhyay and Sharma, 1991). Manganese is absorbed by plants primarily as the free Mn^{2+} ion, though Mn in the soil cycles readily between this plant available form and various plant unavailable fractions. Manganese cycling in the soil is driven primarily by soil pH, redox potential, microbial transformations, and soil moisture. Christenson et al. (1951) found that of these factors, pH drives Mn availability to the greatest extent, followed by organic matter, then soil moisture. Under low soil pH or reducing conditions, Mn exists primarily in the divalent

Mn^{2+} form. As pH and redox potential increase, the Mn valence state increases to Mn^{3+} and Mn^{4+}; shifting Mn to MnOOH and MnO_2 forms (Lindsay, 1979).

Gotoh and Patrick (1972) observed increases in both soluble and exchangeable Mn with decreases in pH and Eh. Lindsay (1991) illustrated that soluble Mn^{2+} decreased 100-fold with each unit increase in pH. These observations of Mn species distribution have been verified by a number of field studies, including Bromfield's (1978) documentation of greater plant Mn uptake under low pH conditions compared to high pH conditions. Manganese oxidation and reduction reactions occur simultaneously and independently at sites in close proximity to one another, leading to active cycling of Mn species (Sparrow and Uren, 1987).

Organic matter can complex with Mn to decrease its solubility to the free Mn^{2+} state through the formation of unavailable chelate compounds and organic complexes (Tisdale et al., 1993). Organic matter complexing is pH dependent, as the bonding of Mn^{2+} with organic solids strengthens as pH increases (McBride, 1982). Page (1962) found increases in soil pH enhance Mn complexation with soil organic matter.

While field observations of Mn deficiency are often associated with soil redox and OM, additional factors contribute to Mn availability in the soil. Microorganisms shift oxidation/reduction potentials; decreases in oxidation from poor drainage have been observed to reduce Mn^{4+} to Mn^{2+} (Stevenson, 1991). Mann and Quastel (1946) reduced the oxidation of soil applied $MnSO_4$ with the addition of microbial inhibitors sodium azide, sodium iodacetate and chloreton. Compaction has often been observed to influence Mn deficiency patterns in the field. Passioura and Leeper (1963) recorded a decreased Mn deficiency in oats as soil bulk density increased.

The specific agronomic management of organic soils in Michigan affects Mn cycling as well. While drainage systems have made these soils agronomically viable, their typically low landscape position and high water holding capacity can still influence Mn availability differently than what is seen on mineral, upland soils. As organic soils are brought into agricultural production, aeration in the soil profile increases organic matter decomposition. The resulting proportional increase in the mineral fraction can increase the total soil Mn and its major forms (Mathur and Lėvesque, 1988). Thus, as histosol soils subside as the result of cultivation, Mn deficiencies may be expected to become less problematic.

The same soil conditions that prevent soil Mn from existing in plant available forms generally negate the effectiveness of soil applied Mn fertilizer in preventing deficiencies. While many workers have found soil applied Mn fertilizers are equally effective as foliar applications to alleviate Mn deficiency in soybean (Randall et al., 1975, Alley et al., 1978), these studies have generally not been conducted on soils with OM and pH levels similar to those seen in Michigan's most problematic fields. Farley and Draycott (1973) observed that on organic soils exceeding 40 mg kg^{-1} OM and with pH values above 7.0, sugarbeets responded to foliar $MnSO_4$ applications, but not soil applied MnO or silicate frit. Manganese fertilizer applied to acidic soil persists in exchangeable forms, but under neutral or alkaline conditions, $MnSO_4$ rapidly oxidizes and precipitates (Follett and Lindsay, 1971). Manganese as $MnSO_4$ was applied to 11 different soils and measured for DTPA-extractable nutrients immediately after and 1 week after fertilization. While 98% of fertilizer was extractable immediately after fertilization, only 36% was extractable after one week. On a soil with a pH of 5.4, 62% was extractable after one week. Mortvedt and Giordana (1970) recorded Mn recovery of $MnSO_4$ applied with granules of soil, mono ammonium phosphate, and tri poly phosphate was less from a Michigan Houghton muck soil with 65% OM compared to Wisconsin Spencer silt (3.6% OM), Florida Lakeland sand (0.8% OM), North Carolina Portsmouth silt (4.3% OM) or Michigan Wisner clay (4.2% OM), attributing differences to OM. Chelated forms of Mn are often recommended for soil applications, though the low relative stability of Mn in comparison to other metals may lead to replacement of Mn in Mn-EDTA by Fe, thereby negating the effectiveness of this product to address Mn deficiencies (Weinstein et al., 1954). Knezek and Greinert (1971) cited this effect as well in their observations of 95% conversion of $MnSO_4$ and Mn-EDTA to unavailable organic complexes on a Michigan Houghton muck.

With the general ineffectiveness of soil applied Mn fertilizers on high OM, high pH soils, foliar Mn applications are recommended to treat deficiencies (Brouder et al., 2003, Vitosh et al., 1995). Timing Mn applications with the onset of visual Mn deficiencies has proven effective as foliar applications of Mn have generally not been found to affect yield in the absence of deficiency symptoms (Nelson et al., 2009). Treatment of deficiency symptoms soon after their appearance is essential to maximize yield, however. Mascagni and Cox (1985b) observed a 30% yield reduction when delaying foliar applicatiaon of $MnSO_4$ from the V4 growth stage to 10 weeks later. Gettier et al. (1985b) found when deficiency appeared between the V2 and V4 growth stages, foliar applications at V6 were more effective than late applications at R1 in increasing seed number and yield across three soils. Heenan and Campbell (1980) found that low Mn concentrations reduced fertile pods and total pods per plant.

Multiple applications are frequently necessary to maintain maximum yield potential. Mascagni and Cox (1985a) increased yield 202% above the control with one application of $MnSO_4$ and 249% when two applications were made. A third application did not increase yields above those seen with two applications, in accordance with observations of Randall et al. (1975) that yield reductions from Mn deficiencies were alleviated if foliar applications eliminated visual deficiency symptoms.

The objective of this study was to evaluate foliar Mn fertilizer products commercially available to producers in the central Michigan area in a manner consistent with on-farm production practices in an attempt to provide specific, relevant recommendations for the treatment of soybean Mn deficiencies.   Chelated Mn fertilizers, particularly those with EDTA chelates, are frequently cited by industry representatives as superior formulations to address deficiencies. Our hypothesis is that fertilizers containing Mn chelated with EDTA will result in greater plant Mn uptake and increased grain yield in comparison to products with alternative Mn formulations.

Materials and Methods

Field experiments were established on two organic soil sites in central Michigan in 2010 and 2011 (Table 2.1). Plots measured 3.0 by 15.2 m in 2010 and 3.0 by 12.2 m in 2011 and were arranged in a randomized complete block design with four replications. Row width was 25 cm and seeded at 400,000 plants ha^{-1} at Stockbridge and 450,000 plants ha^{-1} at Owosso. Corn preceded soybeans at all locations. Soybeans were no-tilled at Stockbridge and established with conventional tillage at Owosso. For soil characterization, fifteen 2.5 cm diameter cores (0-15 cm) were randomly collected and composited for each plot area. Samples were dried at 38°C, ground to pass through a 2 mm sieve, and analyzed for soil organic matter, pH, Bray P1, exchangeable K, and Mn by the Michigan State University Soil and Plant Nutrient Laboratory (East Lansing, MI). Soil organic matter was determined from loss-on-ignition at 500° C, pH by pH meter, Bray P1 extraction using 0.03 N NH_4F – 0.025 N HCl extraction and colorimeter analysis, exchangeable K by 1 N NH_4OAc extraction and photocolorimeter analysis, and Mn with 0.1 N HCl extraction and atomic adsorption spectrometer analysis (Brown, 1998).

Post-emergent weed control consisted of broadcast application of 0.365 L ha^{-1} imazamox [2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid], 0.438 L ha^{-1} fomesafen {5-[2-chloro-4-(trifluoromethyl)phenoxy]-N-(methylsulfonyl)-2-nitrobenzamide}, 1.0 g kg^{-1} crop oil concentrate [Herbimax (paraffinic oil plus emulsifiers plus surfactants), Loveland Industries, Greeley, CO] and 20 g L^{-1} ammonium sulfate [$(NH_4)_2SO_4$] at Stockbridge in 2010 and of 1.6 L ha^{-1} glufosinate [2-amino-4-

Table 2.1. Site descriptions including soil type, selected soil chemical characteristics (0-15 cm), variety, and planting and harvest dates in 2010 and 2011.

Site	Soil series[†]	SOM[‡]	pH	P	K	Mn	Variety[§]	Planting date	Harvest date
		g kg^{-1}		——	mg kg^{-1}	——			
2010									
Owosso	Linwood muck	69.0	7.2	67	368	6.0	DF 9161LL	4 May	4 Oct.
Stockbridge	Adrian muck	71.3	6.4	42	306	5.4	DF 5191	10 May	1 Oct.
2011									
Owosso	Tawas muck	62.0	6.8	57	221	11.6	MCIA 2409LL	12 June	2 Nov.
Stockbridge	Adrian muck	60.0	6.6	35	163	12.7	DF 5211	30 May	30 Oct.

[†] Linwood, a loamy, mixed, euic, mesic Terric Haplosaprists; Adrian, a sandy or sandy-skeletal, mixed, euic, mesic Terric Haplosaprists; Tawas, a sandy or sandy-skeletal, mixed, euic, frigid Terric Haplosaprists

[‡] Soil organic matter content

[§] DF, D.F.Seeds, Dansville, MI; MCIA, Michigan Crop Improvement Association, Lansing, MI (hydroxymethylphosphinyl) with 20 g L^{-1} ammonium sulfate $[(NH_4)_2SO_4]$ at Owosso in 2010 and 2011. Glyphosate [N-(phosphonomethyl)glycine] (formulated as Roundup WeatherMax, Monsanto Co., St. Louis, MO) at 1.6 L ha^{-1} with 20 g L^{-1} ammonium sulfate $[(NH_4)_2SO_4]$ was applied at Stockbridge in 2011.

Treatments included nine foliar Mn fertilizer products in 2010 and ten in 2011, and compared to a control receiving no Mn fertilizer. Fertilizers were applied at low and high rates as recommended by product labels (Table 2.2). $MnSO_4$ (The Pestell Group, New Hamburg, Ont.) is a dry product. Citriaplex (Loveland Products, Loveland, CO) is comprised of $MnSO_4$ with a citric acid chelate. Manni-plex (Brandt Consolidated Inc., Springfield, IL) is a sugar alcohol Mannitol. Eezyman (New Eezy Gro Inc., Carey, OH) contains a proprietary chelate. Mn-EDTA (Nachurs Alpine Solutions, Marion, OH) includes Mn chelated with ethylenediaminetetraacetate (EDTA). Blackjack Mn (Loveland Products Inc., Loveland CO) contains Mn as $MnSO_4$ and 5.0 g humic acid kg^{-1} derived from leonardite. Max-In Ultra Mn (Max-In) (Winfield Solutions LLC, St. Paul, MN), included $MnSO_4$ with CornSorb™ and SureTank ™ adjuvants. Versatile-IDS (Versatile) (Wilbur-Ellis, San Francisco, CA) includes EDTA and iminodisuccinate chelates. Foli-Gro Triple 7 (Crop Production Services, Loveland, CO) includes 7.0 g kg^{-1} urea N, 7.0 g kg^{-1} P_2O_5, 7.0 g kg^{-1} K_2O, 0.1 g kg^{-1} B, 0.1 g kg^{-1} Zn, and 0.03 g kg^{-1} Cu in addition to 0.1 g kg^{-1} Mn chelated with EDTA. 3-16-16 TMR (TMR) (Nachurs Alpine Solutions, Marion, OH) is comprised of 3.0 g N kg^{-1}, 16.0 g P_2O_5 kg^{-1}, 16.0 g K_2O kg^{-1}, 0.11 g Ca kg^{-1}, 0.0034 g B kg^{-1},

Table 2.2. Manganese fertilizer products evaluated in 2010 and 2011.

Product	Mn concentration	Application rate	
		Low	High
	g kg^{-1}	kg Mn ha^{-1}	
$MnSO_4$	32.0	1.12	2.24
Citraplex	20.0	0.24	0.45
Manni-plex	5.0	0.14	0.28
Eezyman	5.0	0.14	0.28
Mn-EDTA	6.0	0.09	0.37
Blackjack Mn	4.0	0.06	0.25
Max-In	5.0	0.14	0.28
Versatile[†]	5.0	0.07	0.28
Triple 7[‡]	0.1	0.003	0.02
TMR[§]	0.02	0.003	0.02

[†]Evaluated in 2011 only

[‡]Evaluated with Versatile-IDS in 2011

[§]Evaluated with Mn-EDTA in 2011

0.0086 g Cu g^{-1}, 0.0167 g Fe kg^{-1}, 0.0008 g Mo kg^{-1}, and 0.24 g Mn kg^{-1} with EDTA chelate. Versatile was evaluated in 2011 only. Poor performance of Triple 7 and TMR in 2010 was attributed to the lower application rates of Mn with these products compared to other treatments. In 2011, Versatile was combined with Triple 7 and Mn-EDTA with TMR. Manganese fertilizer product costs are presented in Table 2.3.

Moderate deficiency symptoms were evident at all sites at the V2 soybean growth stage and Mn fertilizers were applied in response (Table 2.4). Manganese deficiency severity was assessed with visual ratings to evaluate Mn fertilizer effectiveness in preventing redevelopment of Mn deficiency and to determine timing of secondary fertilizer applications. Ratings were conducted on a 0 to 10 scale, with 0 corresponding to no visible Mn deficiency symptoms and 10 corresponding to severe Mn deficiency, evidenced by severe whole-plant chlorosis and plant stunting. Ratings were recorded following initial applications directly before secondary fertilizer application when average visual ratings exceeded a rating of 4.0-5.0. Applications of Mn at this level of deficiency are a common producer management practice. Following secondary applications, visual ratings were conducted in early August. Manganese deficiency severity decreased in late August in Owosso in 2011 and visual ratings were recorded to reflect these treatment differences. In 2011 at Stockbridge, Mn deficiency symptoms were not observed after secondary applications and no ratings were recorded.

Fertilizers were applied with a CO_2 backpack sprayer at 240 kPa and 140 L water ha^{-1} using 8002 flat fan nozzles (TeeJet, Spraying Systems Co., Wheaton, IL). Following foliar Mn applications, twenty of the most recently emerged fully expanded trifoliates were sampled from

Table 2.3. Manganese fertilizer product costs.

Product	Mn concentration	Application rate	
		Low	High
	g kg^{-1}	—— $ ha^{-1} ——	
$MnSO_4$	32.0	3.47	6.95
Citraplex	20.0	12.35	24.70
Manni-plex	5.0	6.18	12.35
Eezyman	5.0	5.16	10.31
Mn-EDTA	6.0	15.25	30.50
Blackjack Mn	4.0	7.10	28.41
Max-In	6.0	9.79	19.58
Versatile-IDS[†]	5.0	5.06	20.25
Triple 7[‡]	0.1	3.40	27.17
TMR[§]	0.02	31.62	63.23

[†]Evaluated in 2011 only

[‡]Evaluated with Versatile-IDS in 2011

[§]Evaluated with Mn-EDTA in 2011

Table 2.4. Manganese fertilizer herbicide application dates, soybean growth stage and tissue sample dates at Owosso and Stockbridge sites in 2010 and 2011.

Site	**1st application**			**2nd application**		
	Date	**Growth stage**	**Tissue sample**	**Date**	**Growth stage**	**Tissue sample**
2010						
Owosso	11 June	V2	16 June	1 July	R1	7 July
Stockbridge	17 June	V2	23 June	17 July	R2	22 July
2011						
Owosso	6 July	V2	15 July	27 July	R1	31 July
Stockbridge	6 July	V2	10 July	26 July	R1	31 July

each plot. Timing of sampling ranged from four to seven days following application, varying by the speed of plant growth. Leaves were washed with a 1.0 g kg^{-1} soap solution and triple rinsed in deionized water, dried at 66°C, and ground to pass through a 1 mm sieve. Manganese concentrations were determined with a hot acid extract open vessel procedure where 0.2 g of plant tissue was combined with 2.0 ml of Nitric acid and headed by microwave oven to 90° C and held for 90 seconds. Following cooling to 50° C, 1.0 of peroxide is combined with the sample and heated by microwave oven to 105° C and held for 10 minutes. Samples are cooled and brought to a final volume of 25 ml with deionized water, for a 1:125 dilution factor. Samples are then analyzed with an inductively coupled plasma emission spectrometer.

Grain yield was determined from a 1.5 m swath in the plot center with a Massey 8XP plot combine (Kincaid Equipment Manufacturing, Haven, KS). Seed moisture and yield was recorded and yield was adjusted to 130 g kg^{-1} moisture.

Data were analyzed with SAS statistical software (SAS Institute, Cary, NC). Analysis of variance was performed using PROC MIXED. Both site and year effects were significant, so data are presented separately for each year and site. Treatment means are considered statistically different at the $P \leq 0.10$ level.

Results

Season growing degree day numbers were near 30 year averages in 2010, but below in 2011 (Table 2.5). Precipitation was below average in 2010 and above average in 2011. August rainfall at both sites in 2010, particularly Owosso, was well below long term averages. Above average March, April, and May precipitation, combined with below average April and May temperatures, delayed planting and early season soybean growth at both sites in 2011.

Visual soybean chlorosis ratings taken preceding the second application event at Owosso in 2010 were lowest for $MnSO_4$ compared to all other treatments (Table 2.6). High application rates resulted in lower deficiency ratings compared to low application rates only for $MnSO_4$ and Citraplex products. All treatments except the high rates of Triple 7 and TMR resulted in lower Mn deficiency ratings than the control. At Stockbridge, the high application rates of Manni-plex and $MnSO_4$ resulted in lower Mn deficiency ratings than low application rates of Citraplex and Max-In, the high application rate of Eezyman, and both application rates of Blackjack, Triple 7, and TMR. Citraplex was the only product where the high application rate resulted in a lower Mn deficiency rating than the low application rate.

Following the second Mn application at Owosso, $MnSO_4$ treatments resulted in lower deficiency ratings than low application rates of Manni-plex, Mn-EDTA, Max-In, the high rate of Blackjack Mn, and both application rates of Triple 7 and TMR. No differences in ratings were observed between application rates for any product. All treatments except both application rates of Triple 7 and TMR resulted in lower deficiency ratings than the control. At Stockbridge following the

Table 2.5. Growing degree day and precipitation for Stockbridge and Owosso sites in 2010 and 2011.

Site	Growing Degree Days†			Precipitation		
	2010	2011	30-yr‡	2010	2011	30-yr
	C°			mm		
Owosso						
March	7	1	12	19	68	54
April	62	25	38	64	125	73
May	175	155	151	106	126	72
June	289	267	281	80	59	83
July	377	399	364	58	107	69
August	356	310	326	6	77	90
September	164	151	197	98	49	93
October	51	58	64	60	63	62
Season	1481	1365	1433	490	674	596
Stockbridge						
March	4	3	13	22	68	46
April	67	26	52	40	134	67
May	175	163	151	114	146	84
June	285	275	296	153	51	83
July	358	386	370	102	253	91
August	336	286	342	42	62	88
September	161	148	206	60	77	88
October	55	9	66	33	77	67
Season	1440	1293	1496	567	866	615

†GDD- Growing Degree Days (C°, base 10°C)

‡30-yr.- 30 year site average

Table 2.6. Soybean Mn deficiency visual ratings at Owosso and Stockbridge sites in 2010.

Product	Rate	Owosso		Stockbridge	
		30 June	10 Aug.	17 July	10 Aug.
Control		6.8g†	6.3e	6.3h	4.8cde
$MnSO_4$	Low	3.0b	1.5ab	2.8ab	2.8ab
	High	1.3a	1.3a	2.3a	1.5a
Citraplex	Low	5.0def	2.5abcd	4.8defg	3.5bcd
	High	3.3bc	2.0abc	3.0abc	3.0ab
Manni-plex	Low	4.0bcd	3.3cd	3.5abcd	3.5bcd
	High	3.0b	2.0abc	2.3a	2.8ab
EezyMan	Low	4.3bcde	2.5abcd	3.5abcd	5.0de
	High	4.0bcd	2.0abc	3.8bcde	4.3bcde
Blackjack Mn	Low	3.8bcd	2.8bcd	4.0bcdef	3.3bc
	High	3.8bcd	3.5d	3.8bcde	5.0de
Mn-EDTA	Low	4.8cdef	3.3cd	5.0efgh	4.8cde
	High	4.0bcd	2.8bcd	4.0bcdef	3.0ab
Max-In	Low	4.5bcde	3.3cd	4.3cdef	3.5bcd
	High	4.3bcde	2.8bcd	3.3abc	3.0ab
Triple 7	Low	5.0def	6.0e	5.8gh	6.8f
	High	5.8efg	5.0e	5.0efgh	4.3bcde
TMR	Low	5.0def	5.0e	5.8gh	5.5ef
	High	6.3fg	5.5e	5.3fgh	5.8ef
$P > F$		0.0010	<0.0001	<0.0001	<0.0001

†Means within a column followed by the same letter are not significantly different at $P > 0.10$.

second fertilizer application, the high application rate of $MnSO_4$ resulted in lower deficiency ratings compared to all products applied at the low rate and EezyMan, Blackjack Mn, Triple 7, and TMR products applied at the high rate. Application of Triple 7 at the low rate resulted in higher deficiency ratings compared to all treatments, including the untreated control.

In 2011 following the first Mn application at Owosso, Mn-EDTA applied at the high rate resulted in a lower deficiency rating than low application rates of $MnSO_4$, Citraplex, Versatile IDS, Mn-EDTA, high application rates of Triple 7, and both application rates of Blackjack Mn and TMR (Table 2.7). Mn-EDTA was the only product where the high application rate resulted in a lower deficiency rating than the low application rate. Low application rates of Citraplex and TMR and high application rates of Blackjack Mn and Triple 7 resulted in similar deficiency rating to the control. At Stockbridge following the first fertilizer application, the low application rate of $MnSO_4$ resulted in a lower deficiency rating compared to the low rate on Manni-plex, Eezyman, Mn-EDTA, Max-In, and Triple 7, the high application rate of Versatile IDS, and both application rates of Blackjack Mn and TMR. High application rates resulted in lower deficiency ratings for $MnSO_4$ and Triple 7 compared to the low application rate. All treatments except for TMR at high and low application rates resulted in lower deficiency ratings compared to the control.

Following the second Mn application at Owosso in 2011 on 16 August, Mn-EDTA applied at the high rate resulted in a lower deficiency rating compared to low application rates of Mn-EDTA and Triple 7, high application rates of TMR, and both application rates of Blackjack Mn. Mn-

Table 2.7. Soybean Mn deficiency visual ratings at Owosso and Stockbridge sites in 2011.

Product	Rate	Owosso			Stockbridge
		25 July	16 Aug.	31 Aug.	25 July
Control		8.8h†	8.5g	6.3e	8.5e
$MnSO_4$	Low	5.3bcdef	4.0abcdef	1.0a	3.5a
	High	4.8abcd	3.5abcde	1.3a	6.0bcd
Citraplex	Low	7.0efgh	3.8abcde	4.5cde	5.0abc
	High	5.0abcde	2.3ab	1.0a	5.0abc
Manni-plex	Low	4.0ab	3.0abc	1.5ab	6.0bcd
	High	4.5abc	3.3abcd	1.8ab	5.0abc
EezyMan	Low	4.8abcd	3.5abcde	2.3abc	6.3cd
	High	4.5abc	2.8ab	2.8abcd	5.0abc
Blackjack Mn	Low	6.5cdefg	5.3ef	2.5abcd	6.8cde
	High	6.8defgh	5.0cdef	5.0ed	5.5bcd
Versatile IDS	Low	5.8bcdefg	5.3ef	6.5e	5.0abc
	High	4.8abcd	5.0cdef	2.3abc	5.8bcd
Mn-EDTA	Low	7.8g	6.0f	6.3e	5.8bcd
	High	3.0a	2.0a	1.0a	5.0abc
Max-In	Low	4.3ab	2.8ab	1.0a	6.5cd
	High	4.5abc	2.5ab	2.0ab	5.3abcd
Triple 7	Low	5.0abcde	5.5ef	3.8bcd	7.0de
	High	6.8defgh	3.5abcde	2.5abc	4.3ab
TMR	Low	7.3fgh	4.0abcdef	3.3abcd	6.8cde
	High	5.5bcdef	4.3bcdef	2.5abcd	6.8cde
$P > F$		0.0018	0.0003	0.0004	0.0004

†Means within a column followed by the same letter are not significantly different at $P > 0.10$

EDTA was the only product where the high application rate resulted in a lower deficiency rating compared to the low application rate. All treatments resulted in lower deficiency ratings compared to the control. In late August, deficiency ratings decreased compared to those two weeks previous for most treatments. While application rate did not resulted in differences in deficiency ratings between Citraplex and Mn-EDTA on 16 August, on 31 August, low application rates of Citraplex and Mn-EDTA had higher deficiency ratings compared to high application rates. At Stockbridge, no Mn deficiency symptoms were observed following the second Mn application and no ratings were recorded.

The first foliar fertilizer application in 2010 at Owosso and Stockbridge resulted in significantly greater Mn tissue concentrations for $MnSO_4$ compared to all other treatments (Table 2.8). Tissue Mn concentrations were greater for the high rate of $MnSO_4$ compared to the low rate at both locations. At Owosso, the high rate of Manni-plex, followed by the high rate of Citraplex, Eezyman and Max-In in decreasing order, resulted in higher concentrations than other products. All products except Triple 7 and TMR increased Mn concentrations above the control treatment. Increasing the application rates of Mn fertilizers tended to increase tissue Mn levels. At Stockbridge, the high rates of Manni-plex and Citraplex, along with both rates of $MnSO_4$, were the only products to increase Mn concentrations above that of the control.

Tissue Mn concentrations were greatest for $MnSO_4$ following the second application in 2010 at both sites. The application of $MnSO_4$ at the high rates resulted in greater tissue Mn concentration compared to the low rate. At Owosso, applications of Citraplex, Manni-plex,

Table 2.8. Soybean trifoliate Mn concentration following foliar fertilizer application at Owosso and Stockbridge sites in 2010.

Product	Rate	Owosso		Stockbridge	
		1st app	2nd app	1st app	2nd app
		mg Mn kg^{-1}		mg Mn kg^{-1}	
Control		10i†	9g	17ef	9ef
$MnSO_4$	Low	74b	537b	31b	46b
	High	108a	1469a	37a	76a
Citraplex	Low	21fg	110cdefg	17ef	20def
	High	32d	187c	23cd	28cd
Manni-plex	Low	22fg	72defg	17ef	23cde
	High	39c	155cd	25c	48b
EezyMan	Low	22fg	79defg	15f	18def
	High	31de	121cdef	15f	19def
Blackjack Mn	Low	14hi	28fg	14f	11ef
	High	25efg	70defg	14f	14def
Mn-EDTA	Low	13i	51efg	14f	11ef
	High	22fg	69defg	16f	36bc
Max-In	Low	20gh	61defg	20de	19def
	High	27def	131cde	22cde	36bc
Triple 7	Low	11i	10g	13f	8f
	High	10i	15g	14f	20def
TMR	Low	12i	16g	13f	8f
	High	12i	20fg	13f	7f
$P > F$		<0.0001	<0.0001	0.0009	<0.0001

†Means within a column followed by the same letter are not significantly different at $P > 0.10$

Eezyman, and Max-In at the high rate resulted in higher numerical Mn concentrations compared to the low rate, but were statistically similar. At Stockbridge, Mn concentrations were similar between application of $MnSO_4$ at the low rate and application of Manni-plex, Mn-EDTA, and Max-In at the high rate. These four products were the only treatments in which application rate influenced Mn concentrations. At Owosso and Stockbridge, Triple 7 and TMR were among the treatments with the lowest Mn concentrations and were statistically similar to the untreated control.

Trifoliate Mn concentration trends in 2011 were similar to those in 2010 (Table 2.9). With the exception of the first application event at Owosso, leaf Mn concentrations were greatest with the high application rate of $MnSO_4$. At Owosso, application of Citraplex at the high rate resulted in greater trifoliate Mn concentrations compared to all treatments except Manni-plex at the high rate and $MnSO_4$ at the low rate. Tissue Mn concentrations of all other treatments were similar to the untreated control. At Stockbridge, $MnSO_4$ applied at the high rate and low rate resulted in significantly greater Mn tissue levels than any other treatment. Application of Citraplex at the low and high rate and Max-In, TMR + Mn-EDTA, Versatile, and Manni-plex at the high rate were the only other treatments that increased Mn concentrations compared to the control.

Following the second fertilizer application at both Owosso and Stockbridge in 2011, clear differences could be observed between the treatments with the highest Mn concentrations. The greatest Mn concentrations resulted from application of $MnSO_4$ at the high rate, followed by

Table 2.9. Soybean trifoliate Mn concentration following foliar fertilizer application at Owosso and Stockbridge sites in 2011.

Product	Rate	Owosso		Stockbridge	
		1st app	2nd app	1st app	2nd app
		mg Mn kg^{-1}		mg Mn kg^{-1}	
Control		14fg†	12j	20f	11j
$MnSO_4$	Low	37ab	112b	413b	144b
	High	32bc	131a	676a	200a
Citraplex	Low	26bcde	46e	82cde	29efghi
	High	45a	63d	128c	50d
Manni-plex	Low	19defg	43ef	45def	33defg
	High	36ab	89c	84cde	69c
EezyMan	Low	218cdefg	23ghij	32ef	28fghij
	High	17defg	41ef	68def	38def
Blackjack Mn	Low	18defg	18hij	30ef	16ghij
	High	16efg	30fgh	67def	27fghij
Versatile	Low	18defg	12j	42def	15hij
	High	20defg	22hij	67cdef	21fghij
Mn-EDTA	Low	12g	16ij	32ef	16ghij
	High	29bcd	44ef	65def	32defgh
Max-In	Low	20cdefg	36efg	46def	26fghij
	High	26bcdef	66d	96cd	46de
Triple 7 + Versatile	Low	21cdefg	15ij	39def	12ij
	High	18defg	39ef	76cdef	30efghij
TMR + Mn-EDTA	Low	16efg	25ghi	40def	16ghij
	High	26bcdef	21hij	96cd	29efghi
$P > F$		<0.0001	<0.0001	<0.0001	<0.0001

†Means within a column followed by the same letter are not significantly different at $P > 0.10$

$MnSO_4$ at the low rate, then Manni-plex at the high rate, and Max-In and Citraplex at the high rate in the next group.

In 2010 at Owosso, $MnSO_4$ applied at both low and high rates and Citraplex at the low rate resulted in significantly greater yield compared to Mn-EDTA, Blackjack, Triple 7, TMR treatments at both low and high rates and Max-In and Manni-plex applications at the low rate (Table 2.10). Triple 7 applied at the low rate and TRM applied at both low and high rates resulted in significantly lower yield compared to other products. Triple 7 applied at the low rate was the only product that did not result in a yield increase compared to the control. At Stockbridge, $MnSO_4$ at both low and high application rates resulted in greater yield compared to Blackjack Mn, Triple 7, and TMR at low and high application rates, Eezyman at the high rate and EDTA at the low rate. $MnSO_4$ and Manni-plex at low and high application rates and Citraplex at the high rate were the only treatments to increase grain yield compared to the control.

At Owosso in 2011, applications of Citraplex, Max-In, Eezyman and $MnSO_4$ were among the highest yielding treatments and resulted in greater yields compared to Blackjack Mn at the high application rate, Citraplex, Versatile, Mn-EDTA, and TMR + Mn-EDTA at low application rates, Triple 7 + Versatile at both low and high application rates and the untreated control. All treatments except TMR + Mn-EDTA applied at the low rate resulted in higher grain yield compared to the control. At Stockbridge in 2011, Max-In and Citraplex at the high application rate, and $MnSO_4$ and Manni-plex at both low and high application rates resulted in higher yields

Table 2.10. Soybean grain yield at Owosso and Stockbridge sites in 2010 and 2011.

Product	**Rate**	**Owosso**		**Stockbridge**	
		2010	**2011**	**2010**	**2011**
		Mg ha^{-1}		**Mg ha^{-1}**	
Control		2.05g†	0.47h	2.14de	1.22f
$MnSO_4$	Low	3.95a	1.64abcd	3.14a	2.54abc
	High	3.96a	1.72abc	3.15a	2.49abc
Citraplex	Low	3.54abcd	1.11defg	2.60abcd	2.17bcde
	High	3.96a	1.97a	2.92ab	2.64ab
Manni-plex	Low	3.41bcd	1.62abcd	2.84abc	2.43abc
	High	3.83ab	1.46abcdef	2.87abc	2.44abc
EezyMan	Low	3.66abcd	1.40abcdef	2.56abcd	1.87de
	High	3.74abcd	1.75abc	2.50bcd	2.30abcd
Blackjack Mn	Low	3.29cde	1.46abcdef	2.21de	2.16bcde
	High	3.34cde	1.03efg	2.44bcd	2.27abcde
Versatile	Low	*n/a*	1.02efg	*n/a*	2.28abcde
	High	*n/a*	1.33bcdef	*n/a*	2.28abcde
Mn-EDTA	Low	3.34de	0.72gh	2.11de	2.17bcde
	High	3.47bcd	1.48abcde	2.56abcd	2.41abc
Max-In	Low	3.47bcd	1.44abcdef	2.65abcd	2.08cde
	High	3.66abcd	1.87ab	2.68abcd	2.66a
Triple 7	Low	2.50fg	*n/a*	1.73e	*n/a*
	High	2.87ef	*n/a*	2.23cde	*n/a*
TMR	Low	2.68f	*n/a*	2.11de	*n/a*
	High	2.63f	*n/a*	1.81e	*n/a*
Triple 7 + Versatile	Low	*n/a*	1.29cdef	*n/a*	1.85de
	High	*n/a*	1.19cdefg	*n/a*	2.25abcde
TMR + Mn-EDTA	Low	*n/a*	0.94fgh	*n/a*	1.81e
	High	*n/a*	1.64abcde	*n/a*	2.29abcde
P > *F*		<0.0001	0.0029	0.0035	0.0029

†Means within a column followed by the same letter are not significantly different at *P* > 0.10

compared to Max-In, Eezyman, Triple 7 + Versatile, and TMR + Mn-EDTA applied at low rates. All treatments resulted in greater yields compared to the control.

Discussion

In-season soybean leaf Mn concentrations were generally an effective indicator of treatment yield response, but the degree of correlation varied by site. The range in plant nutrient concentration from deficient to adequate is characterized by a critical nutrient range. The size and range of this transitional zone can vary depending on factors such as plant growth stage, but has been placed in the range of 17-21 mg kg^{-1} by Gettier et al. (1985a), 15-20 mg kg^{-1} by Randall et al. (1975), 12 mg kg^{-1} by Ohki et al. (1979), 17 mg kg^{-1} by Bell et al. (1995) and 20 mg kg^{-1} at R1 by Melsted et al. (1969). Cox (1968) found yield responses to foliar Mn fertilization when untreated control plot trifoliate Mn concentrations were below 20 mg kg^{-1}. Gettier et al. (1985a) set a critical level as 90% of maximum yield, providing a method of analyzing multiple location results under varying deficiency pressure. Sampling of trifoliates in the current study occurred shortly after fertilization events, presumably at a time of near peak Mn fertilizer uptake and tissue concentration. Of treatments yielding with 90% of the maximum, trifoliate Mn concentrations always exceeded 20 mg kg^{-1}.

Across all sites after the first fertilization event, no treatment yielded over 90% of the maximum when trifoliate concentrations fell below 22.3 mg kg^{-1}. While treatments with higher Mn concentrations were generally associated with higher yields, this relationship was weakest at Stockbridge in 2011. Here, a tissue Mn concentration of at least 50 mg kg^{-1} was required to assure yields at just 80% of the maximum. Tissue Mn concentrations were greater at this site compared to any other site following the first fertilizer application, but tissue Mn concentrations were a poor predictor of yield.

Tissue Mn concentrations following the second fertilization were more poorly correlated with yield than those following the first fertilization. Tissue levels of at least 20 mg kg^{-1} Mn were generally required to attain yields at 80% of the maximum. Treatments with low Mn concentrations following the first fertilization could often be observed to have Mn levels above those commonly accepted as critical levels after the second fertilization, indicating that without effective early season control of Mn deficiency, later season treatment of Mn deficiencies has less bearing on yield.

Dow and Roberts (1982) proposed the use of a critical nutrient range (CNR) rather than a critical nutrient concentration (CNC) determined by other workers in an attempt to account for variability such as crop growth stage in assigning a particular value as the boundary between deficient and sufficient. The variation in tissue Mn concentrations observed in this study between locations, application timing, and effectiveness of prior fertilizer applications suggest that rather than employ a CNC for nutritional analysis, a CNR that accounts for these factors may be more appropriate.

$MnSO_4$ applications were observed to increase tissue Mn concentrations to a much greater extent than other treatments at several locations. Following the first fertilizer application at Stockbridge in 2011 and the second fertilizer applications at Owosso in 2010, tissue Mn concentrations for the high rate of $MnSO_4$ were measured at 676 and 1469 mg kg^{-1}, respectively. In contrast to what others have noted with high trifoliate Mn concentrations, no toxicity symptoms were observed in this study. Ohki et al. (1980) noted severe visual toxicity symptoms and reduced plant weight in soybeans cultured in high Mn concentration solutions, recording leaf blade concentrations as high as 944 mg kg^{-1} Mn. Randall et al. (1975) suggested that yield reductions from 2.24 mg kg^{-1} Mn applications of foliar $MnSO_4$ could be attributed to foliage burn and leaf drop observed at this rate compared to 0.56 and 1.12 mg kg^{-1} Mn rates. Tissue concentrations did not exceed 53.5 mg kg-1 Mn , far below the levels we recorded. More recently, Diedrick (2010) measured trifoliate Mn concentrations of as high as 594 mg kg^{-1} in Ohio with $MnSO_4$ applications. Yields did not differ from untreated controls, suggesting toxicities were not induced.

Four products, $MnSO_4$ at both low and high application rates, and Citraplex, Manni-plex, and Max-In at high rates, were the only treatments among the top yielding group at all four site years. Unchelated $MnSO_4$ has the smallest molar mass of all products at 54.94 u. Citric acid ($C_6H_8O_7$) and Mannitol ($C_6H_8(OH)_6$) chelates have smaller molecular weights than the EDTA ($C_{10}H_{16}N_2O_8$) chelate common to many of the products. Low permeability of cell membranes to compounds with high molecular weight has been suggested as an explanation for reduced foliar uptake of high molecular weight compounds such as EDTA (Marschner, 1986). Randall et al. (1975) found 4.48 kg Mn ha^{-1} applied as $MnSO_4$ increased trifoliate Mn concentrations compared to lower rates of $MnSO_4$ applied at 0.56 and 1.12 kg Mn ha^{-1} or Mn-EDTA applied at

0.17, 0.34, or 0.51 kg Mn ha^{-1}. No treatment resulted in yield differences from an untreated check, however, suggesting plant Mn concentration was not a yield limiting factor. Other workers have compared foliar applications of chelated divalent cations to sulfate forms in crops other than soybean, finding similar fertilizer uptake trends. Stacey and Oosterhuis (2005) recorded reduced sorption of Zn by 96% and Fe by 83% when chelated with EDTA compared to applications of sulfate forms in Valencia orange leaves. In cotton plants, total uptake of foliar applied ZnEDTA and $ZnSO_4$ was similar after 12 hours, though EDTA uptake was lower compared to $ZnSO_4$ at 1, 3, and 6 hours. Kannan (1969) found tomato leaf cuticle penetration of Fe chelated with EDDHA was lower than that of sulfate forms, attributing this to the larger molecular size of chelated compounds. Neumann and Prinz (1975) suggested that reduced root length, root mass, and shoot mass observed in solution cultured bean seedlings when sprayed with Fe-EDDHA compared to $FeSO_4$ may have resulted from reduced diffusion of the larger chelated compound though leaf cuticles and cell walls. Absorption and mobility of Mn in the plant has been observed to be similar to that of other divalent cations, including Zn and Fe, in beans (Bukovac and Wittwer, 1957), suggesting studies investigating movement of these nutrients in the plant may be appropriate for extrapolation of Mn behavior.

Activity of EDTA in the plant has also been suggested as a negative effect of foliar EDTA fertilizers. Vassil et al. (1998) found that EDTA can be accumulated by plants even when present in low concentrations, and this disassociated EDTA in the leaf may complex with divalent cations to an extent that cell health is compromised. Weinstien et al. (1954) suggested competition within the plant between EDTA and enzymes for metals essential for enzyme activity. The combination of negative effects of EDTA in the leaf and a decrease in the absoption and/or translocation of Mn fertilizers inversely proportional to their molecular weight is a possible explanation for the observed tissue Mn concentration and yield responses to fertilizer products. Those products with the lowest molecular weight, either non-chelated such as $MnSO_4$ and Max-In or chelated with smaller weight chelates such as Citraplex and Manni-plex, performed better than those with larger chelates.

Max-In contains the adjuvant CornSorb, a monosaccharide that was originally developed for use with postemergence herbicides. Increases in soybean Mn concentrations have been documented when CornSorb is included with foliar Mn fertilizer applications compared to applications without an adjuvant or when applied with non-ionic surfactant or methylated seed oil (Gednalske et al. 2010). Tissue Mn concentrations were lower for Max-In treatments compared to other products, including $MnSO_4$. These results suggest that the inclusion of adjuvants with Max-In was not sufficient to account for the lower total quantity of Mn applied. Grain yields with the high application rate of Max-In, however, were equivalent to the maximum yielding treatments. The form of Mn included in the fertilizer, in this case $MnSO_4$, appears to be a larger factor in determining yield than the adjuvant package.

Low tissue Mn concentrations and grain yields observed with applications of Triple 7 and TMR products in 2010 were attributed to the low Mn concentration of these products respective to other fertilizer products. In an attempt to better represent a viable agronomic management strategy, Versatile was combined with Triple 7 and Mn-EDTA with TMR in 2011. In 2011, no differences in tissue Mn concentrations were observed between application rates except for the following the second fertililizer application to Owosso, where the high application rate resulted in a higher Mn concentration compared to the low application rate. Trifoliate Mn concentrations for Triple 7 + Versatile and TMR + Mn-EDTA at both application rates tended to be low relative to those recorded following application of other products. Grain yield was greater with the high application rate of TMR + Mn-EDTA compared to the low rate, but grain yield was similar between low and high application rates of Triple 7 + Versatile. Grain yield did not differ between Triple 7 + Versatile and Versatile along or between TMR + Mn-EDTA and Mn-EDTA alone, suggesting that the application of additional macro and micronutrient contained in these products did not increase yield.

Trifoliate Mn concentrations following both the first and second fertilization events were generally increased by the application of $MnSO_4$, Citraplex, Manni-plex and Max-In at high rates compared to low rates. Manganese concentrations were generally not responsive to application rate for other products. In only four instances did application of Mn fertilizer at the high rate result in greater yield than fertilizer application at the low rate. At Owosso in 2011, Citraplex, Mn-EDTA and TMR applied at the high rate resulted in higher yields compared to application at the low rate. At Stockbridge in 2011, Max-In applied at the high rate resulted in a greater yield compared to application at the low rate.

Conclusion

Products with Mn in low molecular weight forms increased or tended to increase plant Mn concentrations and grain yield compared to EDTA chelated products across all site years. $MnSO_4$ was the most consistent product at increasing leaf Mn concentrations and grain yield. Citraplex, Manni-plex and Max-In offered similar, if slightly inferior, performance characteristics and provide growers with alternative options to $MnSO_4$.

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CHAPTER 3. PHOSPHORUS AND POTASSIUM FERTILZIER APPLICATION STRATEGIES IN CORN-SOYBEAN ROTATIONS

Abstract

This study investigated the effects of annual P and K fertilizer applications in a corn and soybean rotation in comparison to the more common biennial approach of applying sufficient quantities of P and K fertilizers for both corn and soybean crops before the corn crop. In an attempt to determine the accuracy of current university fertilizer recommendations, P and K were applied in annual and biennial scenarios at state soil test recommended rates and at twice the recommended rate in corn-soybean rotations. Sites were located in MN, IA, MI, AR, and LA and categorized based on their initial soil test K and P levels as sub-optimal, optimal, or above optimal. At locations with either soil test P or K in the sub-optimal range, corn grain yield was increased with fertilizer application at five of sixteen site years, while soybean grain yield was increased with fertilizer application at one of sixteen site years. At one site year, soybean grain yield was decreased with fertilizer application. At locations with both soil test P and K at optimal or greater levels, corn grain yield was increased at three of thirteen site years and soybean grain yield increased at one of fourteen site years when fertilizer was applied. As soil test values decreased, the likelihood of a yield response from fertilizer applications increased, which is consistent with yield response frequencies outlined in state fertilizer recommendations. For both corn and soybean, fertilizer applied at the recommended rate tended to result in maximum yield. High fertilizer application rates tended to result in lower yield than lower, recommended fertilizer application rates. Soybean yields were similar regardless if fertilizer was applied in the year of crop production or before the preceding corn crop. Based on the results of this work, the practice of applying P and K fertilizers at recommended rates biennially prior to first year corn production in a corn-soybean rotation is not a yield limiting factor in US soybean production.

Introduction

Phosphorus and potassium are essential nutrients for corn and soybean and can be yield limiting in many major crop production areas in the United States. Mineral fertilizers are effective in augmenting soil nutrient levels and are common production inputs. Determining optimum application rates and timings for these fertilizers has been an ongoing research focus for decades and efforts continue to refine recommendations. Perceptions by producers of stagnant crop yield increases, particularly in soybeans, have spurred interest in revisiting the role of production inputs in an attempt to determine yield-limiting factors.

University studies have documented the correlation between soil tests and plant nutrient uptake, and the correlation between soil test values and crop yield response to fertilizer application. Fertilizer recommendations have been developed as a result of this process, providing a guideline for optimal application rates of mineral fertilizers. These recommendations are frequently delineated into management zones based on the probability of yield response to applied fertilizer. A central tenet of these recommendations is the identification of the soil test critical level, the point below which crop growth and yield will be limited by nutritional deficiency. Specific soil critical test values differ by geographic region, soil characteristics, crop, and environment and emphasize the need for regional specific recommendations. Fertilizer recommendations for soils with nutrient values below the critical level include fertilizer to meet intended crop needs and to elevate soil test levels above the critical point. Terminology differs by state for soils testing above the critical level, with soils classified as either optimum or medium. Soils in this range are expected to have a good probability of not responding to additional fertilizer applications. As such, this range is considered the most economical category in which to maintain soil test values.

Fertilizer recommendations for soils in the optimum/medium range often call for fertilizer to be applied in amounts equal to grain nutrient removal. Increasing soil test levels provide a decreasing likelihood of crop yield response. Soils in the high to very high soil test range have little or no fertilizer recommended.

While the specific numerical delineations of soil test ranges vary by states, the premise of these ranges serving as a guide to quantify the likelihood of economic yield response to fertilizer application is standard. The Iowa Crop Nutrient Recommendation perhaps best conveys this message, listing the probability of response for each soil test range as follows: 80% for very low, 65% for low, 25% for medium, 5% for high and under 1% for very high (Sawyer et al., 2011). The use of fertilizer recommendations with these response expectations in mind is important in interpreting research verification studies.

Fertility experiments conducted in the time following the development of these recommendations have generally validated existing fertility standards. As expected, corn and soybean grain yield increases to applications of P and K have generally not been found in soils testing at or above medium ranges (Mozaffari et at., 2011, Buah et al., 2000; Webb et al., 1992; Mallarino et al., 1991; Borges and Mallario, 2000; deMoody et al., 1973). Ebelhar and Varsa (2000) applied increasing rates of K fertilizer at two sites in Illinois on soils testing from 210-280 kg K ha^{-1}, recording corn grain responses in three of six sites years and soybean grain responses at four of six site years. In Arkansas, Slaton et al. (2011) observed soybean yield responses to K fertilization at twenty one of thirty four sites. All sites testing below 91 mg K kg^{-1} responded to

K fertilizer, and nine of fifteen sites with soil test K between 91 and 130 mg K kg^{-1} responded to K fertilizer. Only one yield response was observed when soil test levels were over 130 mg K kg^{-1}. Mallarino et al. (2011) observed corn grain yield increases to broadcast fertilizer applications on five of six Iowa locations with optimum or lower soil test values for P and K. In strip-plot Dodd and Mallarino (2005) noted a greater likelihood for corn to respond to P and K fertilizer applications on optimum soil test sites in Iowa compared to soybeans. Buah et al. (2000) saw fertilizer P applications increase soybean grain yields in two of seven site years in Iowa when soil test values were low or very low, validating existing Iowa fertilizer recommendations. Rehm (1986) noted soybean grain responses to P fertilizer applications in three low soil test P Nebraska sites, but did not see yield responses at seven other higher testing P sites.

In corn-soybean crop rotation, a biennial fertilizer application of P and K preceding corn has become a common management practice. While fertilizer recommendations have been specifically developed to meet a single year of crop production following a soil sample, multiple year fertilization for corn and soybeans produced on soils testing in an optimum or higher range is a reasonable practice when combining the recommended rates for each crop in one application (Murdock and Schwab, 2010; Sawyer et al., 2011). The lack of documented yield response to fertilizer applications on high testing soils supports fertility management that consists of periodic fertilizer application to maintain optimal soil test levels. On high testing soils, extended intervals between maintenance fertilizer applications may be possible. Dodd and Mallarino (2005) found eight to nine years of non-fertilizer corn and soybean production could be conducted on high P testing soils before yield responses could be seen from fertilizer application.

Research evaluations comparing annual to biennial P and K fertilizer applications for corn and soybean have validated this interpretation of soil fertilizer recommendations. Buah et al. (2000) documented conflicting soybean yield results comparing annual and biennial P and K applications at eight site years on Iowa farmer fields, but recorded increased soybean yield from annual P applications compared to biennial in two of three years on research station plots testing optimum for P. McCallister et al. (1987) measured greater extractable P when applying P fertilizer annually rather than equivalent total applications made every two, three, or six years. Corn grain yields were not responsive to application frequency, but the authors do suggest that smaller, more frequent fertilizer applications lead to more plant available P. Randall et al. (2001) recorded soybean yield responses to residual starter and banded P fertilizers applied a year earlier prior to corn on a low P testing site in Minnesota, but not a high P test site. In Arkansas, Slaton et al. (2001) found that annual P applications increased soil test P compared to equal applications applied biennially preceding either soybean or rice.

Evaluating K fertilizer placement in ridge-till systems, Rehm and Lamb (2004) did not observe a soybean yield response when K was applied directly before the soybean crop or when K was applied prior to the corn crop preceding the soybean crop. In their work, all soil tested about 140 mg K kg^{-1}, a level at which would not be expected to respond to additional fertilizer K in Minnesota. Yin and Vyn (2002), measuring soybean response to K fertilizer applications made prior to the previous years' corn crop, observed yield responses in a medium K testing soil, but not in a medium to high testing soil. They concluded these results generally support the current model of soybean fertility recommendations and their applicability to no-till conditions, as well as the practice of applying sufficient fertilizer for both corn and soybean crops prior to corn on higher K testing fields.

Randall et al. (1997a) measured similar soil test P between triennial applications of 150 lb P_2O_5 ac^{-1} and 50 lb P_2O_5 ac^{-1} annual application in 10 out of 12 years in continuous corn for the first 8 years, followed by a corn /soybean rotation over the last four years in Minnesota. Triennial applications of 150 lb K_2O ac^{-1} maintained soil test K at similar levels to annual applications of 50 lb K_2O ac^{-1} over the same twelve year period at one site, but only in two of twelve years at a second site. Triennial application of P and K resulted in equal yields to annual application in seven of eight treatment years (Randall et al., 1997b). They found soybean yields to be nonresponsive to P or K fertilizer applications as long as soil test levels were maintained at a sufficiently high level. When soil test P and K declined, yields suffered due to P rather than K.

Recommendations for soils with P or K soil test values below the critical level include applications that account for crop removal as well as quantities to increase soil test levels to the sufficient range. In these situations, annual applications of fertilizer are advised (Vitosh et al., 1995). deMooy et al. (1973) recorded modest soybean grain responses to P and K fertilizer application on a low fertility site. Corn yields were more responsive, increasing at a higher rate with P and K fertilizer applications than soybean yields. A second cycle of fertilization after two years of crop production increased corn yield, particularly attributable to K fertilization. Soybean yield was similar between direct and residual P and K fertilization timing.

Research studies have demonstrated soybean yield responses when applying fertilizers above recommended levels. Gordon (2005) found on a Kansas site testing very high for K and low for P that recommended applications of 34 kg P_2O_5 ha^{-1} increased yield compared to the untreated control. Recommendations did not call for K fertilizer, but application of 67 kg K_2O ha^{-1} with 34 kg P_2O_5 ha^{-1} increased yield compared to P_2O_5 alone, and 90 kg P_2O_5 ha^{-1} with 67 kg K_2O ha^{-1} further increased yield

The objective of this study was to evaluate the practice of annual and biennial fertilizer applications in a corn-soybean rotation across a five-state area. These fertility programs are evaluated by corn and soybean grain yields and soil P and K levels following the second year of crop rotation. Our hypothesis is that separate application of P and K prior to corn and soybean will increase yield in comparison to combined applications.

Materials and Methods

Research trials were established at four sites in Minnesota, three sites each in Iowa, Arkansas and Louisiana, and two sites in Michigan in 2009 (Table 3.1). Experiments were established on sites with a history of corn-soybean rotations. Corn was established in 2009 for rotation to soybeans in 2010. A second rotation cycle was initiated in 2010 adjacent to existing plots; corn was planted in 2010 for rotation to soybean in 2011. Corn and soybean production was conducted following local cultural practices for tillage, row spacing, population and variety (Tables 3.2, 3.3, 3.4, 3.5).

Fertility treatments consisted of annual applications of P and K prior to corn in 2009 and soybeans in 2010 or biennial applications of P and K for both corn and soybeans applied preceding the corn crop. Fertilizer rates were determined from state specific fertilizer recommendations according to soil test values and applied at 1x and 2x rates in both annual and biennial practices (Tables 3.6, 3.7, 3.8, 3.9, 3.10). Soils testing below optimal or medium were fertilized with specific state recommended rates; crop removal rate combined with additional fertilizer to bring test levels to optimal ranges. Sites testing above the optimal or medium level were fertilized at crop removal rates. These treatments were compared to a control receiving no P or K fertilizer. Fertilizer treatments were broadcast and incorporated in the spring with mono-ammonium phosphate (10-52-0) and potassium chloride (0-0-62). Nitrogen management was conducted in accordance with local practices.

Fertility rates were determined for each site from the composite of 10-15 cores sampled to a 15 cm depth. All samples were analyzed in the originating state's University soil testing lab

Table 3.1. Soil characteristics at research sites.

Site	**Soil type**	**Soil series**	**pH**	**Initial P**[†]		**Initial K**	
				mg kg^{-1}			
Minnesota							
Delavan	Fostoria loam	Aquic Hapludolls	6.8	9	M[‡]	141	H
Lamberton	Ves loam	Calcic Hapludolls	5.5	24	VH	114	M
Morris	Tara silt loam	Aquic Hapludolls	7.9	6	L	150	H
St. Charles	Seaton silt loam	Typic Hapludolls	6.2	14	M	77	L
Iowa							
Lewis	Marshall silty clay loam	Typic Hapludolls	6.8	9	L	160	H
Sutherland	Sac silty clay loam	Oxyaquic Hapludolls	5.9	20	O	198	VH
Ames 2009-2010	Clarion loam	Typic Hapludolls	7.2	9	L	128	L
Ames 2010-2011	Canisteo silty clay loam	Typic Endoaquolls	7.2	11	O	82	VL
Michigan							
Ingham	Capac loam	Aquic Glossudalfs	6.3	37	AO	149	AO
Branch	Matherton loam	Typic Argiaquolls	6.5	25	O	136	AO
Arkansas							
Colt	Calhoun silt loam	Typic Glossaqualfs	6.3	15	L	100	M
Keiser	Sharkey silty clay	Chromic Epiaquerts	6.8	45	O	201	AO
Rohwer	Henery silt loam	Typic Fragiaqualfs	7.3	26	M	58	VL
Louisiana							
Baton Rouge	Commerce silt loam	Fluvaquentic Endoaquepts	6.6	29	M	136	L
St. Joseph	Commerce silt loam	Fluvaquentic Endoaquepts	6.6	51	H	239	H
Winnsboro	Gigger silt loam	Typic Fragiudalfs	6.3	31	M	115	L

Table 3.1. (cont'd).

†Minnesota soil test P determined by the Olson method at Delavan and Morris and with the Bray-P1 method at Lamberton and St Charles. Iowa and Michigan soil test P determined with the Bray-P1 method. Kentucky, Arkansas and Louisiana soil test P determined with the Mehlich 3 method..

‡Soil test ranges determined by state soil test labs. VL, very low; L, low; M, medium; O, optimum; H, high; VH, very high

Table 3.2. Corn agronomic practices, 2009.

Site	Tillage†	Row Space	Variety‡	Population	Planting Date	Harvest Date
		cm		plant ha^{-1}		
Minnesota						
Delavan	NT	76	G86X11 3000GT	88,900	7 May	12 Nov.
Lamberton	F: C; S: FC	76	DK 52-59	84,000	4 May	4 Nov.
Morris	F: C; S: FC	76	P37Y14	88,200	4 May	28 Oct.
St. Charles	F: C; S: FC	76	P37Y14	87,700	12 May	13 Nov.
Iowa						
Lewis	S: C, Dk	76	GH H8953CB/LL/RW	79,100	8 May	22 Oct.
Sutherland	S: Dk, FC	76	NK N40T-3000GT	88,000	21 Apr.	17 Oct.
Ames	S: FC	76	GH H8953CB/LL/RW	79,100	24 Apr.	28 Oct.
Michigan						
Ingham	S: FC (2x)	76	DK N40T-300 GT	79,100	26 May	Oct. 28
Branch	S: FC (2x)	76	DK N40T-300 GT	79,100	16 May	Oct. 22
Arkansas						
Colt	F: Dk, FC; S: FC	76	NK N77P-3000GT	68,000	5 June	4 Nov.
Keiser	F: Dk, HR (2x); S: HR	97	NK N77P-3000GT	69,200	5 June	4 Nov.
Rohwer	F: Dk, HR (2x); S: HR	97	NK N77P-3000GT	69,800	15 Apr.	28 Sept.
Louisiana						
Baton Rouge	S: Dk (2x)	97	NK N78N-3000GT	86,500	15 Apr.	14 Sept.
St. Joseph	F: HR; S: HR, Dg	102	NK N78N-3000GT	79,000	19 Mar.	27 Aug.
Winnsboro	F: HR; S: HR, Dg	76	DK 67-87	74,100	10 Mar.	11 Aug.

†S, Spring; F, Fall; NT, no-till; C, chisel plow; Dk, disk; FC, field cultivator; HR, hipper roller; Dg, drag; RH, reel and harrow
‡DK, Dekalb; GH, Golden Harvest; NK, Northrup King

Table 3.3. Corn agronomic practices, 2010.

Site	Tillage†	Row Space	Variety‡	Population	Planting Date	Harvest Date
		cm		plant ha^{-1}		
Minnesota						
Delavan	NT	76	G 85V88 3000GT	86,500	25 Apr.	21 Oct.
Lamberton	F: C; S: FC	76	DK 50-66	84,000	23 Apr.	12 Oct.
Morris	F: C; S: FC	76	DK46-60	88,200	4 May	11 Oct.
St. Charles	F: C; S: FC	76	P PX9990	87,700	23 Apr	19 Oct.
Iowa						
Lewis	S: C, Dk	76	P 33W84	84,000	4 May	2 Oct.
Sutherland	S: Dk, FC	76	A 6309 VT3	88,000	1 May	5 Oct.
Ames	S: FC (2x)	76	C 209-76r	79,100	22 Apr.	14 Oct.
Michigan						
Ingham	S: FC (2x)	76	DK 36-34	79,100	31 May	20 Oct.
Arkansas						
Colt	F: Dk, FC; S: FC	76	P 1745HR	76,600	22 Apr.	13 Sept.
Keiser	F: Dk, HR (2x); S: HR	76	P 1745HR	76,600	25 Apr.	20 Sept.
Rohwer	F: Dk, HR (2x); S: HR	76	P 1745HR	76,600	25 Apr.	8 Sept.
Louisiana						
Baton Rouge	S: Dk (2x)	97	NK 78N-3000GT	108,000	19 Apr.	20 Aug.
St. Joseph	F: HR; S: HR, Dg	102	NK 78N-GT/CB/LL	79,000	30 Mar.	16 Aug.
Winnsboro	F: HR; S: HR, Dg	102	P 31D59	86,400	15 Mar.	9 Sept.

†S, Spring; F, Fall; NT, no-till; C, chisel plow; Dk, disk; FC, field cultivator; HR, hipper roller; Dg, drag; RH, reel and harrow
‡A, Agrigold; C, ChannelBio; DK, Dekalb; NK, Northrup King; P, Pioneer

Table 3.4. Soybean agronomic practices, 2010.

Site	Tillage†	Row Space	Variety‡	Population	Planting Date	Harvest Date
		cm		plant ha^{-1}		
Minnesota						
Delavan	NT	76	NK S25-F2	370,500	5 May	7 Oct.
Lamberton	F: C; S: FC	76	A 2108	412,500	10 May	4 Oct
Morris	F: C; S: FC	76	P90M80	459,400	17 May	29 Sept.
St. Charles	F: C; S: FC	76	P92Y51	395,200	20 May	6 Oct.
Iowa						
Lewis	F: C; S: Dk, FC	76	P 92Y80	395,400	8 May	2 Oct.
Sutherland	F: C; S: Dk, FC	76	K 201 RR/SCN	395,400	17 May	27 Sept.
Ames	S: FC (2x)	76	P 92M61	395,400	24 May	7 Oct.
Michigan						
Ingham	S: FC (2x)	38	NK-S27-C4	345,900	31 May	8 Oct.
Branch	S: FC (2x)	38	NK-S27-C4	345,900	10 June	9 Oct.
Arkansas						
Colt	F: Dk, FC; S: FC	76	P 94Y90	345,900	21 May	6 Oct.
Keiser	F: Dk, HR (2x); S: HR	98	P 94Y90	345,900	23 May	20 Oct.
Rohwer	F: Dk, HR (2x); S: HR	97	P 94Y90	345,900	10 May	17 Sept.
Louisiana						
Baton Rouge	S: Dk (2x)	97	C RC4877	249,600	19 Apr.	20 Sept.
St. Joseph	F: HR; S: HR, Dg	102	DG 4870	258,200	3 May	13 Oct.
Winnsboro	F: HR; S: HR, Dg	102	P 95Y40	345,900	28 Apr.	7 Sept.

†S, Spring; F, Fall; NT, no-till; C, chisel plow; Dk, disk; FC, field cultivator; HR, hipper roller; Dg, drag; RH, reel and harrow
‡ C; Croplan; DG, Dyna-Gr o; K, Kruger; NK, Northrup King; P, Pioneer

Table 3.5. Soybean agronomic practices, 2011.

Site	Tillage†	Row Space	Variety‡	Population	Planting Date	Harvest Date
		cm		**plant ha^{-1}**		
Minnesota						
Delavan	NT	76	NK S25-F2	370,500	12 May	7 Oct.
Lamberton	F: C; S: FC	76	AG 1931 RR	412,500	4 June	5 Oct.
Morris	F: C; S: FC	76	P 90M80	459,400	6 June	5 Oct.
St. Charles	F: C; S: FC	76	P 92Y30	395,200	15 May	11 Oct.
Iowa						
Lewis	S: Dk, C	76	NK 2.7-CA	407,720	5 May	30 Oct.
Sutherland	F: C; S: FC	76	P 92M32	373,120	11 May	30 Sept.
Ames	S: Dk (2x)	76		345,940	19 May	10 Oct.
Michigan						
Ingham	F: C; S: FC	76	NK S27-C4	345,940	5 June	13 Oct.
Branch	F: C; S: FC (2x)	76	NK S27-C4	345,940	8 June	22 Oct.
Arkansas						
Colt	F: Dk, FC; S: FC, HR	76	P 94Y90	345,940	31 May	17 Oct.
Keiser	F: Dk, HR (2x); S: HR	97	P 94Y90	345,940	24 May	23 Oct.
Rohwer	F: Dk, HR (2x); S: HR	97	P 94Y90	345,940	20 May	17 Oct.
Louisiana						
Baton Rouge	S: Dk (2x)	97	RC 4877	249,570	21 Apr.	28 Sept.
St. Joseph	F: HR; S: HR, Dg	102	DG 4870	345,940	5 May	21 Sept.
Winnsboro	S: HR, Dg	102	AG 4630	345,940	8 Apr.	17 Sept.

†S, Spring; F, Fall; NT, no-till; C, chisel plow; Dk, disk; FC, field cultivator; HR, hipper roller; Dg, drag; RH, reel and harrow
‡AG, Asgrow; DG, Dyna-Gro; NK, Northrup King; P, Pioneer

Table 3.6. Minnesota fertilizer application rates.

Site	2009 Corn		2010 Soybean		2010 Corn		2011 Soybean	
	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O
	kg ha^{-1}							
Delavan								
Control	0	0	0	0	0	0	0	0
Annual 1x	78	78	45	56	78	78	45	56
Annual 2x	157	157	90	112	157	157	90	112
Biannual 1x	123	134	0	0	123	134	0	0
Biannual 2x	246	269	0	0	246	269	0	0
Lamberton								
Control	0	0	0	0	0	0	0	0
Annual 1x	78	78	56	78	78	78	56	78
Annual 2x	157	157	112	157	157	157	112	157
Biannual 1x	134	157	0	0	134	157	0	0
Biannual 2x	269	314	0	0	269	314	0	0
Morris								
Control	0	0	0	0	0	0	0	0
Annual 1x	78	78	56	78	78	78	56	78
Annual 2x	157	157	112	157	157	157	112	157
Biannual 1x	134	157	0	0	134	157	0	0
Biannual 2x	269	314	0	0	269	314	0	0
St Charles								
Control	0	0	0	0	0	0	0	0
Annual 1x	78	134	56	56	78	134	56	56
Annual 2x	157	269	112	112	157	269	112	112
Biannual 1x	134	190	0	0	134	190	0	0
Biannual 2x	269	381	0	0	269	381	0	0

Table 3.7. Iowa fertilizer application rates.

Site	2009 Corn		2010 Soybean		2010 Corn		2011 Soybean	
	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O
	kg ha^{-1}							
Ames								
Control	0	0	0	0	0	0	0	0
Annual 1x	94	59	67	84	94	59	67	84
Annual 2x	188	119	134	168	188	119	134	168
Biannual 1x	161	143	0	0	161	143	0	0
Biannual 2x	323	287	0	0	323	287	0	0
Lewis								
Control	0	0	0	0	0	0	0	0
Annual 1x	78	64	52	97	78	64	52	97
Annual 2x	157	128	103	195	157	128	103	195
Biannual 1x	130	161	0	0	130	161	0	0
Biannual 2x	260	323	0	0	260	323	0	0
Sutherland								
Control	0	0	0	0	0	0	0	0
Annual 1x	78	64	52	97	78	64	52	97
Annual 2x	157	128	103	195	157	128	103	195
Biannual 1x	130	161	0	0	130	161	0	0
Biannual 2x	260	323	0	0	260	323	0	0

Table 3.8. Michigan and Kentucky fertilizer application rates.

Site	2009 Corn		2010 Soybean		2010 Corn		2011 Soybean	
	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O
	kg ha^{-1}							
Branch								
Control	0	0	0	0	0	0	0	0
Annual 1x	75	55	45	101	75	55	45	101
Annual 2x	150	110	90	202	150	110	90	202
Biannual 1x	120	156	0	0	120	156	0	0
Biannual 2x	240	311	0	0	240	311	0	0
Ingham								
Control	0	0	0	0	0	0	0	0
Annual 1x	75	55	45	101	75	55	45	101
Annual 2x	150	110	90	202	150	110	90	202
Biannual 1x	120	156	0	0	120	156	0	0
Biannual 2x	240	311	0	0	240	311	0	0
Hopkinsville								
Control	0	0	0	0	0	0	0	0
Annual 1x	76	67	39	62	76	67	39	62
Annual 2x	152	134	78	123	152	134	78	123
Biannual 1x	115	129	0	0	115	129	0	0
Biannual 2x	231	258	0	0	231	258	0	0

Table 3.9. Arkansas fertilizer application rates.

Site	2009 Corn P_2O_5	2009 Corn K_2O	2010 Soybean P_2O_5	2010 Soybean K_2O	2010 Corn P_2O_5	2010 Corn K_2O	2011 Soybean P_2O_5	2011 Soybean K_2O
	kg ha^{-1}							
Colt								
Control	0	0	0	0	0	0	0	0
Annual 1x	78	78	45	56	78	78	45	56
Annual 2x	157	157	90	112	157	157	90	112
Biannual 1x	123	134	0	0	123	134	0	0
Biannual 2x	246	269	0	0	246	269	0	0
Keiser								
Control	0	0	0	0	0	0	0	0
Annual 1x	78	45	45	62	78	45	45	62
Annual 2x	157	90	90	123	157	90	90	123
Biannual 1x	123	106	0	0	123	106	0	0
Biannual 2x	246	213	0	0	246	213	0	0
Rowher								
Control	0	0	0	0	0	0	0	0
Annual 1x	90	179	67	179	90	179	67	179
Annual 2x	179	358	134	358	179	358	134	358
Biannual 1x	157	358	0	0	157	358	0	0
Biannual 2x	314	717	0	0	314	717	0	0

Table 3.10. Louisiana fertilizer application rates.

Site	2009 Corn		2010 Soybean		2010 Corn		2011 Soybean	
	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O	P_2O_5	K_2O
	kg ha^{-1}							
Baton Rouge								
Control	0	0	0	0	0	0	0	0
Annual 1x	45	67	34	67	45	67	34	67
Annual 2x	90	134	67	134	90	134	67	134
Biannual 1x	78	134	0	0	78	134	0	0
Biannual 2x	157	269	0	0	157	269	0	0
St Joseph								
Control	0	0	0	0	0	0	0	0
Annual 1x	67	67	56	87	67	67	56	87
Annual 2x	134	134	112	175	134	134	112	175
Biannual 1x	101	101	0	0	101	101	0	0
Biannual 2x	202	202	0	0	202	202	0	0
Winnsboro								
Control	0	0	0	0	0	0	0	0
Annual 1x	45	45	45	90	45	45	45	90
Annual 2x	90	90	90	179	90	90	90	179
Biannual 1x	90	90	0	0	90	90	0	0
Biannual 2x	179	179	0	0	179	179	0	0

following standard soil testing procedures. Phosphorus analysis was determined in Minnesota with the Olson method (Frank et al., 1998) at sites with pH levels of 6.8 and greater, the Bray-P_1 method (Frank et al., 1998) at sites with pH below 6.8, in Iowa and Michigan with the Bray-P_1 method, and Arkansas and Louisiana with the Mehlich 3 method (Mehlich, 1984). Potassium analysis was determined by ammonium acetate extraction (Warncke and Brown, 1998) in Minnesota, Iowa and Michigan and by Mehlich 3 in Arkansas, and Louisiana. Soils were categorized as to relative P and K test levels according to state fertilizer recommendations for Minnesota (Rehm et al., 2006), Iowa (Sawyer et al., 2011), Michigan (Vitosh et al., 1995), and Arkansas (Espinoza et al., 2012) (Table 3.11). Categorization of soil test ranges varies by state, both the number and names of categories and the degree to which additional soil information is utilized. Soil texture, cation exchange capacity, subsoil nutrient concentrations and irrigation supplementation may factor into soil test range classification. A commonality between all state classifications is the delineation between sub-optimal, optimal, and above optimal test levels. Sub-optimal ranges include very low and low in Minnesota, Iowa and Louisiana; below optimal in Michigan; and very low, low, and medium in Arkansas. Optimal ranges include medium in Minnesota and Louisiana and optimal in Iowa, Michigan and Arkansas. Above optimal soil test ranges include high and very high in Minnesota and Iowa, above optimal in Michigan and Arkansas, and high in Louisiana. These three ranges, sub-optimal, optimal, and above optimal, are used for delineation of individual sites in this study (Table 3.12).

Plot width varied between 3.9 and 7.8m and ranged from 9.1 and 12.2m in length. Soybean grain yields were obtained by machine from plot centers and adjusted to 130 g kg^{-1} H_2O. Corn grain yields were obtained by either hand or machine harvest and adjusted to 150 g kg^{-1} H_2O.

Table 3.11. State soil test ranges classified by sub-optimal, optimal, and above optimal levels.

Site	Soil test range		
	Sub-optimal	**Optimal**	**Above optimal**
Minnesota	Very low, low	Medium	High, very high
Iowa	Very low, low	Optimum	High, very high
Michigan	Below optimum	Optimum	Above optimum
Arkansas	Very low, low, medium	Optimum	Above optimum
Louisiana	Very low, low	Medium	High

Table 3.12. Site soil test levels.

Site	P range	K range
Ames 2009-2010, Colt, Rohwer	Sub-optimal	Sub-optimal
none	Sub-optimal	Optimal
Lewis, Morris	Sub-optimal	Above optimal
Ames 2010-2011, Baton Rouge, St. Charles, Winnsboro	Optimal	Sub-optimal
none	Optimal	Optimal
Branch, Delavan, Keiser, Sutherland	Optimal	Above optimal
none	Above optimal	Sub-optimal
Lamberton, St. Joseph	Above optimal	Optimal
Ingham	Above optimal	Above optimal

Data were analyzed with SAS statistical software (SAS Institute, Cary, NC). Analysis of variance was performed using PROC MIXED. Coefficient of variance was determined using PROC GLM. Treatment means are considered statistically different at the $P \leq 0.10$ level.

Results

Ames 2009-2010, Colt, and Rowher sites were in the sub-optimal range for soil P and K. At Ames 2009-2010, corn grain yield was increased in 2009 by all fertilizer treatments (Table 3.13). The annual and biennial 1x rates resulted in greater yield than the 2x biennial treatment. Corn grain yield in 2010 was increased at Colt by 1x annual and 2x biennial fertilizer treatments compared to the control and 1x biennial treatments. Corn yield in 2009 was not influenced by fertilizer treatments. At Rowher, the 2x biennial fertilizer treatment reduced 2010 corn grain yield compared to the control. Yield for all other fertilizer treatments were similar to the control. No differences in corn grain yield were observed in 2009. Soybean grain yield was increased by annual 2x and biennial 1x fertilizer applications compared to the biennial 2x and control treatments at Ames in 2009. Soybean grain yield was not affected by fertilizer applications in 2010 or 2011 at Colt and Rohwer locations. At Colt following the 2010-2011 rotation, soil test P and K were increased with biennial 2x application compared to all other treatments (Table 3.14). Following the 2010-2011 rotation at Rowher, all fertilizer treatments increased soil test K compared to the control. Fertilizer rates at the 2x rate increased soil test K compared to 1x rates.

Sub-optimal P and above optimal K levels were present at Lewis and Morris locations. All fertilizer treatments resulted in similar increases in corn grain yield compared to the control at Lewis in 2009 (Table 3.15). No differences in corn grain yield were observed at Lewis in 2010 or at Morris in 2009 or 2010. Soybean grain yield was not affected by fertilizer treatment at either site. No differences in soil test P or K levels were noted at either site following 2009-2010 or 2010-2011 crop rotations (Table 3.16).

Table 3.13. Corn and soybean grain yield by fertilizer treatments at sites with sub-optimal P and sub-optimal K.

Crop rotation	Control	Annual 1x	Annual 2x	Biennial 1x	Biennial 2x	*P > F*	CV
	Mg ha^{-1}						
Ames							
2009 Corn	10.39c†	12.89a	12.29ab	12.91a	11.54b	0.0026	6.37
2010 Soybean	3.62b	4.00ab	4.03a	4.02a	3.80b	0.0132	4.11
Colt							
2009 Corn	7.32	7.98	7.51	7.53	6.90	0.9090	21.44
2010 Soybean	2.62	2.56	2.49	2.26	2.43	0.6031	13.16
2010 Corn	5.32b	6.29a	5.80ab	5.28b	6.04a	0.0856	10.51
2011 Soybean	3.80	3.83	3.78	4.10	4.03	0.2233	5.77
Rohwer							
2009 Corn	12.73	11.79	11.87	12.27	11.81	0.7851	11.45
2010 Soybean	2.95	3.05	3.31	3.11	3.02	0.4121	8.66
2010 Corn	9.38a	9.10a	8.82ab	9.36a	8.50b	0.0293	4.55
2011 Soybean	2.28	2.38	2.21	2.11	2.28	0.3412	8.10

†Letters following numbers within a row represent differences between treatments at the $P \leq 0.10$ level.

Table 3.14. Corn and soybean grain yield by fertilizer treatments at sites with sub-optimal P and sub-optimal K.

Crop rotation	Control	Annual 1x	Annual 2x	Biennial 1x	Biennial 2x	*P > F*	CV
	Mg ha^{-1}						
Ames							
2009 Corn	10.39c[†]	12.89a	12.29ab	12.91a	11.54b	0.0026	6.37
2010 Soybean	3.62b	4.00ab	4.03a	4.02a	3.80b	0.0132	4.11
Colt							
2009 Corn	7.32	7.98	7.51	7.53	6.90	0.9090	21.44
2010 Soybean	2.62	2.56	2.49	2.26	2.43	0.6031	13.16
2010 Corn	5.32b	6.29a	5.80ab	5.28b	6.04a	0.0856	10.51
2011 Soybean	3.80	3.83	3.78	4.10	4.03	0.2233	5.77
Rohwer							
2009 Corn	12.73	11.79	11.87	12.27	11.81	0.7851	11.45
2010 Soybean	2.95	3.05	3.31	3.11	3.02	0.4121	8.66
2010 Corn	9.38a	9.10a	8.82ab	9.36a	8.50b	0.0293	4.55
2011 Soybean	2.28	2.38	2.21	2.11	2.28	0.3412	8.10

[†]Letters following numbers within a row represent differences between treatments at the $P \leq 0.10$ level.

Table 3.15. Corn and soybean grain yield by fertilizer treatments at sites with sub-optimal P and above optimal K.

Crop rotation	**Control**	**Annual 1x**	**Annual 2x**	**Biennial 1x**	**Biennial 2x**	***P > F***	**CV**
	Mg ha^{-1}						
Lewis							
2009 Corn	11.88b†	13.78a	13.98a	14.06a	14.52a	0.0014	5.02
2010 Soybean	4.07	4.19	4.03	4.27	4.18	0.4448	4.61
2010 Corn	13.30	13.19	13.52	12.98	12.91	0.7904	5.76
2011 Soybean	4.32	4.16	4.41	4.46	4.32	0.1176	3.10
Morris							
2009 Corn	9.73	10.41	10.83	10.51	11.26	0.4766	11.38
2010 Soybean	3.01	3.16	2.98	3.14	3.06	0.7899	7.74
2010 Corn	14.77	14.91	14.97	14.81	15.14	0.7201	2.69
2011 Soybean	2.34	3.21	2.68	2.92	2.82	0.3405	20.48

†Letters following numbers within a row represent differences between treatments at the P≤ 0.10 level.

Table 3.16. Soil test P and K by fertilizer treatments at sites with sub-optimal P and above optimal K.

Crop rotation	Control	Annual 1x	Annual 2x	Biennial 1x	Biennial 2x	*P > F*	CV
	Mg ha^{-1}						
Lewis							
2010-2011 P	28	39	40	32	27	0.5467	45.58
2010-2011 K	196	252	213	240	195	0.1098	14.47
Morris							
2009-2010 P	7	9	6	5	4	0.4408	58.29
2009-2010 K	156	157	152	152	144	0.9076	14.56
2010-2011 P	9	11	10	9	9	0.8148	27.63
2010-2011 K	165	170	164	169	166	0.8985	6.65

At four sites, Ames 2010-2011, Baton Rouge, St. Charles, and Winnsboro, soil tests were in the optimal range for P and sub-optimal range for K. At Baton Rouge in 2009, all fertilizer treatments resulted in higher corn yield compared to the control (Table 3.17). Yields were greater for biennial 1x and 2x treatments compared to the annual 2x treatment. No differences in corn grain yield were observed at other sites. In 2010 at Baton Rouge, soybean grain yields were lower with annual 2x and biennial 2x treatments compared to the control (Table 3.18). Soybean grain yield did not differ between fertilizer treatments at other sites. At Baton Rouge, soil test P levels following the 2010-2011 crop rotation were highest with the biennial 2x treatment compared to all other treatments. Soil test P levels were greater with annual 1x, annual 2x, and biennual 1x treatments compared to the control. Soil test P and K following the 2009-2010 rotation and soil test K following the 2010-2011 rotation did not differ by fertilizer treatment at Baton Rouge. At Ames 2010-2011 and St. Charles, no differences in soil test P and K were observed.

Branch, Delavan, Keiser, and Sutherland sites tested in the optimal range for P and above medium in K. Corn grain yield was increased by any fertilizer application at Branch 2009, Delavan in 2010 and Sutherland in 2010 (Table 3.19). All fertilizer applications at Branch in 2009 and Delavan in 2010 resulted in higher corn grain yield compared to the untreated control. At Sutherland in 2010, fertilizer application of any kind increased corn yield above that of the control, but yield was lower for the biennial 1x treatment compared to other fertilizer treatments. Corn grain yield at Delevan in 2009, Keiser in 2009 and 2010, and Sutherland in 2009 was not influenced by fertilizer application. At Branch following the 2009-2010 rotation, all treatments

Table 3.17. Corn and soybean grain yield by fertilizer treatments at sites with optimal P and sub-optimal K.

Crop rotation	Control	Annual 1x	Annual 2x	Biennial 1x	Biennial 2x	*P > F*	CV
	Mg ha^{-1}						
Ames							
2010 Corn	12.31	12.38	13.17	13.13	13.73	0.1405	6.94
2011 Soybean	3.48	3.83	3.62	3.73	3.86	0.9278	20.26
Baton Rouge							
2009 Corn	3.56c†	4.73ab	4.45b	5.12a	5.20a	0.0068	11.67
2010 Soybean	4.32ab	3.94bc	3.76c	4.36a	3.71c	0.0752	9.68
2010 Corn	6.33	8.57	8.62	7.92	8.12	0.1693	12.46
2011 Soybean	2.74	2.58	2.88	2.68	2.58	0.7907	14.47
St. Charles							
2009 Corn	12.10	13.29	12.52	13.02	13.11	0.1372	4.61
2010 Soybean	3.36	3.48	3.61	3.16	3.51	0.4408	10.07
2010 Corn	12.76	12.52	13.19	12.80	12.58	0.8802	7.70
2011 Soybean	3.32	3.28	3.47	3.34	3.26	0.6177	5.78
Winnsboro							
2009 Corn	11.23	11.26	11.44	11.48	10.86	0.9181	9.29
2010 Soybean	4.10	4.03	4.43	4.57	4.63	0.2777	10.36
2010 Corn	10.76	10.41	10.95	11.13	10.68	0.4588	5.70
2011 Soybean	2.06	1.23	2.15	1.87	1.66	0.1494	28.56

†Letters following numbers within a row represent differences between treatments at the $P \leq 0.10$ level.

Table 3.18. Soil test P and K by fertilizer treatments at sites with optimal P and sub-optimal K.

Crop rotation	**Control**	**Annual 1x**	**Annual 2x**	**Biennial 1x**	**Biennial 2x**	***P > F***	**CV**
			Mg ha^{-1}				
Ames							
2010-2011 P	16	20	27	21	34	0.2086	49.28
2010-2011 K	143	58	176	167	199	0.1097	17.28
Baton Rouge							
2009-2010 P	54	56	53	48	54	0.2606	9.62
2009-2010 K	230	244	222	215	228	0.1250	6.59
2010-2011 P	47c†	52b	54b	53b	59a	0.0033	6.39
2010-2011 K	229	230	230	216	234	0.6141	7.73
St. Charles							
2009-2010 P	6	6	6	6	7	0.9577	41.25
2009-2010 K	72	79	77	73	71	0.5816	10.71
2010-2011 P	5	6	5	5	6	0.4382	29.68
2010-2011 K	78	71	70	79	74	0.4112	10.17

†Letters following numbers within a row represent differences between treatments at the P≤ 0.10 level.

Table 3.19. Corn and soybean grain yield by fertilizer treatments at sites with optimal P and above optimal K.

Crop rotation	Control	Annual 1x	Annual 2x	Biennial 1x	Biennial 2x	*P > F*	CV
	Mg ha^{-1}						
Branch							
2009 Corn	5.36b†	6.86a	6.99a	7.01a	7.21a	0.0013	7.46
2010 Soybean	2.70	2.78	2.86	2.83	2.89	0.9775	16.26
2011 Soybean	0.94	0.86	1.06	1.04	0.95	0.6076	20.43
Delavan							
2009 Corn	12.50	13.59	13.45	14.05	13.66	0.3965	8.11
2010 Soybean	2.72	2.73	2.97	3.00	2.94	0.5463	10.68
2010 Corn	9.79b	12.16a	12.82a	11.82a	12.34a	0.0019	6.91
2011 Soybean	2.39b	3.04a	3.11a	3.05a	3.12a	0.0159	9.69
Keiser							
2009 Corn	10.04	10.72	9.98	10.13	10.16	0.6352	7.46
2010 Soybean	3.80	3.76	3.71	3.79	3.76	0.9902	7.79
2010 Corn	10.73	10.71	10.43	11.00	10.63	0.4529	3.91
2011 Soybean	4.31	4.32	4.40	4.37	4.51	0.4181	3.53
Sutherland							
2009 Corn	13.60	14.27	14.30	14.46	14.41	0.3242	4.51
2010 Soybean	4.65	4.60	4.66	4.82	4.63	0.5157	3.67
2010 Corn	12.61c	13.72a	13.90a	13.20b	13.46a	0.0032	2.79
2011 Soybean	3.74	3.94	3.93	4.04	3.96	0.1382	3.90

†Letters following numbers within a row represent differences between treatments at the $P \leq 0.10$ level.

except that biennial 1x treatment increased soil test K compared to the control (Table 3.20). Soil test K was increased at Branch for 2x rate treatments compared to 1x treatments. Soil test K following the 2010-2011 rotation and soil test P following the 2009-2010 and 2010-2011 crop rotations did not differ by fertilizer treatment. At Delavan, soil test P and K following 2009-2010 and 2010-2011 rotations were not affected by fertilizer treatment. No differences in soil test P or K were observed following the 2010-2011 crop rotation at Keiser. Following the 2010-2011 crop rotation at Sutherland, all fertilizer treatments increased soil test P compared to the control. All fertilizer treatments except the biennial 1x treatment increased soil test K compared to the control. Soil test P and K was greater for 2x rate treatments compared to 1x rate treatments.

Lamberton and St. Joseph sites tested in the optimal range for soil P and K. Fertilizer application had no effect on corn or soybean grain yield at Lamberton and St. Joseph (Table 3.21). At Lamberton, no differences in soil test P or K levels following 2009-2010 and 2010-2011 crop rotations were observed (Table 3.22). At St. Joseph following the 2010-2011 crop rotation, the annual 2x fertilizer application resulted in greater soil test P compared to other fertilizer treatments and the control. No differences between soil test K values were noted.

Initial soil test levels at one site, Ingham, tested in the above optimal range for both P and K. At this site, fertilizer application did not influence corn or soybean grain yield (Table 3.23). Annual fertilizer application at the 2x rate increased soil test P following the 2010-2011 rotation compared to all other treatments (Table 3.24). No differences were observed in soil test P

Table 3.20. Soil test P and K by fertilizer treatments at sites with optimal P and above optimal K.

Crop rotation	Control	Annual 1x	Annual 2x	Biennial 1x	Biennial 2x	*P > F*	CV
	Mg ha^{-1}						
Branch							
2009-2010 P	69	68	70	69	69	0.1238	0.85
2009-2010 K	16c†	28b	42a	21c	40a	<0.0001	18.30
2010-2011 P	42	33	54	36	24	0.2943	48.33
2010-2011 K	117	89	126	115	77	0.3497	36.15
Delavan							
2009-2010 P	7	9	10	9	11	0.9223	67.03
2009-2010 K	141	149	148	138	131	0.4673	10.68
2010-2011 P	4	4	8	5	5	0.3789	63.46
2010-2011 K	135	136	133	124	130	0.7199	10.28
Keiser							
2010-2011 P	48	56	54	56	57	0.4226	13.19
2010-2011 K	337	341	338	341	341	0.9981	6.77
Sutherland							
2010-2011 P	17d	28bc	43a	23c	34ab	<0.0001	16.27
2010-2011 K	188d	218bc	241a	200cd	222b	0.0019	7.15

†Letters following numbers within a row represent differences between treatments at the P≤ 0.10 level.

Table 3.21. Corn and soybean grain yield by fertilizer treatments at sites with above optimal P and optimal K.

Crop rotation	Control	Annual 1x	Annual 2x	Biennial 1x	Biennial 2x	*P* > *F*	CV
	Mg ha^{-1}						
Lamberton							
2009 Corn	8.22	8.84	10.31	10.33	9.23	0.3951	20.14
2010 Soybean	3.45	3.64	3.73	3.63	3.48	0.3221	5.74
2010 Corn	11.82	13.00	12.81	12.33	12.99	0.2422	6.40
2011 Soybean	2.89	3.30	3.20	3.15	3.18	0.1348	6.68
St. Joseph							
2009 Corn	11.49	11.35	11.06	11.16	11.41	0.6394	3.67
2010 Soybean	3.58	3.89	3.84	3.80	3.79	0.6005	3.63
2010 Corn	10.29	10.19	10.71	10.53	10.39	0.4447	3.90
2011 Soybean	3.74	3.63	3.52	3.67	3.76	0.1003	3.38

Table 3.22. Soil test P and K by fertilizer treatments at sites with above optimal P and optimal K.

Crop rotation	Control	Annual 1x	Annual 2x	Biennial 1x	Biennial 2x	*P > F*	CV
	Mg ha^{-1}						
Lamberton							
2009-2010 P	12	12	11	10	12	0.9423	31.29
2009-2010 K	111	107	111	115	121	0.7398	14.10
2010-2011 P	6	8	7	7	6	0.2872	15.99
2010-2011 K	104	111	104	106	110	0.3129	5.40
St. Joseph							
2010-2011 P	43b[†]	49b	61a	47b	49b	0.0067	10.57
2010-2011 K	172b	189b	211a	174b	180b	0.0446	9.18

[†]Letters following numbers within a row represent differences between treatments at the P≤ 0.10 level.

Table 3.23. Corn and soybean grain yield by fertilizer treatments at sites with above optimal P and above optimal K.

Crop rotation	Control	Annual 1x	Annual 2x	Biennial 1x	Biennial 2x	*P > F*	CV
	Mg ha^{-1}						
Ingham							
2009 Corn	9.58	9.60	9.68	9.61	10.23	0.9249	12.86
2010 Soybean	2.92	2.90	3.10	3.01	3.04	0.6311	7.05
2010 Corn	9.78	9.65	9.07	9.63	9.88	0.2297	5.01
2011 Soybean	2.81	2.66	2.66	2.70	2.73	0.1842	3.47

Table 3.24. Soil test P and K by fertilizer treatments at sites with above optimal P and above optimal K.

Crop rotation	**Control**	**Annual 1x**	**Annual 2x**	**Biennial 1x**	**Biennial 2x**	***P > F***	**CV**
	Mg ha^{-1}						
Ingham							
2009-2010 P	67	67	67	66	67	0.7257	1.71
2009-2010 K	64	69	90	78	89	0.1411	21.42
2010-2011 P	63b†	69b	80a	59b	66b	0.0415	12.54
2010-2011 K	209	222	238	207	236	0.2243	10.17

†Letters following numbers within a row represent differences between treatments at the P≤ 0.10 level.

following the 2009-2010 crop rotation or soil test K following the 2009-2010 and 2010-2011 crop rotations.

Discussion

Of the seven sites with soil test P and K values at least in the optimal range, corn grain yield was increased by fertilizer application only at Branch in 2009, Sutherland in 2010 and Delavan in 2010. Soybean grain yield was increased with fertilizer treatment at Delavan in 2010. While soils testing at or above the optimal range exceed the critical point and thus may be expected to supply adequate nutrients to support optimal economic growth (Vitosh et al., 1995), variability in soil test values and crop response make yield increases in this range expected with some frequency. Iowa fertilizer recommendations cite the probability of yield responses as 80% on very low testing sites, 65% on low testing, 25% on optimal soils, 5% for soils in the high range and less than 1% in the very high range (Sawyer et al., 2011). Bruulsema (2004) notes that in Ontario, corn and soybean have been documented to have a 59% and 49%, respectively, probability of response to fertilizer applications on soils testing in the medium soil test level. Results from this trial generally agree with these response frequencies and are in line with what others have observed in research studies. Mallarino et al. (2011) observed corn grain responses to broadcast P and K fertilizer treatments at sites five sites with soil test P and K testing at optimal levels or below. The only site they found to be unresponsive to preplant broadcast fertilizer application tested in the very high range for soil P and medium for soil K. In our study, sites with soil test levels in the sub-optimal range for a least one nutrient demonstrated a response on corn grain yield at five of sixteen site years. Bordoli and Mallarino (1998) observed frequent corn grain yield responses to P fertilizer on low testing sites in Iowa, but not every low testing site responded to fertilizer application. Soybean grain yields were increased with fertilizer application at two of these sixteen site years. These responses are less than those predicted in the Iowa Fertilizer recommendations, but following the trend illustrated by Bruulsema (2004) of an increased frequency of fertilizer response in corn compared to soybean.

Increases in corn grain yield with fertilizer application were variable. At Branch in 2009, Delavan in 2010 and Lewis in 2009, all fertilizer treatments resulted in a similar increase in yield. At Baton Rouge in 2009, yield generally increased with increasing fertilizer rate. This was contrasted by high fertilizer rates detrimentally effecting yield at Ames in 2009 and Rowher in 2010. At these locations, the biennial 2x treatment had lower yields than other fertilizer treatments. At Rowher, yield from the untreated control surpassed the biennial 2x treatment, indicating a yield reducing effect of fertilizer application rather than a simple lack of response. Fertilizer applications have been associated with reductions in crop growth and yield. Generally, these responses have been attributed to proximity of fertilizer and seed, though broadcast treatments have been occasionally associated with these effects. Anghinoni and Barber (1980) measured decreasing corn root length with increasing P rate in pots. Heckman and Kamprath (1992) observed decreased early season corn growth and K accumulation with increased broadcast K rates through, a phenomenon they attributed to high salt concentrations. Numerous site years of phosphorus and potassium rate studies in Arkansas have generally observed a lack of response on high testing soils, response to rate on low testing sites, and agreement with established fertilizer recommendations. Muir and Hedge (2001) measured corn yield reductions when increasing fertilizer rate from 101 kg K_2O ha^{-1}, the recommended rate, to 202 kg K_2O ha^{-1}, on both a low and a high K testing site.

Yield responses at several sites failed to follow patterns that could be directly correlated to fertilizer rate. At Colt in 2010 and Sutherland in 2010, yield among the fertilizer treatments was lowest for the 1x biennial treatment compared to other fertilizer treatments. Fertilizer rates for this treatment were neither the lowest nor highest, precluding high fertilizer rate injury as an explanation. The occurrence of this trend at three sites in different production regions suggests more than a statistical anomaly or protocol errors. Soil test values following soybean did not differ between fertilizer treatments at Branch. At Colt, soil test P and K were increased by biennial 2x applications compared to all other treatments. While fertilizer applications at 2x rates would be expected to increase soil test values compared to 1x rates, this effect would be expected to be more pronounced when fertilizer applications were made closer in time to soil sampling. The lack of expected increase in soil test P and K levels, particularly the lack of differences in the annual 1x from the annual 2x that would provide an explanation for differences in yield between these two treatments. At Sutherland in 2010, corn grain yield was maximized with annual 1x, annual 2x, and biennial 2x fertilizer treatments. Grain yield for the biennial 1x treatment was greater than the control, but lagged behind these other treatments. Increases in both soil test P and K following the 2010-2011 crop rotation generally followed the same pattern of increase as corn grain yield. Initial soil test K levels were in the high range and tested in this same range in 2011. Initial soil test P values were initially in the low range, but fertilizer treatments with the highest corn yields in 2010 had soil test P level in the high range when tested following the two year rotation, medium test values for the 1x biennial treatment that was associated with lower corn yield in 2001, and low soil test values for the control. These trends in soil test results seem to explain 2010 corn grain results, but the low yielding biennial 1x treatment received medium amounts of P and K fertilizer in comparison to other treatments.

Examples of decreased yield at medium fertilizer rates have been observed by other researchers as well. Muir and Hedge (2002) noted reduced corn grain yield with a 78 kg P_2O_5 ha^{-1} application compared to 39 kg P_2O_5 ha^{-1}, 157 kg P_2O_5 ha^{-1} and an untreated control at one site. Mozaffari et at. (2011) observed significant corn yield increases with 224 kg K_2O ha^{-1} compared to the control at a low K testing site, though a 179 kg K_2O ha^{-1} rate decreased yield compared to the control. At two medium K testing sites, yield responses were not statistically significant, but a similar trend of decreased yield with a 179 kg K_2O ha^{-1} application was apparent.

Soybean yield responses from fertilizer application were observed at three sites: Ames in 2010 with sub-optimal P and K, Baton Rouge in 2010 with optimal P and sub-optimal K, and Delavan in 2011 with optimal P and above optimal K. All fertilizer applications resulted in similar yields at Delavan. Fertilizer applications at Ames 2009-2010 and Baton Rouge did not always result in yield increases. At Ames 2009-2010, yield was increased by annual 2x and biennial 1x treatments compared to the control, but yield from annual 1x and biennial 2x treatments were similar to the control. At Baton Rouge, annual 2x and biennial 2x fertilizer treatments resulted in yield reductions compared to the control. Instances of yield reduction from high rates of broadcast fertilizer are not commonly observed, but have been noted to occur from both P and K applications. Ebelhar and Varsa's (2000) documented greater soybean yield at 56 kg K ha^{-1} than at higher K fertilizer rates, suggesting sensitivity to salt concentrations impacted yield. Farmaha et al. (2011) saw decreasing soybean yields with increasing K application in no-till systems but were unable to identify a definitive cause. They pointed to Ebelhar and Varsa's postulation of salt injury as a likely explanation. In Arkansas, Slaton et al. (2008) observed a slight decrease in soybean yield with 179 kg K_2O ha^{-1} compared to 90 kg K_2O ha^{-1}. Slaton et al. (2000) observed decreased soybean yield with 134 kg P_2O_5 ha^{-1} compared to 90 kg P_2O_5 ha^{-1} applied annually in a soybean-rice rotation. While maximum P and K rates at Baton Rouge were less than those applied at other sites, salt injury from high rates of broadcast applied fertilizer appear to have negatively impacted yield.

Soybean yield was influenced by the timing of fertilizer application in the rotations at two of thirty two site years of soybean. At Baton Rouge in 2010, the biennial 1x treatment resulted in greater yield than the 1x annual treatment. Both annual and biennial 2x fertilizer treatments resulted in lower yield compared to the control. It is possible that the difference in yield between the 1x annual and 1x biennial occurred due to a greater time interval between fertilizer application and soybean production in the biennial fertilizer treatment. At Ames in 2010, no differences were observed when comparing annual 1x and biennial 1x application, but annual 2x applications resulted in higher yield compared to biennial 2x.

Soil test levels following each crop rotation did not consistently differ between treatments. When responses in soil test P or K were observed, treatments did not tend to have consistent effects. At Branch following the 2009-2010 rotation, Sutherland following the 2010-2011 rotation, and Rowher following the 2010-2011 rotation soil test K levels were increased with 2x application rates compared to 1x rates. At all three sites, corn yield increases were documented in the first year of the rotation. Soil K levels in control treatments at both Branch and Rowher tested in the sub-optimal range, suggesting K levels could be limiting yields. While 2x application rates resulted in higher soil test K levels than 1x rates, these increased levels were still below the critical level at both sites. Soil test K levels at Sutherland were initially characterized as very high and continued to test in this range following thing 2010-2011 crop rotation.

The effects of fertilizer application timing were not consistent when increases in soil test P or K were observed. Soil test P levels at Ingham following the 2010-2011 rotation, soil test K levels at Sutherland following the 2010-2011 rotation, and soil test P and K levels at St Joseph following the 2010-2011 rotation were increased by the annual 2x treatment compared to all other treatments. In contrast, biennial 2x fertilizer applications resulted in the highest soil test P and K at Colt following the 2010-2011 rotation and soil test P following the 2010-2011 rotation at Baton Rouge. Treatment effects on corn grain yield were only observed at the Sutherland and Colt sites. At both sites, biennial 1x application resulted in the lowest yield of all fertilizer treatments. Soil test value responses to fertilizer applications were not consistently increased, but when observed, increases from annual applications appear to be more associated with greater corn grain yields than when soil test values were increased with biennial applications.

Conclusion

Corn grain yields were increased by fertilizer application at four of twelve site years at sites with initial soil test P and K levels in the medium or greater range. At sites where initial soil test values were below the optimal range for at least one nutrient, corn grain yield response to fertilizer application was observed at five of eighteen site years. Yield response to fertilizer rate was variable. While P and K fertilizer applied at any rate increased yield compared to the control at some sites, increasing fertilizer rate resulted in reduced yield at others. Soybean grain yield was increased by P and K fertilization at three of 32 site years, occurring only on sites with medium or lower initial soil test P and K values. At one site, all fertilizer applications resulted in similar yield increases compared to the control, but at two other sites, increasing fertilizer rates were associated with yield reductions. Results of this study indicate that fertilizer applications at rates in excess of current university fertilizer recommendations at best result in no increase in corn or soybean grain yield and at worst result in yield reductions. Soybean demonstrated infrequent yield responses to fertilizer application at medium or low soil test sites, with the clear trend favoring annual P and K fertilizer applications compared to biennial applications. These results justify the use of a corn and soybean rotation fertilizer scheme following regional university recommended rates applied prior to corn production in the first year.

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CHAPTER 4: AGRONOMIC LIMITATIONS OF SOYBEAN YIELD AND QUALITY IN THE SOYBEAN BELT OF THE UNITED STATES- MICHIGAN HIGH INPUT MANAGEMENT AND POPULATION FIELD TRIALS

Introduction

In 2009, research was initiated in six states, Minnesota, Iowa, Michigan, Kentucky, Arkansas and Louisiana, to investigate limitations to soybean yield and quality in the United States. Studies were implemented focusing on high-yield production practices, optimal plant populations, seed quality response to environment, and soil fertility management. This chapter outlines field studies conducted in Michigan pertaining to these objectives.

Manipulation of fundamental yield relationships through agronomic management has been practiced for years in an attempt to maximize yield. Agronomic decisions such as early planting, narrow row spacing, and variety selection are commonly used as best-management practices to enhance soybean seed yield. Additionally, inputs such as seed treatments, foliar fungicide application, soil and foliar fertilization, and inoculants have recently been promoted to increase yield. However, results have been mixed. Each of these practices must ultimately change either total biomass and/or harvest index to influence yield. As long as improvement in one component does not have an off-setting impact on the other (i.e. biomass increases but harvest index decreases), yield will increase. Each management practice mentioned has been studied in isolation, or in some cases, combined with an additional one to two practices. Rarely have all these practices been studied together as potential management scenarios for soybean producers. Potentially, the use of only one or two of these management practices will not have the desired yield benefits; however, when used in concert with additional management practices, the yield benefit may increase. The overall objective of the high input study is to assess the yield benefits and increased production costs associated with sixteen management systems generated from combinations of currently available soybean management practices throughout the United States.

Soybean plant populations continue to be viewed as limiting factor in consistently maximizing soybean yield. Because the relationship between stand establishment and seeding rate is affected by so many factors, it is necessary to determine this relationship for a given genotypic/environmental combination in order to minimize seed expenses for achieving the minimal optimal plant population. While plant populations of 247,000 seeds ha^{-1} at harvest has been suggested as an optimal soybean stand in northern latitudes, questions remain as to latitude effects on optimal final populations and initial seeding rates. Furthermore, effect of adapted maturity group on plant population has not been thoroughly explored. This study compares soybean seeding rates at six populations for two maturity groups at each location, an adapted maturity group and an earlier than adapted maturity group.

Materials and Methods

Field studies were located at three sites in Michigan and arranged in a randomized complete block design. Corn preceded soybeans at all locations. Sites were selected for initial optimum fertility levels and no additional fertilizer was added. Herbicide management consisted of s-metolachlor and metribuzin (Boundry 6.5 EC) applied pre-emergence followed by two applications of glyphosate (Roundup WeatherMaxx). Quizalofop-P-ethyl (Assure II) was applied with the first glyphosate application to control volunteer corn.

In the high input study, treatments were replicated six times. Plots measured 6.1 m wide by 12.2 m long. Individual locations differed in soybean maturity group, planting and harvest date, tillage system and soil type (Table 4.1). Fourteen treatments were included in 2009 and 2010 and sixteen in 2011 (Table 4.2.). Treatments were a combination of seven individual management practices, seed treatment (seed applied fungicide/insecticide), seed applied innoculant, additional soil fertility, row spacing, seeding density, foliar fungicide, and foliar fertility. A knock-out treatment structure was used where all products were applied to a single treatment with each following treatment having a single product removed from the management system. The products and treatment structure for this experiment represent some of the most common inputs and management practices currently implemented by U.S. soybean growers. Treatment combinations were designed in a manner to allow for the most probable systems growers may implement. The seed treatment used in 2009 was Trilex 6000 (Bayer Crop Science LP, Research Park, NC). The seed treatment consisted of a fungicide trifloxystrobin (methyl (*E*)-methoxyimino-{(*E*)-α-[1-(α,α,α-trifluoro-*m*-tolyl)ethylideneaminooxy]-*o*-tolyl}acetate) at 2.47 g ai 50 kg^{-1} of seed; an insecticide methalaxyl (methyl-N-(2,6-dimethylphenyl)-N-(2-

Table 4.1. High input study site agronomic management for 2009-2011.

Site	Soil type	Tillage†	Variety‡	Planting date	Harvest date
Tuscola					
2009	Tappan-Londo loam	F: C; S: FC	AG 2018	19 May	23 Oct.
2010	Tappan-Londo loam	F: C; S: FC	NK S21-N6	8 May	30 Sept.
2011	Tappan-Londo loam	F: C; S: FC	NK S21-N6	19 May	20 Oct.
Ingham					
2009	Capac loam	F: C; S: FC	DKB 27-52	1 June	21 Oct.
2010	Capac loam	F: C; S: FC	NK-S27-C4	24 May	8 Oct.
2011	Capac loam	F: C; S: FC	NK-S27-C4	4 June	18 Oct.
Branch					
2009	Fox sandy loam	F: C; S: FC	DKB 27-52	23 May	22 Oct.
Kalamazoo					
2010	Kalamazoo loam	S: Dk, FC	NK-S27-C4	6 May	27 Sept.
2011	Kalamazoo loam	S: Dk, FC	NK-S27-C4	12 May	3 Nov.

†F, fall; S, spring; C, chisel plow; FC, field cultivator; Dk, disk

‡AG, Asgrow, DKB, Dekalb; NK, Northrup King

Table 4.2. Individual treatment description and omission treatment structure design.

Treatment	**Description**	**Seed treatment**	**Foliar fungicide**	**Seed inoculant**	**Soil fertility**	**Foliar fertility**	**Row spacing**	**Seeding rate**§
								Standard
1	Control (W†)	-	-	-	-	-	Wide	Standard
2	High input (N‡)	+	+	+	+	+	Narrow	Standard
3	High input (W)	+	+	+	+	+	Wide	Standard
4	High input - Foliar fertility	+	+	+	+	-	Narrow	Standard
5	High input - Soil fertility	+	+	+	-	+	Narrow	Standard
6	High input - Seed inoculant	+	+	-	+	+	Narrow	Standard
7	High input - foliar fungicide	+	-	+	+	+	Narrow	Standard
8	High input - seed treatment	-	+	+	+	+	Narrow	Standard
9	Late season management	-	+	-	-	+	Narrow	Standard
10	Early season management	+	-	+	+	-	Narrow	Standard
11	High input (W) - foliar fungicide	+	-	+	+	+	Wide	Standard
12	Control (N)	-	-	-	-	-	Narrow	Standard
13	Ultra high input	+	+	+	+	+	Narrow	High
14	Ultra high input + R5 fungicide	+	R3/R5	+	+	+	Narrow	High
15	Low input + fungicide	-	+	-	-	-	Narrow	Standard
16	Sulfur soil fertilizer	-	-	-	S only	-	Narrow	Standard

† W= Wide row spacing (76 cm)

‡ N= Narrow row spacing (38 cm)

§ Standard seeding rate (432,300 plants ha^{-1} in 2009, and 358,200 plants ha^{-1} in 2010 and 2011), High seeding rate (679,300 plants ha^{-1} in 2009, and 605,200 plants ha^{-1} in 2010 and 2011) methoxyacetyl)-DL-alaninate) at 1.98 g ai 50 kg^{-1}; imidacloprid (1-[(6-Chloro-3-pyridinyl) methyl]-N-nitro-2-imidazolidinimine) at 31.5 g ai 50 kg^{-1} of seed; and a biological fungicide *Bacillus pumilus* at 3.12 x 10^{10} colony forming units 50 kg^{-1} of seed. In 2010 and 2011 the seed treatment was changed to Crusier Maxx (Syngenta Crop Protection, Greensboro, NC) due to availability. This seed treatment was a combination of the insecticide thiamethoxam (3-[(2-Chloro-1,3-thiazol-5-yl)methyl]-5-methyl-*N*-nitro-1,3,5-oxadiazinan-4-imine) at 25 g ai 50 kg^{-1} of seed; and fungicides mefenoxam ((R)-2-[(2,6-dimethylphenyl) methoxyacetylamino] (R)-2-[(2,6-dimethylphenyl) methoxyacetylamino]) at 1.88 g ai 50kg^{-1} of seed; and fludioxonil (4-(2,2-difluoro-1,3-benzodioxol-4-yl)-1*H*-pyrrole-3-carbonitrile) at 1.25 g ai 50 kg^{-1} seeds.

The seed inoculant was Vault (Becker Underwood, Inc Ames, IA) with the active ingredient being *Bradyrhizobium japonicum.* The product was applied at the manufacturer's recommended rate of 102 mL 50 kg^{-1} of seed within one week of planting.

Two row-spacing configurations and seed densities were used at additional management practices. Row spacing consisted of wide (76 cm) or narrow (38 cm) rows. Standard seeding rate was 432,300 seeds ha^{-1} in 2009 and 358,200 seeds ha^{-1} in 2010 and 2011. The high seeding rate added an additional 247,000 seeds ha^{-1} to the standard seeding rate.

The soil fertility treatment comprised an additional 84.0 kg ha^{-1} P_2O_5, 56.0 kg ha^{-1} K_2O, 22.4 kg ha^{-1} S, 2.24 kg ha^{-1} Mn, 0.56 kg ha^{-1} B and 0.56 kg ha^{-1} Zn. All soil fertility components were added to soils that had previously tested at or above optimum fertility levels within each state. Products were hand-applied prior to planting. In 2011, a treatment was established of only S fertilization at 22.4 kg ha^{-1}.

The foliar fertilizer treatment consisted of the application of Task Force 2 at the R1 growth stage (Fehr and Caviness, 1977); providing 0.77 kg N ha^{-1}, 0.56 kg P_2O_5 ha^{-1}, 0.35 kg K_2O ha^{-1}, 0.001 kg B ha^{-1}, 3.5 x 10^{-5} kg Co ha^{-1}, 0.004 kg Cu ha^{-1}, 0.007 kg Fe ha^{-1}, 0.004 kg Mn ha^{-1}, 3.5 x 10^{-5} kg Mo ha^{-1}, and 0.004 kg Zn ha^{-1}. Foliar fungicide applications were made at the R3 and R5 growth stages. The fungicide Pyraclostrobin (methyl N-{2-[1-(4-chlorophenyl)-1H-pyrazol-3-yloxymethyl]phenyl}(N-methoxy)carbamate) was applied at R3(0.22 ai g ha^{-1}). An application of azoxystrobin (Methyl (2*E*)-2-(2-{[6-(2-cyanophenoxy)pyrimidin-4-yl]oxy}phenyl)-3-methoxyacrylate) at 0.11 g ai ha^{-1} and propiconazole (1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl]methyl]-1,2,4-triazole) at 0.19 ai ha^{-1} fungicides were made at the R5 growth stage.

Treatments included two controls in the wide (Treatment 1) and narrow (Treatment 12) row spacing, and two high input systems in wide (Treatment 3) and narrow (Treatment 2) row spacing. The only other wide row spaced treatment was Treatment 7, the high input system minus the foliar fungicide application. Treatments 4-8 involved the removal of a single crop input from the management system under narrow row spacing. Treatment 9 was considered a late season intensive management system including only foliar fertilizer and foliar fungicide. Treatment 10 mimicked an early season intensive management system, including only seed treatment, seed inoculant and the additional soil fertility. Both treatments were planted in the narrow row spacing configuration. Two treatments received an additional 247,000 seeds ha^{-1} (Treatments 13 and 14) in addition to all of the crop inputs. In addition, Treatment 14 received an additional application of fungicide at the R5 growth stage.

In the population study, treatments were replicated six times. An adapted maturity group varieties and an earlier than adapted maturity group varieties were planted at six populations (Table 4.3). Plots measured 2.7 m wide by 12.2 m long and were planted in 38 cm wide rows. Population was calculated from a 1.5 m^2 area at the V4 and R8 growth stages.

In both studies, grain yield for was determined by mechanical harvest from a 1.5 m swath through the plot center and adjusted to 130 g kg^{-1} moisture. Data were analyzed as randomized complete block using the PROC MIXED procedure of SAS (SAS Institute, 2009).

Table 4.3. Population study site agronomic management for 2009-2011.

Site	Soil type	Tillage†	Adapted season variety‡	Earlier than adapted variety	Planting date	Harvest date
Tuscola						
2009	Tappan-Londo loam	F: C; S: FC	P 91M01	P 91Y70	19 May	23 Oct.
2010	Tappan-Londo loam	F: C; S: FC	P 91M01	P 91Y70	8 May	30 Sept.
2011	Tappan-Londo loam	F: C; S: FC	P 91M01	P 91Y70	19 May	20 Oct.
Ingham						
2009	Capac loam	F: C; S: FC	P 91Y70	P 92Y80	1 June	21 Oct.
2011	Capac loam	F: C; S: FC	P 91Y70	P 92Y80	17 May	18 Oct.
Branch						
2009	Fox sandy loam	F: C; S: FC	P 91Y70	P 92Y80	23 May	22 Oct.
Kalamazoo						
2010	Kalamazoo loam	S: Dk, FC	P 91Y70	P 92Y80	6 May	27 Sept.
2011	Kalamazoo loam	S: Dk, FC	P 91Y70	P 92Y80	12 May	3 Nov.

†F, fall; S, spring; C, chisel plow; FC, field cultivator; Dk, disk

‡P, Pioneer

Results

In the high input study, treatment effects were significant at seven of the nine site years (Table 4.4). At Tuscola in 2010 and 2011, no differences were measured between treatments. Low precipitation in July and August in 2010 limited yield potential and may be a likely explanation for the lack of yield differences. Average grain yield at Tuscola in 2011 was comparable to other sites, suggesting that environmental factors that limit yield potential are not the only conditions that may negate yield differences between treatments.

Soybean grain yield was increased at five of the nine site years in systems using high input practices compared to no inputs. At Tuscola in 2009, the omission of any one treatment did not result in yield significantly less that the high input treatment. At Ingham in 2010, the omission of a fungicide application resulted in lower yield compared to the high input treatment. At four sites, Ingham in 2009, Branch in 2009 and Kalamazoo in 2010 and 2011, the omission of pre-plant fertilizer resulted in lower yield that the high input treatment. Pre-plant fertilizer did not have an effect on grain yield at the Tuscola site in any of the study's three years. The response to pre-plant fertilizer was confined to sites with higher sand content and lower cation exchange capacity. An additional fertilizer treatment was added in 2011 containing only S in an attempt to isolate the specific nutrient responsible for the yield response. At only one site in 2011, Kalamazoo, did the omission of pre-plant fertilizer resulted in a yield decrease. A S only treatment resulted in a similar yield decline in comparison to the high input treatment, suggesting S in the pre-plant fertilizer is not responsible for the yield response.

Table 4.4. Soybean grain yield of high input treatments, 2009-2011.

Treatment	Tuscola			Ingham			Branch	Kalamazoo	
	2009	2010	2011	2009	2010	2011	2009	2010	2011
	Mg ha^{-1}			Mg ha^{-1}			Mg ha^{-1}	Mg ha^{-1}	
1	2.64def†	2.81	3.63	2.52cde	2.82f	3.29cd	2.15bcd	3.70def	3.30f
2	2.71abc	2.86	3.98	2.68ab	3.33bc	3.49abc	2.28abc	4.24ab	4.15a
3	2.66cdef	2.97	3.87	2.71a	3.18cde	3.42bcd	2.25abc	3.48f	3.76bcde
4	2.83ab	2.94	3.85	2.64abcd	3.32abc	3.56abc	2.39abc	4.12abc	4.00ab
5	2.71bcde	3.02	3.78	2.42e	3.36bc	3.51abc	1.90de	3.82cdef	3.77bcde
6	2.90a	3.08	4.16	2.56bcd	3.26cd	3.56abc	2.37abc	4.09abc	3.85abc
7	2.76abcd	2.98	3.93	2.64abcd	3.03ef	3.34cd	2.15bcd	3.94abcd	3.69bcde
8	2.69cdef	2.94	4.12	2.68ab	3.55ab	3.56abc	2.32abc	3.98abcd	3.83abcd
9	2.53f	2.94	3.97	2.39e	3.62a	3.79a	2.12cd	3.90bcde	3.87abc
10	2.69cde	2.96	3.94	2.65abcd	3.04def	3.14d	2.47a	4.30a	3.43ef
11	2.60ef	2.94	3.53	2.67ab	3.04def	3.13d	2.28bc	3.52ef	3.52cdef
12	2.65cdef	2.82	3.78	2.51de	3.26cd	3.43bcd	1.82e	3.95abcd	3.49def
13	2.78abcd	3.08	4.26	2.66abc	3.51ab	3.70ab	2.27abc	4.23ab	3.94ab
14	2.80abc	3.12	3.72	2.76a	3.23cde	3.65ab	2.41ab	4.04ab	4.15a
15			3.99			3.57abc			3.74bcde
16			3.85			3.30cd			3.48ef
$P > F$	0.0107	0.6030	0.1556	0.0003	<0.0001	0.0206	0.0087	0.0051	0.0015

†Means within a column followed by the same letter are not statistically different at P=0.10.

Narrow row spacing was compared to wide row spacing within high management, no management, and all inputs but fungicide systems. Differences in grain yield between row spacing were only observed in one management system in one year, 2009, at Tuscola. There, yield was increased in a no-fungicide system when row spacing was narrow compared to wide. At Ingham, narrow row spacing resulted in higher grain yield compared to wide row spacing in the low management system in 2010 and 2011, but in no other management system. Greater yield was recorded for narrow row configurations at Branch in 2009 for the low input system compared to wide row spacing, but for no other management system. At Kalamazoo, narrow rows resulted in greater yield compared to wide rows in high management systems in 2010 and 2011 and no-fungicide systems in 2010.

Yield increases with narrow row spacing were not consistent among management systems but appeared to correlate with geography. Southern locations tended to have higher grain yield in narrow row configurations compared to Ingham or Tuscola locations.

Ultra high populations with an additional 247,000 seeds ha^{-1} did not result in increased yield compared to high input treatments planted at standard populations.

In the population study, as seeding rate increased, the proportion of emerged seeds at the V4 growth stage decreased (Table 4.5). At very low seeding rates, the established population at the V4 growth stage was often greater than the intended seeding rate. This reflects an equipment limitation of seeding low populations in narrow row configurations. At high seeding rates, the

Table 4.5. Early season V4 growth stage population, 2009-2011.

Intended plants ha^{-1}	Tuscola 2009	Tuscola 2011	Ingham 2009	Ingham 2011	Branch 2009	Kalamazoo 2010	Kalamazoo 2011
	plants ha^{-1}		plants ha^{-1}		plants ha^{-1}	plants ha^{-1}	
Early							
61,700	56,500	54,000	75,200	59,000	52,200	70,300	50,700
185,300	182,700	103,000	193,300	180,000	176,100	204,400	117,700
308,800	293,600	294,900	331,100	278,000	282,200	292,700	230,600
432,000	401,200	273,100	418,700	372,800	401,200	417,000	343,400
555,800	505,600	325,400	540,400	472,600	512,100	528,200	466,000
679,300	521,900	443,200	485,000	580,500	629,500	616,500	520,000
Adapted							
61,700	57,100	84,000	66,200	65,400	58,700	68,700	24,500
185,300	176,100	158,600	202,200	171,700	218,500	196,200	135,700
308,800	272,400	245,300	322,100	274,700	257,700	314,000	233,800
432,000	368,600	325,400	449,200	387,600	353,900	420,300	382,700
555,800	474,600	359,800	613,800	459,500	559,400	495,500	467,700
679,300	551,300	510,200	717,600	513,500	655,600	608,300	552,700

lower percentage of emerged plants in relation to intended seeding rate may be a result of increased competition between seedlings.

While some attrition of plants between the V4 and R8 growth stage may be expected, the relationship between these two numbers was poor across all sites (Table 4.6). Slight increases in population between V4 and R8 stand counts may be the results of different areas of the plot selected for stand counts at the early and late season timings.

Grain yield treatment effects were significant for all varieties and locations except one, the adapted variety in Ingham in 2011 (Table 4.7). Soybean grain yield response to population was not consistent between site years. Grain yield of early varieties tended to have lower average yield than adapted varieties. For adapted varieties, yield was maximized at 61,700 seeds ha^{-1} in Ingham in 2011, 185,300 seeds ha^{-1} at Kalamazoo in 2010 and 2011, 308,800 seeds ha^{-1} at Branch in 2009, 432,000 seeds ha^{-1} at Ingham in 2009 and Tuscola in 2009 and 2010, at 555,800 seeds ha^{-1} at Tuscola in 2010. Grain yield tended to be maximized at lower population for early varieties compared to adapted varieties at Tuscola and Ingham. Maximized yield was attained with 185,300 seeds ha^{-1} at Tuscola in 2011, 308,800 seeds ha^{-1} at Tuscola in 2009 and 2010 and 432,000 seed ha^{-1} at Ingham in 2009 and 2011. Yield of the early season varieties at Kalamazoo in 2011 was maximized at 185,300 seed ha^{-1}, just as full season varieties were. At Kalamazoo in 2010, yield was maximized at 308,800 seeds ha^{-1}. At Branch in 2009, 679,300 seeds ha^{-1} were required to attain maximum yield.

Table 4.6. Late season R8 growth stage population, 2009-2011.

Intended plants ha^{-1}	Tuscola	Ingham		Kalamazoo	
	2009	2009	2011	2010	2011
	plants ha^{-1}	plants ha^{-1}		plants ha^{-1}	
Early					
61,700	61,000	69,800	39,200	57,200	57,200
185,300	207,100	177,200	183,100	160,300	75,200
308,800	233,200	259,500	393,200	253,500	263,300
432,000	334,300	354,300	457,800	343,400	356,500
555,800	512,100	451,000	588,600	399,000	428,400
679,300	592,000	383,000	752,100	510,200	538,000
Adapted					
61,700	53,900	68,000	41,400	58,900	52,300
185,300	166,400	170,000	176,600	170,100	150,400
308,800	262,600	309,600	357,500	266,500	253,500
432,000	344,100	406,200	481,800	341,800	335,200
555,800	425,700	502,900	569,000	343,400	421,900
679,300	610,000	662,000	750,000	575,600	562,500

Table 4.7. Soybean grain yield of population treatments, 2009-2011.

Intended plants ha^{-1}	Tuscola			Ingham		Branch	Kalamazoo	
	2009	2010	2011	2009	2011	2009	2010	2011
	Mg ha^{-1}			Mg ha^{-1}		Mg ha^{-1}	Mg ha^{-1}	
Early								
61,700	2.01b†	2.25c	2.68c	0.69c	2.01c	0.86d	3.45c	1.88c
185,300	3.01a	2.42bc	3.08ab	1.92b	2.98b	1.31c	3.71bc	2.82ab
308,800	3.10a	2.56ab	2.98bc	2.30b	3.07b	1.60b	3.94ab	2.97ab
432,000	3.09a	2.58ab	3.37a	2.32a	3.54a	1.57b	4.12a	2.79b
555,800	3.16a	2.67a	3.25ab	2.14b	3.18b	1.75b	4.09a	3.22ab
679,300	3.32a	2.69a	3.3ab	2.52a	3.55a	2.14a	4.11a	3.26a
P > F	<0.0001	0.0057	0.0486	<0.0001	<0.0001	0.0002	0.0169	0.0007
Adapted								
61,700	1.64c	1.87d	3.20c	1.09c	2.91	1.54c	3.69b	2.63b
185,300	2.44b	2.47c	3.31c	2.21b	3.44	2.06b	4.83a	3.74a
308,800	2.76b	2.54bc	3.53b	2.27b	3.24	2.30ab	4.68a	3.59a
432,000	3.04a	2.55bc	3.60ab	2.71a	3.41	2.28ab	4.87a	3.79a
555,800	3.06a	2.71ab	3.72a	2.84a	3.35	2.51a	5.07a	3.85a
679,300	3.04a	2.83a	3.61ab	2.88a	3.49	2.25ab	5.03a	3.73a
P > F	<0.0001	<0.0001	0.0006	<0.0001	0.5927	0.0058	0.0012	0.0001

†Means within a column followed by the same letter are not statistically different at P=0.10.