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Corn Mineral Nutrition Responses to NPSFe Biofertilizer and NPKZn Briquettes

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ABSTRACT

Alternative fertilizers have been increasingly developed during recent years in order to improve crop nutrition. The efficacy of these fertilizers on corn (Zea mays L.) production has not been well examined. Alternative fertilizers of organically enhanced NPSFe biofertilizer (NPSFe) manufactured from sterilized organic additives extracted from municipal wastewater biosolids and NPKZn briquettes (briquettes) produced by compacting commercially available solid fertilizers into a super-granule between 1-3 grams were evaluated for nutrient concentrations in plant biomass and grain of corn compared to commonly used N fertilizers ammonium sulfate and urea at Jackson and Grand Junction, TN during 2011-2013. NPSFe, the briquettes, ammonium sulfate, and urea and four N application rates of 0, 85, 128/170, and 170/255 kg ha-1 were assigned to the main and sub plots, respectively, in a split plot randomized complete block design with four replicates. Aboveground plant biomass at the silking growth stage (R1) and physiological maturity stage (R6) and grain at harvest were analyzed for N, P, K, S, Fe, and Zn concentrations. NPSFe resulted in similar or lower plant N concentrations relative to the conventional fertilizers ammonium sulfate and urea. The briquettes performed equally or better in terms of plant N concentrations compared to ammonium sulfate and urea. In excessive spring precipitation, the briquettes had higher biomass N concentrations at R1. NPSFe tended to have lower P concentrations in plant biomass at R1 and R6. The briquettes had similar or higher plant P levels relative to ammonium sulfate and urea. Both NPSFe and ammonium sulfate increased S concentrations in plant biomass compared to the briquettes and urea. In conclusion, the briquettes do not consistently improve corn N, P, K, and Zn nutrition compared to the conventional fertilizers ammonium sulfate and urea. NPSFe sometimes seems to reduce corn N and P nutrition but increase Zn nutrition relative to ammonium sulfate and urea.

Keywords: Biofertilizer, Briquettes, Corn, Nitrogen, Phosphorus, Potassium, Sulfur, Iron, Zinc

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List of Abbreviations
NPSFe biofertilizer, NPSFe
NPKZn briquettes, briquettes

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INTRODUCTION

Average corn grain yields had a 126% increase from 1960 to 2012, peaking in 2009 at 10.34 Mg ha^{-1} (USDA, 2013). Although corn yields are gaining, nutritional quality in grain is decreasing (Morris and Sands, 2006; Long et al., 2004). There is still a debate as to whether this decline in grain nutrient density is the result of genetics through the development of crop cultivars bred to produce high yields and not necessarily high nutritional quality, or lower grain quality is resultant from the depletion of trace minerals in the soil (Fan et al., 2008).

According to the United States Department of Agriculture (USDA), combined secondary and micronutrient fertilizer applications have increased by 283% during the last 50 years (1960-2010) in the United States (USDA, 2010). This seems to indicate that poorer grain quality over time is more a function of breeding than a lack of nutrient replacement by fertilizer, although the likelihood of micronutrient deficiencies can gradually increase when only macronutrients are regularly applied (Cakmak, 2002). The USDA does not differentiate between secondary and micronutrient fertilizer applications, however, so exactly how much of that figure represents micronutrients as opposed to agricultural lime, for example, is uncertain. It is likely, however, that the combined secondary and micronutrient data are more reflective of agricultural lime applications owing to the fact that long-term use of inorganic fertilizers has been linked to soil acidification (Belay et al., 2002).

To date, urea and ammonium sulfate are two common agronomic N-based fertilizers used in crop production worldwide, particularly in developing nations. Over five billion kilograms of urea and just less than two billion kilograms of ammonium sulfate were produced in the United States of America in 1997 (Pellegrino, 2000). Urea supplies no secondary or micronutrients but N to crops, and ammonium sulfate supplies only S in addition to N. Thus these fertilizers are implausible to satisfy crop nutrient demands without the application of other nutrients.

Organically enhanced NPSFe and NPKZn briquettes, as two innovative alternative fertilizers, are developed for improving mineral nutrition and nutrient density in grain of crops. The organically enhanced NPSFe fertilizer bears 14.9% N, 4.3% P, 18.1% S, and 0.6% Fe, and approximately 8% organic C that is manufactured from sterilized organic additives extracted from municipal wastewater biosolids. Most of its N and all of its P, S, and Fe nutrients are contained in the municipal biosolid. Only a small portion of its N is supplemented with additional chemical N fertilizer to increase the N content of NPSFe during the production process. The briquette fertilizer is in inorganic form and supplies N, P, K, and Zn. The briquettes are manufactured with a briquetter machine that simply compresses commercially available prilled fertilizers into a briquette approximately 2.43 grams in weight without using any additional binding material. Thus the guaranteed analysis of the briquettes can be variable contingent on the proportions of different fertilizers used to form the briquette. Since a briquette has a lower surface area to volume ratio, it dissolves more slowly and thus releases nutrients in a manner that matches up with crop nutrient demands better over time, resulting in reduced losses of nutrients, particularly N. In addition, the briquettes are usually banded below soil surface. A subsoil banding application itself also helps to reduce ammonia volatilization loss (Mengel et al., 1982). This application method may be practical in developing nations where lesser acreages are farmed by one producer and his/her family.

Prior investigations on crop and soil mineral nutrition concentrations under biosolid showed mixed results. Mantovi et al. (2005) found biosolid increased N concentration in wheat grain but only increased in Cu concentration in corn grain. Weggler-Beaton et al. (2003) reported that wheat plants fertilized with biosolids had less P uptake than mineral fertilizer, but wheat and barley uptake of Zn and Cu under biosolid fertilization was similar to that of mineral fertilizer alone. Castillo et al. (2010) observed that among the bioenergy crops they tested, crop N removal was greatest when the proportion of N supplied by municipal biosolids was less than the amount of N being supplied by ammonium nitrate; crop P removal followed the same trend.

Preceding studies about the effects of organic enhanced N fertilizer and briquette fertilization on crop nutrient concentrations were limited. Singh et al. (2012) found via incubation studies that both ammonia volatilization and nitrate leaching losses were significantly reduced with organic enhanced N fertilizer, which could result in increased plant N nutrition. However, no field experiment has been conducted to validate the conclusions from Singh et al. (2012). Khalil et al. (2011) reported a 5.2% increase in wheat straw N uptake under urea super granule fertilization versus conventional prilled urea; the N uptake by wheat grain under super granular fertilization was even higher with a 9.5% increase in N uptake over conventional prilled urea.

Alternative fertilizers are expected to improve crop mineral nutrition and thus crop production relative to conventional fertilizers. The objective of this investigation was to examine the effects of NPSFe and the briquettes on nutrient concentrations in plant biomass and grain and grain yield of corn and nutrient levels after corn harvest in the soil compared to ammonium sulfate (+ P, K, and Zn supplied separately) and urea (+ P, K, Zn and S supplied separately). Only the results about mineral nutrition in plant biomass and grain of corn are reported in this publication.

MATERIALS AND METHODS

The field experiment was carried out at the University of Tennessee West Tennessee Research and Education Center (WTREC) in Jackson, Tennessee from 2011 through 2013 and the Ames Plantation in Grand Junction, Tennessee from 2012 through 2013.

Soil Description

The field experiment was carried out on a Memphis silt loam soil (fine-silty, mixed, active, thermic Typic Hapludalfs) at Jackson and a Lexington silt loam soil (fine-silty, mixed, active, thermic Ultic Hapludalfs) at Grand Junction. Soybean was the previous crop followed by a winter fallow on the fields used for this study at both sites.

Corn Planting

Corn cultivar of Dekalb 6483 (YieldGardVT Triple) was used for all the site-years. The Jackson experiment had plot size of 6.1 m wide by 9.1 m long, and was no-till planted in 76.2 cm row spacing at a seeding rate of 79,000 plants ha^{-1}. The Grand Junction experiment had plot size of 4.6 m wide by 9.1 m long, and was planted as tilled in 76.2-cm rows at a seeding rate of 79,000 plants ha^{-1}. The planting date was on 9 May at Jackson in 2011, 18 April at Jackson and 19 April at Grand Junction in 2012, and 17 April at Jackson and 29 May at Grand Junction in 2013.

Treatments

Four fertilizer types of NPSFe, the briquettes, ammonium sulfate (21% N, 24% S), and urea (46% N) were the main plots and four N application rates were the subplots in this study. A split plot randomized complete block design with four replicates was used with a total of 64 subplots per site-year.

The N application rates used were 0, 85, 170, and 255 kg N ha^{-1} at Jackson in 2011. From 2012 to 2013 at both locations the N rates used were 0, 85, 128, and 170 kg N ha^{-1} (Table 1). Since the 2011 results showed no additional growth or yield benefits resulting from the highest N application rate, the two higher N rates were lowered so as to better reflect a more economical fertilizing regime common to the farming practices in developing nations. As a result, the 2011 data (Jackson only) were analyzed separately from the other datasets, while the data from 2012 and 2013 from Jackson and Grand Junction were pooled and analyzed collectively. For simplicity hereafter the data from Jackson 2011 will be referred to as "J11", and the pooled data from both Jackson and Grand Junction in 2012 and 2013 will be referred to as "JA1213".

Table 1. Treatment descriptions at Jackson and Grand Junction during 2011 to 2013.

Treatment Number	Fertilizer Type	N Rate	P Rate	K Rate	S Rate	Zn Rate
		kg ha^{-1}				
1	Ammonium sulfate	0	45	85	1.25	5
2	Ammonium sulfate	85	45	85	98†	5
3	Ammonium sulfate	128/170*	45	85	147/195	5
4	Ammonium sulfate	170/255**	45	85	195/292	5
5	NPSFe	0	45	85	1.25	5
6	NPSFe	85	45	85	104†	5
7	NPSFe	128/170	45	85	156/207	5
8	NPSFe	170/255	45	85	207/311	5
9	NPKZn briquettes	0	45	85	1.25	5
10	NPKZn briquettes	85	45	85	2.46††	5
11	NPKZn briquettes	128/170	45	85	2.46	5
12	NPKZn briquettes	170/255	45	85	2.46	5
13	Urea	0	45	85	1.25	5
14	Urea§	85	45	85	1.25	5
15	Urea	128/170	45	85	1.25	5
16	Urea	170/255	45	85	1.25	5

*, 2011 rate was 170 kg N ha^{-1}, 2012-13 rate was 128 kg N ha^{-1}.

**, 2011 rate was 255 kg N ha^{-1}, 2012-13 rate was 170 kg N ha^{-1}.

†, S rates were higher under ammonium sulfate and NPSFe and increased with increasing N rate because they contained 24.0% and 18.1% S, respectively.

††, S rates were slightly higher under applied briquette treatments than urea because Zn was supplied as ZnSO4 in the briquettes; in the other Zn applications $ZnO/ZnSO_4$ was used which has less overall SO_4.

§, urea was applied in three equal split applications: basally, V6 and VT growth stages.

All the N fertilizer treatments except urea were applied basally. In 2011 at Jackson fertilizers were applied the day after planting, fertilizers in 2012 were applied five days and 21 days after planting at Jackson and Grand Junction, respectively, and in 2013 fertilizers were applied five days and eight days after planting at Jackson and Grand Junction, respectively. Regardless of locations and years, only one third of the N in the urea fertilizer treatment was applied basally; the other two thirds of N in that treatment were applied as two equal splits later at the six leaf growth stage (V6) and tasseling during the growing season. This treatment was used to mimic the typical N management practice in developing nations to reduce N volatilization losses. NPSFe, ammonium sulfate, and urea were all uniformly broadcast on soil surface over the entire plot. The briquettes were banded approximately 2.54 cm below the soil surface, and in between rows one and two, three and four, five and six, and seven and eight in each plot at Jackson using a small hand-driven plow. At Grand Junction the briquettes were applied in bands at the same depth but in three bands between rows one and two, three and four, and five and six per plot.

Phosphorus, K, and Zn fertilizers were applied at the uniform rates of 45 kg P ha^{-1}, 85 kg K ha^{-1}, and 5 kg Zn ha^{-1}, respectively, for all treatments (Table 1). The S rate was variable for the NPSFe and ammonium sulfate fertilizer treatments because these two fertilizers contained S as part of their guaranteed analysis. With increasing N rates, NPSFe and ammonium sulfate supplied increasing amounts of S (Table 1). For the control (0 kg N ha^{-1}), all plots received an S rate of 1.25 kg S ha^{-1} from the sulfate in the ZnO/$ZnSO_4$ fertilizer which was used to supply the uniform Zn rate.

Phosphorus was applied as triple super phosphate (TSP, 0-45-0) for the ammonium sulfate, urea, and NPSFe treatments. Since NPSFe already contained some P, it required less P supplementation from TSP to meet the uniform P application rate. At the 85, 128, 170, and 255 kg N ha^{-1} rates, NPSFe supplied 23.8%, 35.8%, 47.6%, and 71.4% of the uniform P rate, respectively. The K and Zn fertilizers of KCl (0-0-60) and ZnO/$ZnSO_4$ (36% Zn, 9% S) were applied to the ammonium sulfate, urea, and NPSFe treatments.

In this study, the briquettes were produced by the IFDC. They contained the appropriate mixture of nutrients so as to supply all the P, K, and Zn uniform rates while also applying the different N application rates according to the subplot treatment requirements. The S rate supplied from the briquettes was 2.46 kg S ha^{-1} at N rates above 0 kg N ha^{-1} (Table 1). This occurred because the S in the briquettes was supplied by $ZnSO_4$ (17.5% S). Urea, diammonium phosphate, potassium chloride, and zinc sulfate were used as the N, P, K, and Zn sources, respectively, in the briquettes. More details about the soil and crop management practices used in this study are presented in Winings et al. (2017) and Agyin-Birikorang et al. (2018).

Sampling, Analyses, and Measurements

Plant data collected were N, P, K, S, Fe, and Zn concentrations in the aboveground plant biomass at the silking growth stage (R1) and physiological maturity stage (R6), and N, P, K, S, Fe, and Zn concentrations in grain at harvest. At R1, the corn plant has transitioned from vegetative growth to reproductive growth; a critical point in the life cycle of the corn plant. Nutrient concentrations in plant biomass at R1 can help determine plant health as a function of mineral nutrition from the different fertilizer types at this critical juncture. At R6 when the corn plant has assimilated all the mineral nutrition it will for the season, nutrient concentrations at this growth stage can be used to determine the total nutrient uptake by the plant the total nutrient removal by grain during the entire growing season.

Plant biomass samples at R1 were collected as follows: 12 corn plants were harvested by hand from the center four rows and weighed using a Cardinal Detecto weigh scale model HSDC-40 (Webb City, MO) to obtain a fresh weight. From those 12 plants, two were subsampled and weighed again to obtain a subsample fresh weight. Biomass samples at R6 were collected as follows: in 2011 at Jackson and in 2012 and 2013 at Grand Junction, 12 corn plants were harvested by hand from the center four rows and weighed to obtain a fresh weight. From those 12 plants, three were subsampled and weighed again to obtain a subsample fresh weight. The procedure was the same in Jackson in 2012 and 2013 except 24 corn plants were used instead of 12; the subsamples were still three plants.

Two and three-plant biomass subsamples at R1 and R6, respectively, were oven-dried at 65ºC for approximately three days. Once dry, the sub-samples were weighed. A best dry weight representation for the entire sample was then calculated. Thereafter the biomass samples were ground to pass through a 1-mm sieve for nutrient analysis using a Thomas-Wiley Laboratory Mill model 4 (Arthur H. Thomas company, Philadelphia, PA). Total N concentrations in the plant biomass samples were determined using a combustion method with a Carlo Erba 1500 series Nitrogen/Carbon Analyzer (Carlo Erba Instruments, Milan, Italy) (Gavlak et al., 1994). Total P, K, S, Fe, and Zn concentrations in the plant biomass samples were extracted by digesting the sample in a CEM MDS 2100 series microwave (CEM Corporation, Matthews, NC) using nitric acid and hydrogen peroxide; the digest was analyzed on a Thermo Jarrel Ash 1100 ICP (Thermo Jarrell Ash Corporation, Fanklin, MA) (Gavlak et al., 1994). All the analyses of plant biomass samples were conducted by Brookside Laboratories, Inc. (New Knoxville, OH).

The center four rows at Jackson and the center three rows at Grand Junction of each plot were harvested for grain yield. A subsample of grain from each plot was ground to pass through a 1-mm sieve using the same equipment used to grind the plant biomass samples described above. The grain samples were sent to Brookside Laboratories, Inc. in New Knoxville, OH to have the total grain N, P, K, S, Fe, and Zn concentrations determined.

Statistical Analyses

Analysis of variance was performed with a split plot randomized complete block design using the mixed model macro (%MMAOV) in SAS version 9.3 (SAS Institute, Cary, NC). The four fertilizer treatment types and four N application rates were whole plots and subplots, respectively, and both were treated as fixed experimental factors. The replicates were treated as a random factor. In JA1213, year and location were also treated as fixed experimental factors. The treatment means were separated with the Fisher's protected LSD. Probability values less than 0.05 for all analyses were considered significant.

RESULTS AND DISCUSSION

Weather conditions differed during this study (Figure 1). The spring was particularly wet in April and May of 2011 and 2013 at Jackson. At Grand Junction in 2013, the mean monthly precipitation was a little more moderate during the same time period. On contrary, it was much drier at both Jackson and Grand Junction during April and May in 2012. From June to August, precipitation trends were fairly similar across location-years. However, Jackson and Grand Junction in 2012 had considerably more precipitation in September and October, whereas Jackson in 2011 and 2013 and Grand Junction in 2013 were much drier during the same time period. Mean monthly temperatures also varied across location-years (Figure 2). 2013 was cooler than 2011 and 2012 particularly during March, April, and May. Temperatures in 2012 were as much as 5.6 to 8.3 ^{o}C higher during that same time period. 2011 and 2012 were both about 3.3 ^{o}C warmer than 2013 during July. However, temperatures were more similar across location-years from August to the end of the growing season.

Nitrogen

Nitrogen concentrations in the R1 and R6 plant biomass were impacted by fertilizer types for both J11 and JA1213 but were only affected in the grain in J11. In J11, both NPSFe and the briquettes resulted in lower N concentrations in plant biomass at R1 and R6 than urea (Table 2). In JA1213, the briquettes produced higher biomass N concentrations at R1 than the other fertilizers, whereas NPSFe was similar to ammonium sulfate and urea. In the R6 biomass NPSFe produced less N concentrations than ammonium sulfate and urea; the briquettes produced similar N concentrations to ammonium sulfate and urea. In J11, NPSFe had higher N concentration in grain than the briquettes and ammonium sulfate. Increased N concentrations in wheat grain from biosolid applications were also documented by Mantovi et al. (2005). From the same study, however, only Cu concentrations increased in corn grain with biosolid fertilization. Our results seem to coincide with this finding as NPSFe with its biosolid component did not, on average, improve corn biomass or grain N concentrations relative to ammonium sulfate or urea.

Nitrogen rates had a significant impact on N concentrations in plant biomass at R1 and R6 and in the grain in both J11 and JA1213. As expected, higher N rates tended to produce significantly higher N concentrations in plant biomass and grain (Table 2). This is consistent with other scientific literature (Alfoldi et al., 1994; Al-Kaisi and Kwaw-Mensah, 2007; Ziadi et al., 2009; Sindelar et al., 2013). In J11, however, the two higher N rates did not differ in R1 biomass and grain N concentrations, but produced higher N concentrations than the two lower N rates. A similar trend was observed in JA1213 for the R6 plant biomass.

Figure 1. Average monthly precipitation during the duration of this study.

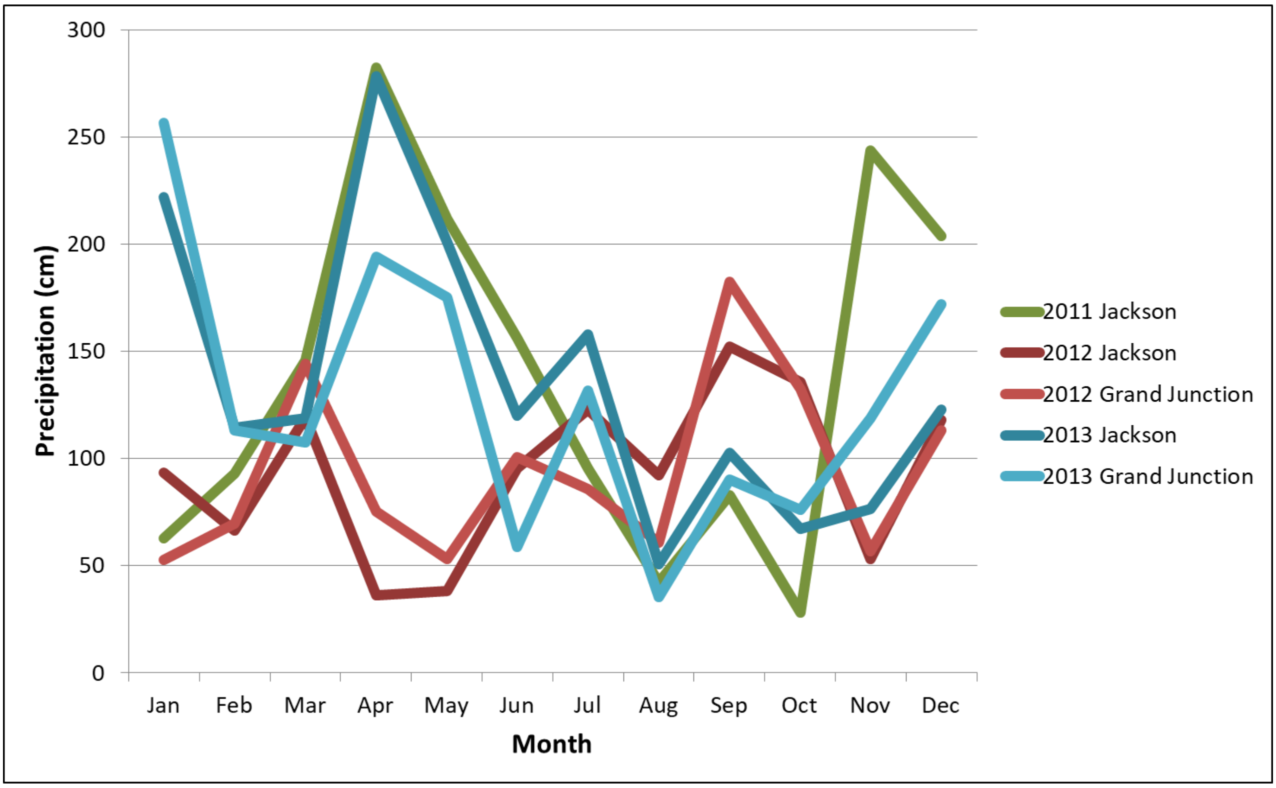

Figure 2. Average monthly temperatures during the duration of this study.

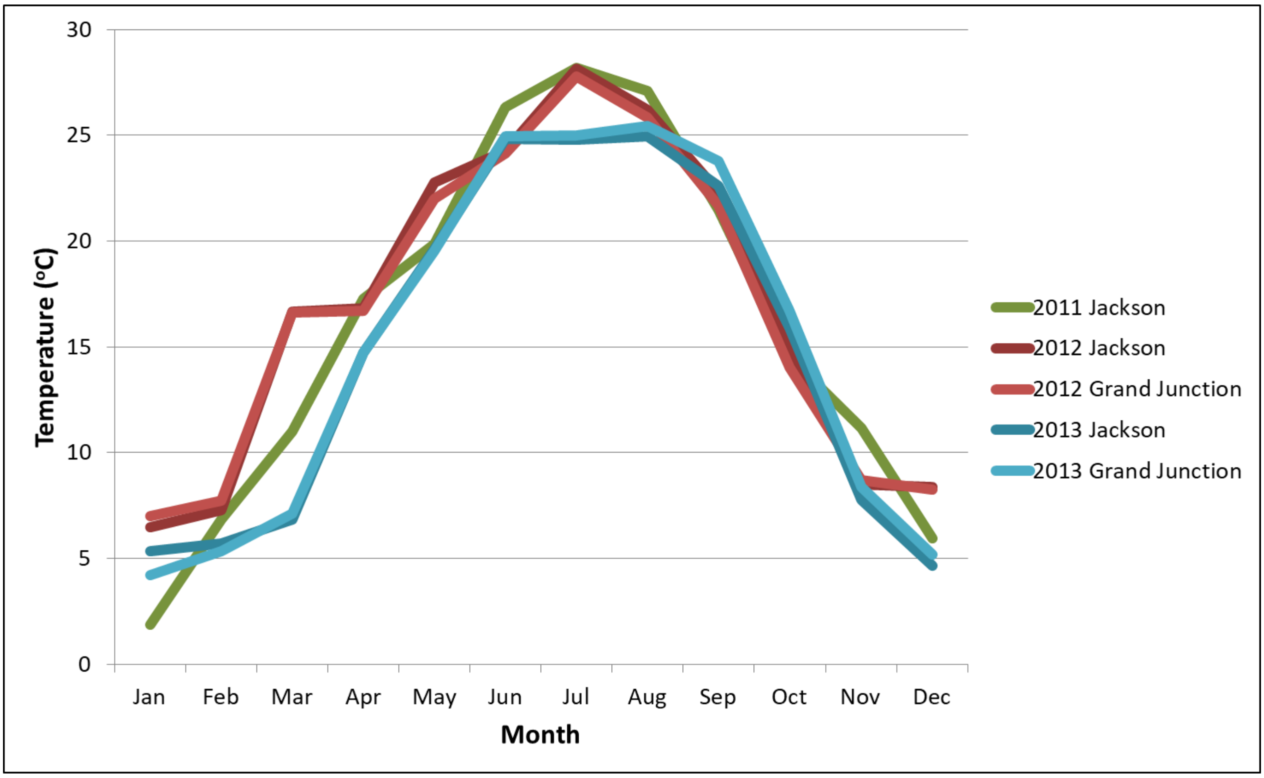

Table 2. Mean nutrient concentrations in the aboveground plant biomass at R1 and R6 and grain of corn for fertilizer types and N rates at Jackson and Grand Junction during 2011 to 2013.

	Nutrient Concentrations																	
	R1 Biomass						R6 Biomass						Harvest Grain					
	N	P	K	S	Fe	Zn	N	P	K	S	Fe	Zn	N	P	K	S	Fe	Zn
	········· $g\ kg^{-1}$ ·········				··· $\mu g\ g^{-1}$ ···		········· $g\ kg^{-1}$ ·········				··· $\mu g\ g^{-1}$ ···		········· $g\ kg^{-1}$ ·········				··· $\mu g\ g^{-1}$ ···	
J11																		
Fertilizer Type																		
NPSFe	11.69bc†	2.08b	14.77a	1.16a	50.92a	27.22a	8.69bc	1.95a	8.85a	0.95a	31.58a	25.22a	12.55a	2.32c	3.61c	0.91a	11.68a	20.72ab
NPKZn briquettes	10.76c	2.28a	15.25a	0.87b	50.16a	19.04b	8.29c	1.86a	9.33a	0.80b	34.47a	18.26c	11.73bc	2.63a	3.90a	0.89a	12.29a	19.62bc
Ammonium sulfate	11.88b	2.31a	16.11a	1.21a	55.00a	27.48a	9.50ab	1.95a	9.72a	0.95a	33.29a	23.24ab	11.65c	2.53ab	3.85ab	0.92a	12.49a	21.01a
Urea	13.30a	2.46a	16.79a	0.92b	50.93a	22.68ab	10.41a	1.91a	9.66a	0.77b	30.39a	19.35bc	12.5ab	2.43bc	3.69bc	0.85b	11.97a	19.32c
N Rate (kg N ha^{-1})																		
0	7.98c	2.32a	16.41a	0.76c	42.56b	21.23a	7.42d	2.28a	10.16a	0.78b	29.18b	25.75a	10.59c	2.56a	3.90a	0.83c	11.23b	20.50a
85	10.98b	2.26a	16.06a	1.02b	55.39a	22.78a	8.58c	1.81b	9.20a	0.84b	31.46ab	20.63b	11.73b	2.43a	3.73a	0.87b	11.42b	19.56a
170	14.06a	2.31a	15.23a	1.15a	51.82a	25.67a	9.93b	1.76b	9.19a	0.93a	34.88a	20.34b	12.79a	2.51a	2.74a	0.93a	12.84a	20.23a
255	14.62a	2.24a	15.22a	1.24a	57.24a	26.74a	10.96a	1.81b	9.01a	0.92a	34.21a	19.36b	13.32a	2.39a	3.69a	0.94a	13.00a	20.39a
JA1213																		
Fertilizer Type																		
NPSFe	10.05b	1.96c	14.21a	1.10a	58.94a	29.97a	8.05b	2.31b	6.36a	0.90a	169.05a	35.85a	10.83a	2.69a	3.57a	0.98a	15.18ab	23.14a
NPKZn briquettes	11.01a	2.19ab	15.48a	0.81c	61.49a	25.65c	8.67ab	2.49a	6.51a	0.75b	177.58a	31.76c	10.85a	2.78a	3.60a	0.94b	15.94a	22.66a
Ammonium sulfate	10.08b	2.03bc	14.62a	1.03b	56.91a	28.49ab	8.85a	2.32b	6.68a	0.87a	143.94a	33.89ab	11.05a	2.74a	3.62a	0.98a	15.61ab	23.59a
Urea	9.56b	2.24a	15.78a	0.73d	51.78a	27.01bc	9.08a	2.52a	6.26a	0.74b	162.14a	33.69b	10.92a	2.74a	3.57a	0.90c	14.86b	22.54a
N Rate (kg N ha^{-1})																		
0	7.84d	2.78a	16.82a	0.68d	62.12a	31.64a	7.44c	3.32a	7.41a	0.74d	311.08a	47.90a	10.20c	2.88a	3.79a	0.93c	13.62c	23.82a
85	9.83c	2.00b	15.45b	0.87c	53.58a	25.23c	8.61b	2.21b	6.35b	0.80c	127.48b	30.02b	10.45c	2.72b	3.62b	0.92c	15.25b	22.60b
128	10.87b	1.80c	13.75c	1.03b	56.68a	25.64c	9.10ab	2.12bc	6.16bc	0.84b	116.72c	29.32b	11.16b	2.72b	3.56b	0.96b	16.08a	22.94b
170	12.17a	1.83c	14.08c	1.10a	56.74a	28.61b	9.50a	2.00c	5.89c	0.88a	97.43d	27.95c	11.85a	2.64b	3.40c	0.99a	16.64a	22.58b

†, means in each column within the fertilizer type or N rate treatments in the J11 or JA1213 data set followed by the same letter are not significantly different at P = 0.05 according to Fisher's protected LSD.

In JA1213 there was a strong year by fertilizer type interactive effect on N concentrations in plant biomass at R1 and R6 when the data were combined across the two locations. In 2012, fertilizer types did not influence biomass N concentrations at R1, but in 2013 the briquettes produced greater N concentrations at R1 than the other treatment types (Table 4). This is most likely because 2013 had an exceptionally wet spring which would have washed prilled N fertilizers out of the soil more readily compared to the briquettes (Figure 1). Biomass N concentrations at R6 differed among the fertilizer types in 2012; NPSFe and the briquettes produced lower biomass N concentrations at R6. In 2013, the fertilizer types did not affect biomass N concentrations at R6.

In JA1213 there was also a highly significant location by fertilizer type interactive effect on biomass N concentrations at R1 in the combined data set across the two years. There was no difference in biomass N concentrations among the fertilizer types at Grand Junction, but at Jackson under no-till conditions the briquettes produced higher biomass N concentrations at R1 than the other fertilizers (Table 4). Jackson had three years of trial whereas Grand Junction only had two, thus the accumulated effects of the fertilizers at Jackson would be greater.

In summary, the performances of NPSFe and the briquettes with respect to plant N concentrations were not influenced by application N rates relative to ammonium sulfate and urea, but were influenced by years and locations. In J11, NPSFe often resulted in similar plant biomass N concentrations at both R1 and R6 as the briquettes and ammonium sulfate, but lower biomass N concentrations at R1 and R6 compared to urea on average. The briquettes reduced biomass N concentrations at R1 and R6 compared to ammonium sulfate and urea. During the 2012 and 2013 growing seasons, NPSFe resulted in similar or lower plant N concentrations relative to the conventional fertilizers ammonium sulfate and urea. The briquettes performed equally or better in terms of plant N concentrations compared to ammonium sulfate and urea.

Phosphorus

Phosphorus concentrations were influenced by fertilizer types in plant biomass at R1 and in the grain in J11 and in the R1 and R6 biomass in JA1213. In J11, NPSFe produced lower biomass P concentrations at R1 (Table 2). In JA1213 the results were somewhat similar. This is an interesting result since NPSFe contains P and therefore required less P supplementation from TSP to fulfill the uniform P application rate for this study. These results suggest that the P found in NPSFe is not as readily available to the plant as the P from the TSP. These findings are consistent with those of Warman (2005) that crop tissue P concentrations were higher under mineral fertilization compared to organic fertilization, and similar too Sneller and Laboski's (2009) findings which suggest that corn P concentrations were at least equal under mineral fertilization compared to organic fertilization. The briquettes had higher grain P concentrations than urea in J11, and higher biomass P levels at R6 than ammonium sulfate in JA1213.

Nitrogen rate effects were only significant on biomass P concentration at R6 in J11. In JA1213, N rates significantly impacted P concentrations in biomass at R1and R6 and in the grain. In all cases where N rates had a significant impact on plant P concentrations, the higher the N rate, the lower the P concentration in the plant. These results seem to suggest that a larger corn biomass stimulated by higher N application rates dilutes biomass P concentrations, but this finding is in contrast to the findings reported by Ciampitti et al. (2013) in which corn tissue P concentrations were not influenced by N rate. Alfoldi et al. (1994) also found P concentrations corn grain to be little influenced by N rate.

In JA1213 there were significant year by fertilizer type interactive effects on biomass P concentration at R1 and on grain P concentration as well. Both R1 biomass and grain P concentrations were not influenced by fertilizer type in 2012. In 2013 however, the briquettes and urea produced higher P concentrations in biomass at R1 and in the grain than NPSFe and ammonium sulfate.

In JA1213 there were also significant location by fertilizer type interactive effects on biomass P concentrations at R1 and R6. At Jackson, the briquettes and urea had higher biomass P concentrations at R1 and R6 compared to NPSFe and ammonium sulfate (Table 4). However, no such trends were observed at Grand Junction.

In summary, NPSFe resulted in similar or lower P concentrations in plant biomass compared to the ammonium sulfate and urea treatments. The briquettes had similar or occasionally higher plant P levels relative to ammonium sulfate and urea. Plant P concentrations typically decreased with an increase in the N application rate. The performances of NPSFe and the briquettes in terms of plant P concentrations were not influenced by N application rates, but were sometimes affected by years and locations. Our results suggest P in the NPSFe biofertilizer product may be less available to the plant relative to TSP, and the banded briquettes occasionally improve plant P nutrition compared to TSP applied as a broadcast.

Potassium

Potassium concentrations in plant biomass at R1 or R6 were not influenced by the fertilizer types in this study. Only in the grain in J11 did fertilizer types have a significant impact, and in this case NPSFe had the lowest grain K concentration, whereas the briquettes had the highest out of the four fertilizer types (Table 2). That NPSFe as an organically enhanced fertilizer had the lowest grain K concentration is consistent with the findings of a previous study in which organically fertilized crop tissues had significantly less K concentration than minerally fertilized crop tissues (Warman, 2005).

Nitrogen rates had no significant impact on K concentrations in plant biomass at R1 or R6 or in grain in J11, but in JA1213 N rates had highly significant influence on K concentrations in biomass at R1 and R6 and in grain. As with the N rate effects on biomass and grain P concentrations discussed above, biomass and grain K concentrations in JA1213 decreased with increasing N rates (Table 2), also in contrast to the findings of Ciampitti et al. (2013) and Alfoldi et al. (1994) in which corn tissue and grain K concentrations were not influenced by the N rate.

In JA1213 there was a significant interactive effect on biomass K concentrations at R6 between year and fertilizer type. In 2012, the briquettes produced higher biomass K concentrations at R6 than urea. However, in 2013 fertilizer types did not affect biomass K concentrations at R6 (Table 4).

In JA1213 there was also a significant interactive effect between location and fertilizer type on biomass K concentrations at R1 and R6. At Jackson, R1 K concentrations were statistically similar and significantly higher under briquette and urea fertilization than ammonium sulfate. Potassium concentrations at R6 at Jackson were significantly higher when the corn was fertilized with ammonium sulfate. However, there was no difference in biomass K concentrations at either R1 or R6 among the fertilizer types at Grand Junction (Table 4).

In summary, plant K concentrations were generally not influenced by either NPSFe or the briquettes relative to the ammonium sulfate and urea treatments. The performances of NPSFe and the briquettes on plant K concentrations were not affected by N application rates, but were sometimes affected by years and locations. Our results suggest that NPSFe and the briquettes do not improve plant K nutrition compared to the common K fertilizer potash of muriate.

Sulfur

In both J11 and JA1213, there was a highly significant interactive effect between fertilizer types and N rates on S concentrations in biomass at R1 and R6 and in grain. In J11 and JA1213, when the N rate was 0 kg N ha^{-1}, there were no differences in S concentration in biomass at R1 or R6 or in grain (Table 3); at the 85, 128, 170, and 255 kg N ha^{-1} N rates, however, biomass S concentrations at R1 and R6 were generally higher under the NPSFe and ammonium sulfate fertilizer treatments than the briquette and urea fertilizers. In J11, grain S concentrations were not different among the fertilizer types at the 85 kg N ha^{-1} rate, but at the 170 and 255 kg N ha^{-1} rates, NPSFe, the briquettes, and ammonium sulfate produced higher grain S concentrations than urea. In JA1213 at the 85, 128, and 170 kg N ha^{-1} rates, grain S concentrations were generally higher under NPSFe and ammonium sulfate than the briquettes and urea.

In general, NPSFe and ammonium sulfate produced higher S concentrations compared to the other fertilizer types because both contain S as part of their guaranteed analysis. These results are to be expected as NPSFe and ammonium sulfate have 18.1% and 24.0% S, respectively, while urea does not contain any S. The briquettes have a small amount of S as part of their make-up coming from $ZnSO_4$. Similarly, Stecker et al. (1995) also found increases in corn leaf and grain S concentrations under ammonium sulfate and ammonium thiosulfate fertilization. Pagani et al. (2008) reported similar results in corn.

In JA1213, there was a significant year by fertilizer type interactive effect on biomass S concentration at R6. In 2012, NPSFe and ammonium sulfate were similar, but produced greater biomass S concentrations at R6 than the other two fertilizers (Table 4). In 2013, however, ammonium sulfate had greater biomass S concentration at R6 than NPSFe, NPSFe had greater biomass S concentration at R6 than the briquettes and urea, and the briquettes had greater biomass S concentration at R6 than urea.

In JA1213, there was a significant location by fertilizer type interactive effect on S concentrations in biomass at R1 and in the grain. At Jackson, biomass S concentrations at R1 were higher under NPSFe and ammonium sulfate than the other two fertilizer types; NPSFe was highest in biomass S concentration (Table 4). Grain S concentrations were equally higher under NPSFe, briquette, and ammonium sulfate fertilization than urea. At Grand Junction, S concentrations in biomass at R1 and in grain were greater under NPSFe and ammonium sulfate than the briquettes and urea.

Generally, plant S concentrations were increased with NPSFe and ammonium sulfate particularly at higher N application rates compared to the briquettes and urea because both NPSFe and ammonium sulfate contain significant proportions of S in their chemical composition. The performances of NPSFe and ammonium sulfate in terms of plant S concentrations were consistently affected by N application rates, but were sometimes influenced by years and locations. Our results suggest NPSFe and ammonium sulfate are reliable S sources for improving corn S nutrition.

Iron

Iron concentrations in biomass at R1 and R6 or in the grain were not influenced by fertilizer types except for the grain Fe concentrations in JA1213. In that case, the briquettes resulted in higher grain Fe concentrations than urea (Table 2). Zheng (2010), however, suggests that Fe capture efficiency improvements are more a function of genetics than fertilizer as Fe is the fourth most abundant element in the earth’s crust. Indeed, iron deficiencies have been associated with soil chemical properties such as high soil pH, calcareous soils, and low Fe availability rather than low total soil Fe concentrations (Vose, 1982; Kraemer et al., 2006). This seems to suggest that even with an Fe contribution, NPSFe stood little chance of enhancing plant Fe concentrations.

Table 3. Interaction means of nutrient concentrations in the aboveground plant biomass at R1 and R6 and grain of corn for fertilizer types by N rates at Jackson and Grand Junction during 2011 to 2013.*

		Nutrient Concentrations				
		R1 Biomass		R6 Biomass		Harvest Grain
		S	Zn	S	Zn	S
		g kg^{-1}	μg g^{-1}	g kg^{-1}	μg g^{-1}	g kg^{-1}
J11						
N Rate (kg N ha^{-1})	**Fertilizer Type**					
0	NPSFe	0.75a†	19.55a	0.86a	—	0.79a
	NPKZn Briquettes	0.75a	20.60a	0.79a	—	0.84a
	Ammonium Sulfate	0.75a	21.75a	0.72a	—	0.87a
	Urea	0.80a	23.00a	0.74a	—	0.83a
85	NPSFe	1.17a	19.08a	0.92ab	—	0.89a
	NPKZn Briquettes	0.85c	20.73a	0.73c	—	0.87a
	Ammonium Sulfate	1.09ab	27.18a	0.94a	—	0.86a
	Urea	0.96bc	24.15a	0.78bc	—	0.85a
170	NPSFe	1.29a	32.15a	1.02a	—	0.99a
	NPKZn Briquettes	0.90b	15.60b	0.80b	—	0.93a
	Ammonium Sulfate	1.46a	32.80a	1.12a	—	0.97a
	Urea	0.96bc	22.13ab	0.78bc	—	0.84b
255	NPSFe	1.44a	38.10a	1.01a	—	0.98a
	NPKZn Briquettes	1.00b	19.25b	0.87b	—	0.93a
	Ammonium Sulfate	1.54a	28.20ab	1.03a	—	1.00a
	Urea	0.98b	21.43b	0.78bc	—	0.86b
	LSD††	0.18	10.76	0.14		0.07
JA1213						
N Rate (kg N ha^{-1})	**Fertilizer Type**					
0	NPSFe	0.67a	29.34a	0.72a	47.12a	0.93a
	NPKZn Briquettes	0.67a	32.91a	0.74a	49.38a	0.93a
	Ammonium Sulfate	0.71a	31.07a	0.75a	46.63a	0.92a
	Urea	0.67a	33.23a	0.75a	48.48a	0.92a
85	NPSFe	0.96a	22.19b	0.86a	29.33a	0.92ab
	NPKZn Briquettes	0.82b	25.57ab	0.73b	28.01a	0.92ab
	Ammonium Sulfate	0.96a	27.39a	0.87a	32.69a	0.95a
	Urea	0.73b	25.76a	0.72b	30.06a	0.88b
128	NPSFe	1.32a	30.61a	0.95a	33.37a	1.01a
	NPKZn Briquettes	0.89c	22.60b	0.76b	26.76b	0.93b
	Ammonium Sulfate	1.17b	25.98b	0.92a	29.02b	1.00a
	Urea	0.72d	23.37b	0.74b	28.14b	0.89b
170	NPSFe	1.47a	37.73a	1.05a	33.58a	1.06a
	NPKZn Briquettes	0.87c	21.51d	0.77c	22.90c	0.95b
	Ammonium Sulfate	1.28b	29.54b	0.96b	27.21b	1.05a
	Urea	0.79c	25.69c	0.75c	28.09ab	0.90c
	LSD	0.12	4.26	0.05	4.66	0.05

*, only significant interactive effects are reported.

†, means in each column within each N rate level in the J11 or JA1213 data set followed by the same letter are not significantly different at P = 0.05 according to the Fisher's protected LSD.

††LSD, least significant difference values across all means within each column.

Nitrogen rates significantly impacted Fe concentrations in biomass at R1 and R6 and in grain except in biomass at R1 in JA1213. In J11, the lowest N rate produced lower biomass Fe concentration at R1 than the other three higher N rates (Table 2); similar trends were

Table 4. Interaction means of nutrient concentrations in the aboveground plant biomass at R1 and R6 and grain of corn for fertilizer types by years or locations at Jackson and Grand Junction during 2012 to 2013.*

		Nutrient Concentrations													
		R1 Biomass				R6 Biomass						Harvest Grain			
		N	P	K	S	N	P	K	S	Fe	Zn	P	S	Fe	Zn
		··········· $g\ kg^{-1}$ ···········				··········· $g\ kg^{-1}$ ···········				··· $\mu g\ g^{-1}$ ···		··· $g\ kg^{-1}$ ···		··· $\mu g\ g^{-1}$ ···	
Year	**Fertilizer Type**														
2012	NPSFe	9.98a†	1.74a	—	—	8.09b	—	5.92ab	0.95a	—	38.71a	2.87a	—	14.82ab	24.53ab
	NPKZn Briquettes	9.35a	1.85a	—	—	8.58b	—	6.16a	0.78b	—	35.82a	2.86a	—	14.13b	23.48bc
	Ammonium Sulfate	10.10a	1.77a	—	—	9.98a	—	6.08a	0.95a	—	36.18a	2.97a	—	15.60a	25.49a
	Urea	9.23a	1.82a	—	—	9.94a	—	5.41b	0.81b	—	34.13a	2.81a	—	14.19b	23.24c
2013	NPSFe	10.13b	2.17b	—	—	8.00a	—	6.80a	0.80b	—	32.99a	2.52b	—	15.54b	21.74a
	NPKZn Briquettes	12.67a	2.53a	—	—	8.76a	—	6.86a	0.72c	—	27.70b	2.71a	—	17.76a	21.84a
	Ammonium Sulfate	10.06b	2.30b	—	—	7.71a	—	7.28a	0.84a	—	31.60a	2.52b	—	15.63b	21.70a
	Urea	9.89b	2.65a	—	—	8.22a	—	7.12a	0.67d	—	33.25a	2.68a	—	15.53b	21.85a
	LSD††	1.13	0.19			0.92		0.51	0.04		3.30	0.15		1.11	1.13
Location	**Fertilizer Type**														
Jackson	NPSFe	10.61b	2.24b	17.45ab	1.15a	—	2.79b	7.27b	—	74.15a	—	—	0.96a	—	—
	NPKZn Briquettes	12.61a	2.75a	20.12a	0.82c	—	3.19a	7.38b	—	63.74a	—	—	0.94a	—	—
	Ammonium Sulfate	10.32bc	2.37b	17.66b	0.99b	—	2.87b	8.11a	—	73.98a	—	—	0.96a	—	—
	Urea	9.25c	2.76a	20.27a	0.67d	—	3.26a	7.18b	—	61.20a	—	—	0.89b	—	—
Grand Junction	NPSFe	9.50a	1.67a	10.98a	1.06a	—	1.84a	5.44a	—	263.94ab	—	—	1.00a	—	—
	NPKZn Briquettes	9.41a	1.63a	10.84a	0.80b	—	1.80a	5.64a	—	291.41a	—	—	0.93b	—	—
	Ammonium Sulfate	9.84a	1.70a	11.59a	1.07a	—	1.77a	5.25a	—	213.91b	—	—	1.01a	—	—
	Urea	9.87a	1.71a	11.30a	0.78b	—	1.79a	5.35a	—	263.08ab	—	—	0.90b	—	—
	LSD	1.13	0.19	1.68	0.09		0.17	0.51		51.62			0.04		

*, only significant interactive effects are reported.

†, means in each column within each year or at each location in the JA1213 dataset followed by the same letter are not significantly different at P = 0.05 according to the Fisher's protected LSD.

††LSD, least significant difference values for means across years or locations within each column.

observed in Fe concentrations in biomass at R6 and in grain. In JA1213, the grain Fe concentration was significantly lower at the lowest N rate than the other N rates. In contrast, biomass Fe concentrations at R6 were higher at the lowest N rate, and decreased significantly with each succeeding increase in N rate. This biomass Fe at R6 result in JA1213 is somewhat of an oddity in that Fe concentrations decreased with increasing N rate whereas all the other plant Fe results tended to be lower with lower N rates. Ciampitti and Vyn (2013) found that at the end of the season corn biomass and grain Fe concentrations were not influenced by N rates. Further still Losak et al. (2011) reported after a two-year study that use of N fertilizers alone did not reduce Fe concentrations in corn biomass or grain. Ogunlela et al. (1988) found similar results in corn.

In JA1213, there was a strong year by fertilizer type interactive effect on grain Fe concentration. In 2012, ammonium sulfate produced greater Fe concentrations than the briquettes and urea (Table 4). In 2013, however, the briquettes produced significantly greater grain Fe concentrations than the other fertilizers.

In JA1213, biomass Fe concentrations at R6 interacted between location and fertilizer type. At Jackson, fertilizer types did not differ in biomass Fe concentrations at R6, but at Grand Junction, briquettes produced higher biomass Fe concentrations at R6 than ammonium sulfate (Table 4).

Overall, plant Fe concentrations were not improved by NPSFe which supplied 0, 3.4, 5.1, 6.8, and 10.3 kg Fe ha $^{-1}$ at the 0, 85, 128, 170, and 255 kg N ha^{-1} rates, respectively. Despite increasing rates of Fe with increasing rates of N, the performance of NPSFe with respect to plant Fe concentrations was not affected by N application rates or years, but were sometimes influenced by locations. Our results seem to support the results reported by Zheng (2010), Vose (1982), and Kraemer et al., (2006) that Fe capture and assimilation by plants is more a function of genetics and bioavailability than actual soil Fe quantities.

Zinc

In J11, Zn concentrations in biomass at R1 and R6 and in grain were impacted by fertilizer type. In general, NPSFe and ammonium sulfate produced higher Zn concentrations in biomass at R1 and at R6 and in grain than the briquettes and urea (Table 2).

Nitrogen rates only had a significant impact on Zn concentrations in biomass at R6 in J11 and in grain in JA1213. In J11, biomass Zn concentration at R6 was higher at the lowest N rate than the other N rates (Table 2). In JA1213 the results were the same: the lowest N rate produced higher grain Zn concentrations than the other N rates. These findings are similar to Ciampitti and Vyn's (2013) findings in which increasing N rates did not increase end of season corn biomass or grain Zn concentrations. Bruns and Ebelhar (2006), Riedell et al. (2009), and Yu et al. (2011) also documented plant Zn concentrations being unaffected by N rates.

In J11 there was a significant interactive effect between fertilizer types and N rates on biomass Zn concentrations at R1. At the 0 and 85 kg N ha^{-1} rates, there were no differences between the fertilizer types in biomass Zn concentrations at R1 (Table 3). However, at the 170 and 255 kg N ha^{-1} rates, NPSFe and ammonium sulfate, in general, produced higher biomass Zn concentrations at R1 than the other two fertilizers.

In JA1213, there was a significant interactive effect between fertilizer types and N rates on biomass Zn concentrations at R1 and R6. At the lowest N rate, there were no differences in biomass Zn at R1 or R6 among the fertilizer types (Table 3). However, NPSFe frequently had higher Zn concentrations at R1 and R6 than the other fertilizer types at the 128 and 170 kg N ha^{-1} rates. Overall, NPSFe tended to produce higher biomass Zn concentrations at higher N application rates.

In JA1213, Zn concentrations in biomass at R6 and in grain were influenced by a year by fertilizer type interactive effect. In 2012, biomass Zn concentrations at R6 were not impacted by fertilizer type, but in 2013 briquettes produced lower biomass Zn concentrations at R6 than the other three fertilizer types (Table 4). In 2012, NPSFe and ammonium sulfate produced greater grain Zn concentrations than urea. In 2013, however, there was no difference in grain Zn concentrations among the fertilizer types.

In summary, plant biomass Zn concentrations were improved with NPSFe relative to ammonium sulfate and urea at higher N rates. Plant Zn concentrations were similar or less with the briquettes compared with ammonium sulfate and urea. Zinc concentrations were usually decreased with increased N application rates. The performances of NPSFe and the briquettes in terms of plant Zn concentrations were sometimes affected by N application rates or years, but were not influenced by location. Our results suggest Zn in the briquettes product may be less available to the plant relative to the commonly used Zn fertilizer zinc sulfate applied as a broadcast.

Previous studies conducted on biosolid agronomic use showed little difference in crop tissue nutrient concentrations (Herencia et al., 2007; Shober et al., 20003). Mantovi et al. (2005) found only higher Cu concentrations in corn grain grown from soil amended by biosolids. From the JA1213 dataset of this study, NPSFe had greater Zn concentrations in plant biomass at R1 than the other fertilizer types at the higher N rates of 128 and 170 kg N ha^{-1}. This same phenomenon occurred in the R6 plant biomass in JA1213 but only at the 128 kg N ha^{-1} N rate. Our results are consistent with other studies where land applied biosolids was found to significantly increased corn leaf Zn concentrations (Granato et al., 2004).

CONCLUSIONS

NPSFe resulted in similar or lower plant N concentrations relative to the conventional fertilizers ammonium sulfate and urea. The briquettes performed equally or better in terms of plant N concentrations compared to ammonium sulfate and urea. In excessive spring precipitation, the briquettes had higher biomass N concentrations at R1. These results suggest that the briquettes may have greater N use efficiency than ammonium sulfate and urea particularly in wet soil conditions. NPSFe tended to have less P concentrations in plant biomass at R1 and R6, thus the P provided by NPSFe may be less available than TSP. The briquettes had similar or higher plant P levels relative to ammonium sulfate and urea, suggesting that the briquettes occasionally improve P use efficiency compared to TSP applied as a broadcast. Biomass K concentrations at R1 and R6 and in the grain were not improved by NPSFe or briquette fertilization. NPSFe and ammonium sulfate both increased S concentrations in plant biomass compared to the briquettes and urea. Plant Fe concentrations were not improved by NPSFe even though only NPSFe supplied Fe and Fe was not applied uniformly across all fertilizer types. NPSFe improved biomass Zn concentrations at R1 and R6 at higher N application rates. In general, higher N rates were equated with lower Zn concentrations in plant biomass and grain. This was also true for P, K, and Fe at R6. Biomass Fe concentrations at R1 and in the grain were lower with lower N application rates. In conclusion, the briquettes do not consistently improve corn N, P, K, and Zn nutrition compared to the conventional fertilizers ammonium sulfate and urea. NPSFe sometimes seems to reduce corn N and P nutrition but increase Zn nutrition relative to ammonium sulfate and urea.

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REFERENCES

1. Agyin-Birikorang, S., J. Winings, X. Yin, U. Singh, and J. Sanabria. 2018. Field evaluation of agronomic effectiveness of multi-nutrient fertilizer briquettes for upland crop production. Nutrient Cycling in Agroecosystems 110:395–406.
2. Alfoldi, Z., L. Pinter, and B. Feil. 1994. Nitrogen, phosphorus, and potassium concentrations in developing maize grains. Journal of Agronomy and Crop Science 172:200–206.
3. Al-Kaisi, M. and D. Kwaw-Mensah. 2007. Effect of tillage and nitrogen rate on corn yield and nitrogen and phosphorus uptake in a corn-soybean rotation. Agronomy Journal 99:1548–1558.
4. Belay, A., A. S. Claassens, and F. C. Wehner. 2002. Effect of direct nitrogen and potassium and residual phosphorus fertilizers on soil chemical properties, microbial components, and maize yield under long-term crop rotation. Biology and Fertility of Soils 35:420–427.
5. Bruns, H. A. and M. W. Ebelhar. 2006. Nutrient uptake of maize affected by nitrogen and potassium fertility in a humid subtropical environment. Communications in Soil Science and Plant Analysis 37:275–293.
6. Cakmak, I. 2002. Plant nutrition research: priorities to meet human needs for food in sustainable ways. Plant and Soil 247:3–24.
7. Castillo, M.S., L.E. Sollenberger, J. M. B. Vendramini, K. R. Woodard, G. A. O'Connor, Y. C. Newman, M. L. Silveira, and J. B Sartain. 2010. Municipal biosolids as an alternative nutrient source for bioenergy crops: i. elephantgrass biomass production and soil responses. Agronomy Journal 102:1308–1313.
8. Ciampitti, I. A., J. J. Camberato, S. T. Murrell, and T. J. Vyn. 2013. Maize nutrient accumulation and partitioning in response to plant density and nitrogen rate: i. macronutrients. Agronomy Journal 105:783–795.
9. Ciampitti, I. A. and T. J. Vyn. 2013. Maize nutrient accumulation and partitioning in response to plant density and nitrogen rate: ii. micronutrients. Agronomy Journal 105:1645–1657.
10. Fan, M., F. Zhao, S. J. Fairweather-Tait, P. R. Poulton, S. J. Dunham, and S. P. McGrath. 2008. Evidence of decreasing mineral density in wheat grain over the last 160 years. Journal of Trace Elements in Medicine and Biology 22:315–324.
11. Granato, T. C., R. I. Pietz, G. J. Knafl, C. R. Carlson, P. Tata, and C. Lue-Hing. 2004. Trace element concentrations in soil, corn leaves, and grain after cessation of biosolids applications. Journal of Environmental Quality 33:2078–2089.
12. Herencia, J. F., J. C. Ruiz-Porraas, S. Meleor, P. A. Garcia-Galavis, E. Morillo, and C. Maqueda. 2007. Comparison between organic and mineral fertilization and soil fertility levels, crop macronutrient concentrations, and yield. Agronomy Journal 99:973–983.
13. Khalil, M. I., U. Schmidhalter, R. Gutser, and H. Heuwinkel. 2011. Comparative efficacy of urea fertilization via supergranules versus prills on nitrogen distribution, yield response, and nitrogen use efficiency of spring wheat. Journal of Plant Nutrition 34:779–797.
14. Kraemer, S. M., D. Crowley, and R. Kretzschomar. 2006. Siderophores in plant iron acquisition: geochemical aspects. Advanced Agronomy 91:1–46.
15. Long, J. K., M. Banziger, M. E. Smith. 2004. Diallel analysis of grain iron and zinc density in southern African-adapted maize inbreds. Crop Science 44:2019–2026.
16. Losak, T., J. Hlusek, J. Martinec, J. Jandak, M. Szostkova, and R. Filipcik. 2011. Nitrogen fertilization does not affect micronutrient uptake in grain maize (*Zea mays* L.). ACTA Agriculture Scandinavica Section B-Soil and Plant Science 61:543–550.
17. Mantovi, P., G. Baldoni, and G. Toderi. 2005. Reuse of liquid, dewatered, and composted sewage sludge on agricultural land: effects of long-term application on soil and crop. Water Research 39:289–296.
18. Mengel, D. B., D. W. Nelson, and D. M. Huber. 1982. Placement of nitrogen fertilizers for no-till and conventional till corn. Agronomy Journal 74:515–518.
19. Morris, C. and D. Sands. 2006. The breeder's dilemma—yield or nutrition? Nature 24:1078–1080.
20. Ogunlela, V. B., G. M. Amoruwa, and O. O. Ologunde. 1988. Growth, yield components and micronutrient nutrition of field-grown maize (*Zea mays* L.) as affected by nitrogen fertilization and plant density. Fertilizer Research 17:189–196.
21. Pagani, A., H. E. Echeverria, F. H. Andrade, H. R. S. Rozas. 2008. Characterization of corn nitrogen status with a greenness index under different availability of sulfur. Agronomy Journal 101:315–322.
22. Pellegrino, J. L. and S. Lou. 2000. Energy and environmental profile of the U.S. chemical industry. Energetics, Inc. Columbia, MD and

U.S. Department of Energy, Washington, D.C. http://www1.eere.energy.gov/manufacturing/resources/chemicals/pdfs/profile_chap5.pdf. Accessed on June 21, 2012.

23. Riedell, W. E., J. L. Pikul, A. A. Jaradat, and T. E. Shumacher. 2009. Crop rotation and nitrogen input effects on soil fertility, maize mineral nutrition, yield, and seed
24. Shober, A. L., R. C. Stehouwer, and K. E. Macneal. 2003. On-farm assessment of biosolids effects on soil and crop tissue quality. Journal of Environmental Quality 32:1873–1880.
25. Sindelar, A. J., J. A. Lamb, C. C. Sheaffer, C. J. Rosen, and H. G. Jung. 2013. Fertilizer nitrogen rate effects on nutrient removal by corn stover and cobs. Agronomy Journal 105:437–445.
26. Singh, U., J. Sanabria, E. R. Austin, and S. Agyin-Birikorang. 2012. Nitrogen transformation, ammonia volatilization loss, and nitrate leaching in organically enhanced nitrogen fertilizers relative to urea. Soil Science of America Journal 76:1842–1854.
27. Sneller, E. G. and C. A. M. Laboski. 2009. Phosphorus source effects on corn utilization and changes in soil test. Agronomy Journal 101:663–670.
28. Stecker, J. A., D. D. Buchholz, P. W. Tracy. 1995. Fertilizer sulfur effects on corn yield and plant sulfur concentration. Journal of Production Agriculture 8:61–65.
29. Vose, P. B. 1982. Iron nutrition in plants: a world overview. Journal of Plant Nutrition 5:233–249.
30. Warman, P. R. 2005. Soil fertility, yield and nutrient contents of vegetable crops after 12 years of compost or fertilizer amendments. Biological Agriculture and Horticulture 23:5–96.
31. Weggler-Beaton, K., R. D. Graham, and M. J. McLaughlin. 2003. The influence of low rates of air-dried biosolids on yield and phosphorus and zinc nutrition of wheat (*Tritcum durum*) and barley (*Hordeum vulgare*). Australian Journal of Soil Research 41:293–308.
32. Winings, J., X. Yin, S. Agyin-Birikorang, U. Singh, J. Sanabria, H. J. Savoy, F. L. Allen, and A. M. Saxton, 2017. Agronomic effectiveness of an organically enhanced nitrogen fertilizer. Nutrient Cycling in Agroecosystems 108:149–161.
33. Zheng, S. J. 2010. Iron homeostasis and iron acquisition in plants: maintenance, functions and consequences. Annals of Botany 105:799–800.
34. Ziadi, N., G. Belanger, F. Gastal, A. Claessens, G. Lemaire, and N. Tremblay. 2009. Leaf nitrogen concentration as an indicator of corn nitrogen status. Agronomy Journal 101:947–957.