

**Effects of Organically Enhanced Biofertilizer and Fertilizer Briquettes on
Mineral Nutrition, Quality, and Yield of Corn and Soil Health**

**A Thesis Presented for the
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Degree
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John Heggie Winings

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Abstract

Interest in alternate fertilizers has increased in recent years in order to improve crop nutrition and soil health. The efficacy of these fertilizers on corn (*Zea mays* L.) production and quality has been scarcely documented. Two alternative fertilizers, organically enhanced NPSFe Unity biofertilizer (Unity) manufactured from sterilized organic additives extracted from municipal wastewater biosolids and NPKZn briquettes (briquettes) produced by compacting solid fertilizers into a super-granule between 1-3 grams, were evaluated for nutrient concentrations, growth, quality, and yield of corn, residual soil nutrient levels, and soil microbial community structure relative to the conventional fertilizers ammonium sulfate and urea at Jackson and Ames, TN from 2011 to 2013. Unity, briquettes, ammonium sulfate, and urea, and four N rates of 0, 85, 128/170, and 170/255 kg ha⁻¹ [hectare] were assigned to the main and sub plots, respectively, in a split plot randomized complete block design with four replicates. Unity sometimes had lower N and P concentrations in plant biomass and grain, but resulted in greater Zn concentrations in plant biomass at higher N rates. Plant Fe concentration was not increased by the application of Unity. The briquettes did not consistently improve N, P, K, and Zn nutrition in the plant. Unity and ammonium sulfate resulted in higher plant S concentrations than the briquettes and urea. Unity increased soil organic C levels, but decreased diversity of soil microbes. The briquettes produced lower soil NO₃⁻-N [nitrate] concentrations particularly under wet soil conditions. Unity and ammonium sulfate generally maintained stronger plant growth through early to middle season of corn than the banded briquettes and split-applied urea. Physiological defects were fewer under briquette fertilization at lower N rates. Unity and the briquettes at lower N rates had greater grain yields; at higher N rates they were only comparable in grain yield to ammonium sulfate and urea. Unity and the briquettes also had greater grain yields under wet soil conditions. In conclusion, the agronomic benefits with the briquettes are not consistent compared to the conventional prilled fertilizers. Unity biofertilizer is a viable source to increase plant S nutrition and soil C sequestration.

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CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

Introduction

Since no farm can be reasonably expected to raise great quantities of high quality crops without providing the necessary amounts of plant nutrients, fertilizer expenses are one of the greatest variable costs to any successful farm operation (Economic Research Service, 2013). Of all the plant nutrients essential for agronomic crop production, N is one of the most important for non-leguminous crops because it is one of the most deficient nutrients in the soil relative to crop needs. Nitrogen is also one of the most critical nutrients required for basic crop growth and development. Nitrogen is a major component of all amino acids and thus proteins; it is also a major component in many important biochemicals including nucleic acids, amides, amines, nucleotides, chlorophyll, and coenzymes (Taiz and Zeiger, 2002).

For all its importance in plant physiology, N is not readily available. The earth's atmosphere is by far the largest reservoir of N in the world comprising 79% N by volume or approximately 3,900,000,000 Mg by weight (Jenkinson, 2001). This omnipresent reservoir of N is in its diatomic form in which two N atoms are chemically bound together by a triple bond that requires an energy intensive process to break in order to convert atmospheric N into a usable N form suitable for fertilizer. Once more, N, in contrast to most other plant nutrients, is not stable in soils escaping easily and thereby becoming unusable for farm production (Robertson and Vitousek, 2009). Nitrogen makes its escape from soils in one of three ways: denitrification, ammonia volatilization, and nitrification which produces nitrate that can readily leach out of soils or runoff with excessive precipitation because of nitrate's naturally high water solubility (Havlin et al., 2005).

Historically the answer to soil N losses was to simply apply additional N fertilizer to offset N losses and still produce substantial yields. Nitrogen fertilizer consumption in the United States has increased dramatically over the last 50 years: a 349% increase from 1960 to 2010 (Economic Research Service, 2012). The great majority of this increase was experienced between 1960 and 1980 with only a 7.7% increase in N fertilizer consumption from 1980 to 2010. Phosphate and K fertilizer use by contrast, increased by 59% and 107%, respectively, over the last 50 years (1960-2010); and from 1980 to 2010 their use actually decreased by 32% and 40%, respectively: a

testament to the bankability of P and K in soil. Internationally, China, India, and the United States were the top three N users in the world in 2000 accounting for 44% of all agronomic N use worldwide (Fixen and West, 2002).

Increasing amounts of N application to agronomic land has been an economically practical method of N management because of readily available and inexpensive synthetic fertilizers, which were manufactured starting in the 1920's and sold en masse during the Green Revolution after World War II up to the present day (Jenkinson, 2001). With tighter environmental regulations and increasing fuel costs over time, however, this approach to reconciling soil N losses has become less practical, and this trend is likely to continue. For example, in 2001, the estimated dollar value of N losses due to ammonia volatilization alone from agricultural fertilizers was 11.6 billion; obviously a very expensive loss (FAO/IFA, 2001). Nitrogen fertilizers are particularly sensitive to increasing costs in non-renewable fossil fuels, more specifically natural gas, because of the energy intensive process required to break triple bonded diatomic atmospheric N as mentioned above (Roberts and Vitousek, 2009).

In the United States, the average price of anhydrous ammonia, ammonium nitrate, ammonium sulfate, and urea has increased by 254%, 388%, 463%, and 283%, respectively, from 1960 to 2010 (USDA, 2012). The sharpest increases in cost occurred in the last decade (2000-2010). Even though P and K are not subject to the same nutrient escape phenomena as N, and as a result have been used less in fertilizer applications than N, nevertheless their prices have also risen considerably over recent years. Triple superphosphate and potassium chloride have increased in price from 1960 to 2010 by 542% and 902%, respectively; again with the steepest increase in cost occurring in the last decade (2000-2010). If future fertilizer prices continue to increase as they have historically, particularly as steeply as they have during the last decade, nutrient use efficiency in agronomic systems will become ever more critical to the economic sustainability of farming operations.

The sustainability of farming operations viewed through the prism of economics is but one key aspect to consider. Another fundamental factor to farming sustainability is maintaining soil health. Indeed the relatively thin layer of soil that covers the earth's surface can quite literally

represent the difference between life and death for most terrestrial life on the planet (Doran, 2002). As far as humans are concerned, soil is a foundation from which crops are grown; a healthy soil is more likely to produce higher quality food and in greater quantities. Since the 1960's, grain yields in the U.S. have increased (USDA, 2013). In the case of some grains the increase is only slight while in others the increase is considerably more pronounced. Corn grain yields, for example, have climbed particularly well with a 126% increase in yield from 1960 to 2012, peaking in 2009 at 10.34 Mg ha^{-1} (USDA, 2013). Although synthetic fertilizers are replacing some soil nutrients fairly well, whether or not they can maintain or restore optimum soil health in perpetuity is yet to be seen. Soil microorganisms play a critical role in maintaining soil function because of their contribution to soil structure formation; decomposition of organic matter; toxin removal; and the biogeochemical cycling of C, N, P, and S (Karlen et al., 1997; Doran and Zeiss, 2000; Paul, 2007). The magnitude of soil microbial diversity in agronomic soils is also imperative for the maintenance of healthy soil (Garbeva et al., 2004; Shen et al., 2008). Disregard for soil health will likely compromise future agricultural productivity in favor of high but short term economic returns (Gleismann, 2007). This is becoming an increasingly serious issue as contemporary agriculture continues to bear the responsibility of feeding the world today and future generations sustainably.

To date, urea and ammonium sulfate are two of the most common agronomic N-based fertilizers employed by farmers to improve soil N fertility and thus increase productivity. More than five billion and just under two billion kilograms of urea and ammonium sulfate, respectively, were manufactured in the United States in 1997 (Pellegrino, 2000). Urea, as an N fertilizer, supplies no secondary or micronutrients to crops; ammonium sulfate only supplies S in addition to N. As such, these fertilizers are unlikely to enhance crop productivity and quality without the addition of other nutrients.

The organically-enhanced NPSFe biofertilizer, branded as “Unity” by its manufacturing company Unity Envirotech, LLC. (St. Petersburg, FL), contains N (14.9%), P (4.3%), S (18.1%), Fe (0.6%), and approximately 8% organic matter that is made from sterilized organic additives extracted from municipal wastewater biosolids. The prospect of creating a fertilizer from municipal biosolid waste certainly has economic potential: in 1950 the estimated dollar value of

total agricultural nutrients tied up in human waste was 6.93 billion (Fahm, 1980). Today, more than 60 years later and with 4.4 billion more people on the earth, we can only assume that that figure is much greater (United Nations, 2010). In the United States, approximately 230 million Mg of municipal solid waste was generated in 1999, 84% of which was dumped in landfills at great expense to local municipalities. The 1999 amount of municipal solid waste represented a 155% increase in waste since 1960 (Cheremisinoff, 2013). Since cities are required to manage, and thus pay the expense of dumping and/or treating their solid wastes, they have a powerful economic incentive to discharge that responsibility to companies such as Unity Envirotech that can manufacture fertilizer from that waste. Unity Envirotech is projected in the next two or three years to use approximately 10% of Florida's total municipal biosolid waste to manufacture 300,000 Mg of Unity fertilizer per year (Weber, 2013).

The NPKZn briquettes are entirely mineral in their formulation and are manufactured by a fertilizer briquetter machine developed by the International Fertilizer Development Center (IFDC) based at Muscle Shoals, Alabama. The briquettes are a unique fertilizer concept apart from the conventional fertilizers in that the fertilizer is manufactured into a briquette approximately the size of the end of one's finger (about 2.43 grams) as opposed to the more common granular prill-sized fertilizers or liquid fertilizers. The land application of the briquettes is also unique in that it is banded below the soil surface between planted rows. The theory behind the briquette is that a smaller surface area to volume ratio of a briquette will dissolve more slowly and thus release its nutrients in a more controlled manner over time thereby reducing nutrient losses. A subterranean land application of the briquette has been shown to significantly reduce N losses through ammonia volatilization (Mengel et al., 1982). Surface applied urea is reported to reach N losses as high as 35%; however, buried briquettes only lose approximately 4% of its N, which is a considerable improvement in N use efficiency (IFDC, 2013).

The briquettes can be buried by hand using a hand-driven plow. In developing countries this may be a practical method of fertilizer application where very small acreages are farmed by a single grower and his/her family. This is the end to which the briquette was designed. The IFDC is a non-profit organization that focuses its efforts on sustaining food security and

agricultural productivity in developing countries through the development and transfer of effective and environmentally sound crop nutrient technology (IFDC, 2013). In developed countries, where agriculture is extensively mechanized, briquettes could potentially be applied using a key-line plowing system which has a dispensing mechanism that places the product underground immediately behind a plow shank that opens up a seam in the earth as it is pulled along by a tractor. The original intent of the plow is to drop seed behind each shank but that could plausibly be modified to drop briquettes as well.

Previous studies have been conducted on crop and soil nutrient concentrations under biosolid and briquette fertilization with mixed results. Mantovi et al. (2005) found increased N concentration in wheat grain but only increases in Cu concentration in corn grain with biosolid fertilization compared to inorganic fertilization. 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 percent of N supplied by municipal biosolids was less than the percent of N being supplied by ammonium nitrate; crop P removal followed the same trend. Khalil et al. (2011) reported a 5.2% increase in wheat straw N uptake under super granular urea fertilization versus prilled urea. The N uptake by wheat grain under super granular urea fertilization was even higher with a 9.5% increase in N uptake over prilled urea. Khalil et al. (2011) also found soil N to be much lower under urea super granules compared to surface applied prilled urea. Savant and Stangel (1990 and 1998) and Wetselaar (1985) observed that N and P concentrations in the flood water of flood irrigated rice to be much lower under briquette fertilization than those with conventionally prilled fertilizer.

Crop growth and yield responses to biofertilizers and NPK briquettes were likewise variable in preceding studies. Ayoola and Makinde (2009) found that corn plant height was comparable between N-enriched organic fertilizers and urea. However, Magdoff and Amadon (1980) observed that corn silage production was greater from biosolid amended fields than those under mineral N fertilization alone. Kaur et al. (2008) found that corn yields from fields that were organically enhanced with farm yard manure in conjunction with NPK fertilization were greater

than those with NPK fertilization alone. Similarly, Sleutel et al. (2006) observed that corn yields increased under NPK fertilization that was organically supplemented with manure. However, Mantovi et al. (2005) reported that corn yields did not differ between biosolid and urea treatments. Terman et al. (1956) found that early crop growth decreased with the application of coarser granular fertilizers, but the reduced early growth from coarser fertilizer granulation did not persist in final yields of corn and wheat. Several prior studies showed that NPK briquette fertilizers reliably outperformed prilled urea in terms of yield under wet soil conditions such as flood irrigated rice paddies (Islam et al., 2011; Darade and Bankar, 2009; Kapoor et al., 2008).

Research on soil microbial community shifts as influenced by biofertilizer applications have been conducted in previous studies also with mixed results. Zerzghi et al. (2010) found that after a 20-year period of biosolid land applications to southwestern soils in the United States there were no significant effects on soil microbial populations compared to un-amended control plots. Sullivan et al. (2006) compared different rates and times of biosolid application to un-amended control plots on western rangeland soil in the United States. Between all the different biosolid application rates and also between the short- and long-term biosolid treatment plots there were no differences in soil microbial community structure. Zhong et al. (2010) studied the effects of mineral fertilizer and organic manure on soil microbial community diversity over a 21-year period on humid subtropical soils in China. Soil microbial community diversity was significantly increased under the organic manure and organic manure plus NPK mineral fertilization compared to the mineral fertilizer combinations alone.

Unity and the briquettes are designed to improve crop growth and yields and crop and soil nutrient concentrations relative to the conventional fertilizers. Unity, with its organic matter contribution, is likely to improve soil microbial community diversity relative to the briquettes, ammonium sulfate, and urea. For the purposes of this study, It was hoped that Unity and the briquettes would not only compare well to their conventional counterparts, ammonium sulfate and urea, but excel in crop quality and quantity without negatively impacting the soil microbial environment. The crop of choice to be used in the evaluation of these fertilizers was corn: one of the most heavily produced crops in the world (FAOSTAT, 2010). The objectives of this study were to compare alternative fertilizers, organically enhanced NPSFe Unity fertilizer and banded

NPKZn briquettes, to conventional fertilizers, ammonium sulfate and urea, in terms of nutrient concentrations in corn plant biomass and grain, residual soil nutrient concentrations, corn growth and yield, corn ear health, and soil microbial community structure.

Literature Review

Agronomic Use of Biosolid Fertilizer

The concept of using manures, even human manures, as an agronomic fertilizer amendment is hardly new. Human manure has been used agriculturally as early as the Shang Dynasty of China some three to four thousand years ago (Jenkins, 2005). In modern history, the earliest record of municipal sewage sludge being processed for fertilizer use in the United States occurred during the 1930's; a process that simply heat-dried sewage sludge (Niles, 1944). There are many scientific studies reporting on the subject of using treated sewage sludge, or biosolids, as an agricultural amendment. Using human manure from municipal biosolid waste to organically enhance inorganic fertilizers is a fairly new concept and the scientific literature on that specific subject is somewhat scant.

Castillo et al. (2010) performed experiments supplementing inorganic N fertilizer with municipal biosolids on varieties of elephant grass grown for biofuel. The authors found that 33% of the N supplied from municipal biosolids was just as effective as having 100% of the N supplied from ammonium nitrate on Merkeron elephant grass variety but not the Chinese Cross variety; higher proportions of N supplied by municipal biosolids, however, lowered yields across both varieties.

Jamil et al. (2006) studied the effects of sewage sludge (SS) fertilization on wheat with SS applied in the following increments: 0, 10, 20, 40, 60, 80, and 100 Mg ha⁻¹. As such, this study did a good job of showing the upper limits of beneficial biosolid application. Plant height increased significantly between treatments ranging from 0–40 Mg SS ha⁻¹, but from 40–100 Mg SS ha⁻¹ plant height remained the same. Spike height increased significantly from treatments 0–20 Mg SS ha⁻¹ but did not differ from 20–100 Mg SS ha⁻¹. Wheat tiller counts were highest at 40 Mg SS ha⁻¹ and declined as SS applications decreased or increased. Wheat grain yield had precisely the same pattern: highest yields, 6.15 Mg ha⁻¹, were observed at 40 Mg SS ha⁻¹ with decreases in yield as treatments departed from that rate either positively or negatively. Wheat straw yield increased significantly as SS application rates increased until 60 Mg SS ha⁻¹ was reached; thereafter straw yields plateaued.

Mantovi et al. (2005) conducted an extensive long term study (from 1988 and still ongoing as of 2005 when the authors published their article) on dewatered sewage sludge (DSS) and its effects on crop yields when surface applied to agricultural lands. They found that DSS applied at the middle application rate of 5 Mg dry matter ha⁻¹ produced greater yields in wheat than urea applied at the highest rate of 300 kg N ha⁻¹. The authors pointed out this was likely due to a high percentage of wheat lodging at the highest urea rate. The other urea application rates (120 and 180 kg N ha⁻¹) outperformed DSS at the application rates of 5 and 10 Mg dry matter ha⁻¹. Aboveground wheat biomass was more promising for biosolids: DSS produced statistically equal amounts of biomass compared to urea. Other analysis showed equal outcomes; for example, corn grain had no statistical difference in the treatments between DSS and urea treatments. Likewise, root yields in sugar beets were statistically the same between DSS and urea. Although DSS primarily did not outperform urea in yield it did produce higher food quality. Dewatered sewage sludge had higher concentrations of N, P, Zn, and Cu in wheat grain; in corn grain only Cu concentration was higher; and in sugar beet roots N and Cu concentrations were higher. Also reported from the same study was the heavy metal accumulation from continuous land application of DSS for several years. Only significant accumulations of Zn and Cu were detected in amended soils; the other heavy metals monitored (Cd, Cr, Ni, and Pb) were all well below the environmental hazard limits.

Weggler-Beaton et al. (2003) compared a biosolid application of 2 Mg ha⁻¹ with mineral supplementation to standard mineral fertilizer application rates of 20 kg N ha⁻¹, 20 kg P ha⁻¹, 1.8 to 2.8 kg Zn ha⁻¹, 1.4 to 1.9 kg Cu ha⁻¹, and 0.5 to 4 kg Mn ha⁻¹ in terms of wheat and barley production. A 2 Mg ha⁻¹ biosolid application was found to improve dry matter production and yield to the same extent as a mineral fertilizer application of 20-20-1.8/2.8 kg NPZn ha⁻¹ in wheat and barley. However, development of wheat fertilized with 2 Mg of biosolids was slower and P uptake was less until the late booting growth stage compared to wheat treated with mineral fertilization. By contrast, wheat fertilized with 4 Mg of biosolid showed statistically equal P uptake values as plants fertilized with mineral fertilizer. Micronutrients Zn and Cu were both taken up equally from biosolid and mineral fertilizer applications.

Reimers et al. (2009) presented their research concerning an acid base reaction derived from the fertilizer industry coupled with sewage sludge to produce an organically enhanced fertilizer at the 5th Canadian Residuals and Biosolids Conference in Niagara Falls, Ontario. The authors showed that their proprietary manufacturing process can take dewatered sludge or manure residue at a concentration of 13 to 30% total solids, precondition that material and convert it into a value-added commercial fertilizer that meets or exceeds all fertilizer industry standards for chemical and physical properties use in the existing worldwide commercial inventory. This is the same process from which Unity was created. From their own research, the authors reported a total N loss of 15%, 2% from volatilization and 13% from leaching. By comparison, conventional urea reportedly lost 74% of its N in the same study, 33% to volatilization and 41% to leaching (Reimers et al., 2009). One of the major benefits to this technology is the ability of the manufactures to increase the N/P ratio such that P is not over supplied. Long-term biosolid applications often results in soil P accumulation because the N/P ratio of biosolids is naturally lower than the N/P ratio taken up by plants, such that when biosolids are applied to meet crop N requirements, P is typically oversupplied (Elliot and O'Connor, 2007).

Unity was independently reviewed in a separate scientific study conducted by Singh et al. (2011). Two variations of Unity (NS and NSFe) were tested against urea in terms of volatilization losses in two different soil types, Gunthrie and Sumter, which were loam and clay soils, respectively. The same fertilizer experiment was also carried out to determine N leaching losses on Lakeland and Greenville soils, a loam and sandy soil, respectively. Both Unity fertilizers had considerably less volatilization losses than urea in both soil types. Approximately 33.3 and 12.2% of applied N through urea was lost by volatilization in the Guthrie and Sumter soils, respectively; the Unity fertilizers lost just 2.3 and 6.8% applied to the same soils, respectively. Under flooded conditions from the Gunther soil, urea lost 57% of applied N whereas the Unity fertilizers only lost 24% of applied N. From the Sumter soil under flooded conditions, both urea and the Unity fertilizers lost approximately 14% of applied N. Nitrate leaching was generally greater for urea compared to the Unity fertilizers. Under continuous irrigation on Lakeland sand, urea lost 87% of applied N whereas the Unity fertilizers only lost between 3.8 and 4.5% of applied N. On Greenville loam, however, leaching losses were the same between the treatments under continuous irrigation: less than 1% of applied N was leached

away. Under intermittent irrigation from the Lakeland soil, urea lost 37% of applied N whereas the Unity fertilizers only lost approximately 2% of applied N to leaching. Under the same irrigation scheme but on Greenville soil, both urea and the Unity fertilizers lost about 18% of applied N. Overall, Unity fertilizers had less ammonia volatilization and less nitrate leaching, which attributes can certainly lead to better N use efficiency by crops.

Biosolid land application has also been studied for its effects on soil microbial communities. Zerzghi et al. (2010) found that after a 20-year period (from 1986 to 2005) of Class B biosolid land applications to arid southwestern soils in the United States, there were no significant effects on soil microbial populations compared to un-amended control plots. Given the duration, this study is a strong example of the long-term effects of continuous biosolid application on soil microbial communities. Inasmuch as Class B biosolids have less stringent standards for treatment and contain small but compliant amounts of bacteria relative to Class A biosolids, it is noteworthy to mention that Zerghi et al. found no bacteria or viral pathogens in soil samples collected from biosolid amended plots 10 months after the last biosolid application.

Sullivan et al. (2006) compared different levels of biosolid application to an un-amended control. The rates of biosolid application were 0, 2.5, 5, 10, 21, or 30 Mg ha⁻¹ on semi-arid rangeland soil in the western United States. They also studied the difference in soil microbial community structure as a function of time. Short-term biosolid applications received a surface-applied biosolid treatment in 1991 and again in 2002, whereas the long-term biosolid applications were only applied in 1991. Between all the different biosolid application rates and also between the short- and long-term biosolid treatment plots there were no differences in microbial community structure.

Zhong et al. (2010) studied the effects of organic manure and mineral fertilizer on soil microbial community diversity over a 21-year period on humid subtropical soils in China. Nine treatments were used: a control; mineral N, P, K, NP, NK, and NPK fertilizer; organic manure alone; and organic manure plus mineral NPK fertilizer. The fertilizer sources were urea, calcium supersphosphate, potassium chloride, and composted swine manure. Soil microbial community

diversity was significantly increased under the organic manure and organic manure plus NPK mineral fertilization compared to the mineral fertilizer combinations alone.

Agronomic Use of Fertilizer Briquettes

Fertilizer briquettes have been developed by the IFDC for over 20 years as part of their Fertilizer Deep Placement Technology program to help farmers of developing nations increase their agronomic productivity and thus their economic stability and profitability. The literature from the IFDC reports an average increase in rice yield by 18% with fertilizer briquettes while decreasing fertilizer use by 33%. Currently there are 2.5 million farmers in Bangladesh using fertilizer briquettes developed by the IFDC with one million additional farmers joining in with briquette use throughout India. Also from the same region through the IFDC, corn yields are reported to increase with decreasing fertilizer use through fertilizer briquette use: the IFDC reports a 15–20% increase in yield while using 15–20% less fertilizer. The IFDC has also been working in other countries; Africa is a recent addition (2009) in which similar results to their work in India have been achieved (IFDC, 2013). Savant and Stangel (1998), when reporting on the IFDC's program, noted that the IFDC had developed a small-scale portable fertilizer briquetter driven by a 5-horse power electric motor, which could be adapted to be driven by combustion motors, that produced good quality urea diammonium phosphate briquettes (UB-DAP). What was particularly advantageous was that the briquettes could be made by simply using commercial grade urea and DAP fertilizers (N:P=4:1) without requiring an additional binder.

There are several other studies dealing with the application of fertilizers in the form of super granules or briquettes, also with promising results, although the scientific literature mostly deals with fertilizer effects on rice, particularly as briquette fertilizers are gaining in popularity throughout sub-tropical and tropical Asia compared to surface applied urea (Khalil et al., 2011). The temperate West, by contrast, uses supergranules, briquettes, tablets, or sticks horticulturally for trees, shrubs, and vegetable production (Trenkel, 1997).

In Bangladesh at the Rice Research Institute, Islam et al. (2011) conducted briquette fertilizer experiments under tidal flooded rice ecosystems during the Boro season in 2010. They reported

that NPK briquettes of 2.4 g size showed a better performance in terms of growth and yield although not statistically different from the other treatments of super-granular and prilled urea. Nitrogen use efficiency from the briquettes was significantly better than prilled urea with an N savings of 33 kg N ha⁻¹.

Darade and Bankar (2009) found that deeply placed urea-diammonium phosphate (U-DAP) briquettes (114 kg N and 25.4 kg P) easily outperformed the recommended dose fertilizer (RDF) (150 kg N and 75 kg P) in all of the criteria observed on rice including more panicles per hill, greater panicle lengths and weights, greater grain weights per panicle, more filled grain per panicle, greater grain weight and yield; even though the U-DAP briquettes contained a smaller concentration of nutrients than the RDF. An even lower nutrient concentration treatment of U-DAP (57 kg N and 12.7 kg P) still performed comparably with RDF in all of the aforementioned attributes; a clear indication of superior nutrient use efficiency in briquette fertilizers.

Kapoor et al. (2008) conducted experiments to determine the amount of NH₄⁺-N free-floating in rice paddy floodwater per fertilizer application. In each case, N, NP, and NPK briquettes all had significantly less free flowing NH₄⁺-N in floodwater than broadcasted prilled urea. In fact the briquettes were often more comparable with the control (0-N) in NH₄⁺-N floodwater concentration than any other treatment in the study maintaining a NH₄⁺-N concentration of less than 0.03 g m⁻² for at least 10 days. The prilled urea treatments had NH₄⁺-N floodwater concentrations between 0.09–0.27 g m⁻² for two to four days after application before falling down to much lower concentrations. The briquettes clearly displayed far greater control in N release than prilled urea. Concerning rice grain yields in the same study, the briquettes had higher yields in 2001 and 2002 for all the different fertilizer guaranteed analyses except 53-14-25 in 2002 where there was no significant difference between the briquettes and prilled urea applied by broadcast.

Durgude et al. (2008) tested fertilizer briquettes with constant amounts of NP but with different amounts of K (56-30-0, 56-30-15, 56-30-30, 56-30-45, and 56-30-60 kg ha⁻¹) against surface applied fertilizer of 100-50-50 kg ha⁻¹. Although deeply placed 56-30-30 NPK briquettes proved to be the best fertilizer for rice grain and straw yield, all of the briquette combinations proved

better than the surface applied 100-50-50 NPK fertilizer each year of the test (2003–2005) in both grain and straw yield even though the surface applied fertilizer was applied in three split applications to reduce N losses.

Kadam (2001) found urea briquette fertilizer to be better than surface split applied urea in rice. The increase varied considerably from as little as 5 to 83% in rice grain yield. Either way, the briquettes were a better fertilizer option than urea surface applied as a split to decrease N losses. Kadam (2001) further observed that it is possible to deeply place urea briquettes mechanically and achieve the agronomic efficiency obtained by hand placement of briquettes. This anticipates the feasibility of agronomic application of briquettes in developed countries where nearly all of agriculture is machine based.

Daftarder et al. (1996) conducted fertilizer briquette experiments on small farms with 77 farmer-participated trials from 1993 to 1994 during the wet seasons of each year. The briquettes were a combination of urea and diammonium phosphate applied at 56 kg N ha^{-1} and 14 kg P ha^{-1} . This N rate was approximately 40% less than the local fertilizer recommendations; nevertheless, it produced substantially higher yields in rice grain and straw in both years. The average grain yield from briquette treated plots was 4.55 and 3.94 Mg ha^{-1} in 1993 and 1994, respectively, compared to 2.99 and 3.11 Mg ha^{-1} in 1993 and 1994, respectively, from conventionally fertilized plots. Average straw yield from briquette treated plots was 6.68 and 5.33 Mg ha^{-1} in 1993 and 1994, respectively, compared to 4.54 and 4.40 Mg ha^{-1} in 1993 and 1994, respectively, from conventionally fertilized plots.

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CHAPTER 2

**EFFECTS OF NPSFE BIOFERTILIZER AND NPKZN BRIQUETTES ON
CORN MINERAL NUTRITION AND SOIL NUTRIENT LEVELS**

Abstract

Interest in the use of alternate fertilizers has increased in recent years in order to improve crop nutrition and soil health. The efficacy of these fertilizers on corn (*Zea mays* L.) production has not been well documented. Alternative fertilizers organically enhanced NPSFe Unity biofertilizer (Unity) 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 the soil and in the corn plant biomass and grain relative to ammonium sulfate and urea at Jackson and Ames, TN from 2011 to 2013. Unity, 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. Soil at a 0-15 cm depth was analyzed for Bray P, NO₃⁻-N, NH₄⁺-N, SO₄²⁻-S, and organic C concentrations before treatment and after harvest. Unity sometimes had lower N and P concentrations in plant biomass at R1 and R6 and in grain. At higher N rates, Unity and ammonium sulfate resulted in higher S concentrations in plant biomass at R1 and R6 and in grain. Unity also had greater Zn concentrations in plant biomass at R1 and R6 than the other fertilizer types at higher N rates. The briquettes produced lower soil NO₃⁻-N concentrations than the other fertilizers particularly under wet soil conditions. Unity had greater residual soil organic C levels than the other fertilizers. In conclusion, the briquettes do not consistently improve corn N, P, K, and Zn nutrition compared to the conventional fertilizers ammonium sulfate and urea. Unity sometimes reduces corn N and P nutrition but increases Zn nutrition relative to ammonium sulfate and urea. Unity consistently increases soil organic C levels, particularly at the higher N rates, within three years of experimentation.

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 among the most common agronomic N-based fertilizers used by farmers to improve soil fertility and thus increase productivity, particularly in developing countries. More than five billion of urea and just under two billion kilograms of ammonium sulfate, were manufactured in the United States in 1997 (Pellegrino, 2000). Urea, as an N fertilizer, supplies no secondary or micronutrients to crops, and ammonium sulfate supplies only S in addition to N. As such, these fertilizers are unlikely to enhance crop mineral quality without the addition of other nutrients.

Two new alternative fertilizers, organically-enhanced NPSFe and NPKZn briquettes, are under development for improving plant mineral nutrition and nutrient density in grain. The

organically-enhanced Unity NPSFe fertilizer contains N (14.9%), P (4.3%), S (18.1%), and Fe (0.6%), and approximately 8% organic matter that is made from sterilized organic additives extracted from municipal wastewater biosolids. Most of the N and all of the P, S, and Fe are contained in the municipal biosolid. Only N is supplemented with additional N mineral fertilizer to increase the N concentration of Unity during the manufacturing process. Unity Envirotech is projected in the next two or three years to use approximately 10% of Florida's total municipal biosolid waste to manufacture 300,000 Mg of Unity per year (Weber, 2013).

The briquette fertilizer is mineral in form and supplies Zn in addition to NPK. The briquettes are made by a briquetter machine that simply compresses commercially available prilled fertilizers into a briquette approximately 2.43 grams in weight without any additional binder material. Thus the guaranteed analysis of the briquettes is variable depending on the proportions of different fertilizers used to form the briquette. A briquette with a smaller surface area to volume ratio will dissolve more slowly and thus release its nutrients in a more controlled manner over time reducing soil nutrient losses, particularly N. The application of the briquettes is by banding a couple of centimeters below the soil surface in between planted rows. A subsoil land application itself will also help to reduce ammonia volatilization (Mengel et al., 1982). In developing countries this may be a practical method of fertilizer application where lesser acreages are farmed by one producer and his/her family. This is the purpose of the International Fertilizer Development Center (IFDC) in developing briquette fertilizers. The IFDC is a non-profit organization that focuses its efforts on sustaining food security and agricultural productivity in developing countries through the development and transfer of effective and environmentally sound crop nutrient technology (IFDC, 2013).

Previous studies have been conducted on crop and soil mineral nutrition concentrations under biosolid and briquette fertilization with mixed results. Mantovi et al. (2005) found increased N concentration in wheat grain but only increases 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. 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. Khalil et al. (2011) also found soil N to be much lower under urea super granules compared to surface applied prilled urea. Savant and Stangel (1990 and 1998) and Wetselaar (1985) confirmed that N and P concentrations in the flood water of flood irrigated rice to be much lower under briquette fertilization compared to conventionally prilled fertilizer.

These alternate fertilizers, Unity and the briquettes, are likely to have a greater impact on crop quality compared to the conventional fertilizers. The overall objectives of this study were to compare alternative fertilizers, Unity and banded briquettes, relative to conventional fertilizers, ammonium sulfate and urea, in terms of mineral nutrition in plant biomass and grain of corn and nutrient concentrations in the soil.

Materials and Methods

The field trial was conducted at the University of Tennessee's West Tennessee Research and Education Center (WTREC) located in Jackson, Tennessee from 2011 to 2013 and at the Ames Plantation, Tennessee from 2012 to 2013. The research project was designed and coordinated by the IFDC and the University of Tennessee. All the daily field operations were managed by the University of Tennessee.

Soil Description

The field trial was conducted on a Memphis silt loam soil (fine-silty, mixed, active, thermic Typic Hapludalfs) at Jackson and on a Lexington silt loam soil (fine-silty, mixed, active, thermic Ultic Hapludalfs) at Ames. At both locations the fields used for this study prior to the experiment were in soybean production followed by a winter fallow.

Corn Planting

Corn cultivar, Dekalb 6483 (YieldGardVT Triple), was used across all locations and years in this study. The Jackson trial was planted under no-tillage as eight row plots with 76.2 cm (30 inch) row spacing at a seeding rate of 79,000 plants ha⁻¹; overall plot dimensions were 9.1 m by 6.1 m (30 feet by 20 feet). The Ames trial was planted as tilled six row plots also with 76.2 cm row spacing at a seeding rate of 79,000 plants ha⁻¹; overall plot dimensions were 9.1 m by 4.6 m (30 feet by 15 feet). In 2011 corn was planted on 9 May at Jackson; in 2012 corn was planted on 18 April at Jackson and on 19 April at Ames; in 2013 corn was planted on 17 April at Jackson and on 29 May at Ames.

Treatments

Sixteen treatments with four blocks (64 plots in total per location) were laid out in a split plot randomized complete block design with fertilizer types as main plots and N rates as subplots. The four fertilizer types were Unity, the briquettes, ammonium sulfate (21% N, 24% S), and urea (46% N).

In 2011 at Jackson the N rates used were 0, 85, 170, and 255 kg N ha⁻¹. From 2012 to 2013 at both locations the N rates used were 0, 85, 128, and 170 kg N ha⁻¹ (Table 1.1). This rate change after 2011 was recommended by the IFDC, the rationale for which was to reduce fertilizer costs since the IFDC's purpose is to design and conduct research that would be most applicable to farmers of developing nations. Furthermore, since the 2011 results showed no additional growth or yield benefits resulting from the highest N application rate, the IFDC adjusted the N rates lower in order to better reflect a more economical fertilizing regime common to third world farming practices. This represented a significant change in the protocol during the experimentation as it was a multi-year study. As a result, the 2011 data (Jackson only) were analyzed independently from the other datasets while the data from 2012 and 2013 from Jackson and Ames were analyzed collectively as a pool. Thus the results are presented for Jackson 2011 alone and as Jackson and Ames in 2012 and 2013 together as a pooled dataset. For reporting purposes hereafter the data from Jackson 2011 will simply be referred to as "J11" and the pooled data from the location-years Jackson and Ames in 2012 and 2013 will be collectively referred to as "JA1213".

All the N fertilizer treatments except urea were applied basally after corn planting: in 2011 at Jackson fertilizers were applied the day after planting, in 2012 fertilizers were applied five days and 21 days after planting at Jackson and Ames, respectively, and in 2013 fertilizers were applied five days and eight days after planting at Jackson and Ames, respectively.

In all 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 in the season at the six leaf growth stage (V6) and at tasseling. This was done, as farmers in developing nations typically do, to reduce N volatilization losses. Unity, ammonium sulfate, and urea were all applied as a uniform surface broadcast across the entire plot. The briquettes were banded using a small hand-driven plow approximately 2.54 cm below the soil surface between rows one and two, three and four, five and six, and seven and eight at Jackson. At Ames the briquettes were banded at the same depth but in three bands between rows one and two, three and four, and five and six.

Phosphorus, K, and Zn were all applied at the following uniform rates across all treatments: 45 kg P ha⁻¹, 85 kg K ha⁻¹, and 5 kg Zn ha⁻¹ (Table 1.1). The S rate was variable for the Unity and ammonium sulfate fertilizer treatments because both of these fertilizers contained S as part of their guaranteed analysis, thus with increasing N rates, Unity and ammonium sulfate supplied increasing amounts of S (Table 1.1). At the 85 kg N ha⁻¹ rate, Unity and ammonium sulfate supplied 104 and 98 kg S ha⁻¹, respectively; at the 128 kg N ha⁻¹ rate, Unity and ammonium sulfate supplied 156 and 147 kg S ha⁻¹, respectively; at the 170 kg N ha⁻¹ rate, Unity and ammonium sulfate supplied 207 and 195 kg S ha⁻¹, respectively; and at the 255 kg N ha⁻¹ rate, Unity and ammonium sulfate supplied 311 and 292 kg S ha⁻¹, respectively. For the control (0 kg N ha⁻¹), all the fertilizer treatment plots had an S rate of 1.25 kg S ha⁻¹ from the sulfate in the ZnO/ZnSO₄ fertilizer that 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 Unity treatments. Unity already contained some P and thus 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, Unity supplied 23.8%, 35.8%, 47.6%, and 71.4% of the uniform P rate, respectively. Potassium and Zn were applied as KCl (0-0-60) and ZnO/ZnSO₄ (36% Zn, 9% S), respectively, for ammonium sulfate, urea, and Unity treatments.

The briquettes were unique in that they were manufactured from already commercially available fertilizers through a fertilizer briquetter machine developed by the IFDC. The briquetter machine allows the manufacturer to manipulate a fertilizer's guaranteed analysis to suit specific needs. In the case of this study, the briquettes were created by the IFDC and 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 1.1). This occurred because the S in the briquettes was supplied by ZnSO₄ (17.5% S) not ZnO/ZnSO₄ (9% S). The N, P, K, and Zn mineral sources used in the briquettes were urea, diammonium phosphate, potassium chloride, and zinc sulfate.

Off-Season Treatments

Between experimental years through the winter, winter wheat was planted as a cover crop and received the same fertilizer types per whole plot but altered subplot N application rates to more appropriately suit winter wheat. The N rates used for the winter wheat were 0, 50.4, 84.0, and 117.7 kg N ha⁻¹, corresponding to the low to high N rates applied to corn previously. Zero, 16.8, 33.6, and 50.4 kg N ha⁻¹ were applied basally in the fall and the remaining N was applied as a top-dress application in the following February. Plots that received the briquette treatments for corn also received additional fertilization as briquettes for winter wheat but only in the initial treatment year (2011 at Jackson and 2012 at Ames) after corn harvest. The briquette N rates used were 0, 50.4, 84.0, and 117.7 kg N ha⁻¹ all applied in the fall with no top-dress application in the spring. After the initial treatment year, plots that received the briquette treatments no longer received additional fertilization after corn harvest so that only the residual briquette fertilizer was allowed to influence the winter wheat. Phosphorus and K were applied basally as blanket applications at 19.6 and 37.2 kg ha⁻¹ respectively. Before corn planting at Jackson in the following spring, the winter wheat cover crop was killed with Gramoxone (Paraquat: 1,1'-Dimethyl-4,4'-bipyridinium dichloride) herbicide; at Ames the winter wheat cover crop was also killed with Gramoxone herbicide and then tilled by disc.

Soil and Plant Sampling, Analyses, and Measurements

Soil sampling was conducted in spring prior to treatment initiation at Jackson and Ames, and after corn harvest in the fall each year using a two-centimeter-diameter soil probe. Ten random soil cores per split plot were collected at a 0-15 cm depth and mixed to create a single composite soil sample per split plot. Each sample was allowed to air-dry before being ground fine enough to pass through a 2-mm sieve using a Quaker City Mill model 4-E (The Staub Co., Philadelphia, PA), and then the sample was thoroughly mixed. Analyses conducted on each sample at the IFDC Soil Testing Laboratory were KCl extractable NH₄⁺-N and NO₃⁻-N, extractable (Bray 1) P, SO₄²⁻-S, and organic C.

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 Ames, 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 65°C for 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 Ames 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 conducted in 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 were whole plots and were treated as a fixed experimental factor; blocks were treated as a random factor. The four N application rates were subplots and were randomized within each whole plot. In JA1213, year and location were also treated as fixed experimental factors. Means where year and location were treated as random factors were also reported in appendix A. For the soil analysis, post-harvest soil samples were analyzed after being adjusted for pre-treatment soil nutrient content. The post-ANOVA analysis method used was mean separation by Fisher's protected LSD. Probability values less than 0.05 for all analyses were designated as statistically significant.

Results and Discussion

Weather conditions throughout the duration of this study varied considerably, most particularly, monthly precipitation averages (Figure 1.1). Jackson had a particularly wet spring in 2011 and 2013 with approximately 494.3 and 479.5 mm of rainfall, respectively, between April and May. At Ames in 2013, the average monthly precipitation was a little more moderate at 369.3 mm between the same time period. In sharp contrast, in 2012 both Jackson and Ames were much drier with only 74.2 and 128.5 mm of rainfall, respectively, between the spring months of April and May. Between June and August, precipitation trends were fairly similar across location-years, but towards the end of the growing season the precipitation trends reversed from what they had been during the spring: Jackson and Ames in 2012 had considerably more precipitation (288.0 and 315.2 mm, respectively) between the months of September and October, whereas Jackson in 2011 and 2013 and Ames in 2013 were much drier (111.0, 170.2, and 166.4 mm, respectively) during the same time period. Average monthly temperatures also varied across location-years (Figure 1.2). In general, 2013 was a cooler year compared to 2011 and 2012 particularly during the spring months of March, April, and May. Temperatures in 2012 were as much as 5.6 to 8.3 °C warmer during that same time period. 2011 and 2012 were both approximately 3.3 °C warmer than 2013 during the whole month of July. Temperatures from August to the end of the growing season, however, were more similar across location-years.

Nutrient Concentrations in Plant Biomass and Grain

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 (Table 1.2). In J11, both Unity and the briquettes resulted in lower N concentrations in plant biomass at R1 and R6 than urea (Table 1.3). In JA1213, the briquettes produced higher biomass N concentrations at R1 than the other fertilizers, whereas Unity was similar to ammonium sulfate and urea. In the R6 biomass Unity produced less N concentrations than ammonium sulfate and urea; the briquettes produced similar N concentrations to ammonium sulfate and urea. In J11, Unity 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 Unity 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 (Table 1.2). As expected, higher N rates tended to produce significantly higher N concentrations in plant biomass and grain (Table 1.3). 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.

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 (Table 1.2). 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 1.5, Figure 1.3). 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 1.1). Biomass N concentrations at R6 differed among the fertilizer types in 2012; Unity 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 (Table 1.2). There was no difference in biomass N concentrations among the fertilizer types at Ames, but at Jackson under no-till conditions the briquettes produced higher biomass N concentrations at R1 than the other fertilizers (Table 1.5). Jackson had three years of trial whereas Ames only had two, thus the accumulated effects of the fertilizers at Jackson would be greater.

In summary, the performances of Unity 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, Unity 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, Unity 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 (Table 1.2). In J11, Unity produced lower biomass P concentrations at R1 (Table 1.3). In JA1213 the results were somewhat similar. This is an interesting result since Unity 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 Unity 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 R1 and R6 and in the grain (Table 1.2). 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. Alföldi 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 (Table 1.2). 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 Unity and ammonium sulfate.

In JA1213 there were also significant location by fertilizer type interactive effects on biomass P concentrations at R1 and R6 (Table 1.2). At Jackson, the briquettes and urea had higher biomass P concentrations at R1 and R6 compared to Unity and ammonium sulfate (Table 1.5). However, no such trends were observed at Ames.

In summary, Unity 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 Unity 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 Unity 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 (Table 1.2). Only in the grain in J11 did fertilizer types have a significant impact, and in this case Unity had the lowest grain K concentration, whereas the briquettes had the highest out of the four fertilizer types (Table 1.3). That Unity 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 (Table 1.2), but in JA1213 N rates had highly significant influence on K concentrations in biomass at R1 and R6 and in grain (Table 1.2). 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 1.3), 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 (Table 1.2). 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 1.5).

In JA1213 there was also a significant interactive effect between location and fertilizer type on biomass K concentrations at R1 and R6 (Table 1.2). 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 Ames (Table 1.5).

In summary, plant K concentrations were generally not influenced by either Unity or the briquettes relative to the ammonium sulfate and urea treatments. The performances of Unity 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 Unity 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 (Table 1.2). 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 1.4); 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 Unity and ammonium sulfate fertilizer treatments than the briquette and urea fertilizers (Figure 1.4). 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, Unity, 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 Unity and ammonium sulfate than the briquettes and urea.

In general, Unity 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 Unity 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 ZnSO₄. 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 (Table 1.2). In 2012, Unity and ammonium sulfate were similar, but produced greater biomass S concentrations at R6 than the other two fertilizers (Table 1.5). In 2013, however, ammonium sulfate had greater biomass S concentration at R6 than Unity, Unity 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 (Table 1.2). At Jackson, biomass S concentrations at R1 were higher under Unity and ammonium sulfate than the other two fertilizer types; Unity was highest in biomass S concentration (Table 1.5). Grain S concentrations were equally higher under Unity, briquette, and ammonium sulfate fertilization than urea. At Ames, S concentrations in biomass at R1 and in grain were greater under Unity and ammonium sulfate than the briquettes and urea.

Generally, plant S concentrations were increased with Unity and ammonium sulfate particularly at higher N application rates compared to the briquettes and urea because both Unity and ammonium sulfate contain significant proportions of S in their chemical composition. The performances of Unity 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 Unity 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 (Table 1.2). In that case, the briquettes resulted in higher grain Fe concentrations than urea (Table 1.3). 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, Unity stood little chance of enhancing plant Fe concentrations.

Nitrogen rates significantly impacted Fe concentrations in biomass at R1 and R6 and in grain except in biomass at R1 in JA1213 (Table 1.2). In J11, the lowest N rate produced lower biomass Fe concentration at R1 than the other three higher N rates (Table 1.3); similar trends were 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 (Table 1.2). In 2012, ammonium sulfate produced greater Fe concentrations than the briquettes and urea (Table 1.5). 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 (Table 1.2). At Jackson, fertilizer types did not differ in biomass Fe concentrations at R6, but at Ames, briquettes produced higher biomass Fe concentrations at R6 than ammonium sulfate (Table 1.5).

Overall, plant Fe concentrations were not improved by Unity 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 Unity 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 (Table 1.2). In general, Unity and ammonium sulfate produced higher Zn concentrations in biomass at R1 and at R6 and in grain than the briquettes and urea (Table 1.3).

Nitrogen rates only had a significant impact on Zn concentrations in biomass at R6 in J11 and in grain in JA1213 (Table 1.2). In J11, biomass Zn concentration at R6 was higher at the lowest N rate than the other N rates (Table 1.3). 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 (Table 1.2). 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 1.4). However, at the 170 and 255 kg N ha⁻¹ rates, Unity 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 (Table 1.2). At the lowest N rate, there were no differences in biomass Zn at R1 or R6 among the fertilizer types (Table 1.4). However, Unity frequently had higher Zn concentrations at R1 and R6 than the other fertilizer types at the 128 and 170 kg N ha⁻¹ rates (Figure 1.5). Overall, Unity 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 (Table 1.2). 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 1.5). In 2012, Unity 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 Unity 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 Unity 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, Unity 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).

The above results and discussion on biomass and grain nutrient concentrations were based on means where years and locations were treated as fixed factors. Biomass and grain nutrient concentration means where years and locations were treated as random factors are also reported in Tables 1.6, 1.7, and 1.8.

Soil Nutrient Concentrations

Phosphorus

There was a significant fertilizer type by N rate interaction effect on soil P concentrations in J11 and JA1213 (Table 1.9). In J11, at the 85 and 255 kg N ha⁻¹ rates, there were no differences between the fertilizer types in soil P concentrations (Table 1.11). At the 170 kg N ha⁻¹ rate however, Unity, briquettes, and urea produced higher soil P concentrations than ammonium sulfate. In JA1213, the results were more confounded (Table 1.11). At the 0 kg N ha⁻¹ rate, soil P did not differ among the four fertilizer types. However, at the 85 and 128 kg N ha⁻¹ rates, the briquettes produced higher soil P concentrations than ammonium sulfate and urea. At the highest N rate, Unity and the briquettes were similar to ammonium sulfate and urea in residual soil P levels. That Unity as a biosolid enhanced fertilizer did not increase soil P concentrations above all the other fertilizers may be an advantage, however because the N:P ratio of many biosolids is considerably lower than what is commonly taken up by plants thus creating oversupplied P with time (Elliot and O'Connor, 2007; O'Connor et al., 2005; Singh et al, 2011).

In JA1213 there was also a strongly significant year by fertilizer interactive effect on P soil concentrations (Table 1.9). In 2012, the briquettes produced higher soil P concentrations than

ammonium sulfate and urea (Table 1.12). In 2013, Unity had higher soil P concentrations than the briquettes and ammonium sulfate.

Overall, The effects of Unity and the briquettes on soil residual P after corn harvest were affected by N rates and years. Our results suggest although P in the Unity biofertilizer product seems to be less available to the plant, Unity is sometimes lower than the other fertilizer types in residual soil P fertility. That Unity did not excel in P soil concentration is in contrast to Edmeades' findings in which organically fertilized soils were more P enriched compared to mineral fertilized soils (Edmeades, 2003). Indeed, other studies conducted on biosolid use as soil amendments found soil P availability to be greater with biosolid use (Cortellini et al., 1996; Huma, 1997; Jamil et al., 2006; Mantovi et al., 2005)

Nitrate-N

As with soil P concentrations, soil NO_3^- -N concentrations after corn harvest experienced fertilizer type by N rate interactive effects in both J11 and JA1213 (Table 1.9). In J11 at the lowest N rate, fertilizer types did not differ in soil NO_3^- -N concentrations (Table 1.11). At the 170 and 255 kg N ha⁻¹ rates, however, urea produced greater soil NO_3^- -N concentrations than Unity and the briquettes. The briquettes had the lowest soil NO_3^- -N levels at the 255 kg N ha⁻¹ N rate (Figure 1.6). In JA1213, the differences between fertilizer types by N rate were less prominent (Table 1.11). For example, at the 85 and 170 kg N ha⁻¹ rates, Unity and the briquettes were fairly similar to ammonium sulfate and urea in soil NO_3^- -N. At 128 kg N ha⁻¹ rate, however, urea had higher soil NO_3^- -N concentrations than Unity and the briquettes.

In JA1213 there were also significant year by fertilizer type and location by fertilizer type interactive effects on soil NO_3^- -N concentrations (Table 1.9). In 2012, there were no differences in soil NO_3^- -N concentrations among the fertilizer types (Table 1.12). In 2013, however, urea had higher soil NO_3^- -N levels than the briquettes and ammonium sulfate, and Unity had higher soil NO_3^- -N concentrations than ammonium sulfate. At Jackson, Unity had less soil NO_3^- -N than urea (Table 1.12). At Ames, however, no differences in soil NO_3^- -N concentrations were observed among the fertilizer types.

In summary, the effects of Unity and the briquettes on residual soil NO_3^- -N after corn harvest were affected by N application rates, years, and locations. After corn harvest, soil NO_3^- -N concentrations were generally lower with Unity and the briquettes than urea. Singh et al. (2011) found that biosolid enhanced fertilizers had delayed nitrification and significantly less NO_3^- -N leaching than urea. That Unity in our study had less soil NO_3^- -N concentrations compared to urea may also be an indication of delayed nitrification and thus greater N use efficiency by the plant. In J11, the briquettes generally produced lower soil NO_3^- -N concentrations at the two highest N rates than the other fertilizer types, and in JA1213 Unity and the briquettes likewise produced lower soil NO_3^- -N concentrations at the 128 kg N ha⁻¹ rate than urea. This seems to suggest that the N in Unity and the briquettes nitrifies more slowly than urea which may lend itself to greater N use efficiency. Khalil et al. (2011) reported soil N to be much lower under urea super granules compared to surface applied prilled urea. They likewise found large soil reserves of fertilizer N at harvest from prilled urea, which was subject to loss and poor recovery by succeeding crops.

Ammonium-N

In J11, only N rates had a significant impact on soil NH_4^+ -N concentrations (Table 1.9). The 170 kg N ha⁻¹ rate resulted in higher soil NH_4^+ -N concentrations than the other N rates which were all similar (Table 1.10). It is interesting that the highest N rate was similar to the lowest two N rates in soil NH_4^+ -N levels after corn harvest.

In JA1213, there was a strong fertilizer type by N rate interactive effect on soil NH_4^+ -N concentrations (Table 1.9). At the 0 kg N ha⁻¹ rate, Unity, the briquettes, and ammonium sulfate had higher soil NH_4^+ -N concentrations than the urea (Table 1.11). At the 85 kg N ha⁻¹ rate, urea had higher soil NH_4^+ -N levels than the other fertilizers followed by the briquettes and Unity which had higher soil NH_4^+ -N than ammonium sulfate. At the 128 and 170 kg N ha⁻¹ N rates, Unity and urea produced greater soil NH_4^+ -N concentrations than the briquettes and ammonium sulfate.

In JA1213 there was also a very significant year by fertilizer type interactive effect and also a very significant location by fertilizer type interactive effect on soil NH_4^+ -N concentrations (Table

1.9). In 2012, Unity and the briquettes were similar to ammonium sulfate and urea in soil NH_4^+ -N levels (Table 1.12). In 2013, however, Unity and urea produced greater soil NH_4^+ -N concentrations than the other fertilizer types. Within the location by fertilizer type interaction, at Jackson, Unity and urea had greater soil NH_4^+ -N concentrations than the briquettes and ammonium sulfate (Table 1.12). At Ames, urea had greater soil NH_4^+ -N concentrations than the other fertilizer types.

In general, Unity and urea sometimes had higher residual soil NH_4^+ -N than the briquettes and ammonium sulfate. The effects of Unity and the briquettes on soil residual NH_4^+ -N were influenced by N rates, years, and locations. Our results suggest that the briquettes may be more N efficient than Unity or urea because both had more residual soil NH_4^+ -N after harvest which is subject to loss or poor recovery by succeeding crops. That ammonium sulfate, like the briquettes, having lower soil NH_4^+ -N is more likely due to ammonia volatilization, however. Vlek and Craswell (1979) found ammonia losses from ammonium sulfate to reach approximately 15% within three weeks of application on non-alkaline soils. Freney et al. (1981) reported 7% N losses from ammonia volatilization within 7 days of ammonium sulfate application. Fenn and Kissel (1973) compared different surface applied ammonium salt fertilizers and found that within 100 hours of application ammonium sulfate had lost 54% of its N to ammonia volatilization.

Sulfate-S

In both J11 and JA1213, there was a significant fertilizer type by N rate interactive effect on soil SO_4^{2-} -S concentrations (Table 1.9). In J11 at the 85 kg N ha⁻¹ rate, Unity and ammonium sulfate had higher soil SO_4^{2-} -S concentrations than urea (Table 1.11). At the 170 kg N ha⁻¹ rate, Unity had higher SO_4^{2-} -S concentrations than the other fertilizer types. At the 255 kg N ha⁻¹ rate, ammonium sulfate produced higher soil SO_4^{2-} -S concentrations than all the other fertilizer types and Unity produced higher soil SO_4^{2-} -S concentrations than the briquettes and urea.

In JA1213, Unity had similar soil SO_4^{2-} -S concentrations than ammonium sulfate at the 85 kg N ha⁻¹ rate (Table 1.11). At the 128 kg N ha⁻¹ rate, Unity and ammonium sulfate had higher soil SO_4^{2-} -S than the briquettes and urea. At the 170 kg N ha⁻¹ N rate, ammonium sulfate had higher soil SO_4^{2-} -S levels than the other fertilizer types.

Overall, the concentrations of residual soil $\text{SO}_4^{2-}\text{-S}$ were generally higher with Unity and ammonium sulfate compared to the briquettes and urea after corn harvest. The effects of Unity and ammonium sulfate on residual soil $\text{SO}_4^{2-}\text{-S}$ were affected by N rates, but were not influenced by years or locations. Our results suggest S in Unity and ammonium sulfate not only improve plant S nutrition, but also increase residual soil S levels after corn harvest, particularly at higher application rates.

Organic Carbon

In J11, soil organic C concentration differed remarkably among fertilizer types (Table 1.9). Unity had higher soil organic C concentrations than the other fertilizer types (Table 1.10). In JA1213 there was a highly significant fertilizer type by N rate interactive effect on soil organic C (Table 1.9). Aside from the control where all the fertilizer types were similar in organic C, Unity consistently had higher soil organic C concentrations than all the other fertilizer types at the 85, 128, and 170 kg N ha⁻¹ rates (Table 1.11, Figure 1.7). At the 128 kg N ha⁻¹ rate, the briquettes had more residual organic C than ammonium sulfate and urea.

In JA1213 there was a significant year by fertilizer type interactive effect on soil organic C concentration (Table 1.9). In both 2012 and 2013, Unity had greater soil organic C concentrations than any of the other fertilizer types (Table 1.12). Within 2013, briquettes produced greater soil organic C concentrations than ammonium sulfate and urea.

Overall, soil organic C concentrations were consistently higher with the Unity biofertilizer product than the other fertilizer treatments after corn harvest. The effects of Unity on soil organic C were affected by years and sometimes by N application rates. Our results suggest organic matter in the Unity biofertilizer product is available to enhance soil organic C levels after two to three years of application, particularly at higher application rates.

The soil data reveal that Unity does in fact impart significantly greater quantities of organic C into the 0-15 cm soil layer than the other fertilizer types in this study. This was true for both J11 and JA1213 and is a strong contrast to Gosling and Shepherd's (2005) findings in which soil

organic C concentrations did not differ between farms that had been organically fertilized for 15 years versus conventionally fertilized farms. Other studies found increases in soil organic C with land applications of biosolids (Jamil et al., 2006; Mantovi et al., 2005). This is an important finding because higher concentrations of soil C have been associated with greater fertility benefits (Herencia et al., 2007) and improvement in soil physical characteristics such as superior soil aggregation and aeration (Dridi and Zerrouk, 2000). If the study had been allowed to continue perhaps Unity's organic C contribution would have amounted to greater corn mineral nutrition and productivity due to increased soil quality.

The above results and discussion on soil nutrient levels after harvest were based on means where years and locations were treated as fixed factors. After harvest soil nutrient level means where years and locations were treated as random factors are also reported in Tables 1.13, 1.14, and 1.15.

Conclusions

Unity 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 and lower residual soil NO_3^- -N levels after corn harvest. These results suggest that the briquettes may have greater N use efficiency than ammonium sulfate and urea particularly in wet soil conditions. Unity tended to have less P concentrations in plant biomass at R1 and R6 even though it was sometimes higher than the other fertilizers in residual soil P concentrations after corn harvest, thus the P provided by Unity 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 Unity or briquette fertilization. Unity and ammonium sulfate both increased S concentrations in plant biomass and residual soil SO_4^{2-} -S levels compared to the briquettes and urea. Plant Fe concentrations were not improved by Unity even though only Unity supplied Fe and Fe was not applied uniformly across all fertilizer types. Unity improves 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. Residual soil organic C levels were consistently highest under Unity. In conclusion, the briquettes do not consistently improve corn N, P, K, and Zn nutrition compared to the conventional fertilizers ammonium sulfate and urea. Unity sometimes seems to reduce corn N and P nutrition but increase Zn nutrition relative to ammonium sulfate and urea. Unity consistently increases soil organic C levels, particularly at the higher N rates, within three years of experimentation. The fact that higher soil organic C levels is associated with greater soil quality in scientific literature suggests that had the study continued longer the greater organic C contributed to the soil by Unity may have translated into higher nutrient concentrations and grain quality of corn with time. Future research conducted for more than three years may be necessary to elucidate Unity's potential for greater soil quality and thus plant mineral nutrition.

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Appendix A

Table 1.1. Treatment descriptions at Jackson and Ames during 2011 to 2013.

Treatment Number	Fertilizer Type	N Rate kg ha ⁻¹	P Rate	K Rate	S Rate	Zn Rate
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	Unity NPSFe	0	45	85	1.25	5
6	Unity NPSFe	85	45	85	104†	5
7	Unity NPSFe	128/170	45	85	156/207	5
8	Unity 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 Unity 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/ZnSO₄ was used which has less overall SO₄.

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

Table 1.2. Analysis of variance p-values for nutrient concentrations in the aboveground plant biomass at R1 and R6 and grain of corn at Jackson and Ames during 2011 to 2013 with years and locations treated as fixed effects in the JA1213 data set.

	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
J11																		
Treatments																		
Fertilizer Type (FT)	***	**	ns	***	ns	**	***	ns	ns	***	ns	**	*	***	**	***	ns	*
N Rate (NR)	***	ns	ns	***	**	ns	***	***	ns	***	*	*	***	ns	ns	***	***	ns
FT x NR	ns	ns	ns	***	ns	*	ns	ns	ns	*	ns	ns	ns	ns	ns	**	ns	ns
JA1213																		
Treatments																		
Fertilizer Type (FT)	**	**	ns	***	ns	**	*	***	ns	***	ns	***	ns	ns	ns	***	*	ns
N Rate (NR)	***	***	***	***	ns	***	***	***	***	***	***	***	***	***	***	***	***	***
FT x NR	ns	ns	ns	***	ns	***	ns	ns	ns	***	ns	**	ns	ns	ns	**	ns	ns
Year (Y)	*	***	***	*	ns	**	***	ns	***	***	**	***	***	***	***	***	***	***
Y x FT	***	*	ns	ns	ns	ns	***	ns	*	**	ns	*	ns	*	ns	ns	***	*
Y x NR	ns	**	ns	*	ns	ns	**	**	**	***	ns	**	ns	***	*	***	*	**
Y x FT x NR	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	**	ns
Location (L)	*	***	***	ns	***	**	***	***	***	**	***	***	*	***	ns	*	*	***
L x FT	***	***	*	*	ns	ns	ns	***	**	ns	*	ns	ns	ns	ns	*	ns	ns
L x NR	ns	***	ns	ns	ns	ns	*	***	**	***	ns	ns	ns	**	***	ns	ns	*
L x FT x NR	ns	ns	ns	ns	ns	*	ns	**	ns	ns	ns	**	ns	ns	ns	ns	ns	ns
Y x L	ns	ns	*	ns	ns	ns	***	ns	ns	ns	ns	ns	***	ns	ns	***	***	*
Y x L x FT	*	ns	**	**	***	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y x L x NR	ns	*	*	ns	ns	ns	ns	***	***	ns	ns	**	ns	ns	*	*	ns	ns
Y x L x FT x NR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	*	ns	ns	ns	ns	*	ns

ns, not significant at the 0.05 probability level.

*, significant at the 0.05 probability level.

**, significant at the 0.01 probability level.

***, significant at the 0.001 probability level.

Table 1.3. 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 Ames during 2011 to 2013 with years and locations treated as fixed effects in the JA1213 data set.

	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						 g kg ⁻¹						 g kg ⁻¹						 µg g ⁻¹ ...
J11																			
Fertilizer Type																			
Unity 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																			
Unity 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.

Table 1.4. 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 Ames during 2011 to 2013 with years and locations treated as fixed effects in the JA1213 data set.*

		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	Unity 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	Unity 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	Unity 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	Unity 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	Unity 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	Unity 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	Unity 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	Unity 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.

Table 1.5. 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 Ames during 2012 to 2013 with years and locations treated as fixed effects in the JA1213 data set.*

		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				... μg g ⁻¹ ...		... g kg ⁻¹ ...		... μg g ⁻¹ ...	
Year	Fertilizer Type														
2012	Unity 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	Unity 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	Unity 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	—	—
Ames	Unity 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.

Table 1.6. Analysis of variance p-values for nutrient concentrations in the aboveground plant biomass at R1 and R6 and grain of corn at Jackson and Ames during 2012 to 2013 with years and locations treated as random effects.

	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
Treatments																		
Fertilizer Type (FT)	ns	**	ns	***	ns	**	ns	*	ns	***	ns	*	ns	ns	ns	***	ns	ns
N Rate (NR)	***	***	***	***	ns	***	***	***	***	***	***	***	***	***	***	***	***	**
FT x NR	ns	ns	ns	***	ns	***	ns	ns	ns	***	ns	*	ns	ns	ns	***	ns	ns

ns, not significant at the 0.05 probability level.

*, significant at the 0.05 probability level.

**, significant at the 0.01 probability level.

***, significant at the 0.001 probability level.

Table 1.7. 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 Ames during 2012 to 2013 with years and locations treated as random effects.

	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				...µg g ⁻¹ ...		g kg ⁻¹				...µg g ⁻¹ ...		g kg ⁻¹				...µg g ⁻¹ ...	
Fertilizer Type																		
Unity NPSFe	10.05a†	1.96c	14.21a	1.10a	58.94a	29.97a	8.05a	2.31b	6.36a	0.90a	169.05a	35.85a	10.83a	2.69a	3.57a	0.98a	15.18a	23.14a
NPKZn briquettes	11.01a	2.19ab	15.48a	0.81b	61.49a	25.65c	8.67a	2.49a	6.51a	0.75b	177.58a	31.76b	10.85a	2.78a	3.60a	0.93b	15.94a	22.66a
Ammonium sulfate	10.08a	2.03bc	14.62a	1.03a	56.91a	28.49ab	8.85a	2.32b	6.68a	0.87a	143.94a	33.89ab	11.05a	2.74a	3.62a	0.98a	15.61a	23.59a
Urea	9.56a	2.24a	15.78a	0.73c	51.78a	27.01bc	9.08a	2.52a	6.26a	0.74b	162.14a	33.69ab	10.92a	2.74a	3.57a	0.90c	14.86a	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	1.83bc	14.08c	1.10a	56.74a	28.61b	9.50a	2.00c	5.89c	0.88a	97.43d	27.94b	11.85a	2.64b	3.40c	0.99a	16.64a	22.58b

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

Table 1.8. 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 Ames during 2012 to 2013 with years and locations treated as random effects.*

		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
N Rate (kg N ha ⁻¹)	Fertilizer Type					
0	Unity 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	0.74a	46.63a	0.92a
	Urea	0.67a	33.23a	0.75a	48.48a	0.92a
85	Unity 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	25.76ab	0.72b	30.06a	0.88b
128	Unity 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	29.02ab	1.00a
	Urea	0.72d	23.37b	0.74b	28.14b	0.89b
170	Unity NPSFe	1.47a	37.73a	1.05a	33.58a	1.06a
	NPKZn Briquettes	0.87c	21.51c	0.77c	22.9c	0.95b
	Ammonium Sulfate	1.28b	29.54b	0.96b	27.21bc	1.05a
	Urea	0.79c	25.69bc	0.75c	28.09b	0.90b
	LSD††	0.13	4.53	0.06	5.19	0.05

*, only significant interactive effects are reported.

†, means in each column within each N rate level 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.

Table 1.9. Analysis of variance p-values for soil nutrient concentrations in the 0-15 cm depth at Jackson and Ames during 2011 to 2013 with years and locations treated as fixed effects in the JA1213 data set.

	Bray P	NO ₃ ⁻ -N	NH ₄ ⁺ -N	SO ₄ ²⁻ -S	Organic C
J11					
Treatments					
Fertilizer Type (FT)	**	***	ns	*	***
N Rate (NR)	ns	***	**	ns	ns
FT x NR	**	**	ns	***	ns
JA1213					
Treatments					
Fertilizer Type (FT)	ns	*	***	***	***
N Rate (NR)	***	***	***	***	***
FT x NR	**	*	***	*	***
Year (Y)	***	***	***	***	***
Y x FT	***	**	***	ns	**
Y x NR	***	***	***	***	***
Y x FT x NR	ns	ns	***	ns	***
Location (L)	ns	***	***	***	*
L x FT	ns	*	***	ns	ns
L x NR	***	ns	***	ns	**
L x FT x NR	*	ns	**	**	ns
Y x L	*	ns	*	ns	ns
Y x L x FT	***	***	***	ns	*
Y x L x NR	ns	ns	ns	ns	***
Y x L x FT x NR	ns	ns	ns	ns	ns

ns, not significant at the 0.05 probability level.

*, significant at the 0.05 probability level.

**, significant at the 0.01 probability level.

***, significant at the 0.001 probability level.

Table 1.10. Means of soil nutrient concentrations in the 0-15 cm depth for fertilizer types and N rates at Jackson and Ames during 2011 to 2013 with years and locations treated as fixed effects in the JA1213 data set.

	Bray P	NO ₃ ⁻ -N	NH ₄ ⁺ -N	SO ₄ ²⁻ -S	Organic C
	mg kg ⁻¹				g kg ⁻¹
J11					
Fertilizer Type					
Unity NPSFe	26.37a†	7.40bc	3.48a	3.64a	10.51a
NPKZn Briquettes	27.46a	5.19c	3.47a	3.29ab	9.70b
Ammonium Sulfate	23.01b	9.98ab	3.79a	3.68a	8.97c
Urea	26.67a	13.97a	3.81a	3.00b	9.44bc
N Rate (kg N ha⁻¹)					
0	25.99a	4.50c	3.60b	3.15b	9.55a
85	25.01a	5.65c	3.43b	3.26ab	9.56a
170	26.60a	10.62b	4.19a	3.53ab	9.45a
255	25.90a	19.58a	3.33b	3.65a	10.05a
JA1213					
Fertilizer Type					
Unity NPSFe	15.19a	0.76ab	1.87a	2.40a	12.67a
NPKZn Briquettes	12.86a	0.62c	1.24b	2.15b	10.66b
Ammonium Sulfate	13.22a	0.70bc	1.06c	2.70a	9.39c
Urea	13.74a	0.82a	2.00a	2.07b	9.87c
N Rate (kg N ha⁻¹)					
0	16.51a	0.72b	0.72c	2.58a	8.67c
85	14.72b	0.70b	1.33b	2.50a	10.72b
128	13.26c	0.92a	2.20a	2.20b	11.00b
170	11.01d	0.59c	2.37a	2.03c	12.19a

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

Table 1.11. Interaction means of soil nutrient concentrations in the 0-15 cm depth for fertilizer types by N rates at Jackson and Ames during 2011 to 2013 with years and locations treated as fixed effects in the JA1213 data set.*

		Bray P	NO ₃ ⁻ -N	NH ₄ ⁺ -N	SO ₄ ²⁻ -S	Organic C
		 mg kg ⁻¹				g kg ⁻¹
J11						
N Rate (kg N ha ⁻¹)	Fertilizer Type					
0	Unity NPSFe	24.37bc†	4.07a	—	3.37b	—
	NPKZn Briquettes	31.77a	4.47a	—	4.22a	—
	Ammonium Sulfate	19.33c	4.79a	—	3.45b	—
	Urea	28.50ab	3.92a	—	3.70ab	—
85	Unity NPSFe	28.17a	3.95b	—	3.91a	—
	NPKZn Briquettes	24.72a	5.34ab	—	3.43ab	—
	Ammonium Sulfate	22.55a	4.93ab	—	3.66a	—
	Urea	24.60a	9.20a	—	3.35b	—
170	Unity NPSFe	27.86a	9.14bc	—	4.28a	—
	NPKZn Briquettes	27.86a	6.20c	—	3.85b	—
	Ammonium Sulfate	21.52b	18.70ab	—	2.74b	—
	Urea	29.18a	25.62a	—	3.80b	—
255	Unity NPSFe	25.07a	26.79b	—	3.95b	—
	NPKZn Briquettes	25.50a	6.12c	—	3.54c	—
	Ammonium Sulfate	28.63a	31.07ab	—	6.46a	—
	Urea	24.39a	48.63a	—	3.38c	—
LSD††		5.48	16.54		0.24	
JA1213						
N Rate (kg N ha ⁻¹)	Fertilizer Type					
0	Unity NPSFe	18.61a	1.44b	1.54a	2.89a	8.03b
	NPKZn Briquettes	22.67a	1.37b	1.56a	2.50ab	9.36a
	Ammonium Sulfate	18.80a	1.32b	1.75a	2.51a	8.65ab
	Urea	17.90a	1.57a	1.52b	2.42b	8.65ab
85	Unity NPSFe	19.08ab	1.38ab	1.80bc	2.71a	12.65a
	NPKZn Briquettes	24.29a	1.57a	2.15b	2.46bc	10.67b
	Ammonium Sulfate	14.44b	1.26b	1.71c	2.58ab	9.50c
	Urea	16.42b	1.41ab	3.02a	2.22c	10.08bc
128	Unity NPSFe	18.35ab	1.37c	3.39a	2.25a	13.75a
	NPKZn Briquettes	23.23a	1.54bc	2.69b	1.98b	11.48b
	Ammonium Sulfate	15.32b	1.60ab	2.18b	2.70a	8.53d
	Urea	16.93b	1.79a	3.29a	1.89b	10.22c
170	Unity NPSFe	13.52b	1.12ab	4.15a	1.75b	16.24a
	NPKZn Briquettes	19.23a	1.09b	3.16b	1.63b	11.15b
	Ammonium Sulfate	17.03a	1.19ab	1.82c	2.99a	10.86b
	Urea	15.10ab	1.27a	4.05a	1.75b	10.51b
LSD		3.55	0.41	0.76	0.60	1.05

*, only significant interactive effects are reported.

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

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

Table 1.12. Interaction means of soil nutrient concentrations in 0-15 cm depth for fertilizer types by years or locations from the JA1213 data set at Jackson and Ames during 2012 to 2013 with years and locations treated as fixed effects.*

		Bray P	NO ₃ ⁻ -N	NH ₄ ⁺ -N	Organic C
		 mg kg ⁻¹			g kg ⁻¹
Year	Fertilizer Type				
2012	Unity NPSFe	22.56ab†	2.37a	3.58ab	11.08a
	NPKZn Briquettes	29.82a	2.51a	3.66ab	9.74b
	Ammonium Sulfate	21.33b	2.43a	3.34b	8.82c
	Urea	21.63b	2.70a	4.36a	9.36bc
2013	Unity NPSFe	12.22a	0.29ab	1.86a	14.25a
	NPKZn Briquettes	14.89ab	0.28b	1.13b	11.58b
	Ammonium Sulfate	11.46c	0.26c	0.39c	9.96c
	Urea	11.55b	0.32a	1.58a	10.37c
	LSD††	2.77	0.39	0.59	0.82
Location	Fertilizer Type				
Jackson	Unity NPSFe	—	1.06b	2.23a	—
	NPKZn Briquettes	—	1.16ab	1.95b	—
	Ammonium Sulfate	—	1.06b	1.68b	—
	Urea	—	1.32a	2.10a	—
Ames	Unity NPSFe	—	1.59a	3.21b	—
	NPKZn Briquettes	—	1.62a	2.84b	—
	Ammonium Sulfate	—	1.63a	2.05c	—
	Urea	—	1.70a	3.84a	—
	LSD		0.40	0.61	

*,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.

Table 1.13. Analysis of variance p-values for soil nutrient concentrations in the 0-15 cm depth at Jackson and Ames during 2012 to 2013 with years and locations treated as random effects.

	Bray P	NO₃⁻-N	NH₄⁺-N	SO₄²⁻-S	Organic C
Treatments					
Fertilizer Type (FT)	***	ns	***	*	***
N Rate (NR)	**	***	***	ns	***
FT x NR	ns	ns	***	ns	***

ns, not significant at the 0.05 probability level.

*, significant at the 0.05 probability level.

**, significant at the 0.01 probability level.

***, significant at the 0.001 probability level.

Table 1.14. Means of soil nutrient concentrations in the 0-15 cm depth for fertilizer types and N rates at Jackson and Ames during 2012 to 2013 with years and location treated as random effects.

	Bray P	NO ₃ ⁻ -N	NH ₄ ⁺ -N	SO ₄ ²⁻ -S	Organic C
	mg kg ⁻¹				g kg ⁻¹
Fertilizer Type					
Unity NPSFe	17.55b†	1.33a	2.74ab	2.45ab	12.88a
NPKZn Briquettes	21.94a	1.41a	2.27bc	2.11b	10.58b
Ammonium Sulfate	16.56b	1.34a	1.90c	2.73a	9.27c
Urea	16.68b	1.50a	3.03a	2.02b	9.85c
N Rate (kg N ha ⁻¹)					
0	19.54a	1.42a	1.58d	2.55a	8.54c
85	18.56a	1.41a	2.19c	2.47a	10.74b
128	18.42a	1.58a	2.87b	2.23a	11.02b
170	16.21b	1.17b	3.30a	2.07a	12.28a

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

Table 1.15. Interaction means of soil nutrient concentrations in the 0-15 cm depth for fertilizer types by N rates at Jackson and Ames during 2012 to 2013 with years and locations treated as random effects.*

N Rate (kg N ha ⁻¹)	Fertilizer Type	NH ₄ ⁺ -N	Organic C
		mg kg ⁻¹	g kg ⁻¹
0	Unity NPSFe	1.58a†	7.97a
	NPKZn Briquettes	1.40a	9.18a
	Ammonium Sulfate	1.77a	8.51a
	Urea	1.57a	8.48a
85	Unity NPSFe	1.84b	12.93a
	NPKZn Briquettes	2.05b	10.52b
	Ammonium Sulfate	1.74b	9.38b
	Urea	3.11a	10.13b
128	Unity NPSFe	3.37a	13.96a
	NPKZn Briquettes	2.56ab	11.48b
	Ammonium Sulfate	2.24b	8.36c
	Urea	3.32a	10.28b
170	Unity NPSFe	4.16a	16.68a
	NPKZn Briquettes	3.07b	11.13b
	Ammonium Sulfate	1.86c	10.84b
	Urea	4.12a	10.49b
	LSD††	0.87	1.44

*, only significant interactive effects are reported.

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

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

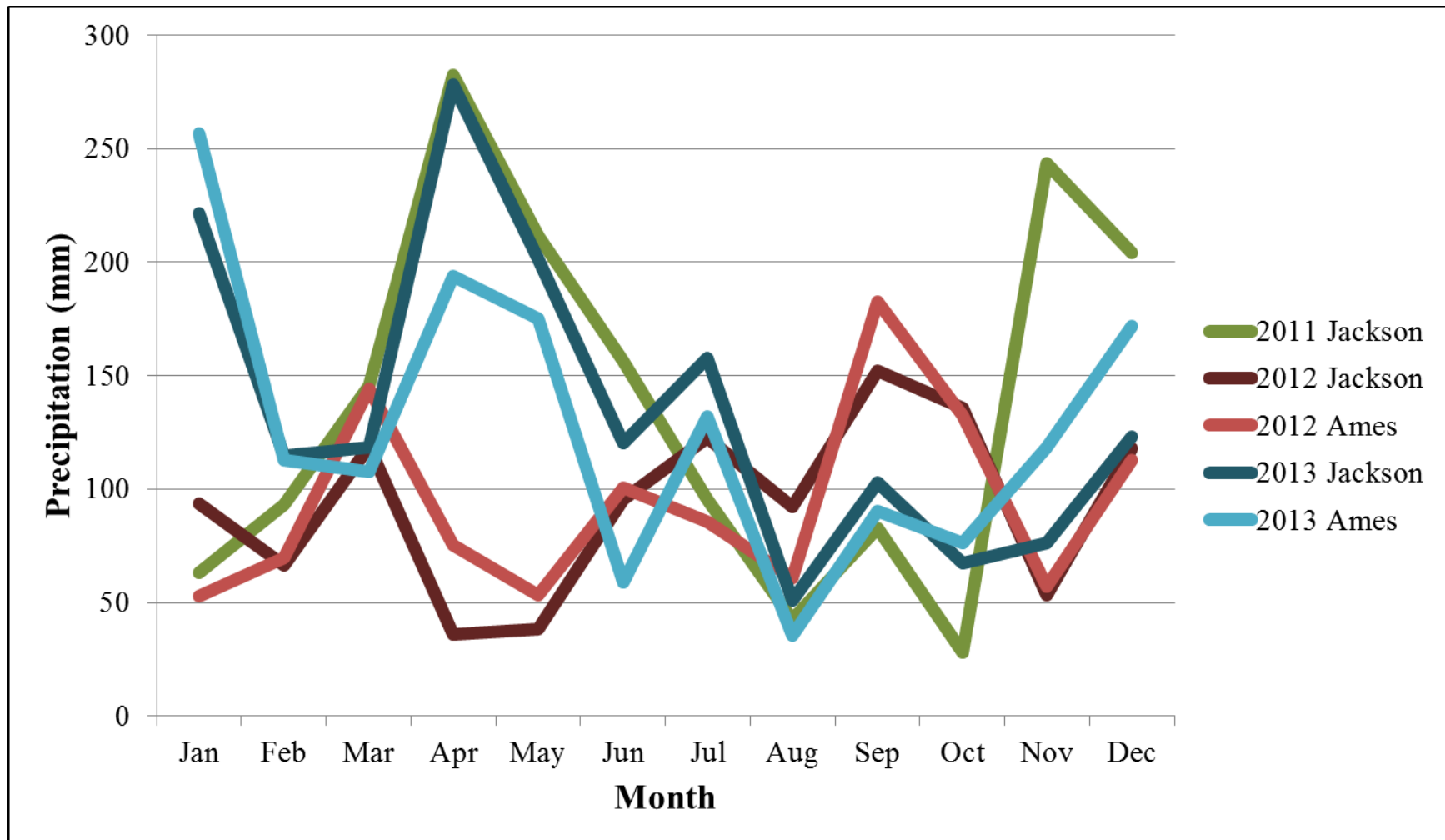


Figure 1.1. Average monthly precipitation during the durations of this study.

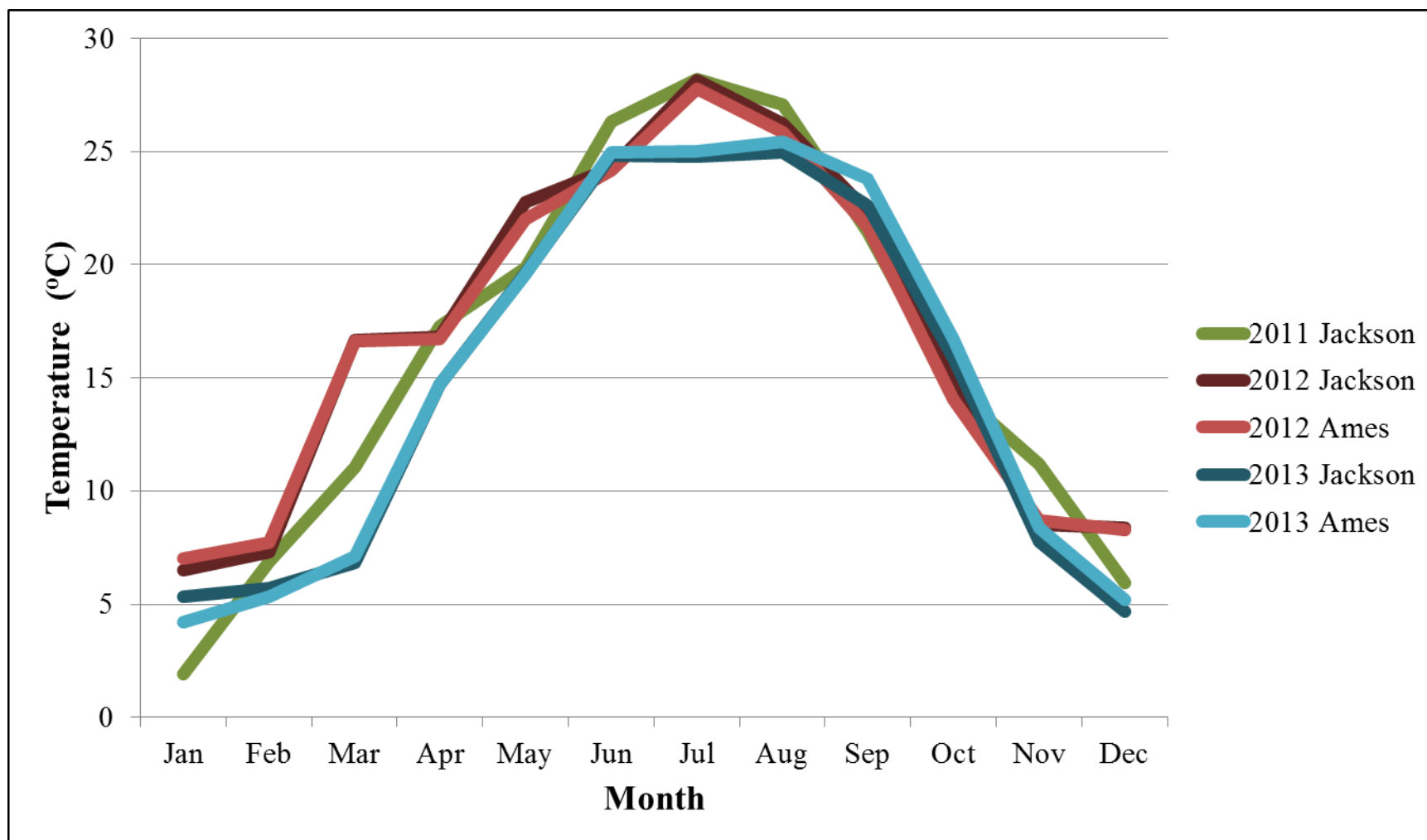


Figure 1.2. Average monthly temperatures during the duration of this study.

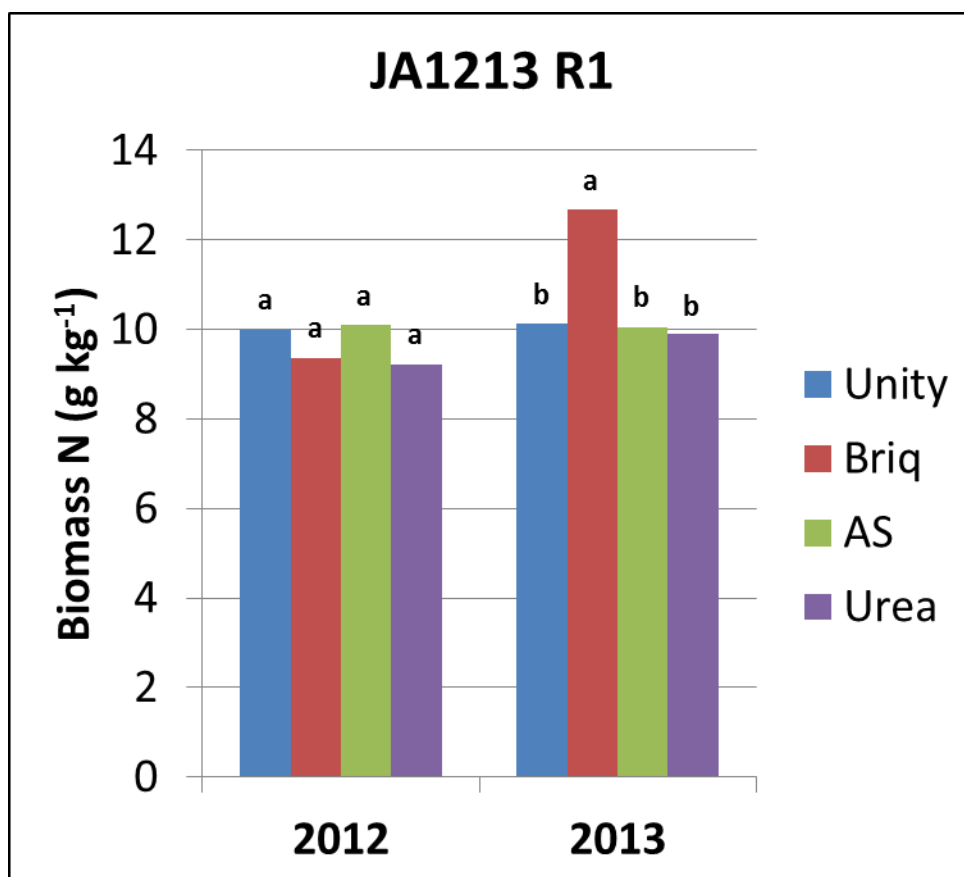


Figure 1.3. Interaction means of N concentrations in the R1 biomass for fertilizer types by years at Jackson and Ames in 2012 and 2013. Biomass N concentrations within year followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD. Abbreviations: Unity, Unity NPSFe; Briq, NPKZn briquettes; AS, ammonium sulfate.

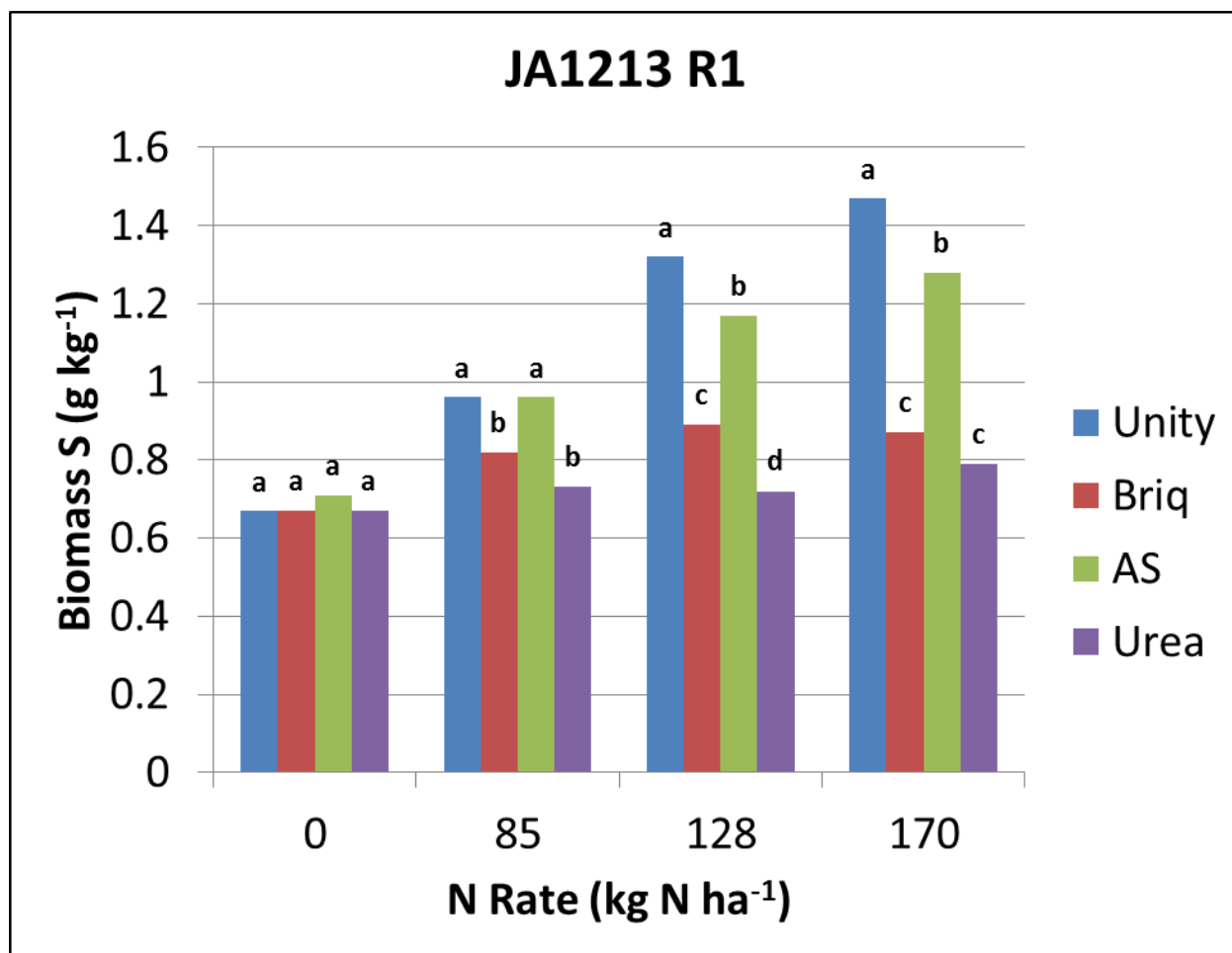


Figure 1.4. Interaction means of S concentrations in the R1 biomass for fertilizer types by N rates at Jackson and Ames in 2012 to 2013. Biomass S concentrations within each N rate followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD. Abbreviations: Unity, Unity NPSFe; Briq, NPKZn briquettes; AS, ammonium sulfate.

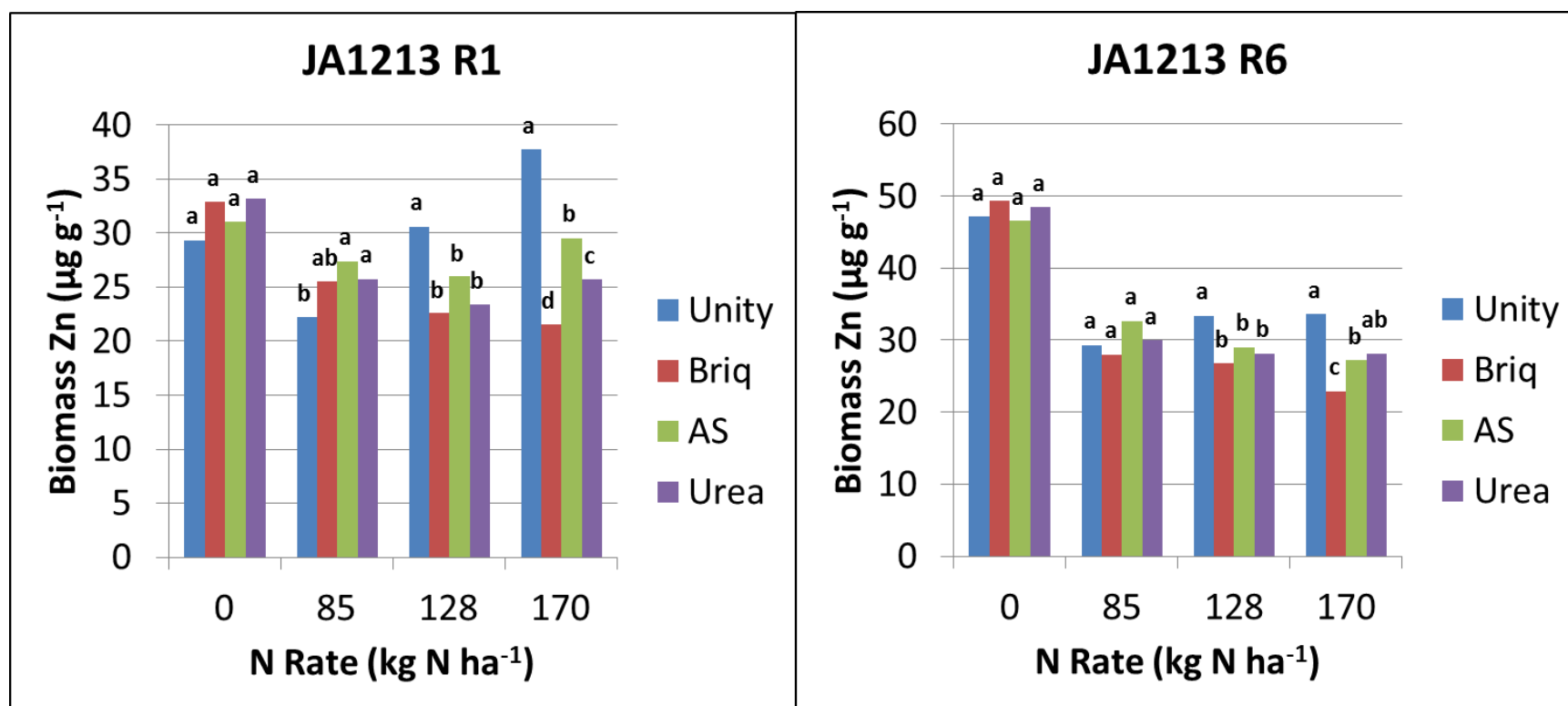


Figure 1.5. Interaction means of Zn concentrations in the R1 and R6 biomass for fertilizer types by N rates at Jackson and Ames in 2012 to 2013. Biomass Zn concentrations within each N rate followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD. Abbreviations: Unity, Unity NPSFe; Briq, NPKZn briquettes; AS, ammonium sulfate.

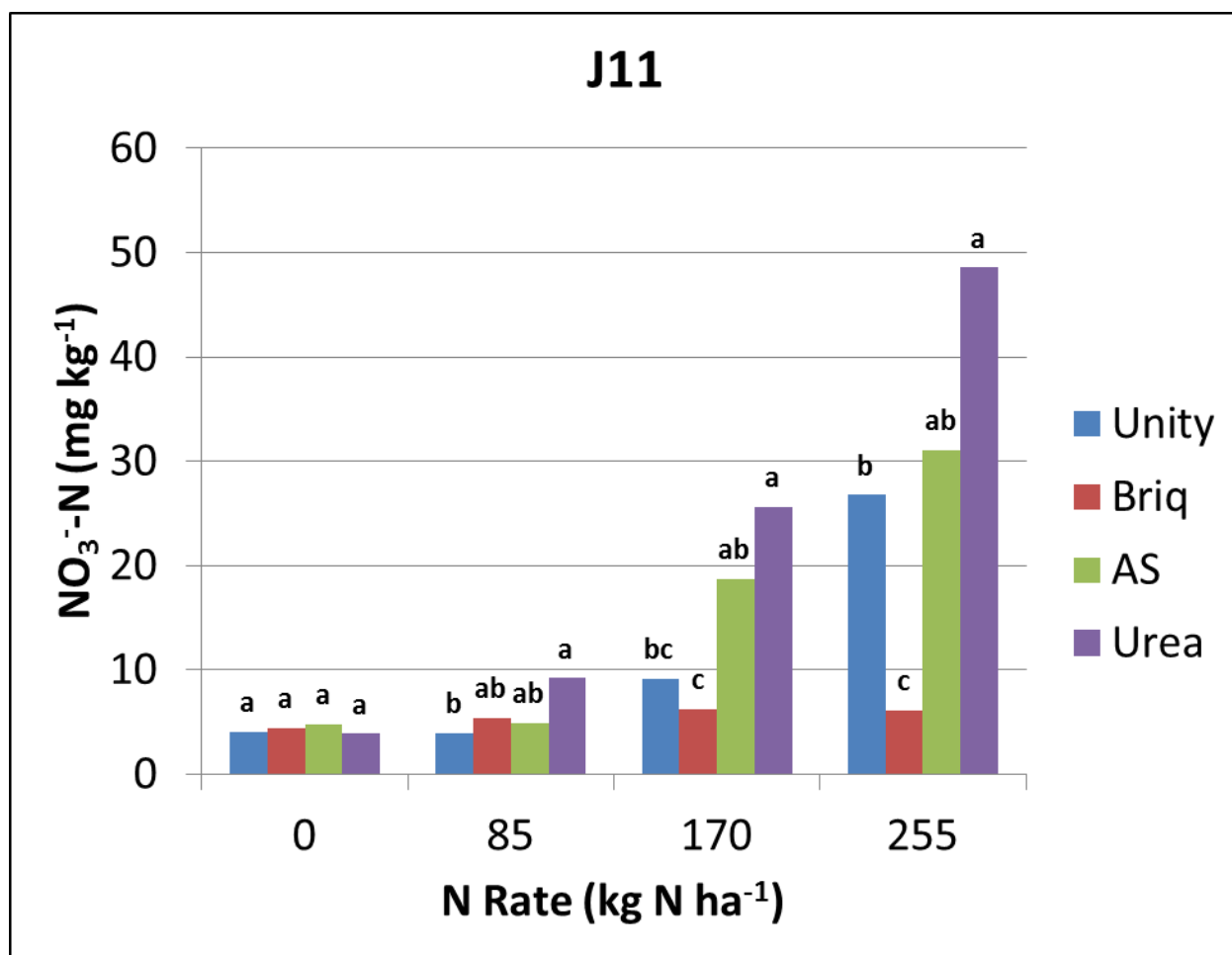


Figure 1.6. Interaction means of residual soil nitrate after harvest for fertilizer types by N rates at Jackson in 2011. Residual soil nitrate within each N rate followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD. Abbreviations: Unity, Unity NPSFe; Briq, NPKZn briquettes; AS, ammonium sulfate.

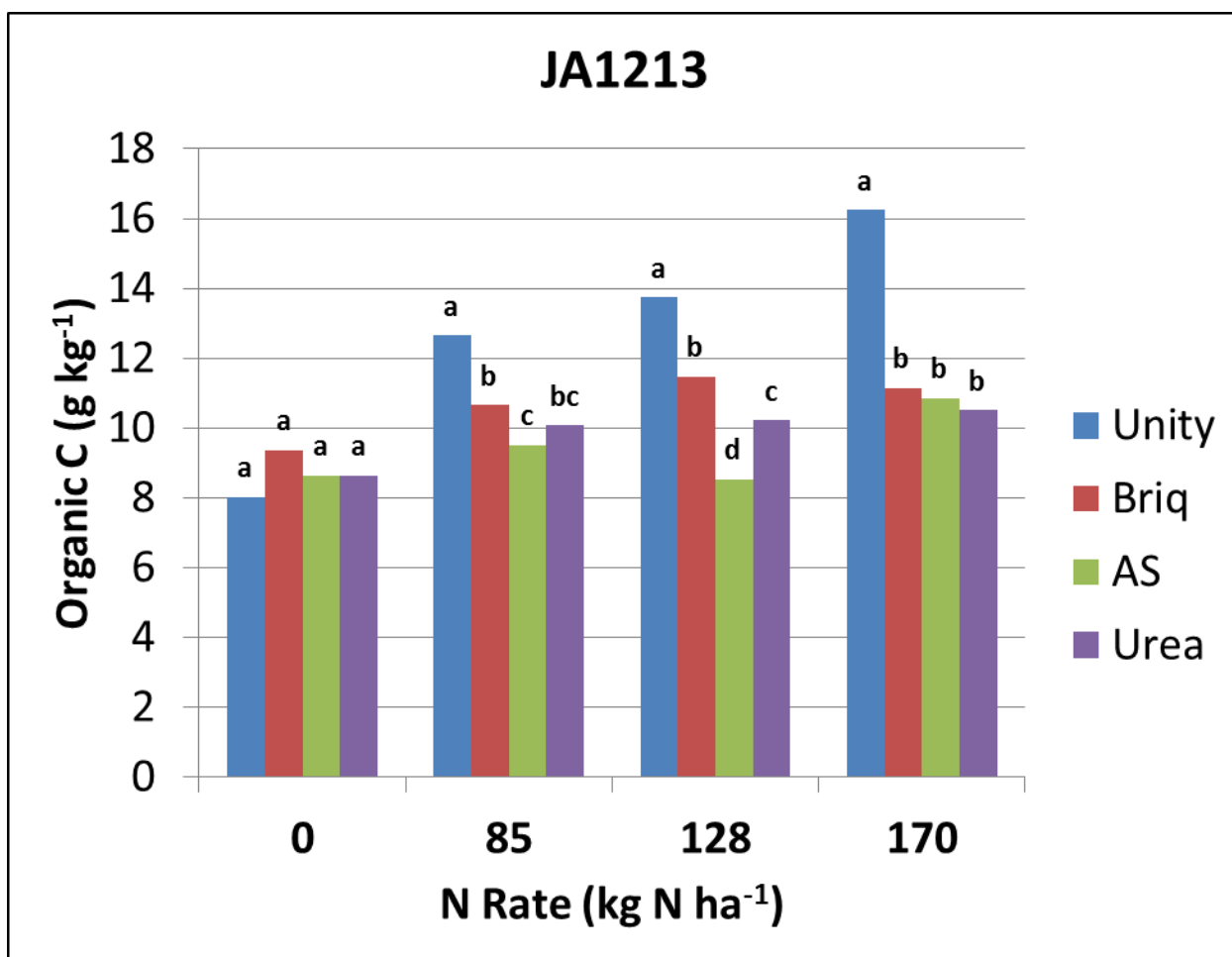


Figure 1.7. Interaction means of residual soil organic C after harvest for fertilizer types by N rates at Jackson and Ames in 2012 to 2013. Residual soil organic C within each N rate followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD. Abbreviations: Unity, Unity NPSFe; Briq, NPKZn briquettes; AS, ammonium sulfate.

CHAPTER 3
EFFECTS OF NPSFE BIOFERTILIZER AND NPKZN BRIQUETTES ON
PLANT GROWTH, GRAIN YIELD, AND EAR HEALTH OF CORN

Abstract

Effects of alternate fertilizers on corn (*Zea mays* L.) growth and productivity has been poorly examined. Organically enhanced NPSFe Unity biofertilizer (Unity) manufactured from sterilized organic additives extracted from municipal wastewater biosolids and alternative fertilizer product NPKZn briquettes (briquettes) produced by compacting solid fertilizers into a super-granule between 1-3 grams in weight were evaluated for growth and grain yields of corn compared to commonly used ammonium sulfate and urea on silt loam soils at Jackson and Ames, TN from 2011 to 2013. Unity, the briquettes, ammonium sulfate, and urea, and N 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 replications. Plant height at the six leaf (V6) and silking (R1) growth stages, aboveground plant dry weight at R1 and physiological maturity (R6), grain yield, and yield components were measured. Corn ears were also given health ratings. Plant height, biomass, grain yield, yield components, and ear health were more affected by N rates than by fertilizer types. Successively higher N rates did not necessarily produce greater yields. Plant heights were higher under Unity and ammonium sulfate during early to middle growth stages. Similar to plant height, Unity and ammonium sulfate sometimes produced more plant biomass. Unity and the briquettes at lower N rates have greater yields; at higher N rates they are comparable to ammonium sulfate and urea in grain yield. Unity and the briquettes also have greater grain yields under wet soil conditions. The briquettes had the heaviest ear weight and ear grain weight at the 85 kg N ha⁻¹ rate, and Unity and the briquettes had higher kernel counts also at the 85 kg N ha⁻¹ rate. Physiological defects were fewer under briquette fertilization at lower N rates. Corn ear health was improved by higher N rates. Our results suggest that Unity and ammonium sulfate generally maintain stronger plant growth from early through middle growth stages in corn than the banded briquettes and split-applied urea. Unity and the briquettes produce at least comparable yields to ammonium sulfate and urea.

Introduction

Nitrogen is one of the most important essential nutrients for crops because it needs to be replaced as it is removed from the agro-ecosystem in the form of a harvested crop. Furthermore, N, in contrast to most other plant nutrients, is not stable in the soil escaping easily and thereby becoming unusable for crop production (Robertson and Vitousek, 2009). This dynamic nature of N has made it one of the most difficult challenges in modern agriculture (Binder et al., 2000). Since no farm can be reasonably expected to raise high yielding crops without providing the necessary amounts of plant nutrients, particularly N, fertilizer expenses are one of the greatest variable costs to any successful farm operation (Economic Research Service, 2013).

Increasing amounts of N application to agronomic land has historically been an economically practical method of N management because of readily available and inexpensive synthetic fertilizers, which were manufactured in great quantities during the Green Revolution after World War II and continues up to the present day (Jenkinson, 2001). With tighter environmental regulations and increasing fuel costs over time, however, this approach to reconciling soil N losses has become less practical, which trend is likely to continue.

Urea and ammonium sulfate are two very commonly used fertilizers to drastically increase crop productive capacity. More than five billion and just under two billion kilograms of urea and ammonium sulfate, respectively, were manufactured in the United States in 1997 (Pellegrino, 2000). Inasmuch as urea and ammonium sulfate are both susceptible to soil N losses from ammonia volatilization, denitrification, and nitrate leaching from nitrification, they are unlikely to enhance crop production potential with increasing application rates (Havlin et al., 2005).

Organically-enhanced NPSFe and NPKZn briquettes are two new alternative fertilizers under development for improving crop production capacity. The organically-enhanced NPSFe fertilizer, branded as “Unity” by its manufacturing company Unity Envirotech (St. Petersburg, FL), contains N (14.9%), P (4.3%), S (18.1%), Fe (0.6%), and 8% organic matter that is derived from sterilized organic additives extracted from municipal wastewater biosolids. Most of the N and all of the P, S, and Fe are contained in the municipal biosolid. Only N is supplemented with

additional N mineral fertilizer to increase the N concentration of Unity during the manufacturing process. Unity Envirotech is projected in the next two to three years to use approximately 10% of Florida's total municipal biosolid waste to manufacture 300,000 Mg of Unity biofertilizer per year (Weber, 2013).

The briquette fertilizer is entirely mineral in form and supplies N, P, K, and Zn nutrients. The briquettes are made by a briquetter machine that simply compresses commercially available prilled fertilizers into a briquette approximately 2.43 grams in weight without any additional binder material. Thus the guaranteed analysis of the briquettes is variable depending on the proportions of different fertilizers used to form the briquette. A briquette with a smaller surface area to volume ratio will dissolve more slowly and thus release its nutrients in a more moderate fashion over a longer time thereby reducing soil nutrient losses, particularly N. The land application of the briquettes is also unique in that it is banded a couple of centimeters below the soil surface in between planted rows. A subterranean land application itself will also help to significantly reduce ammonia volatilization (Mengel et al., 1982). In developing countries this is a practical method of fertilizer application where very small acreages are farmed by a single grower and his/her family. This is the end to which the briquette was designed. In developed countries, briquettes could potentially be applied using a key-line plowing system which has a dispensing mechanism that places product underground immediately behind a deep plow shank that opens up a seam in the earth as it is pulled along by a tractor. The original intent of the plow is to drop seed behind each shank but that could plausibly be modified to drop briquettes as well.

Crop growth and yield responses to biofertilizers and fertilizer briquettes are variable in previous studies. Ayoola and Makinde (2009) found that corn plant height was comparable between N-enriched organic fertilizers and urea; however, Magdoff and Amadon (1980) observed that corn silage production were greater from biosolid amended fields than those under mineral N-fertilization alone. Kaur et al. (2008) found that corn yields from fields that were organically enhanced with farm yard manure in conjunction with NPK fertilization were greater than those with NPK fertilization alone. Similarly, Sleutel et al. (2006) observed that corn yields increased under NPK fertilization that was organically supplemented with manure. Mantovi et al. (2005), however, reported that corn yields did not differ between the biosolids and urea treatments.

Terman et al. (1956) reported that early crop growth decreased with the application of coarser granular fertilizers, but the reduced early growth with coarser fertilizer granulation did not persist in final yields of corn and wheat. Several preceding studies showed that NPK briquette fertilizers reliably outperformed prilled urea in terms of yield in wet soil conditions such as flood irrigated rice paddies (Islam et al., 2011; Darade and Bankar, 2009; Kapoor et al., 2008).

Unity and the briquettes are likely to improve corn growth and yields relative to the conventional fertilizers. Growth measurements in the corn plant lifecycle will be useful in determining relative nutrient availabilities between the fertilizer types at different times during the growing season. The main objectives of this investigation were to compare alternative fertilizers, Unity and briquettes, to conventional fertilizers, ammonium sulfate and urea, in terms of plant growth, grain yield, and ear health of corn.

Materials and Methods

The field experiment was conducted at the West Tennessee Research and Education Center (WTREC) at Jackson, Tennessee from 2011 through 2013 and at the Ames Plantation, Tennessee from 2012 through 2013. The study was designed and coordinated by the International Fertilizer Development Center (IFDC) and the University of Tennessee. The University of Tennessee managed all the daily field operations pertaining to this study.

Soil Description

The field experiment was conducted on a Memphis silt loam soil (fine-silty, mixed, active, thermic Typic Hapludalfs) at Jackson and on a Lexington silt loam soil (fine-silty, mixed, active, thermic Ultic Hapludalfs) at Ames. At both locations prior to experimentation, the fields were under soybean production followed by a winter fallow.

Corn Planting

Dekalb 6483 (YieldGardVT Triple) was the corn hybrid grown across all locations and years in this study. The Jackson test was planted under no-tillage at a seeding rate of 79,000 plants ha⁻¹. Plots were in eight rows with 76.2 cm (30 inches) row spacing; overall plot dimensions were 9.1 m by 6.1 m (30 feet by 20 feet). The Ames test was planted under tilled soil conditions also at a seeding rate of 79,000 plants ha⁻¹. Plots were in six rows also with 76.2 cm row spacing; overall plot dimensions were 9.1 m by 4.6 m (30 feet by 15 feet). At Jackson corn was planted on 9 May in 2011, 18 April in 2012, and 17 April in 2013. At Ames corn was planted on 19 April in 2012 and on 29 May in 2013.

Treatments

A total of 16 treatments with four replicates (64 plots in total per location) were arranged in a split-plot randomized complete block design with fertilizer types as main plots and N rates as subplots. Unity, the briquettes, ammonium sulfate (21% N, 24% S), and urea (46% N) were the four fertilizer types.

In 2011 at Jackson, the N rates used were 0, 85, 170, and 255 kg N ha⁻¹. From 2012 to 2013 at both locations, the N rates were changed to 0, 85, 128, and 170 kg N ha⁻¹ (Table 2.1). This rate change after 2011 was suggested by the IFDC in order to reduce fertilizer costs since the IFDC's purpose is to perform research that is more applicable to farmers in third world countries. Additionally, since the 2011 results had no yield benefits resultant from the highest N application rate, the IFDC lowered the N rates in order to better imitate a more economical fertilizing regime common to farming practices in developing countries. This represented a substantial change in the protocol during the experiment. As a result, the 2011 data (Jackson only) were analyzed independently from the other datasets while the data from 2012 and 2013 from Jackson and Ames were analyzed collectively. For reporting purposes the data from Jackson 2011 will simply be referred to as "J11" and the pooled data from the location-years Jackson and Ames in 2012 and 2013 will be referred to as "JA1213".

The N fertilizer treatments, excluding urea, were applied entirely basally after corn planting: in 2011 at Jackson fertilizers were applied the day after planting, in 2012 fertilizers were applied five days and 21 days after planting at Jackson and Ames, respectively, and in 2013 fertilizers were applied five days and eight days after planting at Jackson and Ames, respectively.

Only one third of N in the urea fertilizer treatment was applied basally, the other two thirds of N in that treatment were applied as two equal splits at the six leaf growth stage (V6) and at tasseling (VT). This was done in imitation of farmers in developing countries in order to reduce N losses. Unity, ammonium sulfate, and urea were all applied uniformly via surface broadcast across the entire plot. The briquettes were banded using a small hand-driven plow approximately 2.54 cm below the soil surface in four bands per plot between rows one and two, three and four, five and six, and seven and eight at Jackson. At Ames the briquettes were banded at the same depth but in three bands between rows one and two, three and four, and five and six.

Phosphorus, K, and Zn were all applied at the following uniform rates across all treatments: 45 kg P ha⁻¹, 85 kg K ha⁻¹, and 5 kg Zn ha⁻¹ (Table 2.1). The S rate was variable for the Unity and ammonium sulfate fertilizer treatments because both of these fertilizers contained S as part of their guaranteed analysis, thus with increasing N rates, Unity and ammonium sulfate supplied

increasing amounts of S (Table 2.1). At the 85 kg N ha⁻¹ rate, Unity and ammonium sulfate supplied 104 and 98 kg S ha⁻¹, respectively; at the 128 kg N ha⁻¹ rate, Unity and ammonium sulfate supplied 156 and 147 kg S ha⁻¹, respectively; at the 170 kg N ha⁻¹ rate, Unity and ammonium sulfate supplied 207 and 195 kg S ha⁻¹, respectively; and at the 255 kg N ha⁻¹ rate, Unity and ammonium sulfate supplied 311 and 292 kg S ha⁻¹, respectively. For the control (0 kg N ha⁻¹), all the fertilizer treatment plots had an S rate of 1.25 kg S ha⁻¹ from the sulfate in the ZnO/ZnSO₄ fertilizer that 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 Unity treatments. Unity already contained some P and thus 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, Unity supplied 23.8%, 35.8%, 47.6%, and 71.4% of the uniform P rate, respectively. Potassium and Zn were applied as KCl (0-0-60) and ZnO/ZnSO₄ (36% Zn, 9% S), respectively, for ammonium sulfate, urea, and Unity treatments.

The briquettes were unique in that they were manufactured from already commercially available fertilizers through a fertilizer briquetter machine developed by the IFDC. The briquetter machine allows the manufacturer to manipulate a fertilizer's guaranteed analysis to suit specific needs. In the case of this study, the briquettes were created by the IFDC and 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 2.1). This occurred because the S in the briquettes was supplied by ZnSO₄ (17.5% S) not ZnO/ZnSO₄ (9% S). The N, P, K, and Zn mineral sources used in the briquettes were urea, diammonium phosphate, potassium chloride, and zinc sulfate.

Off-Season Treatments

Between experimental years through the winter, winter wheat was grown as a cover crop and received the same fertilizer type treatment per whole plot but altered subplot N application rates according to winter wheat requirements. The N rates applied to the winter wheat were 0, 50.4, 84.0, and 117.7 kg N ha⁻¹, corresponding to the low through high N rates among corn fertilizer

rates applied previously. Zero, 16.8, 33.6, and 50.4 kg N ha⁻¹ were applied basally in the fall, and the remaining N was applied as a top-dress in February. Plots that received the briquette treatments also received additional fertilization as briquettes but only in the initial treatment years (2011 at Jackson and 2012 at Ames) after harvest and at 0, 50.0, 84.0, and 117.7 kg N ha⁻¹ all applied in the fall with no spring top-dress application. Phosphorus and K were applied basally as blanket applications at 19.6 and 37.2 kg ha⁻¹, respectively, before corn planting at Jackson in the following spring; zinc was not applied. The winter wheat cover crop was killed with Gramoxone (Paraquat: 1,1'-Dimethyl-4,4'-bipyridinium dichloride) herbicide; at Ames the winter wheat cover crop was also killed with Gramoxone herbicide and then tilled by disc.

Plant Measurements, Sampling, and Analyses

Plant measurements, sampling, and analyses were conducted on a split plot basis: plant height at V6 and R1; above-ground plant dry weight at R1 and R6; grain yield; ear length and weight; ear and kernel count; ear grain weight; kernel mass; and physiological defects, disease infestation, and insect attack health ratings of corn ears.

Plant height was measured with a tall metric measuring stick by randomly selecting and averaging the heights of 10 plants from the center four rows in each plot at V6 and R1 growth stages. Plant height at V6 was determined from the highest fully extended leaf at the point on the leaf where it had leveled-off such that it was parallel to the ground. A fully extended leaf was defined as a leaf outside of the central leaf whorl, extending outwards from the stalk possessing a distinct collar banding at the base of the leaf and with an internode space equivalent to the internode spacing of previous leaves. At R1, plant height was determined from the base of the tassel.

Plant biomass samples at R1 were collected by hand harvesting 12 corn plants from the center four. The 12 plants were weighed using a Cardinal Detecto weigh scale model HSDC-40 (Webb City, MO) to obtain a fresh weight. From those 12 plants a two-plant subsample was taken and weighed again to obtain a subsample weight. Plant biomass samples at R6 were collected as follows: In 2011 at Jackson and in 2012 and 2013 at Ames, 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. Biomass sample collection at R6 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-plant and three-plant biomass subsamples at R1 and R6, respectively, were oven-dried at 65°C for three days. Once dry, the sub-samples were weighed. A best dry weight representation for the entire sample was calculated.

The center four rows at Jackson and the center three rows at Ames of each plot were harvested for grain yield at physiological maturity using small plot combines with automatic weighing scales and moisture meters. The plot combine model used at Jackson was Kincaid; at Ames the plot combine model used was Allis Chalmers Gleaner K2. All grain yields were adjusted to a moisture content of 15.5 g kg⁻¹.

All the ear data were measured from ears that were taken off of corn stalks during the R6 plant biomass harvest that were not from the three sub-sampled corn plants. At Jackson in 2011 and at Ames 2012 and 2013 that amounted to approximately nine ears (nine corn stalks: 12 harvested corn plants minus the three-plant subsample, assuming one ear per stalk) that were harvested for corn ear analysis. At Jackson in 2012 and 2013 that amounted to approximately 21 ears (21 corn stalks: 24 harvested corn plants minus the three-plant subsample, assuming one ear per stalk) were harvested for corn ear analysis. Kernel counts were done using an International Marketing and Design Co. (San Antonio, TX) seed counter model 850-3.

Ear health ratings were evaluated at harvest. The ears were taken off the corn stalks that were not kept as part of the three plant subsamples. As a result, in 2011 at Jackson and in 2012 and 2013 at Ames there were approximately nine ears used for the health ratings and in 2012 and 2013 at Jackson there were approximately 21 ears used for the health ratings. Three types of ear abnormalities were measured: physiological defects, disease infestation, and insect attack were examined. A scale of four degrees was developed and used to describe the magnitude of each abnormality type: no damage (0), low damage (1), medium damage (2), and severe damage (3).

Statistical Analyses

Analysis of variance was conducted in a split plot randomized complete block design using the mixed model procedure (MMAOV) of SAS version 9.3 (SAS Institute, Cary, NC). The four fertilizer types were whole plots and were treated as a fixed experimental factor; blocks were treated as a random factor. The four N application rates were subplots and were randomized within each whole plot. In JA1213, year and location were treated as fixed experimental factors. Means where year and location were treated as random factors were also reported in appendix B. The post-ANOVA analysis method used was mean separation by Fisher's protected LSD. The ear health ratings were analyzed categorically using the proc freq procedure of SAS version 9.3. Probability levels for all analyses lower than 0.05 were designated as statistically significant.

Results and Discussion

Weather conditions throughout the duration of this study varied considerably. In general, 2013 was a cooler year compared to 2011 and 2012 particularly during the spring months of March, April, and May (Figure 2.1). Temperatures in 2012 were as much as 5.6 to 8.3 °C warmer during that same time period. 2011 and 2012 were both approximately 3.3 °C warmer than 2013 during the whole month of July. Temperatures from August to the end of the growing season, however, were more similar to each other across location-years. Monthly precipitation averages were even more variable (Figure 2.2). Jackson had a particularly wet spring in 2011 and 2013 with approximately 494.3 and 479.5 mm of rainfall, respectively, between April and May. At Ames in 2013 the average monthly precipitation was a little more moderate at 369.3 mm between the same time period. In sharp contrast, in 2012 both Jackson and Ames were much drier with only 74.2 and 128.5 mm of rainfall, respectively, between the spring months of April and May. Between June and August, precipitation trends were fairly similar across location-years, but towards the end of the growing season the precipitation trends reversed from what they had been during the spring: Jackson and Ames in 2012 had considerably more precipitation (288.0 and 315.2 mm, respectively) between the months of September and October, whereas Jackson in 2011 and 2013 and Ames in 2013 were much drier (111.0, 170.2, and 166.4 mm, respectively) during the same time period.

Plant Height

In J11, plant height differed among the fertilizer types at V6 but not at R1 (Table 2.2). All the fertilizers were similar except the briquettes which produced shorter plants at V6 compared to the other fertilizers (Table 2.3). This is an unsurprising result as the briquettes are slower dissolving and they were also banded in the middle between planted rows making the nutrients harder to reach for corn roots to uptake at earlier growth stages. By the R1 growth stage, however, the briquettes produced comparably tall corn plants as the other fertilizer types (Table 2.3). These results coincide with the findings of Terman et al. (1956) in that early crop growth responses decreased with coarser granular sizes, but the smaller early growth response of crops did not reflect in final yields of corn or wheat in their experiments.

Nitrogen rates had significant impacts on plant heights at both V6 and R1 in J11 (Table 2.2). All of the N rates above the zero N control produced equally tall plants at V6 and R1 (Table 2.3). These results suggest that N rates higher than 85 kg ha⁻¹ do not necessarily produce taller plants. Abbasi et al. (2012) found that corn plant height plateaus at R1 occurred at N rates above 120 kg N ha⁻¹ in the first year and above 150 kg N ha⁻¹ in the second year of their study. Ibrahim and Hala (2007) likewise reported plant heights were not enhanced with N rates above 120 kg N ha⁻¹. Liu and Wiatrak (2011) also observed plant heights to not be significantly impacted at N rates above 135 kg N ha⁻¹.

In JA1213, there were significant fertilizer type by N rate interactive effects on plant height at both V6 and R1 (Table 2.2). At V6, the briquettes had shorter plants than the other fertilizer types at each N rate except the control where there were no height differences between fertilizers (Table 2.4). Also at each N rate above the control, Unity and ammonium sulfate had the tallest plants at V6. At R1, Unity and ammonium sulfate continued to produce taller plants but only at the two highest N rates. The briquettes were similar in plant height at R1 to Unity and ammonium sulfate at the 85 kg N ha⁻¹ rate. At the 128 and 170 kg N ha⁻¹ rates, however, the briquettes had shorter plants than Unity and ammonium sulfate, but similar plant heights to urea (Figure 2.3). That Unity as an organically enhanced fertilizer was superior to urea in plant height contrasts with the results of Ayoola and Makinde's (2009) in that plant heights were only comparable between urea and N-enriched organic fertilizers. In our study, urea was not applied all at once at treatment initiation, which was likely the cause for short plants.

In JA1213, there were also significant fertilizer type by year and fertilizer type by location interactive effects at V6 and R1 (Table 2.2). In 2012, only the briquettes had shorter plants at V6. By R1, however, the briquettes were similar to the other fertilizers in plant height (Table 2.5). In 2013 at both V6 and R1, Unity and ammonium sulfate had taller plants than the briquettes and urea. The briquettes had similar plant heights to urea even at V6 which is in contrast to the 2012 results for the briquettes. This is most likely because of the briquettes' superior nutrient use efficiency in wet soils as 2013 had an exceptionally wet spring (Figure 2.2). At Jackson at V6, the briquettes had shorter plants than the other fertilizer types, and Unity and ammonium sulfate had the tallest plants (Table 2.5). At R1, Unity and ammonium sulfate

continued to have taller plants compared to the briquettes and urea which produced similar heights at R1. Unlike Jackson, Ames showed no differences between fertilizer types at V6 and R1. This is likely because Ames had one less year of experimentation and therefore had less carryover effects from the fertilizer treatments.

In JA1213, plants were taller under Unity and ammonium sulfate than urea and the briquettes, and urea produced taller plants than the briquettes at V6 averaged over the N application rates; in wetter years, however, the briquettes were similar to urea in plant at V6 (Table 2.3). At R1, Unity and ammonium sulfate still produced taller plants than the briquettes and urea, while the latter two had similar plant height. Our results suggest that plant growth at early growth stages might be slowed down with the use of the briquettes compared to Unity and ammonium sulfate. Unity and ammonium sulfate, by contrast, stimulate and maintain stronger plant growth from early to middle growth stages in corn.

Plant Biomass

In J11, plant biomass weights did not differ among fertilizer types at R1 or R6 (Table 2.2). In JA1213, only the plant biomass weights at R1 differed among fertilizer types. In that case, Unity and ammonium sulfate had heavier biomass at R1 than urea and the briquettes, and the briquettes had less biomass than urea (Table 2.3). The fact that Unity did not out-yield ammonium sulfate in our study is in contrast to the finding of Magdoff and Amadon (1980) that silage yields from biosolid amended fields were greater than mineral N-fertilization alone.

Different N rates had very significant impacts on plant biomass at R1 and R6 in J11 and JA1213 (Table 2.2). In J11 and JA1213 at the R1 growth stage, all the N rates above the zero N control had heavier plant biomass. The two highest N rates produced the heaviest biomass, which suggests that between 128 and 255 kg N ha⁻¹ there is no plant biomass benefit associated with increasing N. Cox et al. (1993) likewise reported no differences in biomass at R1 at N rates of 56, 140, and 225 kg N ha⁻¹. At R6 the results between J11 and JA1213 were more distinct. In J11, all the biomass weights were equally heavier than the control. In JA1213, however, plant biomass weights increased with each succeeding N rate increase. In contrast to J11, the JA1213 results suggest that there is a plant biomass benefit at R6 to at least 170 kg N ha⁻¹. These

findings are in contrast to those of Katsvairo et al. (2003) that N rates had no effect on biomass weights at R6.

In JA1213, there was also a significant fertilizer type by location interactive effect at R1 which was similar to the plant height fertilizer type by location interactive effect described above: fertilizer types differed at Jackson but not at Ames (Table 2.2). At Jackson, Unity and ammonium sulfate had heavier plant biomass at R1 than the briquettes and urea (Table 2.5).

In summary, plant biomass weights at R1 and R6 were much more influenced by N rate than by fertilizer type. Our results suggest that there is no plant biomass benefit above 128 kg N ha⁻¹ at R1. At R6, N rates at and above 85 kg N ha⁻¹ increase biomass weights. Where fertilizer types had an impact on plant biomass weights, Unity and ammonium sulfate had the greatest plant biomass.

Grain Yield

In J11, grain yields were comparable between fertilizer types: Unity and the briquettes did not produce greater yields than ammonium sulfate and urea (Tables 2.2 & 2.3). And in fact, though statistically similar with ammonium sulfate and urea, Unity and the briquettes both produced numerically lower yields. Unity's grain yield results are consistent with the findings from Mantovi et al. (2005) that no significant yield difference in corn fertilized with biosolids as compared to urea was observed, but are in contrast to those of Kaur et al. (2008) who found that corn grain yields from fields that were organically enhanced with farm yard manure in conjunction with NPK fertilization were greater than with NPK fertilization alone. Sleutel et al. (2006) likewise reported that corn yields increased under NPK fertilization that was organically supplemented with manure.

Nitrogen rates, as expected, had a significant impact on grain yield (Table 2.2). In J11, all the N rates above the zero N control had equal grain yields suggesting no yield benefit above 85 kg N ha⁻¹ (Table 2.3). This is in contrast to JA1213 in which each successive N rate increase had successively greater grain yields (Figure 2.4). Several previous studies have shown yield plateaus that occur in corn at N rates much higher than 85 kg N ha⁻¹ (Crozier et al., 2014; Sindelar et al.,

2012; Halvorson and Reule, 2007; Miao et al., 2006; Shapiro and Wortmann, 2006; Durieux et al., 1995).

In JA1213, there was a significant fertilizer type by N rate interactive effect in which Unity outyielded ammonium sulfate, and the briquettes had greater grain yields than ammonium sulfate and urea at the 85 kg N ha⁻¹ rate (Tables 2.2 & 2.4). At the other N rates there were no differences in grain yield between fertilizer types (Figure 2.5).

In JA1213, there was also a significant fertilizer type by year interactive effect (Table 2.2). In 2012, there were no yield differences between fertilizer types, but in 2013, which had a particularly wet spring, the briquettes had higher grain yields than ammonium sulfate and urea (Table 2.5, Figures 2.2 & 2.6). This is consistent with other research where NPK briquette fertilizers reliably outperform prilled urea in terms of yield under wet soil conditions such as flood irrigated rice paddies (Islam et al., 2011; Darade and Bankar, 2009; Kapoor et al., 2008)

Our results suggest that Unity and the briquettes at lower N rates have greater yields than conventional fertilizers ammonium sulfate and urea; at higher N rates they are comparable to ammonium sulfate and urea in grain yield. The briquettes also have greater grain yields under wet soil conditions compared to ammonium sulfate and urea. Nitrogen rates at and above 85 kg N ha⁻¹ also produce greater grain yields.

Yield Components

In J11, all the corn ear measurements were not significantly influenced by the different fertilizer types (Table 2.2). Nitrogen rates, however, did impact all the ear measurements except ear counts. Ear weight, kernel count, and kernel mass were all significantly greater but equally influenced by all the N rates above the zero N control (Table 2.3). Ear length and ear grain weight were numerically greatest at the 170 kg N ha⁻¹ rate suggesting that N rates higher than that will not necessarily produce longer ears or heavier ear grain. Similarly, Abbasi et al. (2011) reported maximal 1000-kernel weights at 180 kg N ha⁻¹. Hammad et al. (2011), by contrast, found greatest kernel weights at 250 kg N ha⁻¹.

In JA1213, ear counts and kernel mass were affected by N rate but not by fertilizer types (Table 2.2). These findings are in agreement with those of Vaca et al. (2011) that ear counts did not increase under biosolid fertilization compared to mineral fertilizers. Ear counts were equally higher under all N rates above the zero N control; however, kernel mass increased incrementally with each increase in N rate (Table 2.3). For ear length, ear weight, grain weight, and kernel count, there were fertilizer type by N rate interactive effects in JA1213 (Table 2.2). Ear weight and grain weight were higher under briquette fertilization than the other three fertilizer types at the 85 kg N ha⁻¹ rate; at all the other N rates they were equal (Table 2.4). The briquettes had higher kernel counts than ammonium sulfate and urea at the 85 kg N ha⁻¹; Unity had higher kernel counts than urea at the same rate. At the 128 kg N ha⁻¹ rate, both Unity and the briquettes had higher kernel counts than urea.

JA1213 also had significant fertilizer type by year interactive effects for ear length, ear weight, and grain weight (Table 2.2). In 2012, a particularly dry year, the briquettes had shorter ear length than the other fertilizer types (Table 2.5, Figure 4.1). In 2013, which had a particularly wet spring, however, urea had shorter ears than the other fertilizer types. In 2012, ear and grain weights did not differ between fertilizer types. In 2013, however, the briquettes had greater ear and grain weight than urea.

In JA1213, there was also significant fertilizer type by location interactive effect for kernel mass and kernel count (Table 2.2). At Jackson, Unity had lower kernel mass than the briquettes and urea (Table 2.5). Unity and ammonium sulfate had more kernel counts than the briquettes and urea. At Ames, as seen previously with other data, there were no differences in fertilizer types on either kernel mass or count.

Overall, yield components were more often affected by N rate than by fertilizer type. In some instances N rates only improved measurements above the zero control, in other cases measurements improved with increasing N rates. In no case, however, did N rates above 170 kg N ha⁻¹ prove beneficial. In general, the briquettes had the heaviest ear weight and grain weight at the 85 kg N ha⁻¹ rate, and Unity and the briquettes had higher kernel counts at the 85 and 128 kg N ha⁻¹ rates than urea. The briquettes have shorter ears in drier years whereas urea has shorter

ears in wetter years. These results suggest that briquettes are a good fertilizer choice at lower or moderate N rates and particularly under wet soil conditions.

The above results and discussion on corn growth, grain yield, and yield components were based on means where years and locations were treated as fixed effects. Corn growth, grain yield, and yield component means where years and locations were treated as random factors are also reported in tables 2.6, 2.7, and 2.8.

Ear Health

Fertilizer types impacted physiological health ratings in J11 and JA1213 (Table 2.9). In J11, Unity had the fewest no-damage ratings at only 15% of those counts, but Unity also had the majority of the low-damage ratings at 33% of those counts compared to the other fertilizer types (Table 2.10). Also from J11, urea had significantly fewer moderate-damage ratings than the other fertilizer types at only 12% of those counts. In JA1213, the only significant difference in physiological health ratings between fertilizer types was that urea had the fewest no-damage ratings of just 17% (Table 2.11).

Nitrogen rates also had different effects on physiological health in both J11 and JA1213 (Table 2.9). In J11, the lowest N rate had the fewest no-damage ratings (4%), and the 170 and 255 kg N ha⁻¹ rates had similarly greater no-damage ratings of 36% and 37%, respectively (Table 2.10). The lowest N rate also had the majority of moderate and severe-damage ratings of 70% and 64%, respectively. In JA1213, the results were similar (Table 2.11). The 0 and 85 kg N ha⁻¹ rates had the fewest no-damage ratings of 0% and 9%, respectively, whereas the 128 and 170 kg N ha⁻¹ rates had the greatest number of no-damage ratings of 38% and 53%, respectively. As with J11, the lowest N rate also had the majority of severe-damage ratings with 39% of those counts compared to the 128 and 170 kg N ha⁻¹ rates which only accounted for only 20% and 16%, respectively, of the severe-damage ratings.

Physiological health rating interaction effects between fertilizer types and N rates only occurred in a few cases between J11 and JA1213 (Table 2.9). In J11, fertilizer types differed only when controlling for the 85 and 170 kg N ha⁻¹ rates (Table 2.10). At the 85 kg N ha⁻¹ rate, Unity had

the fewest no-damage ratings (4%), while urea had the most no-damage ratings of 43%. Unity did have a significant majority of the low-damage ratings at 37%, however. At the 170 kg N ha⁻¹ rate the only significant difference between fertilizer types was the briquettes which had the majority of moderate-damage ratings (75%). In JA1213 fertilizer types differed only when controlling for the 85 kg N ha⁻¹ rate. At that rate, the briquettes had the most no-damage ratings (74%) compared to the other fertilizer types, and also the fewest severe-damage ratings of only 21% (Table 2.11).

Disease infestation ratings were not significantly different among fertilizer types or N rates in J11 (Table 2.9). In JA1213, they only differed among N rates (Table 2.11). Similar to the physiological health ratings by N rate, the 0 kg N ha⁻¹ rate had the fewest no-damage ratings (19%) and also the most severe-damage ratings (48%). The 128 and 170 kg N ha⁻¹ rates had the fewest same severe-damage ratings of 17%.

Insect attack ratings were not significantly different among fertilizer types alone but they did differ among fertilizer types when controlling for the 170 kg N ha⁻¹ in J11; and in JA1213 they only differed among N rates (Table 2.9). In J11 at the 170 kg N ha⁻¹ rate, the briquettes had the fewest no-damage ratings with only 10% of the counts, whereas urea had the most no-damage counts at 39% (Table 2.10). In JA1213, the 0 kg N ha⁻¹ rate had the most severe-damage ratings with 64% of those counts. In contrast, the 170 kg N ha⁻¹ had the most low-damage ratings with 31% of those counts (Table 2.11).

Overall ear health was little influenced by fertilizer types. In general, the briquettes produced physiologically healthier ears at lower N rates than the other fertilizer types. At higher N rates, the briquettes tended to produce corn ears more susceptible to insect attack. Nitrogen rates were a far more significant influence on ear health. In general, higher N rates produced ears that were physiologically sound and less prone to disease infestations and insect attacks; lower N rates produced the reverse effect. The two highest N rates, 170 and 255 kg N ha⁻¹, had similar superior physiological ratings suggesting no additional physiological health benefits to ears are achieved at N rates over 170 kg N ha⁻¹.

Conclusions

Plant heights and biomass, grain yield, yield components, and ear health were more affected by N rates than by fertilizer types. Successively higher N rates did not necessarily provide greater quantities from our measured criteria; for example, grain yield was the same between 85 and 255 kg N ha⁻¹ in J11, but in JA1213 grain yield did increase progressively with each increase in N rate. Plant heights were higher under Unity and ammonium sulfate than urea and briquettes during early to middle growth stages. At earlier growth stages the briquettes had shorter corn plants. As with plant height, Unity and ammonium sulfate had the greatest plant biomass weights. Unity and the briquettes at lower N rates have greater yields than conventional fertilizers ammonium sulfate and urea; at higher N rates they are comparable to ammonium sulfate and urea in grain yield. The briquettes also have greater grain yields under wet soil conditions compared to ammonium sulfate and urea. The briquettes had the heaviest ear weight and ear grain weight at the 85 kg N ha⁻¹ rate and Unity and the briquettes had higher kernel counts at the 85 and 128 kg N ha⁻¹ rates than urea. Physiological defects were fewer under briquette fertilization at lower N rates. Corn ear health, in general, was improved by higher N rates. Our results suggest that Unity and ammonium sulfate generally maintain stronger plant growth during early to middle season of corn than the banded briquettes and split-applied urea. Unity and the briquettes produce at least comparable yields relative to ammonium sulfate and urea.

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Appendix B

Table 2.1. Treatment descriptions at Jackson and Ames during 2011 to 2013.

Treatment Number	Fertilizer Type	N Rate kg ha ⁻¹	P Rate	K Rate kg ha ⁻¹	S Rate	Zn Rate
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	Unity NPSFe	0	45	85	1.25	5
6	Unity NPSFe	85	45	85	104†	5
7	Unity NPSFe	128/170	45	85	156/207	5
8	Unity 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 Unity 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/ZnSO₄ was used which has less overall SO₄.

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

Table 2.2. Analysis of variance p-values for plant height, plant biomass, grain yields, and yield components of corn at Jackson and Ames during 2011 to 2013 with years and locations treated as fixed effects in the JA1213 data set.

	V6 Plant Height	R1 Plant Height	R1 Dry Weight	R6 Dry Weight	Grain Yield	Ear Count	Ear Length	Ear Weight	Kernel Mass	Kernel Count	Grain Weight
J11											
Treatments											
Fertilizer Type (FT)	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
N Rate (NR)	**	***	***	***	***	ns	***	***	***	***	***
FT x NR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
JA1213											
Treatments											
FT	***	**	***	ns	ns	ns	ns	ns	ns	*	ns
NR	***	***	***	***	***	***	***	***	***	***	***
FT x NR	***	*	ns	ns	**	ns	*	**	ns	**	**
Year (Y)	**	***	ns	**	***	**	***	***	***	*	***
Y x FT	*	*	ns	ns	*	ns	*	*	ns	ns	*
Y x NR	***	***	***	***	***	ns	***	***	***	***	***
Y x FT x NR	ns	ns	ns	ns	***	ns	ns	ns	ns	ns	ns
Location (L)	***	***	***	ns	ns	**	*	ns	***	***	ns
L x FT	***	***	**	ns	ns	ns	ns	ns	*	*	ns
L x NR	***	***	***	ns	***	ns	***	**	***	***	**
L x FT x NR	***	ns	ns	ns	ns	*	ns	ns	ns	ns	ns
Y x L	***	***	ns	*	ns	***	ns	ns	**	ns	*
Y x L x FT	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Y x L x NR	ns	***	ns	ns	***	***	***	***	ns	***	**
Y x L x FT x NR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

ns, not significant at the 0.05 probability level.

*, significant at the 0.05 probability level.

**, significant at the 0.01 probability level.

***, significant at the 0.001 probability level.

Table 2.3. Means of plant height, plant biomass, grain yield, and yield components of corn for fertilizer types and N rates at Jackson and Ames during 2011 to 2013 with years and locations treated as fixed effects in the JA1213 data set.

	V6 Plant Height cm.....	R1 Plant Height	R1 Dry Weight Mg ha ⁻¹	R6 Dry Weight Mg ha ⁻¹	Grain Yield Mg ha ⁻¹	Ear Count ear stalk ⁻¹	Ear Length cm	Ear Weight g.....	Kernel Mass g.....	Kernel Count kernel cob ⁻¹	Grain Weight g ear ⁻¹
J11											
Fertilizer Type											
Unity NPSFe	48.47a†	233.57a	9.20a	18.53a	6.09a	0.97a	16.89a	139.19a	0.26a	432.23a	116.19a
NPKZn Briquettes	41.58b	225.23a	9.12a	18.51a	6.09a	0.96a	17.00a	148.63a	0.27a	443.20a	122.65a
Ammonium Sulfate	48.10a	232.82a	9.24a	18.03a	6.22a	0.97a	16.92a	140.91a	0.26a	444.37a	118.13a
Urea	47.80a	226.98a	8.67a	17.87a	6.68a	0.99a	17.11a	152.86a	0.27a	453.06a	124.69a
N Rate (kg N ha⁻¹)											
0	42.88b	209.76b	6.48c	13.59b	4.35b	0.96a	15.00c	106.92b	0.23b	362.48b	85.77c
85	47.01a	233.73a	9.23b	19.14a	6.68a	0.99a	17.17b	151.45a	0.27a	459.27a	124.78b
170	48.01a	236.57a	10.36a	20.16a	7.09a	0.96a	17.93a	165.58a	0.29a	478.76a	139.04a
255	48.05a	238.55a	10.14a	20.04a	6.97a	0.98a	17.82ab	157.64a	0.28a	472.34a	132.06ab
JA1213											
Fertilizer Type											
Unity NPSFe	48.50a	181.93a	7.94a	13.06a	5.47a	0.89a	14.27a	101.66a	0.23a	387.55a	89.96a
NPKZn Briquettes	43.26c	169.32b	6.47c	13.30a	5.77a	0.90a	13.98a	103.52a	0.24a	377.96a	91.70a
Ammonium Sulfate	49.36a	182.55a	8.02a	13.35a	5.15a	0.88a	14.43a	102.50a	0.23a	382.96a	90.53a
Urea	46.15b	170.68b	7.24b	12.96a	5.37a	0.90a	13.97a	98.28a	0.24a	357.74b	86.30a
N Rate (kg N ha⁻¹)											
0	41.07c	142.20c	4.55c	7.61d	2.05d	0.78b	10.68d	49.55d	0.21d	212.92d	43.19d
85	48.10b	181.11b	7.56b	13.53c	5.55c	0.93a	14.62c	101.65c	0.23c	398.53c	90.19c
128	49.30a	189.62a	8.62a	14.93b	6.62b	0.93a	15.35b	118.42b	0.24b	429.98b	104.86b
170	48.80ab	191.55a	8.95a	16.60a	7.54a	0.93a	15.99a	136.34a	0.26a	464.79a	120.26a

†, 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.

Table 2.4. Interaction means of plant height, grain yields, and yield components of corn for fertilizer types by N rates from the JA1213 dataset at Jackson and Ames during 2012 to 2013 with years and locations treated as fixed effects.*

		V6 Plant Height cm	R1 Plant Height	Grain Yield Mg ha ⁻¹	Ear Length cm	Ear Weight g	Kernel Count kernel cob ⁻¹	Grain Weight g ear ⁻¹
N Rate (kg N ha ⁻¹) Fertilizer Type								
0	Unity NPSFe	40.07a†	141.13a	1.93a	10.79a	51.96a	230.81a	45.83a
	NPKZn Briquettes	41.39a	139.84a	1.87a	10.00b	42.20a	180.00b	36.62a
	Ammonium Sulfate	41.23a	144.86a	2.20a	11.15a	53.57a	225.03a	47.08a
	Urea	41.61a	142.95a	2.20a	10.78a	50.45a	215.83a	43.22a
85	Unity NPSFe	50.12a	186.68a	5.61ab	14.73a	99.02b	404.69ab	87.80b
	NPKZn Briquettes	43.61c	179.02ab	6.29a	14.96a	114.08a	429.61a	101.34a
	Ammonium Sulfate	51.78a	185.45a	4.88c	14.60a	97.83b	393.56bc	86.93b
	Urea	46.89b	173.29b	5.41bc	14.21a	95.67b	366.26c	84.71b
128	Unity NPSFe	51.85a	198.36a	6.69a	15.68a	121.43a	445.81a	107.65a
	NPKZn Briquettes	44.58c	179.58b	7.01a	15.36a	124.02a	448.50a	110.13a
	Ammonium Sulfate	52.13a	197.45a	6.11a	15.46a	115.23a	422.80ab	102.08a
	Urea	48.63b	183.10b	6.68a	14.90a	113.01a	402.81b	99.59a
170	Unity NPSFe	51.96a	201.53a	7.64a	15.89a	134.23a	468.88a	118.58a
	NPKZn Briquettes	43.47c	178.83b	7.91a	15.58a	133.79a	453.74a	118.73a
	Ammonium Sulfate	52.31a	202.44a	7.40a	16.50a	143.37a	490.46a	126.05a
	Urea	47.48b	183.38b	7.20a	15.98a	133.98a	446.06a	117.67a
	LSD††	2.94	10.13	0.69	0.68	11.45	34.09	10.07

*, only significant interactive effects are reported.

†, means in each column within each N rate level 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.

Table 2.5. Interaction means of plant height, plant biomass, grain yields, and yield components of corn for fertilizer types by years and fertilizer types by locations from the JA1213 dataset at Jackson and Ames during 2012 to 2013 with years and locations treated as fixed effects.*

		V6 Plant Height cm	R1 Plant Height	R1 Dry Weight Mg ha ⁻¹	Grain Yield	Ear Length cm	Ear Weight g	Kernel Mass	Kernel Count kernel cob ⁻¹	Grain Weight g ear ⁻¹
Year	Fertilizer Type									
2012	Unity NPSFe	50.28a†	187.29a	—	3.96a	12.95a	84.36a	—	—	74.42a
	NPKZn Briquettes	44.85b	177.44a	—	3.90a	12.33b	79.67a	—	—	70.49a
	Ammonium Sulfate	49.79a	186.63a	—	3.45a	13.16a	86.84a	—	—	76.34a
	Urea	49.67a	186.16a	—	4.29a	12.98a	86.73a	—	—	75.92a
2013	Unity NPSFe	46.71a	176.57a	—	6.97ab	15.60a	118.96ab	—	—	105.50ab
	NPKZn Briquettes	41.67b	161.19b	—	7.63a	15.62a	127.38a	—	—	112.91a
	Ammonium Sulfate	48.93a	178.46a	—	6.88b	15.70a	118.16ab	—	—	104.73ab
	Urea	42.63b	155.21b	—	6.46b	14.95b	109.83b	—	—	96.68b
	LSD††	3.03	10.60		0.72	0.57	10.26			9.12
Location	Fertilizer Type									
Jackson	Unity NPSFe	48.83a	199.66a	7.71a	—	—	—	0.24b	367.70a	—
	NPKZn Briquettes	36.14c	172.61b	5.22b	—	—	—	0.26a	335.22b	—
	Ammonium Sulfate	49.11a	198.31a	7.52a	—	—	—	0.25ab	365.87a	—
	Urea	43.43b	174.81b	5.85b	—	—	—	0.26a	318.76b	—
Ames	Unity NPSFe	48.16a	164.19a	8.16a	—	—	—	0.22a	407.40a	—
	NPKZn Briquettes	50.38a	166.02a	7.73a	—	—	—	0.21a	420.70a	—
	Ammonium Sulfate	49.62a	166.79a	8.52a	—	—	—	0.22a	400.05a	—
	Urea	48.87a	166.56a	8.63a	—	—	—	0.22a	396.72a	—
	LSD	3.03	10.60	0.89				0.01	27.28	

*, only significant interactive effects are reported.

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

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

Table 2.6. Analysis of variance p-values for plant height, plant biomass, grain yields, and yield components of corn at Jackson and Ames during 2012 to 2013 with years and locations treated as random effects.

	V6 Plant Height	R1 Plant Height	R1 Dry Weight	R6 Dry Weight	Grain Yield	Ear Count	Ear Length	Ear Weight	Kernel Mass	Kernel Count	Grain Weight
Treatments											
Fertilizer Type (FT)	**	**	***	ns	ns	ns	ns	ns	ns	*	ns
N Rate (NR)	***	***	***	***	***	***	***	***	***	***	***
FT x NR	**	ns	ns	ns	ns	ns	ns	ns	ns	*	ns

ns, not significant at the 0.05 probability level.

*, significant at the 0.05 probability level.

**, significant at the 0.01 probability level.

***, significant at the 0.001 probability level.

Table 2.7. Means of plant height, plant biomass, grain yield, and yield components of corn for fertilizer types and N rates at Jackson and Ames during 2012 to 2013 with years and locations treated as random effects.

	V6 Plant Height cm.....	R1 Plant Height	R1 Dry Weight Mg ha ⁻¹	R6 Dry Weight Mg ha ⁻¹	Grain Yield Mg ha ⁻¹	Ear Count ear stalk ⁻¹	Ear Length cm	Ear Weight g.....	Kernel Mass	Kernel Count kernel cob ⁻¹	Grain Weight g ear ⁻¹
Fertilizer Type											
Unity NPSFe	48.50ab†	181.93a	7.94ab	13.06a	5.47a	0.89a	14.27a	101.66a	0.23a	387.55a	89.96a
NPKZn Briquettes	43.26c	169.32b	6.47c	13.30a	5.77a	0.90a	13.98a	103.52a	0.24a	377.96ab	91.70a
Ammonium Sulfate	49.36a	182.55a	8.02a	13.35a	5.15a	0.88a	14.43a	102.50a	0.23a	382.96a	90.53a
Urea	46.15bc	170.68b	7.24b	12.96a	5.37a	0.90a	13.97a	98.28a	0.24a	357.74b	86.30a
N Rate (kg N ha⁻¹)											
0	41.07b	142.20c	4.55c	7.61d	2.05d	0.78b	10.68d	49.55d	0.21d	212.92d	43.19d
85	48.10a	181.11b	7.56b	13.53c	5.55c	0.93a	14.62c	101.65c	0.23c	398.53c	90.19c
128	49.30a	189.62a	8.62a	14.93b	6.62b	0.93a	15.35b	118.42b	0.24b	429.98b	104.86b
170	48.80a	191.55a	8.95a	16.60a	7.54a	0.93a	15.99a	136.34a	0.25a	464.79a	120.26a

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

Table 2.8. Interaction means of plant height, grain yields, and yield components of corn for fertilizer types by N rates at Jackson and Ames during 2012 to 2013 with years and locations treated as random effects.*

		V6 Plant Height cm	Kernel Count kernel cob⁻¹
N Rate (kg N ha⁻¹)	Fertilizer		
0	Unity NPSFe	40.07a†	230.81a
	NPKZn Briquettes	41.39a	180.00b
	Ammonium Sulfate	41.23a	225.03a
	Urea	41.61a	215.83ab
85	Unity NPSFe	50.12ab	404.69ab
	NPKZn Briquettes	43.61c	429.61a
	Ammonium Sulfate	51.78a	393.56ab
	Urea	46.89bc	366.26b
128	Unity NPSFe	51.85a	445.81a
	NPKZn Briquettes	44.58b	448.50a
	Ammonium Sulfate	52.13a	422.80ab
	Urea	48.62ab	402.81b
170	Unity NPSFe	51.96a	468.88ab
	NPKZn Briquettes	43.48b	453.74ab
	Ammonium Sulfate	52.31a	490.46a
	Urea	47.48b	446.06b
	LSD††	4.25	42.36

*, only significant interactive effects are reported.

†, means in each column within each N rate level 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.

Table 2.9. Analysis of variance p-values for corn ear health ratings at Jackson and Ames during 2011 to 2013.

	Physiological Defects	Disease Infestation	Insect Attack
J11			
Fertilizer Types (FT)	***	ns	ns
N Rate (kg N ha⁻¹)	***	ns	ns
FT			
Controlling for 0 kg N ha ⁻¹ rate	ns	ns	ns
Controlling for 85 kg N ha ⁻¹ rate	***	ns	ns
Controlling for 170 kg N ha ⁻¹ rate	*	ns	*
Controlling for 255 kg N ha ⁻¹ rate	ns	ns	ns
JA1213			
Fertilizer Types (FT)	*	ns	ns
N Rate (kg N ha⁻¹)	***	***	***
FT			
Controlling for 0 kg N ha ⁻¹ rate	ns	ns	ns
Controlling for 85 kg N ha ⁻¹ rate	***	ns	ns
Controlling for 128 kg N ha ⁻¹ rate	ns	ns	ns
Controlling for 170 kg N ha ⁻¹ rate	ns	ns	ns

ns, not significant at the 0.05 probability level.

*, significant at the 0.05 probability level.

***, significant at the 0.001 probability level.

Table 2.10. Rating frequencies for fertilizer types, N rates, and interaction effects of fertilizer types by N rates on corn ear health ratings in Jackson 2011.*

		Physiological Defects				Insect Attack			
		0**	1	2	3	0	1	2	3
Fertilizer Types									
Unity NPSFe		31†	82	18	9	-	-	-	-
NPKZn briquettes		51	58	22	7	-	-	-	-
Ammonium sulfate		58	56	19	7	-	-	-	-
Urea		67	54	8	13	-	-	-	-
N Rate (kg N ha⁻¹)									
0		8	61	47	23	-	-	-	-
85		49	79	11	3	-	-	-	-
170		74	55	4	5	-	-	-	-
255		76	55	5	5	-	-	-	-
Controlling									
N Rate (kg N ha⁻¹)	Fertilizer Types								
0	Unity NPSFe	-	-	-	-	-	-	-	-
	NPKZn briquettes	-	-	-	-	-	-	-	-
	Ammonium sulfate	-	-	-	-	-	-	-	-
	Urea	-	-	-	-	-	-	-	-
85	Unity NPSFe	2	29	3	1	-	-	-	-
	NPKZn briquettes	11	22	3	0	-	-	-	-
	Ammonium sulfate	15	16	3	2	-	-	-	-
	Urea	21	12	2	0	-	-	-	-
170	Unity NPSFe	14	21	0	0	5	29	1	0
	NPKZn briquettes	21	8	3	1	3	33	0	0
	Ammonium sulfate	21	11	1	1	11	21	2	0
	Urea	18	15	0	3	12	23	1	0
255	Unity NPSFe	-	-	-	-	-	-	-	-
	NPKZn briquettes	-	-	-	-	-	-	-	-
	Ammonium sulfate	-	-	-	-	-	-	-	-
	Urea	-	-	-	-	-	-	-	-

*, only significant effects are reported.

**, the degree of abnormalities is ranked as follows: no damage (0), low damage (1), medium (2), and severe (3).

†, numbers in cells denote frequencies of each rating; only significant ratings differences are reported (P<0.05).

Table 2.11. Rating frequencies for fertilizer types, N rates, and interaction effects of fertilizer types by N rates on corn ear health ratings at Jackson and Ames during 2012 to 2013.*

		Physiological Defects				Disease Infestation				Insect Attack			
		0**	1	2	3	0	1	2	3	0	1	2	3
Fertilizer types													
Unity NPSFe		70†	126	207	432	-	-	-	-	-	-	-	-
NPKZn briquettes		79	130	186	456	-	-	-	-	-	-	-	-
Ammonium sulfate		62	149	176	439	-	-	-	-	-	-	-	-
Urea		43	125	197	478	-	-	-	-	-	-	-	-
N rate (kg N ha⁻¹)													
0		0	3	31	697	403	141	114	76	520	139	53	18
85		23	128	260	467	570	182	97	30	628	189	58	4
128		96	181	246	355	553	208	83	27	622	201	47	5
170		135	218	229	286	556	189	95	27	579	236	41	1
Controlling													
N rate (kg N ha⁻¹)	Fertilizer Types												
0	Unity NPSFe	-	-	-	-	-	-	-	-	-	-	-	-
	NPKZn briquettes	-	-	-	-	-	-	-	-	-	-	-	-
	Ammonium sulfate	-	-	-	-	-	-	-	-	-	-	-	-
	Urea	-	-	-	-	-	-	-	-	-	-	-	-
85	Unity NPSFe	3	22	81	113	-	-	-	-	-	-	-	-
	NPKZn briquettes	17	40	71	97	-	-	-	-	-	-	-	-
	Ammonium sulfate	2	42	51	127	-	-	-	-	-	-	-	-
	Urea	1	24	57	130	-	-	-	-	-	-	-	-
128	Unity NPSFe	-	-	-	-	-	-	-	-	-	-	-	-
	NPKZn briquettes	-	-	-	-	-	-	-	-	-	-	-	-
	Ammonium sulfate	-	-	-	-	-	-	-	-	-	-	-	-
	Urea	-	-	-	-	-	-	-	-	-	-	-	-
170	Unity NPSFe	-	-	-	-	-	-	-	-	-	-	-	-
	NPKZn briquettes	-	-	-	-	-	-	-	-	-	-	-	-
	Ammonium sulfate	-	-	-	-	-	-	-	-	-	-	-	-
	Urea	-	-	-	-	-	-	-	-	-	-	-	-

*, only significant effects are reported.

**, the degree of abnormalities is ranked as follows: no damage (0), low damage (1), medium (2), and severe (3).

†, numbers in cells denote frequencies of each rating; only significant ratings differences are reported ($P < 0.05$).

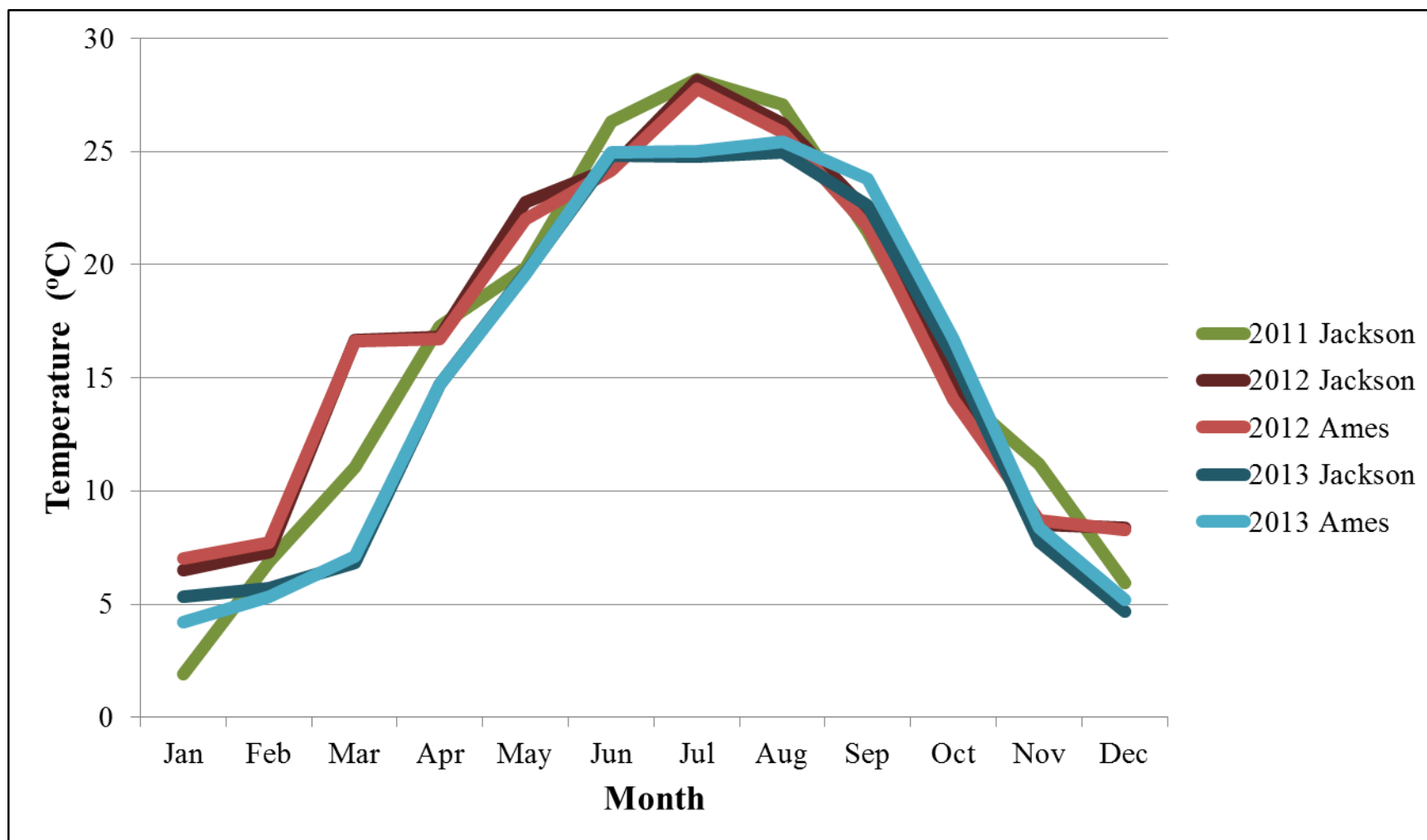


Figure 2.1. Average monthly temperatures during the duration of this study.

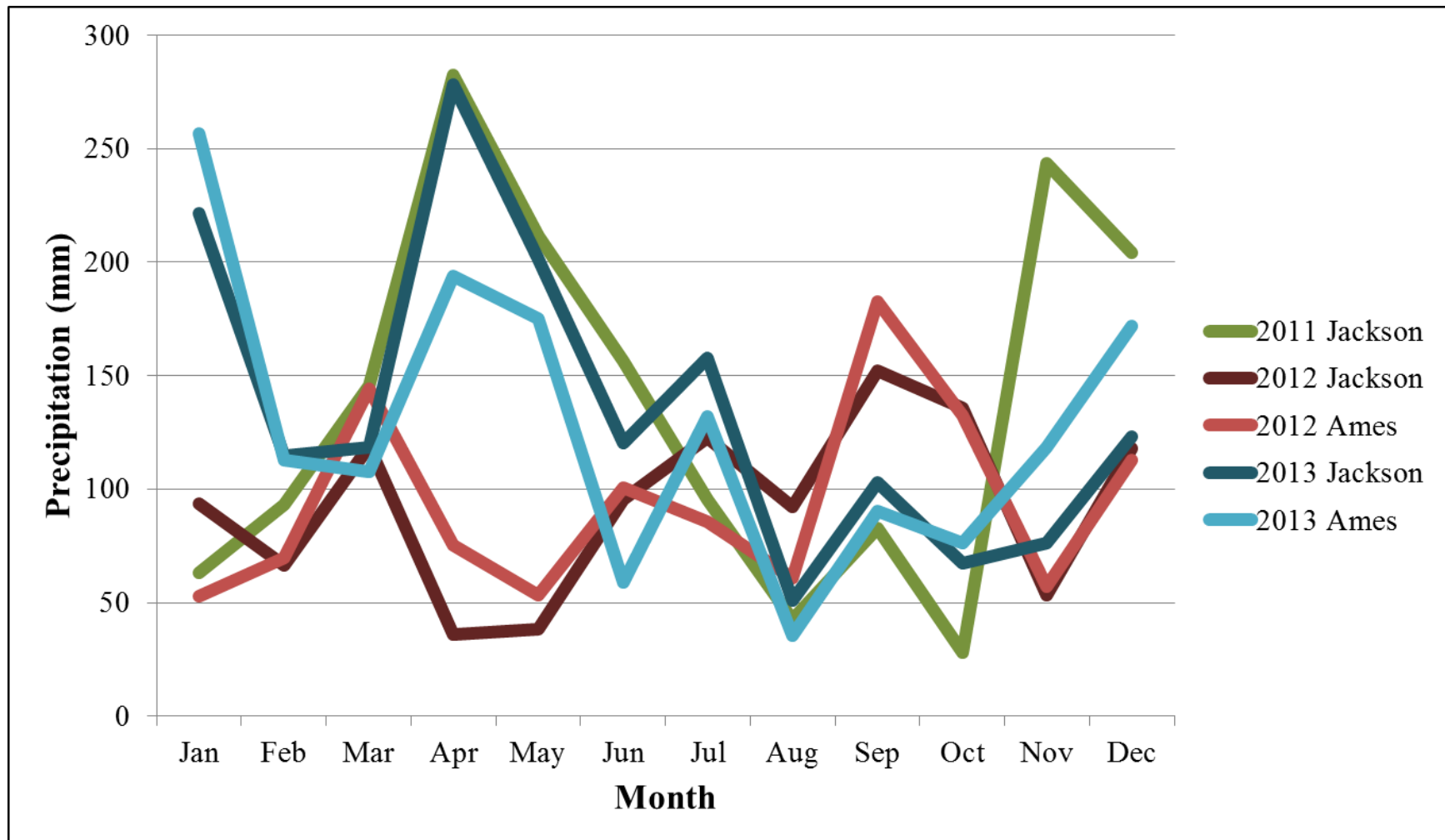


Figure 2.2. Average monthly precipitation during the duration of this study.

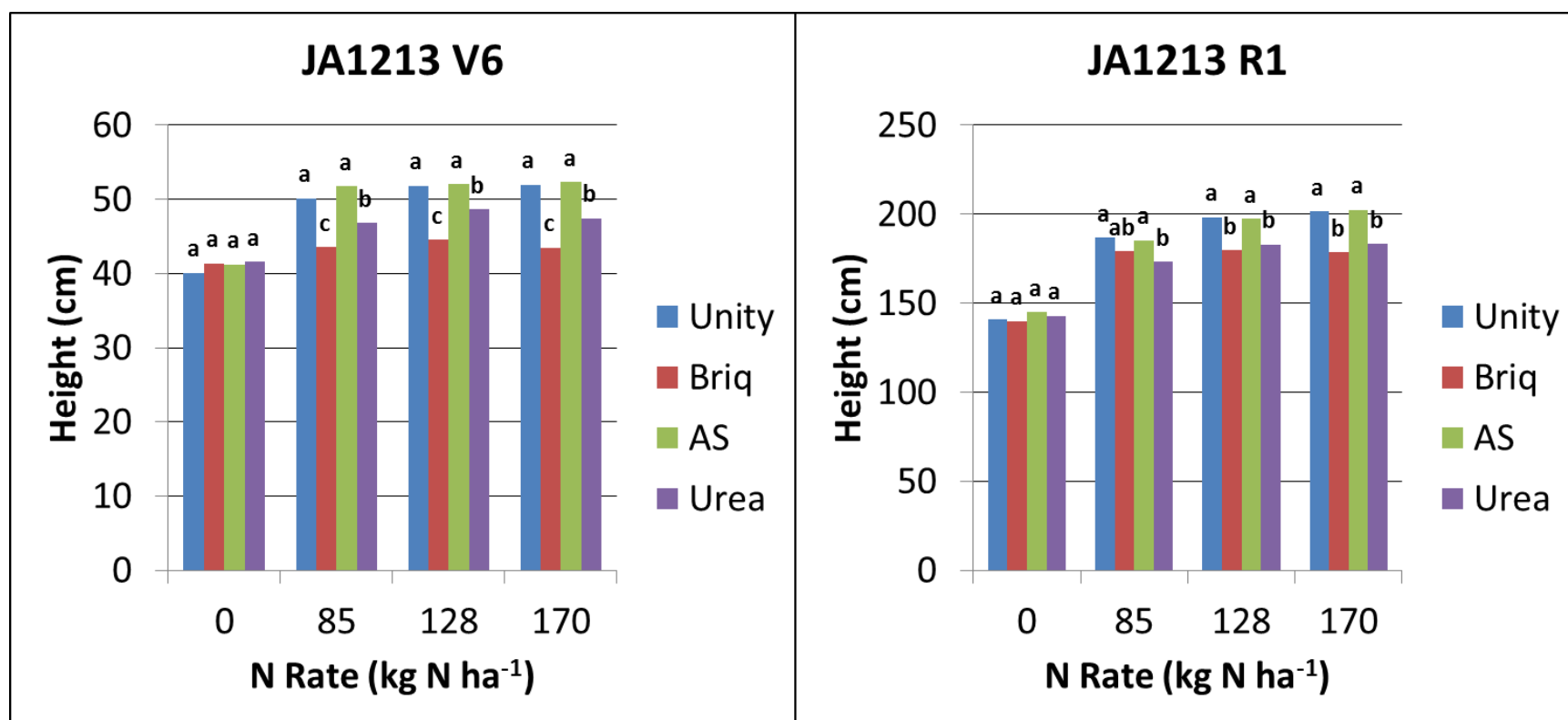


Figure 2.3. Interaction means of plant height at the V6 and R1 growth stages for fertilizer types by N rates at Jackson and Ames in 2012 to 2013. Plant heights at V6 and R1 within each N rate followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD. Abbreviations: Unity, Unity NPSFe; Briq, NPKZn briquettes; AS, ammonium sulfate.

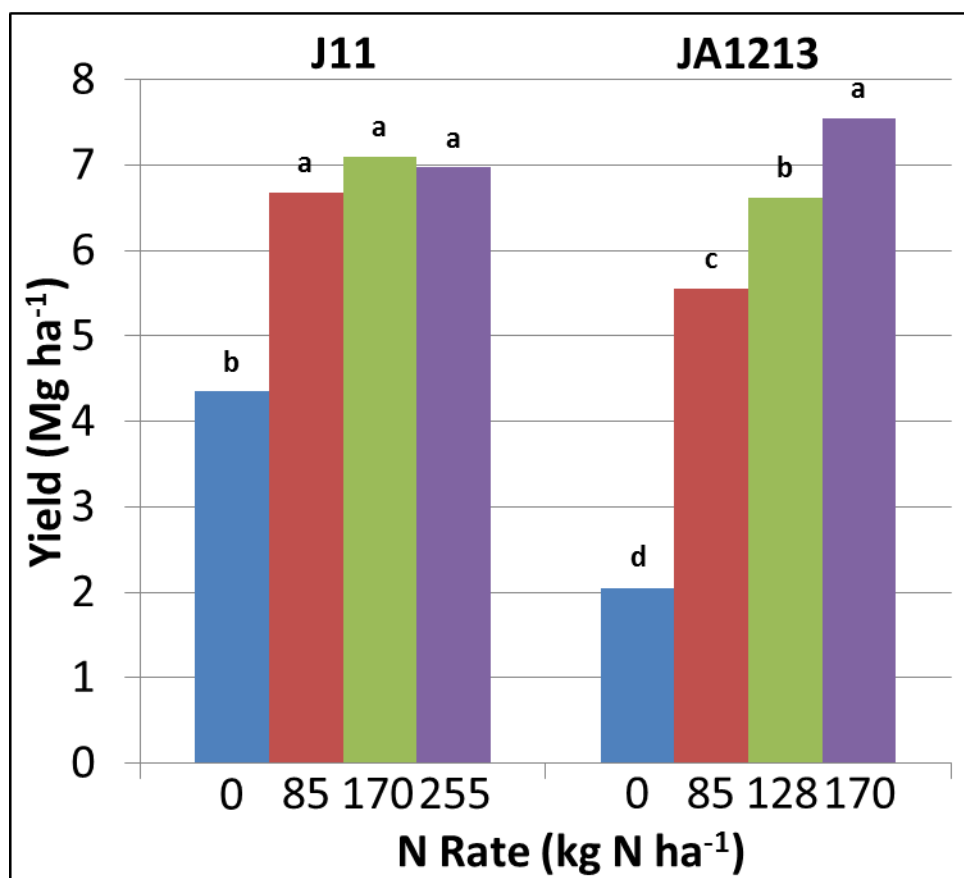


Figure 2.4. Corn grain yield by N rate at Jackson in 2011 and at Jackson and Ames in 2012 to 2013. Grain yield within J11 or JA1213 followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD.

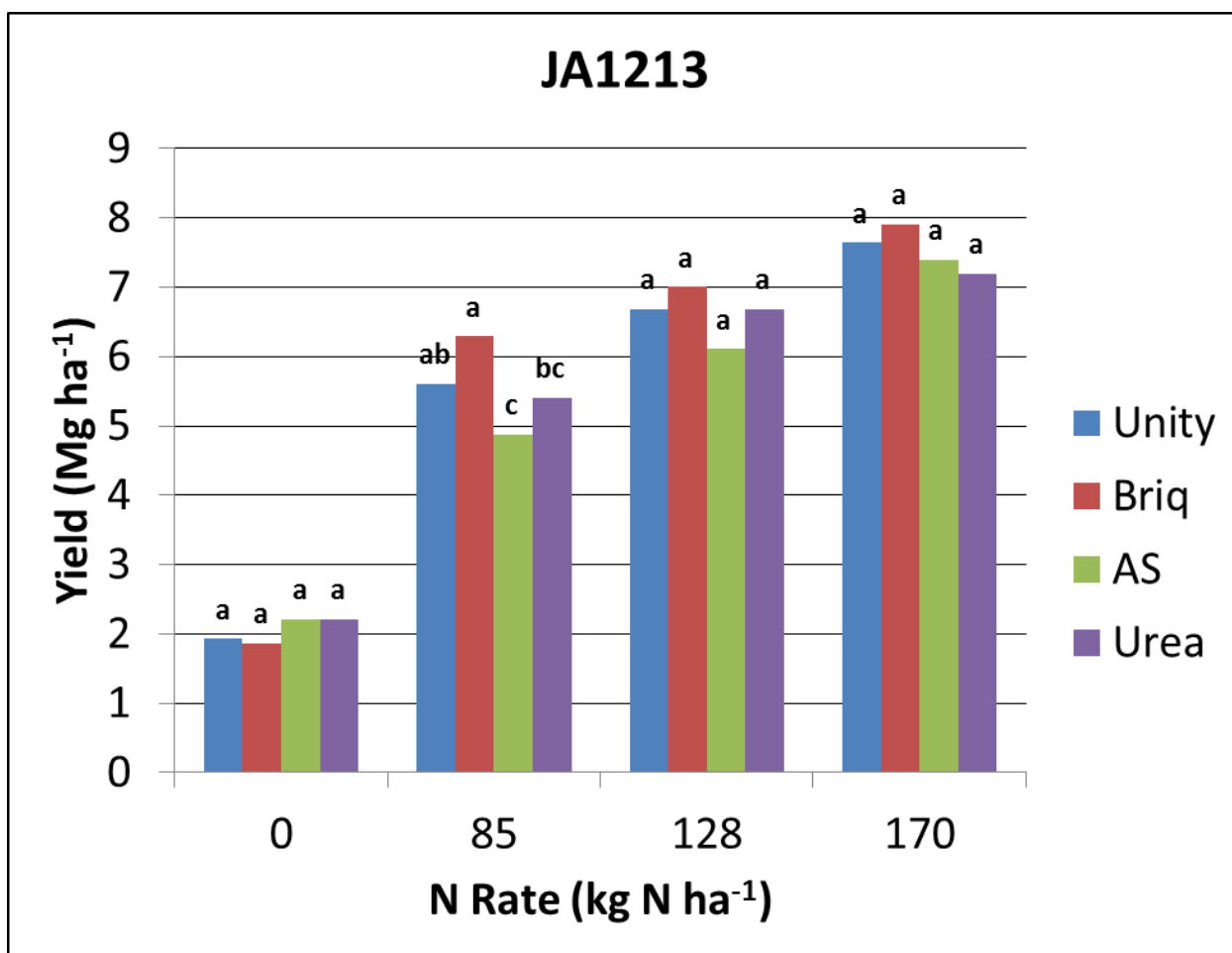


Figure 2.5. Interaction means of corn grain yields for fertilizer types by N rates at Jackson and Ames in 2012 to 2013. Grain yield within each N rate followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD. Abbreviations: Unity, Unity NPSFe; Briq, NPKZn briquettes; AS, ammonium sulfate.

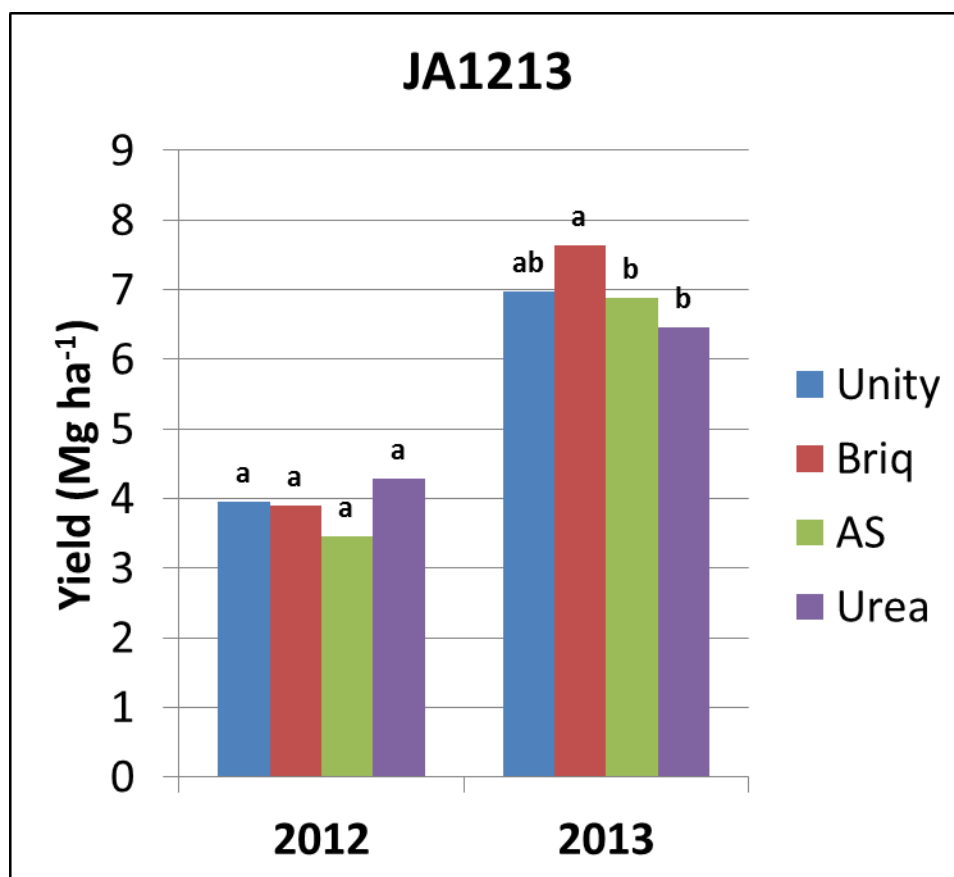


Figure 2.6. Interaction means of corn grain yields for fertilizer types by years at Jackson and Ames. Grain yield within each year followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD. Abbreviations: Unity, Unity NPSFe; Briq, NPKZn briquettes; AS, ammonium sulfate.

CHAPTER 4
EFFECTS OF NPSFE BIOFERTILIZER AND NPKZN BRIQUETTES ON
SOIL MICROBIAL COMMUNITY STRUCTURES

Abstract

Interest in the use of alternate fertilizers has increased in recent years in order to improve soil health without compromising crop yields, but the effects of alternate fertilizers on the soil health have been poorly examined. Alternative fertilizer products NPKZn briquettes (briquettes) produced by compacting commercially available solid fertilizers into a super-granule between 1-3 grams in weight per briquette, and organically enhanced NPSFe Unity (Unity) biofertilizer manufactured from sterilized organic additives extracted from municipal wastewater biosolids were evaluated for their effect on the soil microbial population relative to conventional fertilizers ammonium sulfate and urea over three years and two separate locations using non-irrigated corn as the test crop on silt loam soils in western Tennessee. Four fertilizer types of Unity, 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. Soil at a 0-15 cm depth was analyzed for microbial population shifts before treatment and after harvest from 2011 to 2013. Soil microbial populations were more often effected by soil accumulated fertilizer effects than by fertilizer types. In the few instances where fertilizer types had a significant impact on microbial population shifts, Unity, ammonium sulfate, and urea tended to decrease soil microbial population diversity relative to the briquettes and the zero N control. Unity, the briquettes, and ammonium sulfate all equally decreased arbuscular mycorrhizae populations relative to the control. With respect to accumulated fertilizer effects, actinomycetes and gram positive bacteria benefited from accumulated fertilizer effects. Eukaryotes and gram negative bacteria were negatively impacted by increasing fertilizer accumulation in the soil. Fungi and soil microbial diversity seemed to benefit from accumulated fertilizer effects in the soil to a point, after which they both declined with continued fertilizer accumulation effects in the soil. Unity seemed to be more beneficial for eukaryotic microbial populations than the zero N control. Overall, the effects of Unity NPSFe biofertilizer and the NPKZn briquettes on soil microbial community structure are not steadily noticeable within three years of experimentation.

Introduction

A fundamental factor to farming sustainability is maintaining soil health. Indeed the relatively thin layer of soil that covers the earth's surface can quite literally represent the difference between life and death for most terrestrial life on the planet (Doran, 2002). As far as humans are concerned, soil is a foundation from which high quality crops are grown; a healthy living soil is more likely to produce higher quality food and in greater quantities. Indeed the living microbial fraction of soil fulfills critical roles in nutrient cycling, as a relative labile source of plant nutrients, and in promoting soil aggregation (Shannon et al., 2002).

Although synthetic fertilizers are replacing some soil nutrients fairly well, whether or not they can maintain or restore optimum soil health in perpetuity by not harming soil microbial communities is yet to be seen. Soil microbes play a critical role in maintaining soil functions because of their contribution to soil structure formation; decomposition of organic matter; toxin removal; and the biogeochemical cycling of C, N, P, and S (Karlen et al., 1997; Doran and Zeiss, 2000; Paul, 2007). The magnitude of soil microbial diversity in agronomic soils is also imperative for the maintenance of healthy soil (Garbeva et al., 2004; Shen et al., 2008). Disregard for soil health will likely compromise future agricultural productivity in favor of high but short term economic returns (Gleismann, 2007). Soil health is becoming an increasingly serious issue as contemporary agriculture continues to bear the responsibility of feeding the world today and future generations sustainably.

The scientific literature concerning the long-term influences of inorganic fertilizers on soil health and thus farming production capacity is conflicting (Belay et al., 2002). Some studies have shown that continuous inorganic fertilizer use negatively impacts soil health (Gliessman, 1984; Doran and Werner, 1990; Dick, 1992; Cassman and Pingali, 1995; Doran et al., 1996). Some studies suggest both positive and negative soil health effects result from long-term inorganic fertilizer use (Hera and Mihaila, 1981; Johnston, 1994; Goyal et al., 1999; Belay et al., 2002), and still others report no significant changes in soil health or production capacity (Aref and Wander, 1998). These conflicting views reflect a need for future research into the subject of long-term inorganic versus organic fertilizer use on soil health in agronomic systems.

The organically-enhanced NPSFe fertilizer, called “Unity” by the company that manufactures it, Unity Envirotech (St. Petersburg, FL), contains N, P, S, and Fe, approximately 8% organic matter that is made from sterilized organic additives extracted from municipal wastewater biosolids. Most of the N and all of the P, S, and Fe are contained in the municipal biosolid. Only N is supplemented with additional synthetic N fertilizer to increase the N concentration of Unity during the manufacturing process. The organic matter contribution of Unity may improve soil health and thus productivity. Soil organic matter does contain, after all, most of the soil reserve of N and large portions of other nutrients such as P and S (Stockdale et al., 2002). Unity Envirotech is projected in the next two or three years to use approximately 10% of Florida’s total municipal biosolid waste to manufacture 300,000 Mg of Unity biofertilizer per year (Weber, 2013).

The briquettes are entirely mineral in their formulation and are manufactured at a facility operated by the International Fertilizer Development Center (IFDC) based at Muscle Shoals, Alabama. The briquette fertilizer is mineral in form and supplies Zn in addition to NPK. The briquettes are made by a briquetter machine that simply compresses prilled fertilizers into a briquette approximately 2.43 grams in weight without any additional binder material. Thus the guaranteed analysis of the briquettes is variable depending on the proportions of different fertilizers used to form the briquette. A briquette with a smaller surface area to volume ratio will dissolve more slowly in the soil and thus release its nutrients in a more controlled manner over time thereby likely reducing any negative impacts on soil health from sudden high concentrations of nutrient entering the soil from more quick-releasing fertilizers. In a previous study where briquettes were used in a flooded rice paddy cropping system, the briquettes exhibited such excellent controlled nutrient releasing properties that, unlike conventional N fertilizers, the briquettes did not inhibit N₂ fixation by algae in paddy fields (Savant and Stangel, 1996). The lack of inhibition of N₂ fixing algae was mainly due to the absence of fertilizer N in the flood water from flooded soils under briquette fertilization (Roger et al., 1980).

The briquettes were designed for developing countries in which this may be a practical method of fertilizer application where very small acreages are farmed by a single grower and his/her

family. The IFDC is a non-profit organization that focuses its efforts on sustaining food security and agricultural productivity in developing countries through the development and transfer of effective and environmentally sound crop nutrient technology (IFDC, 2013). In developed countries, briquettes could potentially be applied using a key-line plowing system which has a dispensing mechanism that places product underground immediately behind a deep plow shank during plowing.

Like the scientific literature concerning overall soil health, preceding scientific literature comparing the effects of organic and inorganic fertilizers on soil microbial community structure is also conflicting. For instance, Zerzghi et al. (2010) found over a 20-year period that land applications of biosolids had no significant effect on soil microbial populations compared to un-amended control plots. Sullivan et al. (2006) who compared many different levels of biosolid application to an un-amended control also reported no differences in microbial community structure. In a four-year study, Bredecke et al. (1993) also observed that land applications of biosolids did not adversely affect soil microbial populations. Sarathchandra et al. (2001) compared different mineral N and P fertilizer treatments and likewise found very few differences in soil microbial community structure under different fertilizer treatments. But these findings are in contrast to other scientific literature that report microbial community shifts as influenced by fertilizer treatments. Erland et al. (1994) found that fungi populations fell more than bacteria after wood-ash fertilization; the decrease in fungi was discovered to be the result of the mineral application and not the rise in pH. Zhong et al. (2010) confirmed that microbial diversity increased under organic and organic plus mineral fertilization compared to mineral fertilization alone. And Bossio et al. (1997) reported that the relative abundance of actinomycetes increased under mineral fertilization compared to organic fertilization. These differences reflect a need for further research on the effects of inorganic and organic fertilizer applications on soil microbial community structure.

The objectives of this study were to compare alternative fertilizers, Unity and banded briquettes, relative to conventional fertilizers, ammonium sulfate and split-applied urea, in terms of their effects on soil microbial community structures.

Materials and Methods

The field trial was conducted at the University of Tennessee's West Tennessee Research and Education Center (WTREC) located in Jackson, Tennessee from 2011 to 2013 and at a second location at the Ames Plantation, Tennessee from 2012 to 2013. The research project was designed and coordinated by the International Fertilizer Development Center (IFDC) and the University of Tennessee. All the daily field operations were managed by the University of Tennessee.

Soil Description

At Jackson the field trial was conducted on a Memphis silt loam soil (fine-silty, mixed, active, thermic Typic Hapludalfs), and at Ames the field trial was conducted on a Lexington silt loam soil (fine-silty, mixed, active, thermic Ultic Hapludalfs). At Jackson and Ames locations the fields used for this study prior to the experiment were in soybean production followed by a winter fallow. In the spring (2011 Jackson and 2012 Ames) following the winter fallow, experimental treatments were initiated.

Corn Planting

Corn hybrid, Dekalb 6483 (YieldGardVT Triple), was used across all locations and years in this study. The Jackson trial was planted under no-tillage as eight row plots with 76.2 cm (30 inch) row spacing at a seeding rate of 79,000 plants ha⁻¹; overall plot dimensions were 9.1 m by 6.1 m (30 feet by 20 feet). The Ames trial was planted as tilled six row plots also with 76.2 cm row spacing at a seeding rate of 79,000 plants ha⁻¹; overall plot dimensions were 9.1 m by 4.6 m (30 feet by 15 feet). At Jackson corn was planted on 9 May in 2011, 18 April in 2012, and 17 April in 2013. At Ames corn was planted on 19 April in 2012 and on 29 May in 2013.

Treatments

A total of 16 treatments with four replicates (64 plots in total per location) were arranged in a split plot randomized complete block design with fertilizer types as main plots and N rates as subplots. Unity, the briquettes, ammonium sulfate (21% N, 24% S), and urea (46% N) were the

four fertilizer types. In 2011 at Jackson the N rates used were 0, 85, 170, and 255 kg N ha⁻¹. From 2012 to 2013 at both locations, the N rates were changed to 0, 85, 128, and 170 kg N ha⁻¹.

For the soil microbial sampling, however, only certain treatments were chosen because of the high cost associated with Phospholipid Fatty Acid (PLFA) analysis. Plot selections were made to emphasize comparing Unity to the other fertilizer types and a control (Table 3.1). In 2011 at Jackson, plots that received Unity, ammonium sulfate, and urea at a rate of 170 kg N ha⁻¹ and briquette plots at a 0 kg N ha⁻¹ rate were sampled. The 0 kg N ha⁻¹ rate briquette plots served as a zero N control. From 2012 through 2013 at Jackson, plots that received Unity and ammonium sulfate at a rate of 128 kg N ha⁻¹ were sampled. From 2012 through 2013 at Ames, plots that received Unity at a 128 kg N ha⁻¹ rate, and briquette plots at a 0 kg N ha⁻¹ rate were sampled. The 0 kg N ha⁻¹ rate briquette plots served as a zero N control. In 2013 at Ames, plots that received Unity, briquettes, and ammonium sulfate at a rate of 128 kg N ha⁻¹ and briquette plots at a 0 kg N ha⁻¹ rate were sampled. The 0 kg N ha⁻¹ rate briquette plots again served as a zero N control.

The N fertilizer treatments, apart from urea, were applied entirely basally after corn planting: in 2011 at Jackson fertilizers were applied the day after planting, in 2012 fertilizers were applied five days and 21 days after planting at Jackson and Ames, respectively, and in 2013 fertilizers were applied five days and eight days after planting at Jackson and Ames, respectively.

Only one third of N in the urea fertilizer treatment was applied basally, the other two thirds of N in that treatment were applied as two equal splits at the six leaf growth stage (V6) and at tasseling (VT). This was done as farmers in developing countries typically do to reduce N losses. Unity, ammonium sulfate, and urea were all applied uniformly via surface broadcast across the entire plot. However, the briquettes were banded using a small hand-driven plow approximately 2.54 cm below the soil surface in four bands per plot between rows one and two, three and four, five and six, and seven and eight at Jackson. At Ames the briquettes were banded at the same depth but in three bands between rows one and two, three and four, and five and six.

Phosphorus, K, and Zn were all applied at the following uniform rates across all treatments: 45 kg P ha⁻¹, 85 kg K ha⁻¹, and 5 kg Zn ha⁻¹ (Table 3.1). The S rate was variable for the Unity and ammonium sulfate fertilizer treatments because both of these fertilizers contained S as part of their guaranteed analysis, thus with increasing N rates, Unity and ammonium sulfate supplied increasing amounts of S (Table 3.1). At the 128 kg N ha⁻¹ rate, Unity and ammonium sulfate supplied 156 and 147 kg S ha⁻¹, respectively; at the 170 kg N ha⁻¹ rate, Unity and ammonium sulfate supplied 207 and 195 kg S ha⁻¹, respectively. For the control (0 kg N ha⁻¹), all the fertilizer treatment plots had an S rate of 1.25 kg S ha⁻¹ from the sulfate in the ZnO/ZnSO₄ fertilizer that 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 Unity treatments. Unity already contained some P and thus required less P supplementation from TSP to meet the uniform P application rate. At 128 and 170 N ha⁻¹ rates, Unity supplied 35.8% and 47.6% of the uniform P rate, respectively. Potassium and Zn were applied as KCl (0-0-60) and ZnO/ZnSO₄ (36% Zn, 9% S), respectively, for ammonium sulfate, urea, and Unity treatments.

The briquettes were unique in that they were manufactured from already commercially available fertilizers through a fertilizer briquetter machine developed by the IFDC. The briquetter machine allows the manufacturer to manipulate a fertilizer's guaranteed analysis to suit specific needs. In the case of this study, the briquettes were created by the IFDC and 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 3.1). This occurred because the S in the briquettes was supplied by ZnSO₄ (17.5% S) not ZnO/ZnSO₄ (9% S). The N, P, K, and Zn mineral sources used in the briquettes were urea, diammonium phosphate, potassium chloride, and zinc sulfate.

Off-Season Treatments

Between experimental years through the winter, winter wheat was planted as a cover crop and received the same fertilizer type treatments per plot but with altered N application rates to more

appropriately suit winter wheat. The N rates used for the winter wheat were 0 and 84.0, kg N ha⁻¹. Zero, and 33.6 kg N ha⁻¹ were applied basally in the fall and the remaining N was applied as a top-dress application in the following February. Plots that received the briquette treatments for corn also received additional fertilization as briquettes for wheat but only in the initial treatment year (2011 at Jackson and 2012 at Ames) after corn harvest. The briquette N rates used were 0 and 84.0 kg N ha⁻¹ all applied in the fall with no top-dress application in the spring. After the initial treatment year, plots that received the briquette treatments no longer received additional fertilization after corn harvest so that only the residual briquette fertilizer was allowed to influence the winter wheat. Phosphorus and K were applied basally as blanket applications at 19.6 and 37.2 kg ha⁻¹, respectively. Before corn planting at Jackson in the following spring, the winter wheat cover crop was killed with Gramoxone (Paraquat: 1,1'-Dimethyl-4,4'-bipyridinium dichloride) herbicide; at Ames the winter wheat cover crop was killed with Gramoxone herbicide and then tilled by disc.

Microbial Data Collection and Soil Health Quantification

A composite soil sample totaling 10 cores per plot was taken at a 15-cm depth from the center four rows at Jackson and Ames before treatment application and after corn harvest each year in selected plots. Each sample was mixed by gloved hand, ground to pass through a 2 mm sieve, and shipped immediately by overnight delivery under dry ice to Microbial Insights (Rockford, TN) for the samples beginning in 2011 pre-treatment through 2013 pre-treatment; post-harvest 2013 samples were similarly handled, packaged, and shipped but sent to Dr. Jared DeForest of the University of Ohio for analysis. Phospholipid fatty acid analysis was conducted on all these samples to determine the soil microbial community structure. This was done by extracting PLFA biomarkers from the soil samples and then identifying specific biomarkers by gas chromatography with flame ionization detection (Microbial Insights, 2014). The following categories of microorganisms and their relative proportion to each other were determined: actinomycetes, arbuscular mycorrhizal fungi, eukaryotes, fungi, general, gram negative bacteria, and gram positive bacteria.

Statistical Analyses

Analysis of variance was used in a randomized complete block (RBD) design with either single factor or repeated measures designs using SAS version 9.3 (SAS institute, Cary, NC). In the single factor RBD design, fertilizer types were the fixed experimental factor and in the repeated measures RBD design, fertilizer types were the fixed experiment factor and the soil sampling times, post-harvest 2012 (PH12), pre-treatment 2013 (PT13), and post-harvest 2013 (PH13) were the repeated measures. In both designs, blocks were treated as a random factor. The post-ANOVA analysis method used was mean separation by Fisher's protected LSD. Probability values for all analyses lower than 0.05 were designated as statistically significant.

Results and Discussion

Soil microbial community structure was occasionally influenced by the different fertilizer types in this study. In 2011 at Jackson, only the general microbial category was different among fertilizer types, and in that case urea increased the proportion of general microbes relative to the zero N control which indicates a decrease in microbial diversity under urea fertilization (Table 3.2, Figure 3.1) (Microbial Insights, 2009). Unity and ammonium sulfate were similar to both urea and the control. Sarathchandra et al. (2001) found very few differences in soil microbial community structure under different mineral N and P fertilizer treatments. Sullivan et al. (2006) also reported no differences in microbial community structure from many different amounts of biosolid land application compared to a control on semi-arid rangeland in Colorado.

At Jackson from 2012 to 2013, there were no differences in soil microbial community structure between Unity and ammonium sulfate but there were community shifts through time (Table 3.3). Actinomycetes, arbuscular mycorrhizae, eukaryotes, fungi, and general microbes all shifted with time and in unique ways. Soil actinomycete populations were lower at PH12 and PT13, but by PH13 they increased in number. Arbuscular mycorrhizae were similar to the actinomycetes but their population increased sooner at PT13 and remained the same by PH13. These findings suggest that actinomycetes and arbuscular mycorrhizae benefit from accumulated fertilizer effects. The eukaryote population change was opposite of the actinomycetes in that they were higher at PH12 and PT13 but decreased by PH13 suggesting a negative influence of accumulated fertilizer effects on eukaryotes. Fungi populations increased from PH12 to PT13 but fell to its lowest population levels by PH13. This seems to suggest that fungi, in general, benefit from accumulated fertilizer effects in the soil only for so long before it strongly negatively impacts their numbers. Erland et al. (1994) found fungi populations to be more sensitive than bacteria after wood-ash fertilization. They discovered that the decrease in relative abundance of fungi was in fact a result of the mineral application and not the rise in pH from the ash. General microbial community was highest at PT13. This is somewhat similar to the fungi result in that the microbial diversity benefited from accumulated fertilizer effects in the soil to a point.

At Ames from 2012 to 2013, there were significant differences in soil microbial community structure between Unity and the zero N control (Table 3.4, Figure 3.2). Arbuscular mycorrhizae decreased in population under Unity fertilization compared to the control. This is a disappointing result because the organic matter contribution of Unity was believed to be more supportive of soil microbial community health but in this case it seemed to negatively impact arbuscular mycorrhizae population. Unity also increased the general microbial population compared to the control which suggests that Unity decreases soil microbial community diversity. These findings are in contrast to those of Zerzghi et al. (2010) who found over a 20 year period that land applications of biosolids had no significant long-term effect on soil microbial populations compared to un-amended control plots. Bredecke et al. (1993) likewise reported over a four-year period that land applications of biosolids did not adversely affect soil microbial populations; both of these studies were conducted on soils from the southwestern United States.

Microbial community structures also differed as a function of time at Ames from 2012 to 2013; in fact, all of the microbial population proportions measured were significantly impacted by time (Table 3.4). Actinomycete and gram positive bacteria population abundance were highest at PH13 when accumulated fertilizer effects in the soil were highest. The abundances of soil eukaryote and fungi followed the exact same pattern at Ames from Jackson 2012-2013: the eukaryotes are negatively impacted by accumulated fertilizer effects in the soil while fungi seem to benefit from accumulated fertilizer effects in the soil initially but are then strongly negatively impacted as the accumulated fertilizer effects continue. Gram negative bacteria populations followed the exact same trend as the eukaryotes. Soil microbial diversity was lowest at PH13 which suggests that greater accumulated fertilizer effects negatively impact soil microbial diversity.

Also at Ames from 2012 to 2013 there was a significant fertilizer type by sampling time interactive effect for eukaryote populations (Table 3.4). Under the control eukaryote abundances declined with each successive sampling time, whereas under Unity fertilization eukaryote abundances only declined by the very last sampling time (PH13). This seems to suggest that Unity is more beneficial for eukaryotic microbial populations than un-amended soil.

At Ames in 2013, arbuscular mycorrhizal fungi and general soil microbes were impacted by fertilizer types at post corn harvest (Table 3.5, Figure 3.3). Unity, the briquettes, and ammonium sulfate all decreased the proportion of arbuscular mycorrhizal fungi compared to the control. Arbuscular mycorrhizal fungi are obligate symbionts with plants and are often associated with positive plant outcomes from root infection such as enhanced plant nutrient uptake, growth, and tolerance to environmental stresses (Fitter and Moyersoen, 1996; Smith and Read, 1997). In our study, Unity, the briquettes, and ammonium sulfate equally decreased these fungi in the soil compared to the control. The general microbe proportion increased under Unity and ammonium sulfate compared to the briquettes or the control. This result suggests that the briquettes, in contrast to Unity and ammonium sulfate, are better at promoting soil microbial diversity. This is in contrast to the findings of Zhong et al. (2010) that soil microbial diversity increased under organic manure and organic manure plus mineral fertilization compared to mineral fertilization alone.

In 2012 at Jackson and Ames, there were no differences in soil microbial community structure between Unity and ammonium sulfate (Table 3.6). That actinomycete populations did not increase under ammonium sulfate compared to Unity is in contrast to the findings of Bossio et al. (1997) that the relative abundance of actinomycetes increased under mineral fertilization compared to organic fertilization.

Conclusions

Soil microbial community structures were more often affected by accumulated fertilizer in the soil than by fertilizer type treatments. In the few instances where fertilizer types had a significant impact on microbial population shifts, Unity, ammonium sulfate, and urea tended to decrease soil microbial population diversity relative to the briquettes and the zero N control. Unity, the briquettes, and ammonium sulfate all equally decreased arbuscular mycorrhizae populations compared to the control. With respect to accumulated fertilizer effects, actinomycetes, arbuscular mycorrhizae, and gram positive bacteria benefited from accumulated fertilizer effects. It is interesting that arbuscular mycorrhizal fungi seemed to benefit from accumulated fertilizer effects while they were negatively impacted by fertilizer treatments compared to the control. Eukaryotes and gram negative bacteria were negatively impacted by increasing fertilizer accumulation in the soil. Fungi and soil microbial diversity seemed to benefit from accumulated fertilizer effects in the soil to a point, after which they both declined with continued fertilizer accumulation effects in the soil. Unity seemed to be more beneficial for eukaryotic microbial populations than the zero N control. Overall, the effects of Unity NPSFe biofertilizer and the NPKZn briquettes on soil microbial community structure are not steadily noticeable relative to the common fertilizers ammonium sulfate and urea and the zero N control within three years of experimentation.

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Appendix C

Table 3.1. Selected treatments for soil microbial analysis at Jackson and Ames during 2011 to 2013.

Fertilizer	N Rate	P Rate	K Rate	S Rate	Zn Rate
Type	 kg ha ⁻¹				
Jackson 2011					
Unity NPSFe	170	45	85	207*	5
Ammonium sulfate	170	45	85	195*	5
Urea†	170	45	85	1.25	5
Control	0	45	85	1.25	5
Jackson 2012-2013					
Unity NPSFe	128	45	85	156	5
Ammonium sulfate	128	45	85	147	5
Ames 2012-2013					
Unity NPSFe	128	45	85	156	5
Control	0	45	85	1.25	5
Ames 2013					
Unity NPSFe	128	45	85	156	5
NPKZn briquettes	128	45	85	2.46††	5
Ammonium sulfate	128	45	85	147	5
Control	0	45	85	1.25	5
Jackson & Ames 2012					
Unity NPSFe	128	45	85	156	5
Ammonium sulfate	128	45	85	147	5

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

†, urea was applied in three equal split applications: basally, 30 and 60 days after basal application.

††, S rates were slightly higher under the briquettes than urea because Zn was supplied as ZnSO₄; in the other Zn applications ZnO/ZnSO₄ was used which has less overall SO₄.

Table 3.2. Mean relative abundance of soil microbes for fertilizer types on the post-harvest soil microbial community at Jackson in 2011.

	Actinomycetes	Arbuscular Mycorrhizal Fungi	Eukaryotes	Fungi	General Microbes	Gram Negative Bacteria	Gram Positive Bacteria
	 %						
Significance	ns	ns	ns	ns	*	ns	ns
Fertilizer Type							
Unity NPSFe	11.86a†	4.66a	3.56a	4.84a	20.89ab	33.83a	21.45a
Ammonium Sulfate	11.09a	4.31a	7.04a	5.30a	21.03ab	31.47a	20.86a
Urea	12.02a	4.53a	0.61a	4.20a	21.83a	33.80a	21.40a
Control	11.49a	5.31a	3.74a	4.11a	19.98b	33.52a	21.03a

ns, not significant at the 0.05 probability level.

*, significant at the 0.05 probability level.

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

Table 3.3. Mean relative abundance of soil microbes for fertilizer types and repeated measures on the soil microbial community at Jackson 2012-2013.

	Actinomycetes	Arbuscular Mycorrhizal Fungi	Eukaryotes	Fungi	General Microbes	Gram Negative Bacteria	Gram Positive Bacteria
	 %						
Significance	ns	ns	ns	ns	ns	ns	ns
Fertilizer Types (FT)							
Unity NPSFe	11.95a†	4.64a	3.33a	3.80a	24.56a	28.92a	23.01a
Ammonium Sulfate	11.72a	4.20a	3.29a	4.62a	22.90a	30.00a	23.06a
Significance	*	*	***	***	*	ns	ns
Repeat (R)							
Post-harvest 2012	11.40b	3.65b	3.82a	4.34b	25.96a	27.30a	23.54a
Pre-treatment 2013	11.26b	4.71a	4.13a	6.57a	21.44b	28.14a	23.76a
Post-harvest 2013	12.85a	4.90a	1.99b	1.73c	23.79a	32.95a	21.81a
Significance	ns	ns	ns	ns	ns	ns	ns
FT x R††							

ns, not significant at the 0.05 probability level.

*, significant at the 0.05 probability level.

***, significant at the 0.001 probability level.

†, means in each column within the fertilizer treatments or repeat measurements followed by the same letter are not significantly different at P = 0.05 according to Fisher's protected LSD.

††, non-significant interaction means were not reported.

Table 3.4. Mean relative abundance of soil microbes for fertilizer types and repeated measures on the soil microbial community at Ames 2012-2013.

	Arbuscular Mycorrhizal				General	Gram Negative	Gram Positive
	Actinomycetes	Fungi	Eukaryotes	Fungi	Microbes	Bacteria	Bacteria
	 %						
Significance	ns	**	ns	ns	**	ns	ns
Fertilizer Types (FT)							
Unity NPSFe	11.57a†	3.62b	3.32a	6.12a	24.27a	26.17a	24.49a
Control	11.48a	4.26a	3.26a	5.69a	22.80b	27.94a	25.01a
Significance	***	***	***	***	**	*	***
Repeat (R)							
Post-harvest 2012 (PH12)	11.46b	3.99a	3.83a	6.70b	23.40b	27.92a	22.71b
Pre-treatment 2013 (PT13)	10.21c	4.53a	3.78a	8.10a	22.23b	28.22a	22.94b
Post-harvest 2013 (PH13)	12.90a	3.31b	2.26b	2.91c	24.98a	25.03b	28.60a
Significance	ns	ns	*	ns	ns	ns	ns
FT x R††							
Unity NPSFe x PH12	—	—	3.64a	—	—	—	—
Unity NPSFe x PT13	—	—	4.11a	—	—	—	—
Unity NPSFe x PH13	—	—	2.22b	—	—	—	—
Control x PH12	—	—	4.03a	—	—	—	—
Control x PT13	—	—	3.45b	—	—	—	—
Control x PH13	—	—	2.30c	—	—	—	—
§LSD			0.61132				

ns, not significant at the 0.05 probability level.

*, significant at the 0.05 probability level.

**, significant at the 0.01 probability level.

***, significant at the 0.001 probability level.

†, means in each column within the fertilizer type treatments, repeated measures, or the interaction of both followed by the same letter are not significantly different at P = 0.05 according to Fisher's protected LSD.

††, only significant means are reported.

§ LSD, least significant difference value across fertilizer type treatments.

Table 3.5. Mean relative abundance of soil microbes for fertilizer types on the post-harvest soil microbial community at Ames in 2013.

	Actinomycetes	Arbuscular Mycorrhizal Fungi	Eukaryotes	Fungi	General Microbes	Gram Negative Bacteria	Gram Positive Bacteria
	 %						
Significance	ns	*	ns	ns	*	ns	ns
Fertilizer Types							
Unity NPSFe	12.84a†	3.12b	2.21a	2.97a	25.44a	24.28a	29.03a
NPKZn Briquettes	13.10a	2.88b	1.95a	2.91a	24.39b	25.72a	28.57a
Ammonium Sulfate	12.86a	3.01b	2.02a	3.39a	25.74a	25.95a	28.23a
Control	12.95a	3.63a	2.29a	2.82a	24.54b	24.57a	28.57a

ns, not significant at the 0.05 probability level.

*, significant at the 0.05 probability level.

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

Table 3.6. Mean relative abundance of soil microbes for fertilizer types on the post-harvest soil microbial community at Jackson and Ames in 2012.

	Actinomycetes	Arbuscular Mycorrhizal Fungi	Eukaryotes	Fungi	General Microbes	Gram Negative Bacteria	Gram Positive Bacteria
							
							
Significance	ns	ns	ns	ns	ns	ns	ns
Fertilizer Type							
Unity NPSFe	12.90a†	4.03a	2.13a	2.30a	24.85a	28.22a	25.61a
Ammonium Sulfate	12.78a	3.90a	1.97a	2.59a	24.54a	29.05a	25.13a

ns, not significant at the 0.05 probability level.

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

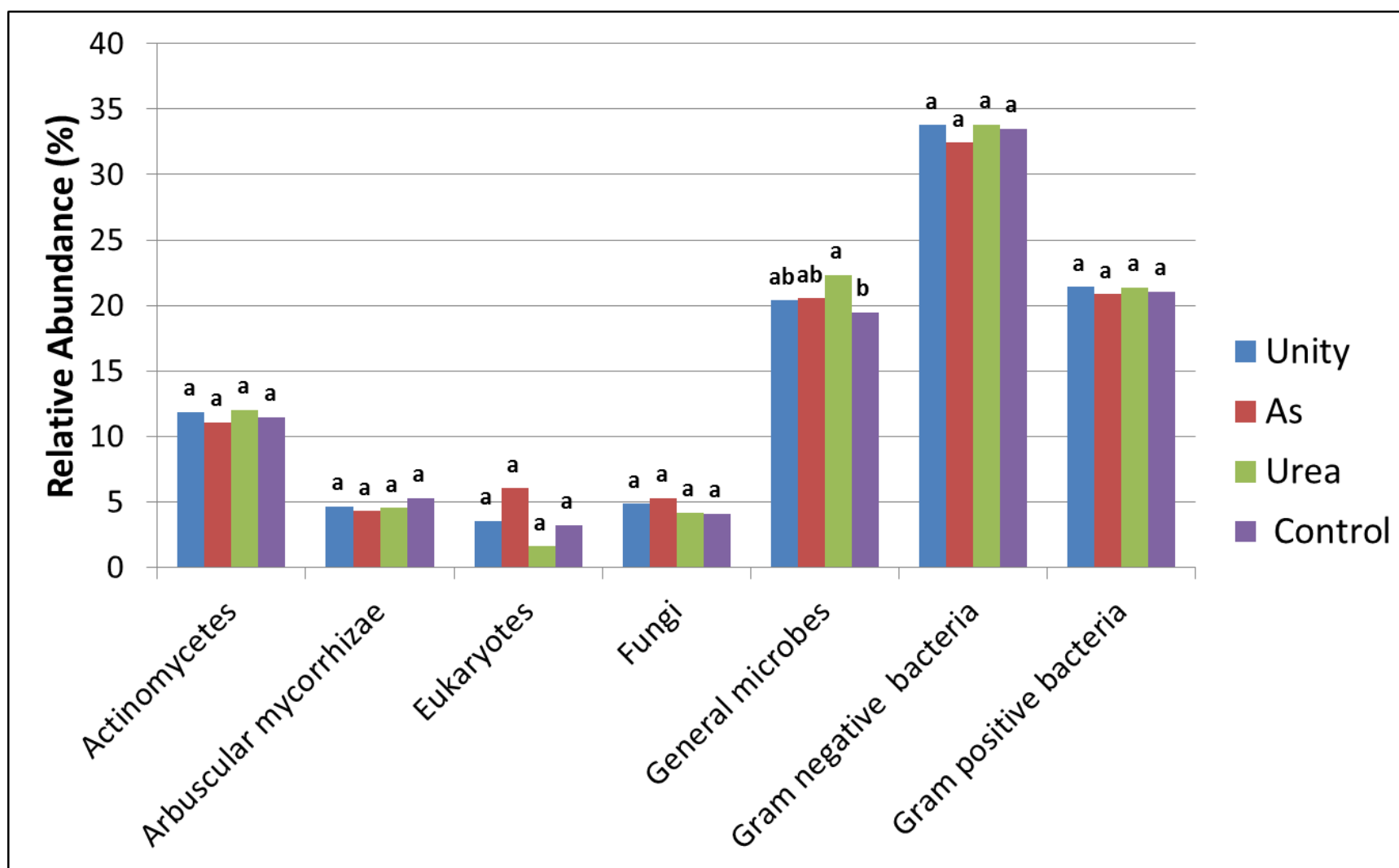


Figure 3.1. Mean relative abundance of soil microbes by fertilizer types after corn harvest at Jackson in 2011. Relative abundances within each microbe classification followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD. Abbreviations: Unity, Unity NPSFe; AS, ammonium sulfate.

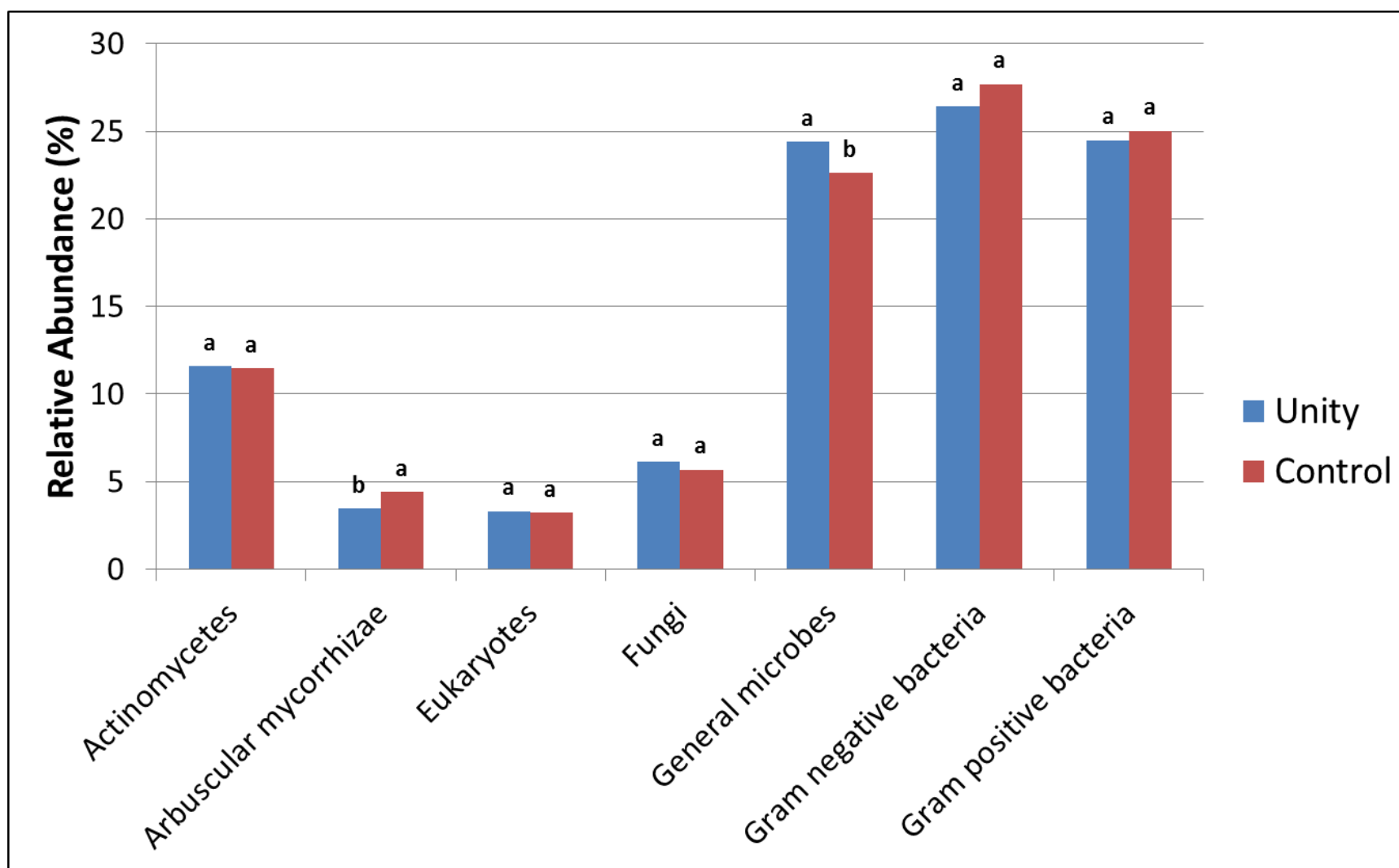


Figure 3.2. Mean relative abundance of soil microbes by fertilizer types at Ames in 2012 to 2013. Relative abundances within each microbe classification followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD. Abbreviation: Unity, Unity NPSFe.

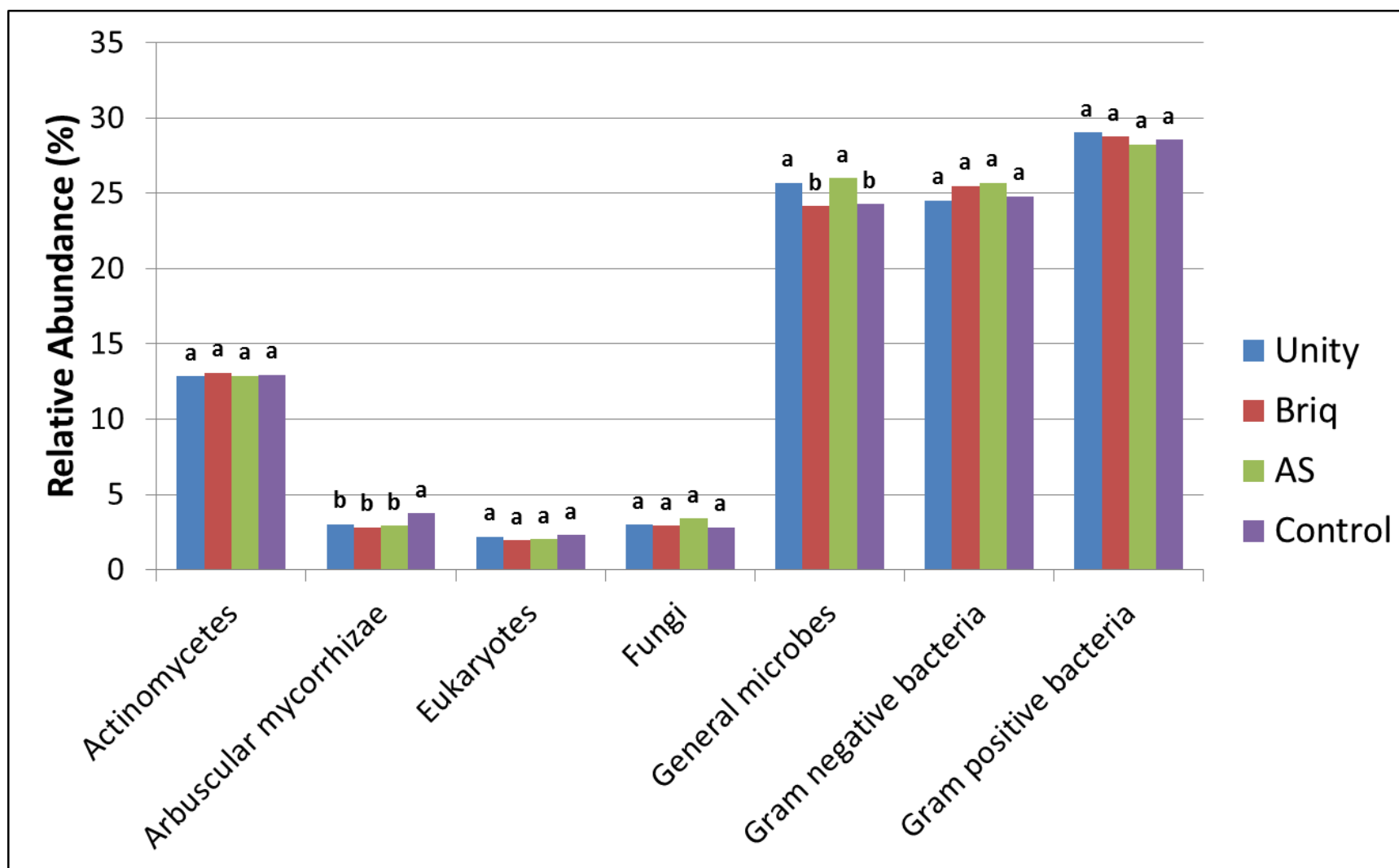


Figure 3.3. Mean relative abundance of soil microbes after corn harvest at Ames in 2013. Relative abundances within each microbe classification followed by the same letter are not significantly different at $P = 0.05$ according to Fisher's protected LSD. Abbreviations: Unity, Unity NPSFe; Briq, NPKZn briquettes; AS, ammonium sulfate.

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH

Conclusions and Future Research

Alternative fertilizers, Unity and the briquettes, were generally comparable to ammonium sulfate and urea. In some instances they performed better than ammonium sulfate and urea, in other cases they were equal, and in still other cases they performed worse. In corn mineral nutrition, Unity sometimes reduced N and P concentrations but increased Zn concentration compared to ammonium sulfate and urea. Plant Fe concentration was not increased by the application of Unity. The briquettes did not consistently improve N, P, K, or Zn concentrations compared to ammonium sulfate and urea. Both Unity and ammonium sulfate resulted in higher plant S concentrations compared with the briquettes and urea. In the soil, Unity consistently increased organic C levels suggesting that given more time, this organic contribution from Unity biofertilizer would have potentially contributed to greater soil health and crop productivity compared to the other fertilizers. The briquettes had lower soil NO_3^- -N levels after harvest suggesting a potential for greater N use efficiency in the briquettes compared to ammonium sulfate and urea. Corn plant growth and yields and ear health were much more impacted by N rates than by fertilizer types. In general, higher N rates performed better from the various measurements, although plateauing was typically observed at N rates greater than 170 kg N ha^{-1} . Between fertilizer types, Unity and ammonium sulfate resulted in stronger plant growth during the early to middle season of corn than the briquettes and urea. Concerning corn grain yield, Unity and the briquettes were at least comparable to ammonium sulfate and urea. The briquettes produced greater corn grain yields than the other fertilizer types under wet soil conditions. Soil microbial community structures were more often affected by fertilizer accumulation in the soil than by fertilizer types. The briquettes increased microbial diversity compared to the other fertilizers, and the eukaryotes benefited from Unity fertilization.

In as much as Unity and the briquettes did not demonstrate consistent superior yields compared to ammonium sulfate and urea, their use in agronomic systems will strongly depend on economics. An economic analysis was not conducted as a part of this research, however, with only 14.9% N, it can be readily discerned that Unity will have to be considerably less expensive than urea (46% N) to be competitive as an N fertilizer. Unity will likewise have to be less expensive than ammonium sulfate (21% N, 24% S) since Unity has less N and S than ammonium

sulfate. In developing countries where the briquettes are intended to be used, the increased amount of labor associated with their application (subterranean banding) makes them less desirable as a fertilizer alternative unless, as with Unity, they can be produced at lower costs compared to other fertilizers. This is unlikely, however, since the briquettes are produced from already commercially available fertilizers and then shaped into briquettes with a briquetter machine which would obviously cost more than fertilizer by itself even if the briquetter machine were to be owned and operated by an agricultural retailer and not the farmer him/herself.

Both Unity and the briquettes had some promising results: higher soil organic C from Unity and lower residual soil NO_3^- -N from the briquettes, but neither of these results translated into better yields and quality of corn or soil health within three years of experimentation. Had the study continued for longer, perhaps Unity and the briquettes would have distinguished themselves as superior fertilizers to the conventional fertilizers ammonium sulfate and urea whereas now they are mainly comparable.

VITA

John H. Winings was born in Oakland County, Michigan in 1981. His family moved to Salt Lake County, Utah when he was two years old and then to Howard County, Maryland when he was five years old, where he was raised for most of his growing-up years. During his senior year in high school, his family moved again this time to Cache County, Utah where he graduated from high school in 1999. He applied and was accepted into Brigham Young University (BYU) where he began his studies in the horticultural sciences during the summer semester of 1999. During his baccalaureate studies, John deferred his academic career for two years to accept a full-time voluntary missionary service assignment from The Church of Jesus Christ of Latter-day Saints. He was assigned to serve in northern Germany from 2000 to 2002. After returning from Germany, John continued his studies at BYU and received his Bachelor's degree in 2005 in Plant Biology with minors in Organic Chemistry and Business Management. After college, John worked in the green industry in northern Utah for a couple of years and then started his own landscape maintenance company in 2007. After successfully running his own business for four years, John decided to sell his company and go back to school to pursue further education in the agricultural sciences. John applied and was accepted to the University of Tennessee Knoxville as a Graduate Research Assistant under Dr. Frank Yin in August 2011. John completed his Master's degree in Crop Sciences with a minor in Statistics in May 2014. John has been married for seven years and he and his wife are the proud parents of two beautiful daughters.