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Co-Granulated and Blended Zinc Fertilizer Comparison for Corn and Soybean

Matthew Caldwell[1], Kelly A. Nelson[2] & Manjula Nathan[1]

[1] College of Agriculture, Food and Natural Resources, Division of Plant Sciences, University of Missouri, Columbia, Missouri, USA

[2] Greenley Research Center, Division of Plant Sciences, University of Missouri, Novelty, Missouri, USA

Correspondence: Kelly A. Nelson, University of Missouri Greenley Research Center, 64399 Greenley Place, Novelty, MO 63460, USA. Tel: 660-739-4410. E-mail: nelsonke@missouri.edu

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Abstract

A new co-granulated formulation of monoammonium phosphate (MAP) including S and Zn could allow for more uniform nutrient distribution. A six site-year study evaluated the effects of blended phosphorus (P) sources [MAP and diammonium phosphate (DAP)] and zinc amounts (0, 2.2, and 5.6 kg Zn ha^{-1}) compared to co-granulated fertilizer, MicroEssentials® Sulfur-10 (MES10™) (12-40-0-10S) and MicroEssentials Sulfur and Zinc (MESZ™) (12-40-0-10S-1Zn), on corn and soybean response. Fertilizers were broadcast applied for corn and the carry-over effect on soybean was determined. Ear leaf P, S, and Zn concentrations at Novelty in 2013 and 2014 were within the sufficiency range regardless of treatment, even though initial soil test values were low-medium. Yields were similar to the N only control for all site-years except at Novelty in 2013, where MAP+$ZnSO_4$ at 2.2 kg Zn ha^{-1}, MAP+Super Zn at 5.5 kg Zn ha^{-1}, and DAP+AMS were 540 to 570 kg/ha greater. The amount of Zn fertilizer (2.2 vs. 5.6 kg Zn ha^{-1}) also showed no significant effect on yield. Applications of P or Zn generally increased their concentrations in post-harvest soil samples. Fertilizer applied for corn indicated some differences in soybean plant nutrient concentrations, but it had no effect on total plant nutrient uptake, grain yield or quality. At Novelty, soybean plant Zn concentration was greater at 5.6 kg Zn ha^{-1} compared to 2.2 kg Zn ha^{-1}, while Albany showed an increase in whole soybean plant Zn concentration with SuperZn compared to $ZnSO_4$. Carry-over fertilizer from corn showed limited effects on soybean response the following year.

Keywords: corn, fertilizer, phosphorus, soybean, sulfur, and zinc

1. Introduction

Zinc (Zn) is essential to plant survival, with the average plant containing 20 ppm of the micronutrient based on dry weight (Mahler, 2004). Typical soils can contain 0.3 to 2.0 ppm (Mahler, 2004) of plant-available Zn, which is the most common deficient micronutrient in high pH soils (Graham, Asher, & Hynes, 1992). Zn is found in N metabolism pathways that can affect protein synthesis (Fageria, 2004). Deficiencies can cause interveinal chlorosis, bronzing, internode shortening, and epinasty. In severe deficiencies, the root apex can become necrotic. Although Zn is mobile in the plant, its mobility is poor and deficiency symptoms appear first in the upper, young plant leaves. Since Zn is a micronutrient, Zn toxicity is possible, but unlikely (Broadley, White, Hammond, Zelko, & Lux, 2007). Zn fertilizers are available in three major forms: Zn chelate, ZnO, and $ZnSO_4$ (Schulte, 2004). Water solubility greatly influences the availability and effectiveness of Zn fertilizer. In Zn chelate, commonly sold as ZnEDTA, a large organic molecule surrounds Zn and keeps it from leaching, oxidizing, and precipitating (Schulte, 2004). Zinc sulfate is the most common form, due to its low cost and greater solubility (Schulte, 2004), and has traditionally been a steadfast source in Zn fertilizer (Olsen, 1982).

Although soil may contain enough Zn to support a crop through the season, 90% of the Zn is in forms that make it unavailable (fixed, insoluble, or unexchangeable) (Broadley et al., 2007). In most soils, only 0.1 to 2 µg of Zn per gram are exchangeable (Broadley et al., 2007). Soils with large phosphate levels can cause an imbalance in a crops' physiology including a reduction in Zn uptake (Olsen, 1982). This phenomenon is known as P-induced Zn deficiency (Singh, Karamanos, & Stewart, 1986). Zinc-phosphorous interactions are well documented (Halim, Wassom, & Ellis, 1968; Keefer, Singh, Horvath, & Henderlong, 1972; Rehm, Sorensen, & Wiese, 1981, 1983; Robson & Pitman, 1983; Singh, Karamanos, & Stewart, 1988). Phosphorus fertilizer applied in large amounts can induce zinc deficiency in soils with low plant-available zinc (Robson & Pitman, 1983). In soil, P can decrease zinc's solubility (Huang, Barker, Langridge, Smith, & Graham, 2000). When P requirements are met in the plant, root growth is reduced and mycorrhizae infection less common (Amijee, Stribley, & Tinker, 1990). Deficiencies in plants could also be induced by a small concentration of Zn due to rapid growth response to P. Alternatively, large P-to-Zn ratios could cause a metabolic imbalance in cells and lead to P-induced Zn deficiencies (Singh et al., 1988). Zinc deficiency may increase in response to an expression of high-affinity phosphate transporters when P is deficient, likely because the plant utilizes resources from Zn for phosphate transporters (Huang et al., 2000). Increasing applications of both Zn fertilizer and P could help optimize yield (Schnappinger, Martens, & Hawkins, 1969), even though crops take up little Zn during the growing season.

More than 30% of the world's arable land has P-limiting yield potential (Vance, Uhde-Stone, & Allen, 2003). Phosphorus is an essential plant macronutrient that accounts for 3 to 5 g kg^{-1} of a plant's dry weight (Schalchtman, Reid, & Ayling, 1998). Phosphorus, a structural component in nucleic acids (DNA, RNA), transfers energy as adenosine triphosphate (ATP) and maintains cell structure with phospholipids. Though abundant in soil, P occurs primarily in a fixed form or outside of the rhizosphere and so is unavailable for plant uptake. When P is not available in adequate amounts, at least 0.2 mg L^{-1} in soil solution (Pierzynski, McDowell, Sims, & Sharpley, 2005), plants can become deficient. Visual signs of P deficiency include overall stunting of the plant, a purple tint from anthocyanin accumulation, and small necrotic leaf spots. Deficiency typically appears in the lower more mature leaves because P is mobile and translocates to new developing tissue (Briskin, Bloom, Taiz, & Zeiger, 2010). To overcome limited P availability in the soil and maintain soil test P levels, todays growers use P fertilizers commonly available as monoammonium phosphate (MAP) and diammmonium phosphate (DAP).

It is important to optimize sulfur (S) in crops to achieve high yields and grain quality (Tabatabai, 1984). As current environmental laws reduce sulfur emissions from power plants, crop sulfur deficiencies may become more common (Camberato, Maloney, Casteel, & Johnson, 2012). Correspondingly, the need to apply S fertilizers likely will increase in coming years. Sandy soils with small amounts of organic matter and no-till or heavy residue can increase the likelihood of sulfur deficiencies (Camberato & Casteel, 2010). Although S is considered a secondary plant nutrient (primarily because of amount needed), deficiency seriously affects plant growth and yields (Sawyer & Barker, 2012). As organic matter decomposes, it releases sulfate (SO_4^{-2}) into the soil through the process of mineralization (Hergert, 2000). For every one g kg^{-1} of organic matter, 2.25 to 3.36 kg ha^{-1} of sulfate are released annually into the soil, while 10 Mg ha^{-1} of corn (*Zea mays* L.) removes approximately 6.11 kg ha^{-1} of sulfur in grain alone (Schulte & Kelling, 1992).

A patented technology employed in co-granulated fertilizers combine nitrogen, P, S, and Zn into a single prill (MicroEssentials, Mosaic, Plymouth, MN). This allows for uniform distribution and possibly increased uptake of nutrients across a range of crops. MES10 (MicroEssentials Sulfur) contains MAP plus equal amounts of AMS (ammonium sulfate) and elemental sulfur (S) as 100 g kg^{-1} in the co-granulated material. The sulfate is immediately available for plant uptake, though the elemental sulfur must be oxidized by soil bacteria, which allows for season-long sulfur availability (Schulte & Kelling, 1992). MESZ is the same formulation as MES plus one percent ZnO. Microessential Sulfur and Zinc (MESZ) utilizes ZnO as the primary Zn source (Mosaic, 2007). Zinc oxide has the greatest percent of Zn at 72-80% compared to other Zn sources, but it is less water soluble than $ZnSO_4$.

Researchers have studied the effects of co-granulated fertilizers in Iowa with corn (Sawyer & Barker, 2009), and in Arkansas with rice (*Oryza sativa* L.) (Slaton et al., 2010), winter wheat (*Triticum aestivum* L.) (Freeman, Ruffo, & Mann, 2014), and canola (*Brassica napus* L.) (Woolfork, Olson, Mann, & Perez, 2014); however, results have been mixed. Some studies show limited yield differences (Sawyer & Barker, 2009), while others indicate an advantage of MES and MESZ compared to a blend of the same nutrients (Slaton et al., 2010). MESZ increased yields 5.7% compared to MAP and 3.4% compared to MAP+AMS+$ZnSO_4$ (Freeman et al., 2014). In canola, Woolfolk et al. (2014) reported yield increases of 4% at 19 kg P_2O_5 ha^{-1} and 7.1% at 56 kg P_2O_5 ha^{-1}, which were related to less injury to germinating seedlings. Few studies report on the effects of the new co-granulated fertilizers on corn response in the Midwestern U.S., as well as their carry-over impact on soybean [*Glycine max* (L.) Merr.]. The objective of this research was to evaluate corn response to MES10 and MESZ formulations to equivalent blends of DAP or MAP, S, and Zn at two amounts of Zn (2.2 and 5.6 kg Zn ha^{-1}) for the impact on corn (ear leaf nutrient concentration at VT, grain yield, grain quality, and changes to soil test nutrient levels post-harvest) and soybean response (population, plant nutrient uptake, yield, and grain quality).

Table 1. Initial soil characteristics (average ± 1 standard deviation of the mean) 0-15 cm deep at Albany (2013-2014) and Novelty (2011-2014)

Soil characteristics	2011 Novelty	2012 Novelty	2013		2014	
			Novelty	Albany	Novelty	Albany
pH (0.01 M $CaCl_2$)	6.0±0.1	6.2±0.2	5.1±0.6	5.1±0.2	5.7±0.2	5.9±0.3
Neutralizable acidity (cmol$_c$ kg^{-1})	1.9±0.2	1.1±0.4	5.4±5.5	4.5±1.1	2.5±0.1	2.0±0.9
Organic matter (g kg^{-1})	23±1	29±2	20±2	26±3	22±4	29±1
Bray 1P (kg ha^{-1})	15.7±2.4 (VL)[†]	15.7±2.1 (VL)	21.9±8.9 (L)	24.6±7.5 (L)	25.7±2.5 (L)	35.3±4.4 (M)
Exchangeable (1 M NH_4OA_C)						
Ca (kg ha^{-1})	4547±235	4805±314	3674±381	3618±426	4797±415	5728±235
Mg (kg ha^{-1})	392±37	347±34	328±49	459±64	412±52	716±48
K (kg ha^{-1})	161±11	160±20	128±38	234±44	228±30	206±16
SO_4-S (mg kg^{-1})	5.8±1.1 (M)	6.4±0.7 (M)	1.6±0.3 (M)	5.7±0.4 (M)	4.5±0.2 (M)	5.6±0.6 (M)
Zn (mg kg^{-1})	0.2±0.1 (L)	0.5±0.1 (L)	0.3±0.1 (L)	1.0±0.3 (M)	0.8±0.6 (M)	1.0±0.6 (M)
Mn (mg kg^{-1})	16.7±0.8	49.3±7.4	17.2±1.7	-	19.3±3.2	9.8±1.7
Fe (mg kg^{-1})	38±1.0	49.3±7.4	48.3±12.4	-	40.3±3.9	43.3±11.8
Cu (mg kg^{-1})	0.6±0.1	0.6±0.1	0.4±0.1	-	0.6±0.1	0.8±0.1
CEC (cmol$_c$ kg^{-1})	13.7±0.8	13.3±0.7	14.2±3.2	14.6±1.1	14.7±1.2	17.7±0.7

Note. [†] Abbreviations: L, low; M, medium; VL, very low (Buchholz et al., 2004).

2. Materials and Methods

2.1 Corn

In 2011 and 2012, field research was conducted at the Greenley Memorial Research Center (39°56′N, 92°3′W) near Novelty, Missouri. In 2013 and 2014, field research was also conducted at the Hundley-Whaley Center (40°14′N, 94°20′W) near Albany, Missouri. Soil test Bray 1P at Novelty and Albany was very low (15 kg ha^{-1}) to medium (36 kg ha^{-1}) (Table 1). The Novelty sites were a Putnam silt loam (fine, smectitic, mesic Vertic Albaqualfs), while Albany sites were a Grundy silt loam (fine, smectitic, mesic Aquertic Argiudolls). Treatments were arranged in a randomized complete block design with five replications at Novelty and four replications at Albany. Initial (15 cm) soil samples from each replication were collected and analyzed by the University of Missouri Soil and Plant Testing Laboratory using the recommended soil test procedures for Missouri (Nathan, Stecker, & Sun, 2012).

Fertilizer treatments were applied pre-plant for corn in the corn-soybean rotation. Treatments included P source (MAP or DAP), Zn rate (2.2 and 5.6 kg Zn ha^{-1}), and multiple fertilizer technologies (traditional blends or co-granulated fertilizers). Zinc rates were in line with other research showing corn yield increases (Schnappinger et al., 1969). In 2013 and 2014, SuperZn (liquid Zn oxide) (1-0-0-0-40Zn) (Helena, Collierville, TN) was impregnated on the dry fertilizer prills and added at both Novelty and Albany. Co-granulated fertilizers included MicroEssentials Sulfur and Zn (MESZ) (12-40-0-10S-1Zn) and MicroEssentials Sulfur (MES10) (12-40-0-10S-1Zn). In 2013 and 2014, Novelty and Albany had sixteen treatments, including: non-treated control (no fertilizer), nitrogen (N) only, DAP, DAP+ ammonium sulfate (AMS), DAP+$ZnSO_4$ at 2.2 kg Zn ha^{-1}, DAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1}, DAP+SuperZn at 2.2 kg Zn ha^{-1}, DAP+SuperZn at 5.6 kg Zn ha^{-1}, MAP, MAP+AMS, MAP+$ZnSO_4$ at 2.2 kg Zn ha^{-1}, MAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1}, MAP+SuperZn at 2.2 kg Zn ha^{-1}, MAP+SuperZn at 5.6 kg Zn ha^{-1}, MES10, and MESZ. In 2011 and 2012 at Novelty, SuperZn or DAP+AMS were not included, resulting in a total of eleven treatments.

Corn was planted in April or May, depending on yearly weather conditions using no-till (Novelty) or minimum tillage (Albany) into 3 by 9 to 15 m plots, with 76 cm row spacing. Corn followed soybean at all sites, except in 2013 at Albany, a continuous corn site. Management information is available in Table 2.

In 2013 and 2014 at Novelty, ten ear leaves were randomly selected from the middle two rows of each plot. Ear leaf samples were analyzed for P, SO_4-S, and Zn concentrations (Bryson, Mills, Sasseville, Jones, & Barker, 2014). The two middle rows of the four-row corn plots were harvested using a plot combine (Wintersteiger Delta, Salt Lake City, UT or Massey 8, Haven, KS) measuring corn grain yields and moisture content. Corn grain yields were adjusted to 150 g kg^{-1} prior to analysis. Individual plot grain samples were collected during harvest and evaluated for oil, protein, and starch using a near infrared (NIR) spectroscopy (Foss Infratec, Eden Prairie, MN).

2.2 Soybean

Soybean was planted into the same plots as corn in April or May, depending on yearly weather conditions. The fields were no-till (Novelty) or minimum tillage (Albany), and plots were 3 by 9 to 15 m. In 2015, soybean was planted in July due to an extremely wet spring. Soybean was planted in 76 cm wide rows at Albany and in 19 cm rows at Novelty. Soybean followed corn in all years. Management information is available in Table 3. Whole plant tissue samples were taken in 2014 and 2015 at Novelty and Albany at R6 (Fehr & Caviness, 1971). Quadrats (0.23 m^2) were randomly selected from the middle two rows of each plot. The plant samples were ground, dried, and analyzed with standard extraction methods for P, S, and Zn concentrations (Bryson et al., 2014).

To determine soybean grain yields and moisture content, the two middle rows of soybean were harvested at Albany (Massey 8, Haven, KS), and a 1.5 m wide section of the plot (four, 38 cm wide rows) was harvested at Novelty (Wintersteiger Delta, Salt Lake City, UT). During harvest, individual plot grain samples were collected and evaluated for oil and protein concentration using near infrared (NIR) spectroscopy (Foss Infratec, Eden Prairie, MN). Soybean yields were adjusted to 130 g kg^{-1} prior to analysis.

2.3 Statistical Protocol

All corn data were analyzed with the Statistical Analysis System (SAS Institute, Cary, NC) using PROC GLIMMIX, and means were separated using Fisher's Protected LSD (P = 0.05). Corn data for Novelty in 2011 and 2012 were analyzed separately from 2013 and 2014 data due to the addition of SuperZn in the latter years. Data were combined by year and location when appropriate. Soybean data were combined over years for individual sites for all measurements. Planned contrasts were used to compare Zn sources (SuperZn vs. $ZnSO_4$) and Zn amounts (2.2 vs. 5.6 kg Zn ha^{-1}).

3. Results and Discussion

3.1 Growing Conditions

Research at Novelty from 2011 to 2014 and at Albany in 2013 and 2014 experienced a wide range of precipitation during the growing seasons (March 31 to September 29) (Figure 1). At Novelty in 2011, corn experienced an abnormally dry spring (USDM, 2015) followed by average summer precipitation (532 mm) throughout the growing season. In 2012, the Midwestern U.S. experienced an extreme drought (USDM, 2015), with Novelty receiving only 273 mm of precipitation during the growing season. In 2013, precipitation was average at Novelty (453 mm), and above average at Albany (607 mm).

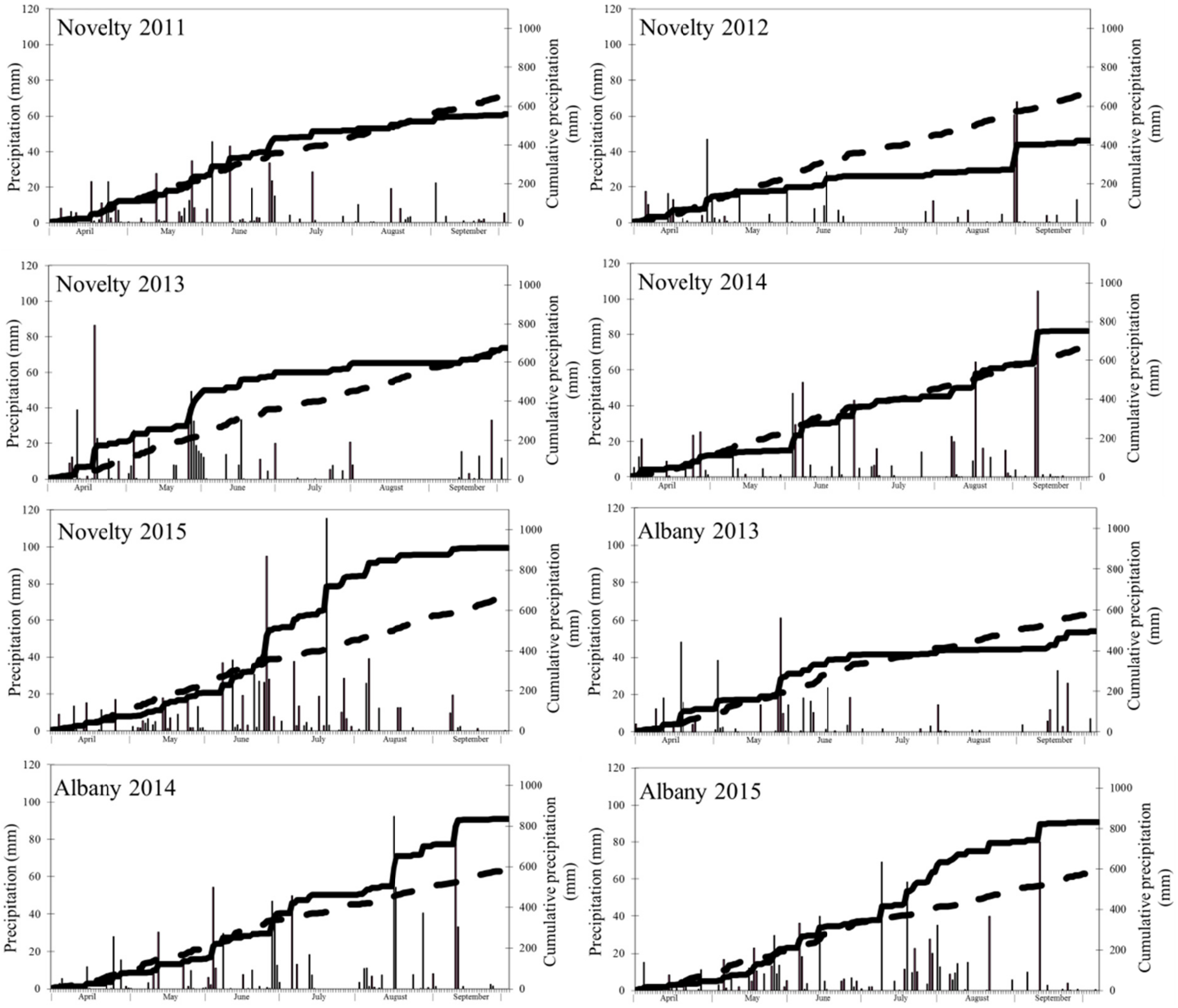

Figure 1. Precipitation over the six site-years for corn (2011-2014) and the following soybean (2012-2015) crop. Bars represent individual precipitation events (left vertical axis). The solid line represents cumulative precipitation throughout the season, and the dashed line represents 10-year average precipitation (right vertical axis)

Table 2. Field and management information for corn sites at Novelty (2011-2014) and Albany (2013-2014)

Management information	2011 Novelty	2012 Novelty	2013		2014	
			Novelty	Albany	Novelty	Albany
Plot size (m)	3 by 12	3 by 12	3 by 15	3 by 11	3 by 15	3 by 11
Hybrid or cultivar	DKC 63-84	DKC 63-84	DKC 63-25 VT3	DKC 64-69	DKC 63-25	DK 64-69
Planting date	12 Apr.	2 Apr.	15 May	14 May	18 Apr.	5 May
Seeding rate (seeds ha^{-1})	76,600	79,100	81,1500	71,700	81,500	74,100
Harvest date	22 Sep.	28 Aug.	7 Oct.	10 Oct.	10 Oct.	16 Oct.
Maintenance fertilizer	31 Mar. 2011	18 Nov. 2011			11 Nov. 2013	NA
Nitrogen	200 kg N ha^{-1} (AA)[†]	213 kg N ha^{-1} (AA) + nitrapyrin at 2.34 L ha^{-1}	200 kg N ha^{-1} (AA)	200 kg N ha^{-1} (AN)	245 kg N ha^{-1}	200 kg N ha^{-1} (AN)
P-S-Zn application	6 May	28 Nov. 2011	29 Apr.	7 May	25 Mar.	5 May
Tillage	No-till	No-till	No-till	Minimum	No-till	Minimum
Weed management						
Burndown/ Pre-emergence[‡]	5 Apr., glyphosate 1.2 kg ae ha^{-1} + saflufenacil 0.03 kg ai ha $^{-1}$ + dimethenameid-P 0.2 kg ai. ha^{-1} + AMS 18 g L^{-1}	19 Mar., saflufenacil 0.03 kg ai. ha $^{-1}$ + dimethenameid-P 0.2 kg ai ha^{-1} + glyphosate 1.2 kg ae ha^{-1} + AMS 18 g L^{-1}	17 May, atrazine 1.5 kg ai ha^{-1} + S-metolachlor 1.5 kg ai ha^{-1} + mesotrione 0.2 kg ai ha^{-1} + MSO 1% v/v + UAN 2.34 L ha^{-1} + Glyphosate 1.2 kg a.e. ha^{-1}	14 May, atrazine 1.5 kg ai ha^{-1} + S-metolachlor 1.5 kg ai ha^{-1} + mesotrione 0.2 kg ai ha^{-1}	13 Nov. 2013, simazine 1.1 kg ai ha^{-1} + glyphosate 0.6 kg a.e. ha^{-1} + 2, 4-D 2.7 kg ae ha^{-1} + COC 2.34 L ha^{-1}	5 May, atrazine 1.5 kg ai ha^{-1}+ s-metolachlor 1.5 kg ai ha^{-1}+ mesotrione 0.2 kg ai ha^{-1} + glyphosate 1.2 kg a.e. ha^{-1}
Postemergence	17 May, acetochlor 3.2 kg ai ha^{-1}	10 May, atrazine 1.5 kg ai ha^{-1} + S-metolachlor 1.5 kg ai ha^{-1} + glyphosate 1.2 kg a.e. ha^{-1} + 0.25% v/v NIS		11 June, glyphosate 1.2 kg a.e. ha^{-1}	24 May, atrazine 1.5 kg ai ha^{-1} + S-metolachlor 1.5 kg ai ha^{-1} + glyphoshate 1.2 kg a.e. ha^{-1} + 0.25% v/v NIS	
Insect management	17 May, Lambda-cyhalothrin 0.02 kg ai ha^{-1}	10 May, Lambda-cyhalothrin 0.02 kg ha^{-1}	NA	NA	NA	NA
Disease management	NA	NA	NA	NA	10 July, azoxystrobin 0.08 kg ai ha^{-1}	NA

Note. [†] Abbreviations: AA, anhydrous ammonia; ae, acid equivalent; ai, active ingredient; AN, ammonium nitrate; COC, crop oil concentrate; MSO, Methylated seed oil; NA, none applied; and UAN, urea ammonium nitrate.

[‡] Chemical Names: acetochlor, 2-chloro-N-(ethoxymethyl)-N-(2-ethyl-6-methylphenyl)acetamide; atrazine, 1-Chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine; azoxystrobin, Methyl (2E)-2-(2-{[6-(2-cyanophenoxy) pyrimidin-4-yl]oxy}phenyl)-3-methoxyacrylate; dimethenameid-P, 2-chloro-N-(2,4-dimethylthiophen-3-yl)-N-[(2S)-1-methoxypropan-2-yl]acetamide; glyphosate, N-(phosphonomethyl)glycine; lambda-cyhalothrin, 3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethyl-cyano(3-phenoxyphenyl)methyl cyclopropanecarboxylate; S-metolachlor, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(2S)-1-methoxypropan-2-yl]acetamide; nitrapyrin, 2-chloro-6-(trichloromethyl)pyridine; simazine, 6-chloro-2-N,4-N-diethyl-1,3,5-triazine-2,4-diamine; and sulflufenacil, 2-chloro-4-fluoro-5-[3-methyl-2,6-dioxo-4-(trifluoromethyl)pyrimidin-1-yl]-N-[methyl(propan-2-yl)sulfamoyl]benzamide.

Table 3. Field management information for soybean sites following corn fertilizer treatments at Novelty (2012-2015) and Albany (2014-2015)

Management information[†]	2012 Novelty	2013 Novelty	2014		2015	
			Novelty	Albany	Novelty	Albany
Plot size (cm)	3 by 12	3 by 12	3 by 15	3 by 10	3 by 10	3 by 15
Hybrid or cultivar	Ag3730	Morsoy LL 3759N	Stine 38LE02	AG 3731	Stine 38LEO2	Asgrow 3934
Planting date	25 Apr.	17 May	8 May	15 May	2 Jul.	2 Jul.
Row spacing (cm)	38	19	20	76	19	76
Seeding rate (seeds ha^{-1})	444,800	395,400	444,800	385,500	469,000	370,000
Harvest date	9 Oct.	10 Oct.	18 Oct.	27 Oct.	20 Oct.	12 Nov.
Tillage	No-till	No-till	No-till	Minimum	No-till	No-till
Weed management						
Burndown/PRE[‡]	25 Apr., saflufenacil 0.035 kg ai ha^{-1} + 0.25% v/v NIS + UAN 2.5 L ha^{-1} + glyphosate 1.2 kg ae ha^{-1}	17 May, saflufenacil 0.035 kg ai ha^{-1} + glyphosate 1.2 kg ae ha^{-1} + UAN 2.5 L ha^{-1} + MSO 1% v/v	23 May glufosinate 0.8 kg ai ha^{-1} + AMS 18 g L^{-1}	15 May, S-metolachlor 2.2 kg ai ha^{-1} + metribuzin O.53 kg ai ha^{-1}	3 Apr., duflufenacil 0.3 kg ai ha^{-1} + dimethenamid-P 0.17 kg ai ha^{-1} + glyphosate 0.87 kg ae ha^{-1} + 0.25% v/v NIS+ AMS 18 g L^{-1}	S-metolachor 1.5 kg ai ha^{-1} + metribuzin 0.4 kg ai ha^{-1}
Postemergence	24 May, fomesafen 0.35 kg ha^{-1} + glyphosate 1.2 kg ae ha^{-1} + UAN 2.3 L ha^{-1} + 0.25% v/v NIS	4 June, glufosinate 0.8 kg ai ha^{-1} + AMS 18 g L^{-1} 1 July, glufosinate 0.8 kg ai ha^{-1} + S-metolachor 1.36 kg ai ha^{-1} + fomesafen 0.3 kg ai ha^{-1} + AMS 18 g L^{-1} + 0.25% v/v NIS	25 May S-metolachor 1.36 kg ai ha^{-1} + fomesafen 0.3 kg ai ha^{-1} + AMS 18 g L^{-1} + 0.25% v/v NIS	3 June, glyphosate 1.2 kg ae ha^{-1}	6 Jul., glyphosate 1.58 kg ae ha^{-1} + fomesafen 0.3 kg ai ha^{-1} + S-metolachor 1.2 kg ai ha^{-1}	Glyphosate 1.26 kg ae ha^{-1}
	22 June, glyphosate 1.2 kg ae ha^{-1} + AMS 18 g L^{-1} + 0.25% v/v NIS		9 July, glufosinate 0.8 kg ha^{-1} + flumiclorac-pentyl 0.48 kg ai ha^{-1} + AMS 18 g L^{-1} + 0.25% v/v NIS			
Insect management	NA	NA	NA	NA	NA	NA
Disease management	NA	NA	10 July, azoxystrobin 0.08 kg ai ha^{-1}	NA	NA	NA

Note. [†] Abbreviations: ae, acid equivalent; a.i., active ingredient; COC, crop oil concentrate; MSO, Methylated seed oil; NIS, non-ionic surfactant; NA, none applied; and UAN, urea ammonium nitrate.

[‡] Chemical name: azoxystrobin, Methyl (2E)-2-(2-{[6-(2-cyanophenoxy)pyrimidin-4-yl]oxy}phenyl)-3-methoxyacrylate; flumiclorac-pentyl, pentyl 2-[2-chloro-5-(1,3-dioxo-4,5,6,7-tetrahydroisoindol-2-yl)-4-fluorophenoxy]acetate; dimethenameid-P, 2-chloro-N-(2,4-dimethylthiophen-3-yl)-N-[(2S)-1-methoxypropan-2-yl]acetamide; fomesafen, 5-[2-chloro-4-(trifluoromethyl)phenoxy]-N-methylsulfonyl-2-nitrobenzamide; glufosinate, 2-amino-4-[hydroxy(methyl)phosphoryl]butanoic acid; glyphosate, N-(phosphonomethyl)glycine; metrabuzin, 4-amino-6-tert-butyl-3-methylsulfanyl-1,2,4-triazin-5-one; S-metolachlor, 2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(2S)-1-methoxypropan-2-yl]acetamide; and sulflufenacil, 2-chloro-4-fluoro-5-[3-methyl-2,6-dioxo-4-(trifluoromethyl)pyrimidin-1-yl]-N-[methyl(propan-2-yl)sulfamoyl]benzamide.

In 2014, upstate Missouri experienced record yields due not only to cool summer temperatures (data not presented), but also to uniform distribution of precipitation, with Novelty receiving 771 mm and Albany receiving 751 mm. In 2015, precipitation at Albany and Novelty was above average, which delayed soybean planting.

Initial soil samples were taken from each site (Table 1). Soil test P levels were very low (Novelty in 2011, 2012), low (Novelty in 2013, 2014, and Albany in 2013), and medium (Albany in 2014) according to Buchholz et al. (2004). Soil test Zn levels were low (Novelty in 2011, 2012, and 2013) or medium (Novelty in 2014, Albany in 2013 and 2014) (Buchholz, Brown, Garret, Hanson, & Wheaton, 2004). Finally, soil test S was medium across all site-years (Buchholz et al., 2004).

3.2 Corn Response

Corn plant population was similar at all site-years (Novelty in 2011 and 2012, $P = 0.86$, and Novelty and Albany in 2013 and 2014, $P = 0.92$). Ear leaf tissue concentration at VT for P, S, and Zn were combined over the two years (Novelty in 2013 and 2014) where the measurements were collected due to an absence of a significant interaction between years. These sites had low soil test P and low-to-medium soil test Zn. Ear leaf P concentrations ranged from 2.38 to 3.13 g kg^{-1} (Table 4). All treatments, except the non-treated control, were similar and were within the sufficiency range for ear leaf P concentrations (2.5 to 5.0 g kg^{-1}) (Jones et al., 1967; Bryson et al., 2014). The non-treated control had 2.4 g kg^{-1} P, which was below the plant sufficiency range (Jones et al., 1967; Bryson et al., 2014). Concentrations of ear leaf S and ear leaf P were similar. All treatments were similar, and they were up to 0.2 g kg^{-1} greater than the non-treated no N or no P controls. All treatments including P and N were within the ear leaf sufficiency range (1.5 to 4.0 g kg^{-1}) for Zn (Jones, 1967; Bryson et al., 2014). Ear leaf S concentrations ranged from 1.6 to 2.1 g kg^{-1} and were greater than the no N and no P controls. Similar results for ear leaf P and S concentrations were reported in Iowa (Sawyer & Barker, 2010). There was no clear effect of Zn on P concentration, similar to other research evaluating P-Zn interactions (Keefer et al., 1972; Rehm et al., 1981).

Table 4. Corn ear SO_4-S concentration for Zn treatments at Novelty from 2013-2014. Data were combined over years. All P amounts were 80 kg P_2O_5 ha^{-1}

Zn treatments[†]	Zn amount	P	Zn	SO_4-S
	---- kg ha^{-1} ----	---- g kg^{-1} ----	---- mg kg^{-1} ----	---- g kg^{-1} ----
Non-treated control	0	2.4	20.9	1.7
N only control	0	2.9	30.2	2.1
DAP	0	2.8	28.6	2.0
DAP + $ZnSO_4$	2.2	3.0	29.4	2.1
DAP + $ZnSO_4$	5.6	3.0	30.4	2.1
MAP	0	3.0	28.5	2.1
MAP + $ZnSO_4$	2.2	2.9	27.5	2.0
MAP + $ZnSO_4$	5.6	2.8	27.7	1.9
MES10	0	2.8	26.1	1.9
MESZ	2.2	2.9	27.1	2.0
MAP + AS	0	3.1	27.7	2.1
MAP + SuperZn	2.2	3.1	27.7	2.0
MAP + SuperZn	5.6	3.0	29.1	2.0
DAP + AS	0	3.0	27.2	2.1
DAP + SuperZn	2.2	3.0	26.5	2.0
DAP + SuperZn	5.6	3.1	29.2	2.0
LSD ($P = 0.05$)		0.3	2.9	0.2

Note. † Abbreviations: AMS, ammonium sulfate; DAP, diammonium phosphate; MAP, monoammonium phosphate.

Ear leaf Zn concentrations were interesting because the N-only control treatment had the second highest Zn concentration, which indicated sufficient plant available Zn in the soil. An application of DAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1} and N-only treatments had 4.13 to 9.43 mg kg^{-1} greater ear leaf Zn concentration than MES10 and the non-treated control. The non-treated, no N control was 5.15 to 9.43 mg kg^{-1} less than all other treatments for ear leaf Zn concentration, but this was probably due to N affecting Zn uptake. These data indicate no clear impact of the Zn treatments on ear leaf Zn concentration over the two years ear leaves were collected since the N-only control had ear leaf Zn concentrations similar to the Zn treatments. A corn fertilizer study in West Virginia with three amounts of Zn (0, 3.36, and 6.72 kg Zn ha^{-1}) also observed no-yield response to Zn treatment (Stout & Bennett, 1983). An efficacy study of ZnO concluded that it and $ZnSO_4$ had similar plant nutrient recovery when incorporated in the soil; however, $ZnSO_4$ had a greater plant recovery than ZnO when the fertilizer was band- or surface-applied (McBeath & McLaughlin, 2014). In Michigan, a three-year study with 220 kg of fertilizer ha^{-1} comparing MAP and DAP observed no change in tissue P or Zn concentration and detected no yield difference between MAP and DAP (Yerokun & Christenson, 1990). In addition, P fertility did not appear to decrease Zn uptake, similar to Halim et al. (1968).

A significant two-way interaction occurred between treatments and site-years for corn grain yield; therefore, data were analyzed by individual site-years and reported separately (Table 5). In a planned comparison, contrasts comparing Zn amounts (2.2 vs 5.6 kg Zn ha^{-1}), Zn sources (SuperZn vs. $ZnSO_4$), and P sources (MAP vs. DAP) showed no significant differences in yield for the four site-years (Novelty and Albany in 2014 and 2015) that were evaluated (data not presented). At Novelty in 2011, all treatments yielded 6,670 to 7,860 kg ha^{-1} greater than the non-treated, no-N control with yields from 9,090 to 10,280 kg ha^{-1} (Table 5). With the extreme drought in 2012, yields were low (1,120 to 1,770 kg ha^{-1}). The non-treated control, N-only, and MESZ yielded 531 to 643 kg ha^{-1} greater than MAP, MAP+$ZnSO_4$ at 2.2 kg Zn ha^{-1}, MAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1}, and MAP+AMS. At Novelty in 2013, MAP+SuperZn at 5.6 kg Zn ha^{-1} and DAP+AMS increased yields 560 to 2,850 over the non-treated control, N-only control, DAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1}, and DAP+$ZnSO_4$ at 2.2 kg Zn ha^{-1}.

Table 5. Corn grain yield response to Zn treatments at Novelty (2011-2014) and Albany (2013-2014). Phosphorus was applied at 90 kg P_2O_5 ha^{-1}

Zn treatments[†]	Zn amount	Novelty				Albany	
		2011	2012	2013	2014	2013	2014
	-- kg ha^{-1} --						
Non-treated control	0.0	2,420	1,770	6,800	12,700	6,520	7,240
N only control	0.0	9,090	1,710	9,080	16,180	6,990	8,970
DAP	0.0	9,420	1,380	9,420	15,950	6,930	9,200
DAP + $ZnSO_4$	2.2	9,230	1,600	9,040	16,800	6,520	10,420
DAP + $ZnSO_4$	5.6	9,480	1,620	9,010	15,820	6,520	8,760
MAP	0.0	9,740	1,180	9,200	16,480	6,590	10,540
MAP + $ZnSO_4$	2.2	10,270	1,120	9,620	16,340	6,590	9,870
MAP + $ZnSO_4$	5.6	9,660	1,130	9,470	16,800	6,660	10,420
MES10	0.0	9,890	1,420	9,500	16,710	6,590	8,810
MESZ	2.2	10,280	1,750	9,610	16,130	6,790	7,210
MAP + AS	0.0	9,800	1,120	9,350	16,140	6,660	8,710
MAP + SuperZn	2.2	-[‡]	-	9,500	16,280	7,260	10,200
MAP + SuperZn	5.6	-	-	9,650	16,730	6,660	10,230
DAP + AS	0.0	-	-	9,640	16,490	6,660	9,470
DAP + SuperZn	2.2	-	-	9,510	14,790	6,660	10,220
DAP + SuperZn	5.6	-	-	9,400	16,580	6,930	8,560
LSD (P = 0.05)		1,260	450	540	806	NS	1,580

Note. [†] Abbreviations: AMS, ammonium sulfate; DAP, diammonium phosphate; MAP, monoammonium phosphate.

[‡] Treatments were not applied at these two locations.

All other treatments had similar grain yields. Grain yields at Albany in 2013 were similar among treatments (P = 0.57). In 2014, both Novelty and Albany experienced exceptionally high yields (12,700 to 16,800 kg ha^{-1} and 7,210 to 10,540 kg ha^{-1}, respectively), due to good overall precipitation (Figure 1) and low temperatures during pollination and grain fill (data not presented). At Novelty, DAP+$ZnSO_4$ at 2.2 kg Zn ha^{-1}, MAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1}, MES10, and MAP+SuperZn at 5.6 kg Zn ha^{-1} had 763 to 4098 kg ha^{-1} greater yields than the non-treated control, DAP, DAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1}, or DAP+SuperZn at 2.2 kg Zn ha^{-1}. At Albany in 2014, MAP alone yielded 1,570 to 3,300 kg ha^{-1} greater than the non-treated control, N-only, MES10, MESZ, DAP+SuperZn at 5.6 kg Zn ha^{-1}, DAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1}, and MAP+AMS. Albany had medium soil test P, S, and Zn, which likely resulted in limited yield differences among treatments (Table 1). An increase in corn grain yield has been related to P uptake which has been greater than Zn fertility (Rehm et al., 1983), and there was no apparent Zn-P interaction which was similar to other research (Rehm et al., 1981).

Table 6. Corn grain protein concentrations at Novelty (2011-2014) and Albany (2013-2014). Data combined over years were denoted. Phosphorus was applied at 90 kg P_2O_5 ha^{-1}

Zn treatments[†]	Zn amount	Novelty 2011	Novelty 2013 and 2014[‡]	Albany 2013 and 2014[‡]
	---- kg ha^{-1} ----	------------------------------ g kg^{-1}	------------------------------	------------------------------
Non-treated control	0	70	69	73
N only control	0	94	84	75
DAP	0	96	85	79
DAP + $ZnSO_4$	5.6	96	85	80
DAP + $ZnSO_4$	2.2	95	85	80
MAP	0	89	84	77
MAP + $ZnSO_4$	5.6	94	84	83
MAP + $ZnSO_4$	2.2	96	85	75
MES10	0	95	84	77
MESZ	2.2	94	83	81
MAP + AS	0	95	85	82
MAP + SuperZn	2.2	-	84	82
MAP + SuperZn	5.6	-	83	82
DAP + AS	0	-	83	83
DAP + SuperZn	2.2	-	83	80
DAP + SuperZn	5.6	-	83	83
LSD ($P = 0.05$)		7	2	5

Note. [†] Abbreviations: AMS, ammonium sulfate; DAP, diammonium phosphate; MAP, monoammonium phosphate.

[‡] Data were combined over years.

[§] Treatments were not applied during these two years.

Grain oil, protein, and starch concentrations were observed at Novelty (2011, 2013, and 2014) and Albany (2013 and 2014), but none of the treatments affected grain oil concentration at any site-year [(Novelty in 2011 and 2012, $P = 0.41$) (Novelty and Albany in 2013 and 2014, $P = 0.16$)] (data not presented). Grain protein at Novelty in 2013 and 2014 as well as Albany in 2013 and 2014 had no treatment-by-year interaction, so data were combined over years (Table 6). At Novelty in 2011, protein concentration ranged from 70 to 96 g kg^{-1}. All fertilizer treatments were similar, but they were 19 to 26 g kg^{-1} greater than the no N, non-treated control. Novelty in 2012 showed no significant difference ($P = 0.11$) among treatments, which likely was due to extreme drought (data not presented). At Novelty and Albany in 2013 and 2014, protein concentration with MAP+AMS was significantly greater than MAP+SuperZn at 5.6 kg Zn ha^{-1} and the non-treated control by 3 and 15 g kg^{-1}, respectively. All other fertilized treatments had similar protein concentrations that ranged from 83 to 85 mg kg^{-1}. At Albany in 2013 and 2014, protein concentrations ranged from 73 to 83 g kg^{-1}. DAP+AMS, MAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1}, and DAP+SuperZn at 5.6 kg Zn ha^{-1} had 6 to 11 g kg^{-1} greater protein concentration than the non-treated control, N-only, MAP, MES10, and MAP+$ZnSO_4$ at 2.2 kg Zn ha^{-1}. At Novelty in 2011, the non-treated control had 64 to 170 g kg^{-1} higher starch concentration than all other treatments (Table 7). MAP had 68 to 124 g kg^{-1} greater starch concentration than all other fertilizer treatments. Novelty in 2012 showed no differences among treatments ($P = 0.87$). At Novelty in 2013 and 2014, the non-treated control was 52 to 96 g kg^{-1} greater than all treatments except DAP+AMS. At Albany in 2013 and 2014, DAP, DAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1}, MAP+$ZnSO_4$ at 2.2 kg Zn ha^{-1}, and DAP+SuperZn at 2.2 kg Zn ha^{-1} had 59 to 100 g kg^{-1} greater grain starch concentration than MAP+SuperZn at 2.2 kg Zn ha^{-1}, DAP+SuperZn at 5.6 kg Zn ha^{-1}, DAP+SuperZn at 2.2 kg Zn ha^{-1}. At Albany in 2013 and 2014, all treatments had similar starch concentrations ($P = 0.17$). Although significance occurred at five site-years for protein and three site-years for starch concentrations, differences were inconsistent. The relationship between nitrogen and corn protein concentration is commonly observed (Uribelarrea, Below, & Moose, 2004); however, Kaiser and Lamb (2008) showed protein contents were lower when P was applied, compared to no P application, especially at 120 kg N ha^{-1} and greater N applications. However, we did not observe this in our research.

3.3 Soil Test P, S, and Zn Following Corn

Treatments with applied P fertilizer had 16 to 37 kg ha^{-1} greater soil test P than the non-treated control and the N-only treatment (Table 8). The largest soil test P was DAP+SuperZn at 5.6 kg Zn ha^{-1}, which had 16 to 33 kg ha^{-1} greater soil test P than the non-treated control, N-only, MAP, DAP, DAP+SuperZn at 2.2 kg Zn ha^{-1}, and MAP+SuperZn at 2.2 kg Zn ha^{-1}. However, the DAP treatment had 14.8 kg ha^{-1} less soil test P than MAP+SuperZn at 5.6 kg Zn ha^{-1}, while all other treatments with P had similar soil test P.

Table 7. Grain starch concentrations at Novelty (2011, 2013-2014) and Albany (2013-2014). Data were combined over years were denoted. Phosphorus was applied at 90 kg P_2O_5 ha^{-1} for all treatments including P

Zn treatments[†]	Zn amount	Novelty 2011	Novelty 2013-2014[‡]
	kg ha^{-1}	----------------------------- g kg^{-1}	--------------------------
Non-treated	0	731	739
N-Only	0	716	732
DAP	0	712	730
DAP + $ZnSO_4$	2.2	716	732
DAP + $ZnSO_4$	5.6	716	730
MAP	0	724	732
MAP + $ZnSO_4$	2.2	715	730
MAP + $ZnSO_4$	5.6	714	732
MES10	0	718	732
MESZ	2.2	718	732
MAP + AS	0	714	730
MAP + SuperZn	2.2	-[§]	732
MAP + SuperZn	5.6	-	734
DAP + AS	0	-	734
DAP + SuperZn	2.2	-	730
DAP + SuperZn	5.6	-	730
LSD (*P* = 0.05)		61	49

Note. [†] Abbreviations: AMS, ammonium sulfate; DAP, diammonium phosphate; MAP, monoammonium phosphate.

[‡] Data were combined over years. No differences among treatments were observed in 2012.

[§] Treatments were not applied during these two years.

Table 8. Soil test P, Zn, and SO_4-S after corn harvest at Novelty and Albany (2013-2014). Phosphorus was applied at 90 kg P_2O_5 ha^{-1} for all treatments including P

Zn treatments[†]	Zn amount	P[‡]	Zn		SO_4-S	
			Novelty[§] 2013 and 2014	Albany[§] 2013 and 2014	Novelty[§] 2013 and 2014	Albany[§] 2013 and 2014
	--- kg ha^{-1} ---	kg ha^{-1}	------ mg ha^{-1} -----	------ mg ha^{-1} ------	----- mg ha^{-1} -----	------ mg ha^{-1} ------
Non-treated	0	33.8	0.58	0.80	4.48	5.40
N-Only	0	31.6	0.56	0.70	4.08	4.19
DAP	0	48.3	0.61	1.20	4.26	4.61
DAP + $ZnSO_4$	2.2	50.8	0.84	2.20	5.40	4.64
DAP + $ZnSO_4$	5.6	55.1	1.42	1.00	5.02	5.23
MAP	0	49.4	0.66	2.00	4.57	5.88
MAP + $ZnSO_4$	2.2	58.7	1.08	1.30	4.86	4.69
MAP + $ZnSO_4$	5.6	53.3	2.32	2.00	5.34	5.48
MES10	0	55.4	0.62	1.40	6.64	5.24
MESZ	2.2	56.1	1.08	1.10	5.55	4.59
MAP + AS	0	55.5	0.67	0.90	5.40	6.20
MAP + SuperZn	2.2	50.2	0.84	1.10	4.89	5.33
MAP + SuperZn	5.6	61.5	1.37	1.56	4.79	5.93
DAP + AS	0	53.9	0.67	0.90	4.76	5.45
DAP + SuperZn	2.2	48.7	1.10	1.10	5.41	5.50
DAP + SuperZn	5.6	64.8	2.44	1.50	4.80	5.13
LSD		12.9	0.58	NS	0.96	0.75

Note. [†] Abbreviations: AMS, ammonium sulfate; DAP, diammonium phosphate; MAP, monoammonium phosphate.

[‡] Data were combined over sites and years.

[§] Data were combined over years.

Soil test S and Zn had a significant site-year-by-treatment interaction, but due to similar soil series, data were combined over years for individual sites and analyzed. Soil test Zn ranged from 0.56 to 2.44 mg ha^{-1} and 0.71 to 1.56 mg ha^{-1} at Novelty and Albany, respectively. All treatments had at least medium soil test Zn at the end of the growing season (Buchholz et al., 2004). When Zn was applied at Novelty in 2013 and 2014, soil test Zn generally increased compared to fertilizer treatments that had no Zn. DAP+SuperZn at 5.6 kg Zn ha^{-1} and MAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1} had significantly greater soil test Zn than all other treatments, while all other treatments with P, S, or Zn, were similar. At Albany, DAP+$ZnSO_4$ at 2.2 kg Zn ha^{-1} and MAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1}, and MAP had 1.1 to 1.5 mg kg^{-1} greater soil test Zn than DAP+AMS, MAP+AMS, N-only, and the non-treated control, but all other treatments were similar. This indicates that even though there was no crop yield response to Zn, soil buildup occurred.

Table 9. Soybean plant population, grain yield, oil, and protein concentration response to fertilizer treatments applied the previous year at Novelty (2012-2015) and Albany (2014-2015)

Zn treatments[†]	Zn amount	Population		Yield		Oil		Protein	
		2012-13	2014-15	2012-13	2014-15	2012-13	2014-15	2012-13	2014-15
	-- kg ha^{-1} --	------- plants ha^{-1} -------		-------- kg ha^{-1} -------		--------------------- g kg^{-1} ----------------------			
Non-treated	0	307,600	321,700	2,640	2,900	197	189	352	349
N-only	0	314,300	317,000	2,670	3,120	193	189	357	348
DAP	0	310,100	292,300	2,570	3,170	192	188	360	349
DAP + ZnSO4	2.2	331,600	312,100	2,620	3,080	193	188	358	347
DAP + ZnSO4	5.6	122,800	336,800	2,620	3,130	192	189	358	347
MAP	0	340,300	321,000	2,550	3,120	191	188	360	348
MAP + ZnSO4	2.2	316,500	333,600	2,590	3,140	192	188	359	349
MAP + ZnSO4	5.6	280,000	309,400	2,600	3,120	193	188	357	347
MESZ	2.2	333,600	333,100	2,623	3,140	191	189	360	349
MES10	0	340,300	311,600	2,650	3,130	193	188	357	346
MAP + AMS	0	323,000	302,500	2,660	3,130	192	188	358	348
MAP + SuperZn	2.2	-[‡]	317,500	-	3,210	-	189	-	347
MAP + SuperZn	5.6	-	299,700	-	3,190	-	189	-	344
DAP + AMS	0	-	299,700	-	3,230	-	189	-	346
DAP + SuperZn	2.2	-	295,000	-	3,060	-	190	-	347
DAP + SuperZn	5.6	-	333,100	-	3,130	-	189	-	348
P-value		0.5	0.15	0.85	0.16	0.42	0.37	0.33	0.46

Note. [†] Population and yield data were determined for all site-years. Grain oil and protein data were determined at all site-years except Albany in 2014. Data were combined over site-years unless denoted otherwise.

Abbreviations: AMS, ammonium sulfate; DAP, diammonium phosphate; MAP, monoammonium phosphate.

[‡] Treatments were not applied during these two years.

Soil test S ranged from 4.1 to 6.6 mg kg^{-1} and 4.2 to 6.2 mg kg^{-1} at Novelty and Albany, respectively. All treatments had medium soil test S. At Novelty, all treatments with S or Zn had similar soil test S levels (Buchholz et al., 2004). MESZ and MES10 had 0.98 to 2.56 higher soil test S amounts than the non-treated control, N-only, DAP, and MAP. At Albany, MAP+AMS had a 1.07 to 2.01 mg kg^{-1} greater soil test S concentration than DAP+SuperZn at 5.6 kg Zn ha^{-1}, MAP+ZnSO$_4$ at 2.2 kg Zn ha^{-1}, DAP+ZnSO$_4$ at 2.2 kg Zn ha^{-1}, DAP, and N-only. Treatments that included AMS, MES10, and MESZ had similar soil test S concentrations. Post-harvest soil samples showed no significant differences among treatments for potassium (P = 0.7), magnesium (P = 0.75), calcium (P = 0.54), or organic matter (P = 0.2) levels (data not presented).

3.4 Soybean Response Following Corn

Soybean plant population ranged from 303,000 to 340,200 plants ha^{-1}, but was non-significant (P = 0.52) between treatments (Table 9). At Novelty and Albany in 2014 and 2015, whole-plant samples taken before physiological maturity at R6 (Fehr & Caviness, 1971) were analyzed for P, S, and Zn concentration. At Novelty in 2014 and 2015, no differences were seen in plant P (P = 0.69) or S (P = 0.26) concentration (Table 10). At Albany in 2015, no significance differences appeared between plant P (P = 0.64), S (P = 0.66), or Zn (P = 0.98) concentration; however, at Albany in 2014, P, S, and Zn concentrations were significantly different. At Albany in 2014, plant P concentration ranged from 2.48 to 3.81 g kg^{-1}. Plant P concentration in the DAP+AMS treatment was 0.57 to 1.33 g kg^{-1} greater than all treatments. The N-only control had a plant Zn concentration similar to 7 of the 16 treatments, indicating there may be no strong effect regarding application of P for soybeans between treatments applied for corn and plant P concentrations observed in soybean the following year. A 14-site study in Iowa showed increased P uptake at eight sites (Borges & Mallarino, 2003).

At Albany in 2014, whole-plant S concentration ranged from 1.95 to 2.99 g kg^{-1} (Table 10). Similar to plant P concentration, DAP+AMS had the greatest plant S concentration, which was 0.33 to 1 g kg^{-1} greater than all treatments except MAP+SuperZn at 5.6 kg Zn ha^{-1} and DAP+SuperZn at 5.6 kg Zn ha^{-1}. Interestingly, treatments including SuperZn generally had a greater plant S concentration than treatments including ZnSO$_4$. Again, this could point to the lack of a good relationship between fertilizer treatments and plant S concentrations. Similarly, when S fertilizer was applied to wheat in a wheat-soybean rotation, no significant differences were reported in soybean S concentrations (Singh et al., 2014).

Plant Zn concentration was significantly affected at both locations in 2014 and Novelty in 2015 (Table 10). At Albany in 2014, plant Zn concentrations ranged from 24.2 to 35.6 mg kg^{-1}. Similar to both plant P and S concentration data, DAP+AMS had the highest plant Zn concentration at 35.6 mg kg^{-1}, which was 5.0 to 11.4 mg kg^{-1} greater than all treatments except DAP+SuperZn at 5.6 kg Zn ha^{-1} and MAP+SuperZn at 2.2 or 5.6 kg Zn ha^{-1}. In a planned contrast comparing Zn rate (2.2 vs. 5.6 kg Zn ha^{-1}) and Zn source (SuperZn vs. $ZnSO_4$), SuperZn had significantly higher plant Zn concentration than $ZnSO_4$ (P = 0.0005), while Zn rate showed no significant difference (P = 0.12). At Novelty in 2014 and 2015, plant Zn concentration ranged from 26.1 to 34.7 mg kg^{-1}. MAP+SuperZn at 5.6 kg Zn ha^{-1} increased plant Zn concentration by 4.9 to 10.3 mg kg^{-1} over all treatments except DAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1}. In a planned contrast comparing Zn rate (2.2 vs 5.6 kg Zn ha^{-1}) and Zn source (SuperZn vs $ZnSO_4$), Zn at 5.6 kg Zn ha^{-1} increased plant Zn concentration compared to 2.2 kg Zn ha^{-1} (P = 0.0008), while Zn source was not significant (P = 0.72). These results showed completely different responses at Novelty compared to Albany.

Table 10. Soybean whole plant P, S, and Zn concentrations as affected by Zn treatments at Albany and Novelty in 2014-2015

Zn treatments†	Zn amount	Leaf P			Leaf S			Leaf Zn		
		Novelty‡	Albany		Novelty‡	Albany		Novelty‡	Albany	
			2014	2015		2014	2015		2014	2015
	kg ha^{-1}	------------ g kg^{-1} -----------			------------ g kg^{-1} -----------			------------ mg kg^{-1} ------------		
Non-treated control	0	3.1	2.58	3.8	2.2	2.10	2.5	27.3	29.5	24.9
N-only	0	3.1	2.83	3.6	2.2	2.14	2.5	28.6	28.8	24.7
DAP	0	3.1	2.55	3.7	2.1	2.18	2.5	26.1	26.0	25.4
DAP + $ZnSO_4$	2.2	3.3	2.98	3.6	2.4	2.32	2.5	34.7	28.3	24.8
DAP + $ZnSO_4$	5.6	3.1	2.65	3.8	2.3	2.28	2.5	29.6	27.7	25.4
MAP	0	3.0	2.48	3.7	2.1	1.94	2.4	29.1	24.2	24.9
MAP + $ZnSO_4$	2.2	3.2	2.60	3.4	2.3	2.14	2.4	31.5	25.7	26.1
MAP + $ZnSO_4$	5.6	3.2	2.48	3.6	2.2	2.28	2.5	28.9	27.0	25.0
MESZ	2.2	3.2	2.73	3.7	2.3	2.08	2.5	28.2	25.0	26.1
MES10	0	3.2	3.14	3.7	2.2	2.35	2.5	28.5	29.0	25.0
MAP + AMS	0	3.2	3.24	3.6	2.3	2.63	2.5	27.5	30.6	26.1
MAP + SuperZn	2.2	3.0	3.0	3.7	2.2	2.40	2.5	26.3	31.3	25.4
MAP + SuperZn	5.6	3.3	3.59	3.6	2.3	2.80	2.5	36.4	32.0	24.4
DAP + AMS	0	3.3	3.81	3.9	2.3	2.99	2.5	26.5	35.6	25.0
DAP + SuperZn	2.2	3.2	2.86	3.6	2.2	2.67	2.5	30.5	29.0	25.4
DAP + SuperZn	5.6	3.2	3.03	3.5	2.2	2.67	2.4	30.7	34.5	24.6
LSD (P = 0.05)		NS	0.04	NS	NS	0.03	NS	3.4	4.7	NS

Note. † Abbreviations: AMS; Ammonium sulfate; DAP, diammonium phosphate; MAP, monoammonium phosphate.

‡ Data were combined over years.

Nutrient concentration and total plant tissue weights were used to calculate total plant uptake of P, S, and Zn (Table 11). Although significant differences were observed in plant nutrient concentrations, all treatments were similar when total plant uptake was calculated [P (P = 0.52), S (P = 0.49), and Zn (P = 0.60)]. In 2012 and 2013, grain yields ranged from 2,380 to 2,490 kg ha^{-1}, and all treatments yielded similarly (P = 0.85) (Table 9). Seed oil and protein content were measured to determine any impact of treatments on seed quality. Seed oil ranged from 191 to 197 g kg^{-1}, with no difference between treatments (P = 0.42). Protein concentration ranged from 352 to 360 g kg^{-1}, but also showed no effects of the treatments (P = 0.46). In 2014 and 2015, soybean population, yield, oil, and protein combined over years and locations (Novelty and Albany). Soybean plant population ranged from 293,300 to 336,800 plants ha^{-1} and showed no difference among treatments (P = 0.15). Similarly, yields (2,900 to 3,200 kg ha^{-1}) showed no differences among treatments (P = 0.16) (Table 9). Grain quality (oil, protein) was also similar among treatments (P = 0.37, P = 0.46, respectively). Between treatments, seed oil concentration had a small range, 180 to 190 g kg^{-1}, and protein concentration had a narrower range, 346 to 349 g kg^{-1}.

Fertilizer applications to corn in a corn-soybean rotation had inconsistent effects on soybean yield and seed quality. Anthony et al. (2012) and Buah, Polito, and Killorn (2000) reported no difference in yield between 0 and 56 kg P ha^{-1}. However, others have shown increased yields, but at low soil test P levels (Borges & Mallarino, 2000, 2003). An Iowa study at over 112 locations showed positive yield effects from P fertilizer at only 20 sites (Haq & Mallarino, 2005). Applications of S fertilizer have also had mixed results. Divito, Echeverria, Andrade, and Sadras (2015) reported increased yields with S application, while Singh et al. (2014) reported no response to S fertilizer.

Table 11. Total soybean plant P, S, and Zn uptake at Novelty and Albany in 2014-2015. Data were combined over all site-years

Zn treatments†	Zn amount	P uptake	S uptake	Zn uptake
	kg ha^{-1}	---------- kg ha^{-1} ----------		
Non-treated control	0	17.5	12.7	1.2
N-only	0	18.1	13.4	1.3
DAP	0	21.8	15.4	1.5
DAP + $ZnSO_4$	2.2	19.0	13.9	1.5
DAP + $ZnSO_4$	5.6	19.8	14.5	1.4
MAP	0	18.0	12.9	1.4
MAP + $ZnSO_4$	2.2	18.7	13.8	1.3
MAP + $ZnSO_4$	5.6	21.1	15.0	1.5
MESZ	2.2	19.8	14.8	1.4
MES10	0	20.5	14.8	1.4
MAP + AMS	0	20.0	14.3	1.4
MAP + SuperZn	2.2	20.8	15.3	1.4
MAP + SuperZn	5.6	19.2	14.2	1.6
DAP + AMS	0	19.0	13.8	1.2
DAP + SuperZn	2.2	21.8	15.8	1.6
DAP + SuperZn	5.6	21.7	15.5	1.6
P-value		0.52	0.49	0.60

Note. † Abbreviations: AMS; Ammonium sulfate; DAP, diammonium phosphate; MAP, monoammonium phosphate.

4. Conclusion

Variation in precipitation over site-years strongly affected corn grain yields. Ear leaf P tissue concentration at VT showed fertilized treatments within the sufficiency range, with no significant difference among treatments. Ear leaf S tissue concentration at VT showed no significant differences, except for the non-treated control. All fertilized treatments were within the ear leaf S sufficiency range. All treatments were similar for ear leaf Zn concentration at VT, except for the non-treated control, which was significantly lower than all other treatments and for MES10, which was significantly lower than N-only and DAP+$ZnSO_4$ at 5.6 kg Zn ha^{-1}. Yields showed no significant differences at Novelty in 2013, and all treatments were similar at Novelty in 2011. In 2012, because of a severe drought, yields in the non-treated control were the greatest. At Novelty in 2014 and Albany in 2013 and 2014, adding S and/or Zn had no effect on yield. The rate of Zn fertilizer (2.2 vs 5.6 kg Zn ha^{-1}) also showed no significant effect on yield. When P was determined post-harvest, soil samples reflected the application of P fertilizer. Generally, when Zn was applied, soil test Zn increased. At Novelty, MES10 and MESZ had the greatest increase in soil test S, while at Albany MAP+AMS had the greatest amount of soil test S. Carry-over fertilizer from corn experiments showed differences in plant nutrient concentrations, but this had no effect on total plant nutrient (P, S, or Zn) uptake, grain yield or quality. However, at Novelty plant Zn concentration was increased with 5.6 kg Zn ha^{-1} compared to 2.2 kg Zn ha^{-1}, while Albany showed an increase in soybean Zn concentration with SuperZn when compared to $ZnSO_4$. This indicates that micro-nutrient uptake was affected by Zn rate and source, depending on the soil type.

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