INNOVATIVE FOLIAR MICRONUTRIENT SOURCES IN HIGH-YIELDING CORN ENVIRONMENTS

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THESIS

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ABSTRACT

Under high-yield conditions, adequate nutrient availability often limits corn (*Zea mays* L.) growth and productivity. Nitrogen (N), potassium (K), and boron (B) accumulation mainly occurs before flowering compared to the uptake of phosphorus (P), sulfur (S), and zinc (Zn), which primarily occurs during grain-filling. Increased planting densities and hybrid selection create a high-yield potential in today's modern corn production systems, necessitating greater nutrient supply or efficiency. Limited plant remobilization and translocation of Zn requires greater root accumulation of Zn. Alternatively, peak demand for B occurs immediately prior to pollination and is subsequently remobilized from leaf tissues to developing reproductive organs (ear and tassel) during the initiation of reproductive growth. The objective was to quantify yield responses to foliar B and/or Zn nutrition when used in intensive corn production systems. The experiment was conducted at Champaign, IL in 2014 and 2015. Hybrids were evaluated at planting densities of 79,000, 94,000 and 109,000 plants ha^{-1}. Treatment applications were designed to supply nutrients based on known patterns of nutrient accumulations and included a foliar B application of 72 g ha^{-1} using a chelated B source at V16 and a foliar Zn application of 202 g ha^{-1} using a chelated Zn source at R2 in 2014. In 2015, foliar B and/or Zn applications were made at the V6 and VT growth stages using the same rates as 2014. In no instance did foliar micronutrient applications significantly affect grain yield when averaged across both years. However, foliar Zn applications did significantly increase Zn accumulation by 13% when averaged across all three planting densities. Greatest yields were obtained with the "racehorse" hybrid (versus the "workhorse" hybrid), and higher populations in 2015. In modern corn production, greater planting densities provide the opportunity for increased grain yield and as a result, optimum nutritional management that includes foliar nutrient applications also becomes more important.

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TABLE OF CONTENTS

LITERATURE REVIEW 1
INTRODUCTION 13
MATERIALS AND METHODS 17
RESULTS AND DISCUSSION 23
SUMMARY AND CONCLUSIONS 28
TABLES 30
REFERENCES 42

LITERATURE REVIEW

Corn (*Zea mays*, L.) ranks as one of the most important agricultural crops in the world, with about 177 million hectares devoted to corn production worldwide (USDA, 2016). The United States, which produces over 35 percent of the world's crop, plants about 33 million hectares. Illinois, the second largest corn producing state behind Iowa, produces around 51 million metric tons of corn grain per year. (USDA NASS, 2015). Grain yield potential of corn is twice as high as other cereal crops, which results in a substantial amount of research conducted on corn (Tollenaar and Lee, 2002). In addition to its high yield potential, the corn plant possesses a flexible yield response to various agronomic-management practices. One of the most important factors affecting crop yield is a balanced supply of essential nutrients (Fageria, 2001).

Nutrients and Foliar Fertilization

Essential nutrients are chemical elements that are absolutely needed by plants for their growth and development. The term "essential nutrient" was proposed by Arnon and Stout (1939) using the following criteria: (a) a deficiency of the element makes it impossible for the plant to complete its life cycle; (b) the deficiency is specific for the element as the function of the element is not replaceable by another element; (c) the element is directly involved in the metabolism of the plant. Nutrients involved in plant life cycle processes are often categorized according to their typical nutrient concentration within a plant: structural elements including carbon (C), hydrogen (H), and oxygen (O), and macronutrients such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) are required in the greatest quantities. Micronutrients, such as boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn) are utilized in smaller proportions. Although micronutrients are needed in smaller quantities than macronutrients, they are equally essential for crop growth. Increased interest in micronutrients as limiting factors in crop growth and yield is due to numerous reasons including: today's crop yields requiring larger amounts of these nutrients, long-time cropping systems removing measureable amounts of these nutrients, widespread use of animal manures decreasing, the use of high-analysis fertilizers low in nutrient impurities increasing, topsoil being removed through erosion, land leveling, or terrace construction resulting in deficiency of certain micronutrients, and variability of nutrients across fields being recognized alongside the technology to manage variability continually developing (Bell and Dell, 2008). Of all the micronutrients, B and Zn are usually the most limiting for crop growth and yield (Aref, 2010).

The necessity of B for the growth of corn plants was first mentioned by Maze (1914) in France. However, it was the work of Warington (1923) in England that provided firm knowledge of the B requirement for a variety of crops. Boron plays an important role in cell wall structure, lignifications, photosynthesis, accumulation of carbohydrates, cell wall synthesis, vegetative growth and retention of flowers and fruits, phenol and indole acetic acid metabolism as well as membrane transportation; whereas its deficiency leads to browning of plant tissues along with stunting of young plants (Takano et al., 2007; Miwa et al., 2008; Dordas et al., 2007). Plant roots come in contact with B primarily through mass flow, while movement within the plant is regulated by transpiration through the xylem (Raven, 1980). Boron is relatively immobile in plants, and thus its availability is essential at all stages of growth. The portion of a nutrient residing in the soil that can be readily absorbed by plants is referred to as nutrient "availability" (Tiller, 1983). Many factors and conditions affect the availability of B in the soil including: parent material, texture, nature of clay minerals, pH, liming, organic matter content, interrelationship with other elements, and environmental conditions like heavy rainfall, dry weather, and high light intensity (Gupta, 1979). Of these factors, soil pH, organic matter content, and weather conditions play the biggest role in the availability of B in the soil. Boron availability is greatly reduced at higher pH (Gupta, 1979). Organic matter is the storehouse for most nutrients in the soil and is known to improve the availability of plant nutrients; thus crops grown in soils high in organic matter typically do not show B deficiencies. Because of boron's non-ionic nature, under heavy rainfall condition, B can be easily leached from the soil (Gupta and Cutcliffe, 1978). Similar reduced availability of B has been documented under drought conditions whereby mobility of B via mass flow through the soil to roots is reduced (Chang, 1993; Barber, 1995). The concentration of B within a plant also effects yield, as excess B can be toxic while insufficient amounts can be detrimental to yield (Smit and Combrink, 2004; Ben-Gal and Shani, 2002; Davis et al., 2003). Since a narrow range exists between plant deficiency and toxicity, careful attention needs to be used when managing B in soils (Byers et al., 2001).

Besides B, among the essential micronutrient elements for plants, Zn has received the most global attention due to numerous reports of deficiency problems (Hotz and Brown, 2004). Research has shown that if a given crop responds with positive growth to an applied nutrient, that nutrient was deficient for the crop (Fageria and Baligar, 2005). Zinc availability to plants can be affected by factors such as total soil Zn content, soil pH, organic matter, soil temperature and moisture regimes, root distribution, and rhizosphere effects (Alloway, 2004). Zinc availability is most affected by soil pH, as increasing soil pH stimulates zinc adsorption to the surfaces of various soil components, such as metal oxides and clay minerals; resulting in decreased solubility and availability (Bruemmer et al., 1988; Barrow, 1993). Zinc primarily enters the plant via absorption of Zn^{2+} from the soil solution by the roots. Diffusion is the main mechanism in which Zn is transported to the roots (Barber and Silberbush, 1984). However, when Zn concentration in the soil solution is high, mass flow becomes the dominant mechanism bringing zinc to the root surface (Barber, 1995). Once in the plant, Zn plays a key role as a structural constituent or regulatory co-factor of a wide range of different enzymes and proteins in many important biochemical pathways relating to: carbohydrate metabolism, both in photosynthesis and in the conversion of sugars to starch, protein metabolism, auxin metabolism, pollen formation, the maintenance of the integrity of biological membranes, and the resistance to infection by certain pathogens (Alloway, 2004). Optimal Zn levels within the plant are critical in order to help regulate these important functions and to maximize crop potential.

One way to circumvent soil availability issues is through foliar fertilization, or supplying nutrients to the plant through their leaves. The ability of plant leaves to absorb water and nutrients was recognized approximately three centuries ago (Fernández and Eichert, 2009). However, foliar nutrition was not fully understood until the first half of the 20th century with the emergence of fluorescent and radio-labelling techniques. These techniques made it possible to develop accurate methods to investigate the mechanisms of leaf cuticular penetration and translocation within the plant following foliar application of nutrient solutions (Fernández and Eichert, 2009; Fernández et al. 2009; Kannan, 2010). Interest in foliar fertilization by producers is rising because of the development of highly concentrated soluble fertilizers and the increasing use of machinery for spraying fungicides, herbicides, and insecticides along with overhead irrigation that facilitate the application of nutrients to crops in the form of sprays. Variable and inconsistent field crop responses to foliar- applied nutrients have been documented, ranging from significant yield increases to no effect (Barraclough and Haynes, 1995; Freeborn et al., 2001; Haq and Mallarino, 2005; Ma et al., 2004; Ma et al., 1998; Mallarino et al., 2001; Schreiner, 2010; Seymour and Brennan, 1995; Tomar et al., 1988), and sometimes negative effects (Bremner, 1995; Fageria et al., 2009; Kaya and Higgs, 2002; Phillips and Mullins, 2004). Typically, negative effects from foliar fertilization can be attributed to leaf burning from excess salts or nutrient toxicity. Even with the variable and inconsistent results, there is general agreement that foliar application of fertilizer is not intended to replace soil- applied nutrients but rather supplement soil fertility management (Fritz, 1977).

The uptake mechanisms of foliar- applied nutrients have been studied to a great extent. Green leaves are organs with a vital function of using sunlight, carbon dioxide, and water to synthesize carbohydrate energy through photosynthesis. However, there is evidence that absorption of inorganic and organic materials can also take place through the surfaces of leaves (Franke, 1967). As described by Franke (1967), substances applied to the leaf surface penetrate the cuticle and the cellulose wall by diffusion. These substances, having penetrated the free space, are then adsorbed to the surface of the plasma membrane and are moved into the cytoplasm using metabolically derived energy. The absorption of nutrient solutions by plant surfaces may also occur through cuticular cracks and imperfections and through the stomata (Eichert et al., 1998; Eichert and Burkhardt, 2001). Several requisites must be met in order to produce a positive effect from foliar nutrition including: the applied nutrients must be in the available form for leaf absorption, reach the target organ, penetrate the cuticle, and be transportable to the target tissues if different from the intercepted organ (Alexander, 1986). There are many factors that influence the uptake of foliar- applied nutrients. Environmental conditions play the largest role in the effectiveness of foliar fertilization. Ideal conditions to apply foliar nutrients include moderate temperatures to reduce the risk of leaf burn and the leaf stomata should be open (Fageria et al., 2009). Similar to pesticide applications using spray solutions, windy days should also be avoided as drift can occur. Foliar- applied nutrients take 3 to 4 hours to be absorbed by plant foliage, therefore, applications should be avoided if rain is possible during that timeframe (Fageria et al., 2009). Another condition for optimal effectiveness of foliar nutrient application is that the plant is cool and turgid (Girma et al. 2007). When the plant is actively growing and not water stressed, foliar fertilization is most effective (Denelan, 1988). After foliar uptake, translocation takes place as the nutrients move from the leaves to where they are used or stored. Nutrients move toward the center of the leaf to the vascular tissue via the symplastic and/or apoplastic pathways, transported through the phloem with photosynthetic assimilates (Wittwer and Teubner, 1959). The effectiveness of the nutrient applications depends on phloem mobility within the plant to the target tissues. Phloem mobility depends on the ability of the nutrient to enter the phloem, move within the phloem, and move out of the phloem to the target tissues. Phloem- mobile nutrients are not only effective in the leaves where the absorption process takes place, but also may benefit other plant organs, such as reproductive structures, as these nutrients can move to all areas of the plant (Fernández et al., 2013).

Until the 1970's, inorganic compounds, such as sulfates, dominated the foliar micronutrient fertilizer market (Moran, 2004). During the 1980's, chelated forms like ethylenediaminetetraacetic acid (EDTA) and other acidified compounds, such as, polyphenolic acid, lignosulfonate, citric acid, amino acids, etc, were offered as foliar fertilizer alternatives to inorganic compounds (Fernández et al., 2013). A chelate is an organic compound which combines with and protects from precipitation certain metallic cations such as iron, manganese, zinc, and copper. The word chelate derives from a Greek word 'chel', meaning a crab's claw, and refers to the pincer-like manner in which the mineral is bound (Wallace and Wallace, 1983). Chelation occurs when large molecules form multiple bonds with a micronutrient, protecting it from reacting with other elements and increasing its availability to the plant. Chelates of foliar nutrients cause fewer phytotoxicity problems than inorganic sources because chelation favors the penetration of nutrients rather than the nutrients sitting on the leaves for long periods of time (Finck, 1979; Basiouny and Biggs, 1976). Soluble sources of foliar nutrients are more efficient at correcting nutrient deficiencies compared to insoluble or slightly soluble sources. Chelates are more soluble and compatible with a wide range of pesticides compared to inorganic sources, resulting in a lower chance to cause crop scorch (Alexander and Schroeder, 1987). In addition, chelated sources of micronutrients are more efficiently absorbed compared to non-chelated sources. However, chelated sources are more expensive, which may make them cost prohibitive to many farmers.

There are many advantages and disadvantages to foliar fertilization. Applying nutrients directly to the leaves provides for more rapid utilization of the nutrients and permits the correction of observed deficiencies in less time than would be required by soil application. Responses to foliar applications of nutrients can often be observed within 3 to 4 days under favorable climatic conditions. On the other hand, visible crop responses to soil- applied nutrients takes 5 to 6 days (Fageria et al., 2009). A disadvantage of foliar fertilization is that, unlike soil- applied nutrients that can leave a lasting residue effect on the soil, foliar- applied nutrients do not contribute to a residual buildup in the soil. An example would be in the case of a severe nutrient deficiency, where several foliar applications are usually necessary to compared to a single larger application of soil fertilizer. Due to the large quantity of macronutrients required for plant growth, foliar fertilization with these nutrients would be insufficient to meet plant needs, or economically impractical. However, the smaller quantities of micronutrients essential for plant growth can be easily provided with foliar fertilization, and these nutrients tend to be applied more uniformly through foliar applications compared to soil applications (Mengel, 2001). In addition, foliar application tends to be more effective then soil fertilizer applications for some of the immobilized nutrients in the soil, such as Zn, Fe, and Cu. Another advantage of foliar fertilization is the opportunity for farmers to tank mix and apply them with other agrochemicals, allowing savings in labor, machinery, and energy costs (Gooding and Davies, 1992). In some cases, tank mixes of nutrients and agrochemicals have been shown to have a synergistic effect on plant growth (Alexander and Schroeder, 1987).

Optimizing nutrient management uses the 4R approach: the right source, at the right rate, right time, and right place (Bruulsema et al., 2012). Each of the 4Rs can be easily implemented with foliar fertilization, with some decisions being easier and more researched compared to others. The right place is applying to the foliage compared to soil fertilization, while the right source is decided between chelated and non-chelated forms along with chemical formulations. The right rate is highly variable depending on the crop stage, tissue tests, field conditions, and production practices. The biggest decision to make is the right time aspect of the 4R approach as supplying nutrients when then are needed is critical to effective foliar fertilization.

As part of the 4R approach, the right time focuses on supplying nutrients during critical crop growth stages throughout the season. The most common staging system for corn divides plant development into vegetative (V) and reproductive (R) stages (Abendroth, 2011). Because the system defines development on individual plants, when staging in the field, each specific V or R stage is defined as when 50% or more of the plants are in or beyond that stage. For vegetative growth, each stage is defined according to the uppermost leaf with a visible collar. The collar is the area where the leaf blade and the leaf sheath meet. Tasseling (VT) is the stage where the corn plant is completing its vegetative growth and reproductive growth begins. The reproductive stages are concerned with development of the kernel and its parts, with kernels from the middle of the ear used to judge the stage (Abendroth, 2011). Nutrients vary in the tissues to which they are partitioned as well as the timing, rate, and duration of uptake. Applying the right source at the right rate and right time is the key to optimizing fertility practices by matching in-season plant nutrient uptake. Bender et al. (2013), using modern corn hybrids, determined that the maximum rate of nutrient uptake coincided with the greatest period of dry matter accumulation during vegetative growth for all observed nutrients. The majority of corn N, K, and B accumulation in corn occurs before flowering compared to the uptake of P, S, and Zn, which primarily occurs during grain-filling (Bender et al, 2013). Unlike N, P, K, and S, which have a sigmoidal (S-shaped) or a relatively constant rate of nutrient uptake, micronutrients frequently exhibit more intricate uptake patterns. Zinc and B, for example, begin with a sigmoidal uptake pattern in the early vegetative stages and plateau at VT/R1 (Bender et al, 2013). Thereafter, Zn exhibits a sharp increase in demand as it binds to the phytate of developing grain tissues (Bender et al, 2013). Limited plant remobilization and translocation of Zn requires greater root accumulation of Zn in the absence of supplemental foliar nutrition. Alternatively, peak demand for B occurs immediately prior to pollination and is subsequently remobilized from leaf tissues to developing reproductive organs (ear and tassel) during the initiation of reproductive growth (Bender et al, 2013). Fertilizer sources that supply nutrients at the rate and time that match corn nutritional needs are critical for optimizing nutrient use and yield.

Research focusing on foliar fertilization of B and Zn has been extensive in vegetables, fruits, and nuts; however, experimentation on corn production is limited. Recently, work has been done in Missouri by Kaur and Nelson (2014) applying foliar B to corn at two different growth stages, early season (V4-V6) and mid-season (VT). Results from that trial showed that applying foliar B at the highest application rate early in the growing season produced yields significantly greater than applications at mid-season. Additionally, foliar B applications at VT increased ear leaf tissue B concentration compared to the non-treated control but had no significant effect on corn yields. This data indicates that supplying the plant with extra B early in season is more beneficial than foliar applications made during other critical growth stages. Similar findings were observed when foliar Zn was applied to corn plants during various growth stages to determine critical times of high zinc accumulation (Grzebisz, et al., 2008). They found that rapid Zn accumulation occurs early in the growing season from V7 to V9, and to a lesser extent, during tasseling and again at the maximum grain fill stage known as milking (Grzebisz et al., 2008). Plants in that study also grew and yielded more in response to foliar Zn applications, even when the Zn tissue concentration measurements suggested the plants initially had an adequate amount. These results suggest that soil and plant tests may not be calibrated to today's hybrids and that corn crop requirements for Zn are much greater and more sophisticated than those currently recommended to farmers. Supporting this view, Potarzycki and Grzebisz (2009) applied foliar Zn early in the growing season (at V5) and found an 18% yield increase when averaged over three years. These early foliar Zn applications led to increases in the number of kernels per plant as the main yield component factor contributing to the increase in yield (Potarzycki and Grzebisz, 2009). Hence, the physiological role of zinc may be related to a potential increase of the number of viable ovules per cob, which is a component of kernel sink size during grain filling.

Planting Density and Hybrid

The average U.S. corn grain yield has increased steadily over the past 50 years from 4.6 Mg ha^{-1} in 1965 to 10.6 Mg ha^{-1} in today's modern corn production systems (USDA NASS, 1965; USDA NASS, 2015). Advancements in plant breeding and changes in cultural practices are responsible for the yield gains (Duvick, 2005). Of the cultural practices, planting density has played the largest role in the increase of grain yield intensifying from 37,000 plants ha^{-1} to 79,000 plants ha^{-1} in 1965 to 2015, respectively (USDA NASS, 1965; USDA NASS, 2015). Cultivation has changed from minimal fertilizer inputs and low population densities to intensive fertilization and denser populations (York et al., 2015). Corn grain yield is often limited at lower planting populations by having too few plants, while at higher planting populations, kernel abortion and barren stalks can limit yield (Hashemi et al, 2005). Seeding rate acts as a key factor in regulating plant competition and optimal plant densities are important for efficient agronomic production (Jiang et al, 2013). Plants compete above-ground for better light interception using canopy structure, but more importantly, plants compete with each other underground for nutrients, water, and root space (Casper and Jackson, 1997). There are two ways neighboring roots interact: first roots exude toxic substances that cause non-specific inhibitory effects on root development, and secondly, genetically identical plants may use non-toxic chemical signals that affect the roots of neighbors (Schenk et al., 1999). Plants have been found to have less root biomass when spaced closer together (Jiang et al., 2013). Larger root systems associated with low planting densities allow plant roots to better explore the soil profile and acquire nutrients in the soil solution. In contrast, higher planting populations tend to decrease individual plant root volume, and may limit the ability to accumulate nutrients even in soils with nutrient test levels considered 'adequate' (Caassen and Barber, 1976). Attention to nutritional management under these intensive growing conditions may be necessary.

Since the introduction of double cross hybrids in the 1930's and single crossed hybrids in the 1960's, corn grain yield has increased drastically at nearly 0.13 Mg ha^{-1} per year (Crow, 1998). Stress tolerance, pest resistance, and herbicide resistance are responsible for the vast yield improvement of today's modern hybrids. Plant breeding has created high genetic diversity in the hybrids that farmers plant each year as hybrids vary in relative maturity, genetic traits, tolerance to pests, leaf orientation, root system, standability, etc. The largest difference between hybrids is their response to environmental conditions and cultural practices, such as soil type, tillage, crop rotation, plant population, and soil fertility. Previous hybrid characterization studies have demonstrated variation in corn germplasm response to management (Sprague and Eberhart, 1977; Hallauer et al., 1981; Castleberry et al., 1984; Sabata and Mason, 1992; Duncan, 1954). The amount of nutrients taken up by a corn plant also differs amongst hybrids (Bender et al., 2013). The agriculture industry, in particular seed agronomists, generally characterize hybrids as "offensive/defensive", "fix/flex", or "racehorse/workhorse" (Lauer and Hicks, 2005). "Workhorse" hybrids typically produce good yields over a wide range of soil and weather conditions and are usually able to tolerate lower fertility (e.g. they have high yield under minimal fertility and generally exhibit a large initial response to increases in fertility). On the other hand, hybrids that have an above- average increase in yield in response to intensified crop management (increased fertility and population) are generally referred to as "racehorse" hybrids.

As planting densities increase and root mass size decreases, sound nutritional management becomes challenging. Innovative management strategies are becoming more adopted in the agricultural industry as farmers continue to aim for higher yields. Foliar fertilization is a potential management strategy to supplement the nutritional needs of corn grown in high-yield environments.

INTRODUCTION

The world of agriculture is changing. Farmers today live in a world where environmental concerns and increased demand for food are creating challenges never seen before. With world population projected to reach 9.7 billion people by the year 2050 (United Nations, 2015), food security will continue to grow as a major concern throughout the world. By 2050, agricultural production will need to increase by nearly 70 percent in order to meet the nutritional needs of a growing world population (FAO, IFAD, WFP, 2015). It is projected that 90 percent of this growth in crop production would come from greater yields and increased crop intensity, with the remainder coming from land expansion (Bruinsma, 2009). In particular, corn (*Zea mays* L.) production is expected to increase by 57 percent with the majority of the production increase coming from greater yields (FAO, IFAD, WFP, 2015). Genetic and biotech seed industries continue to produce higher-yielding hybrids every year. However, to optimize the yields of these advanced crops, fertilizer inputs must be enhanced to provide the greatest potential for success.

Regulatory pressures to limit the use of fertilizers is increasing due to numerous accounts of nutrient runoff causing harm to the environment (Hochmuth et al., 2011). High levels of nitrate in the Gulf of Mexico has been traced back to agriculture (Burkart and James, 1999). In California, where half of the country's vegetables are grown, there are about 120 water sources classified as containing "excessive nutrients" (Kannan, 2010). Increases in algae due to higher levels of nutrient concentrations in Lake Erie have been causing problems to the surrounding ecosystem. In addition, the Environmental Protective Agency (EPA) has named agriculture responsible for nearly half of the nitrogen and phosphorus being delivered into the Chesapeake Bay (Pionke et al., 2000). Legislative, regulatory and non-government organization activities, including legal action pertaining to nutrients in the environment, are taking place on national, regional, state and local levels to combat the potential causes of these problems. However, fertilizer is a necessary component of sustainable crop production systems. Furthermore, the fertilizer industry recognizes the need to efficiently utilize these nutrients, and the need of science-based information for stakeholders to use for education, advocacy, and implementation of crop nutrient stewardship, such as the 4R principles.

Foliar fertilization is the liquid spray application of one or more mineral nutrients to plant leaves to supplement traditional soil applications of fertilizers. Foliar fertilization is a more efficient method of fertilization than soil applications and has been advocated as a viable economic way to supplement the plants' nutrients (Girma et al., 2007). Through foliar fertilization, nutrients are delivered directly to the target organs during critical periods of rapid uptake creating little opportunity for their runoff and waste. Generally, foliar applications cause less environmental impact than most soil-applied fertilizers, as the risk of soil or water contamination is minimized with foliar fertilization (Fernández et al., 2013). Currently, there are no specific regulations governing foliar fertilizers. While the environmental advantages of foliar fertilization are clear, crop growth and yield benefits are still uncertain. Research conducted on various crops show how foliar nutrient sprays can be an effective way to correct micronutrient deficiencies, which sometimes results in higher yields and better crop quality (Asad et al., 2003; Perveen, 2000). Negative effects from foliar fertilization are typically associated with leaf burn or toxicity. Environmental conditions (relative humidity, temperature, precipitation, and light intensity) and cultural practices can create conditions for optimal foliar fertilization benefits. Foliar- applied nutrients are most beneficial when plant demand for nutrients exceeds the capacity for root nutrient uptake.

Planting population and hybrid selection influence the nutritional demand of a corn crop. Hybrid selection and greater planting densities provide the foundation for high grain yield levels, although subsequent agronomic management is required to maximize that yield potential. Hybrids classified as “workhorse” hybrids are less responsive to intensified management and contain similar yield potential over a wide range of environmental and cultural conditions. In contrast, “racehorse” hybrids are more responsive to intensive management and have a higher yield potential with increased management. However, when optimal management is not provided, yield can decrease. In order to maintain a high-yield potential, sound nutritional management is necessary.

Among micronutrients, Zn and B play key roles in pollination and seed set processes; whereby their deficiency can reduce seed formation and subsequent yield (Ziaeyan and Rajaie, 2009). Matching corn micronutrient requirements in high-yielding conditions necessitates supplying sufficient nutrients when the crop needs them most. Agronomic effectiveness of a micronutrient is defined as the degree of positive crop yield response per unit of applied micronutrient. Therefore, lower application rates of more effective nutrient sources are needed to produce maximum yield response. Chelated sources have been documented to be more effective than non-chelated sources of micronutrients (Mortvedt, 1991). Albion Plant Nutrition (Albion Plant Nutrition, Clearfield, UT) developed an innovative foliar source for micronutrients using an amino-acid chelate known as Metalosate®. Although chelated micronutrients are protected against some chemical reactions, these forms of the mineral elements are assimilated fairly readily by growing plants. A study conducted by Wallace and Wallace (1983) found a significant increase in tissue concentration of various micronutrients applied to the foliage using the Metalosate technology in wheat, but inconsistent results were found in corn. In both cases, yield was not significantly affected by the foliar application of B, Cu, Fe, Mn, and Zn, however, no deficiencies of these nutrients were observed either before or after foliar applications.

As high-yielding hybrids mine the soil more than ever and planting densities continue to increase, the importance of sound nutritional management becomes even greater. The use of foliar fertilization in field crops is continuing to expand as a way to supplement the nutritional needs of the crop in- season. In order to pinpoint conditions most conducive to optimizing foliar nutrition in corn, experiments were conducted over two years evaluating foliar fertilization in high-yield potential environments. The objective of this research was to evaluate the impact of different combinations and application times of foliar Zn and/or B on corn biomass and nutrient accumulation, and grain yield when grown in intensive production systems. The hypothesis of this research was that timely applications of foliar micronutrients during critical growth stages of rapid nutrient accumulation would result in greater corn productivity. The results of this research could provide corn producers with a valuable guide describing which environmental conditions and cultural practices provide the best opportunity to maximize corn grain yield using foliar fertilization as a complementary tool to soil- applied nutrients.

MATERIALS AND METHODS

Location

This experiment was conducted at the Crop Science Research and Education Center (CSREC) (40° 3'38"N, 88°13'49"W) in 2014 and 2015 near Champaign, IL. The 2014 field was tile drained and water was provided by rainfall. The 2015 field was tile drained with a subsurface drip irrigation system used to supply adequate amounts of water throughout the growing season to prevent any drought stress (Table 1). The fields were within close proximity to each other, approximately 2.5 km apart. Field Connect moisture probes (John Deere, Moline, IL) were used to detect when soil moisture dropped below 50 % field capacity, then subsequently the subsurface drip irrigation was used to supply enough water to approach field capacity across all plots. The soils in Champaign in both years were level (0-2% slope) and classified as highly productive Drummer silt clay loam and Flanagan silt clay loam. A composite soil sample of the site was taken from 0-15 cm depth before planting each year. Soil test results using Mehich-3 extraction were: 3.5% organic matter; 16.0 meq/100g CEC, 5.7 pH, 23 ppm P, 95 ppm K, 0.9 ppm Zn, and 0.3 ppm B for 2014, and 3.6% organic matter; 22.4 meq/100g CEC, 6.1 pH, 15 ppm P, 136 ppm K, 1.3 ppm Zn, and 0.7 ppm B for 2015. All trials had soybean (*Glycine max*) as the previous crop in a corn-soybean rotation. Soil preparation consisted of a fall chisel plow pass followed by two field cultivations in the spring. A nitrogen rate of 202 kg nitrogen ha^{-1} was applied pre-plant as urea ammonium nitrate (32-0-0) in both 2014 and 2015. Due to abundant precipitation during vegetative growth in 2015, a sidedress of 67 kg nitrogen ha^{-1} as urea (46-0-0) was applied at the V4 growth stage.

Experimental Design

The experiment in 2014 involved two different treatment factors: planting density and foliar applications (Table 2). Treatments were arranged in a randomized complete block experimental design with six replications. Each experimental unit consisted of plots four rows wide and 11.43 m in length with 0.76 m row spacing. Three plant densities (79,000, 93,800, and 108,600 plants ha^{-1}) were selected to represent a range of average (79,000 plants ha^{-1}), above-average (93,800 plants ha^{-1}), and extreme (108,600 plants ha^{-1}) densities for Illinois. Treatment applications were designed to supply B and Zn based on known patterns of nutrient accumulation and are outlined in Table 2. The study evaluated the amino-acid chelate technology (Metalosate) developed by Albion Plant Nutrition for in-season supply of boron and zinc. Foliar applications of Metalosate B and Metalosate Zn were applied with a CO_2 pressurized backpack sprayer using a 140 L ha^{-1} application rate on 10 July (VT) and 28 July (R2), respectively. The boom was approximately 1.5 m in width with nozzles spaced 0.5 m apart. Flat fan nozzles (TeeJet XR1102) with 110^{o} spray pattern were used. A population tolerant hybrid (DKC63-33 GENSS) was selected based on its high-yield potential for the location. A use rate of 1.2 L $ha^{-1}$for Metalosate B and 2.4 L ha^{-1} for Metalosate Zn was applied supplying 72 g ha^{-1} and 202 g ha^{-1} of B and Zn, respectively. No surfactant was included in the foliar application.

The experiment in 2015 was modified based on 2014 results to evaluate different characterized hybrids along with additional foliar application timings and combinations. This experiment involved three different treatment factors: hybrid, planting density, and foliar application (nutrients and timing) (Table 3). Treatments were arranged in a split-split experimental plot design with hybrid being the whole plot and planting density being the subplot. Each split plot was divided into split-split plots with foliar treatment being randomly assigned to each split-split plot. This design was replicated five times. Each experimental unit consisted of plots four rows wide and 5.33 m in length with 0.76 m row spacing. The same three planting densities were used as in 2014 (79,000, 93,000 and 108,600 plants ha^{-1}). Treatment applications were altered to evaluate the theory of supplementing the plant early in the growing season (V6) with surplus B and/or Zn to provide a reserve that could supply the nutritional needs throughout the growing season (Table 3). Mid-season applications at VT along with multiple applications of B and/or Zn were also evaluated. Foliar applications of Metalosate B and Metalosate Zn were applied with a CO_2 pressurized backpack sprayer using a 140 L ha^{-1} application rate on 1 June (V6) and/or 30 June (VT), respectively. Application rates of 1.2 L ha^{-1} Metalosate B (supplying 72 g B ha^{-1}) and 2.4 L ha^{-1} Metalosate Zn (supplying 202 g Zn ha^{-1}) were used with no surfactant included. A corn hybrid responsive to management, i.e. racehorse-type, (DKC64-87 GENSS) and the same population tolerant hybrid (DKC63-33 GENSS), i.e. workhorse- type, from 2014 were evaluated in this experiment.

Agronomic Management

An ALMACO SeedPro 360 planter (ALMACO, Nevada, IA), equipped with variable seeding rate technology, was used to plant plots on 8 May and 24 April for 2014 and 2015, respectively. The pre-emergence herbicide was S-metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide] +atrazine (1-Chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine) + mesotrione (2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione), commonly known as Lumax (Syngenta AG, Basel, Switzerland), applied at a rate of 7.0 L ha^{-1}. Post emergence weed control was obtained with an application of glyphosate (N-

(phosphonomethyl) glycine, in the form of its trimethylsulfonium salt) as Touchdown (Syngenta AG, Basel, Switzerland) at a rate 2.6 L ha^{-1}.

Plant Sampling and Nutrient Uptake

To evaluate seasonal biomass and nutrient accumulation in 2014, six plants were manually excised at the soil surface seven days after the last foliar application (R2 + 7 days). The total fresh weights (TFW) of the whole plants were measured. Samples were chipped (Vermeer BC600XL Chipper, Vermeer Corporation, Pella, IA) to obtain a representative subsample which was used to determine subsample tissue % moisture content (% MC), fresh weight (FW), and dry weight (DW). Subsamples were dried to a constant weight at 75 ^{o}C before weighing. Percent moisture content was determined according to Equation 1.

$$\%\,MC = \left(\frac{FW - DW}{FW}\right) \times 100 \qquad (1)$$

Equation 2 was used to estimate total dry weight (TDW) using subsample % moisture content (%MC).

$$TDW = \frac{TFW - \left(TFW\ \times \frac{\%MC}{100}\right)}{Number\ of\ Plants\ Sampled} \qquad (2)$$

Dried subsamples were ground using a Wiley Mill (Thomas Scientific, Swedesboro, NJ) to pass through a 2 mm mesh screen. An approximate 50 mg subsample was randomly selected for nutrient concentration analysis. Subsamples were analyzed for B and Zn (A & L Great Lakes Laboratories, Inc., Fort Wayne, IN) using a two-part process of acid-microwave digestion and Inductively Coupled Plasma (ICP) analysis. Micronutrient concentrations were reported as micrograms per kilogram dry weight (µg kg^{-1}). Total aboveground biomass is expressed on a dry weight per hectare basis and was derived algebraically from biomass per plant and stand counts. Total aboveground biomass and nutrient concentrations were used to calculate the total aboveground nutrient uptake seven days after the R2 growth stage. Equation 3 was used to calculate B and Zn nutrient contents.

$$Biomass\ Micronutrient\ Content\ (g\ ha^{-1}) =$$

$$Biomass(Mg\ ha^{-1})\ \times\ Micronutrient\ Concentration(\mu g\ g^{-1}) \qquad 3)$$

Grain Yield

Prior to harvest, stand counts were enumerated each year to assess emergence issues and to identify any planting anomalies that may have taken place. The middle two rows of each plot were harvested with an ALMACO SPC-40 combine (ALMACO, Nevada, IA) on 20 October and 30 September in 2014 and 2015, respectively. The combine is equipped with HarvestMaster's graingauge system (Juniper Systems, Logan, UT) to provide grain weights and moistures directly to an in-cab mounted field computer (Allegro MX). A subsample of grain from each plot was collected from the combine at harvest. These subsamples were subsequently cleaned of debris and broken grain, and then 300 kernels were mechanically counted (Old Mill 850-2, San Antonio, TX) and weighed to determine average individual kernel weight. Kernel number (KN) per plot was calculated using total plot grain weight and individual kernel weight (KW) according to Equation 4.

$$KN = \frac{Total\ Plot\ Grain\ Weight}{KW} \qquad (4)$$

Individual kernel weight and grain yield are both presented at 0% moisture. Grain subsamples from each plot were also analyzed for grain quality (protein, starch, and oil concentration) using near-infrared transmittance spectroscopy (Infratec 1241 Grain Analyzer; FOSS).

Statistical Analysis

Statistical analysis for grain yield, yield components, grain quality, plant biomass, nutrient concentration, and nutrient uptake data was performed using PROC MIXED of SAS (SAS 9.4; SAS Institute Incorporated, Cary, NC) with the assumption of equal variances. Experimental designs between 2014 and 2015 were not consistent, and as a result, data were analyzed separately for each year. Significance was declared at $P \leq 0.10$.

In 2014, the experiment was set up as a randomized complete block design. Planting density and foliar treatment were included in the model as fixed effects, and replication as a random effect. Normality of residuals and potential outliers were assessed using PROC UNIVARIATE.

In 2015, the experiment was set up as a split-split plot design. Hybrid, planting density and foliar treatment were included in the model as fixed effects, and replication and its interactions with fixed effects were included as random effects.

RESULTS AND DISCUSSION

Weather

Weather conditions in Champaign during 2014 and 2015 resulted in relatively average temperatures with above-average precipitation (Table 4). During the growing season, Champaign experienced precipitation 14.1 cm and 20.4 cm above the 20-year average during 2014 and 2015, respectively (Table 4). In 2014, above-average precipitation in June during vegetative growth was followed by more increased precipitation and cooler temperatures in July during pollination and early grain-fill (Table 4). The increase in cloud cover during June and July likely decreased photosynthetic activity within the plants from late vegetative to early grain- fill, resulting in decreased yield potential from less kernel set in 2014 (Reed et al., 1988). Afterwards, during the middle to late grain-fill growth stages, plants experienced limited precipitation. In 2015, precipitation in the month of June was well above-average followed by near-normal precipitation and temperatures in July and August (Table 4). There were no planting issues and overall weather in 2014 and 2015 provided relatively good growing conditions resulting in little weather-induced heat or moisture stress.

Grain Yield, Plant Biomass, and Nutrient Uptake

The overall grain yield for Champaign in 2014, when averaged over all the populations and treatments was 12.5 Mg ha^{-1}. The Analysis of Variance (ANOVA) showed no significant effects of treatment or population on grain yield (Table 5). Contrary to what was expected, increasing planting population above the currently common 79,000 plants ha^{-1} did not increase yield in 2014 (Table 5). These results contradict what Stanger and Lauer (2006) found, as their yield increased with greater planting densities and maximum yields were achieved at densities exceeding 100,000 plants ha^{-1}. Given the high amount of rainfall throughout the growing season, it is likely that there was an increase in N loss through leaching and denitrification, leading to an insufficient amount of N available for the greater amount of plants to utilize and produce more yield. The increase in plant population did increase kernel number per area, but this was accompanied by a corresponding decrease in individual kernel weight (Table 5). Additionally, in 2014, while increasing population increased grain starch, there was a corresponding decrease in grain protein and oil concentration (Table 5).

In no instance did foliar micronutrient applications at VT or R2 significantly affect grain yield, yield components, or grain qualities (Table 5). Although the yield components kernel weight and kernel number were not significantly altered from foliar micronutrient applications, both components tended to change with grain yield. Increases in kernel number for the higher populations were associated with a decrease in kernel weight, and in some cases there is an indication that foliar Zn and B applications partially alleviated this kernel weight decrease (Table 6). Borrás et al. (2003) had similar findings of decreases in both kernel weight and kernel number on a per-plant basis at increased planting densities.

Aboveground plant biomass accumulation was not significantly impacted by plant population or foliar micronutrient applications at VT or R2 in 2014 (Table 7). However, foliar B applications tended to increase plant biomass at the higher populations while foliar Zn tended to decrease plant biomass at these same populations (Table 8). Foliar B and Zn application rates were based the products' label recommendations. These rates were similar to those used by Kaur and Nelson (2014) and Potarzycki and Grzebisz (2009) in corn for B and Zn, respectively. Contrary to the results of this study, in both Kaur and Nelson (2014) and Potarzycki and Grzebisz (2009) significant yield increases were observed, however, the soils in their experiments were severely deficient in either B or Zn.

There was a significant effect of foliar spray treatment on tissue Zn concentration (*P*=0.002) and on whole plant Zn uptake (*P*=0.092) (Table 7). Applying foliar Zn, at the R2 growth stage, significantly increased the concentration and content on Zn in the plant by 16% and 13%, respectively (Table 7). However, this increase in Zn uptake did not translate into an increase in yield indicating that Zn was not the limiting factor for maximizing yield in 2014. Although not statistically significant, the application of supplemental B at VT increased stover B concentrations by 13% at the lowest population, and had the opposite effect at the highest population (Table 8). Conversely, foliar Zn applied at R2 tended to increase stover Zn by 29% at the lowest populations, and by approximately 10% at the intermediate and highest populations (Table 8).

In 2015, the overall grain yield for Champaign was 13.2 Mg ha^{-1} when averaged over hybrids, populations, and foliar treatments. There was no significant effects of foliar treatment on grain yield (Table 9). However, there were significant effects due to hybrid (*P*=0.0008) and planting populations (*P*=0.0085): where hybrid DKC64-87, on average, yielded 0.6 Mg ha^{-1} more than DKC63-33 and where corn grown at increased populations yielded more than at decreased populations (Table 9). The greater yield of hybrid DKC64-87 is attributed to a significant increase in kernel number, while kernel weight remained unchanged (Table 9). The intensive management practice of increasing planting densities above 79,000 plant ha^{-1} resulted in yield increases of 0.4 and 0.5 Mg ha^{-1} at 93,800 and 108,600 plants ha^{-1}, respectively when averaged over varieties and foliar treatments (Table 9). Kernel weight decreased notably at these higher planting densities, however, the concurrent increase in kernel number was greater than the decrease in kernel weight resulting in the overall yield increase observed (Table 9). Additionally, at the higher planting densities, oil and protein concentration within the grain decreased while starch concentration increased (Table 9). Due to the abundant early-season rainfall (Table 4), it is likely that the higher populations lacked sufficient nitrogen throughout the growing season and were unable to store adequate amounts of N in the leaves. This lack of stored N was detrimental late in the season during grain fill when the corn plant is remobilizing stored nitrogen from the leaf tissues to the grain where it is stored as protein (MacGregor et al., 1961). Therefore, the greater planting densities contained a smaller percentage of protein in the grain and a higher percentage of starch, as starch is the predominant reserve carbohydrate and is an important source of energy and structural reserves for a germinating seed (Lang et al., 1956). In no instance did foliar micronutrient applications significantly affect grain yield, yield components, or grain quality although there were some interesting trends, which are summarized in Tables 9 through 12. There was a tendency for B applications at V6 and VT to increase yield, especially with the higher-yielding 'racehorse' hybrid (DKC64-87), at the highest planting density (Table 12). When averaged over both hybrids and all populations, the 0.3 and 0.5 Mg ha^{-1} yield increase from B applications at V6 and VT, respectively, were the largest yield increases out of all foliar treatments (Table 12). Interestingly, these greater yields were due to increased kernel weights while maintaining kernel number (Table 12). Typically, kernel weights are determined late in the growing season during grain fill, as opposed to kernel number, which is determined early in the growing season but that can gradually decrease due to late season kernel abortion (Gardner et al. 2003).

Foliar treatments that included both B + Zn applications tended to decrease corn yield, especially at the highest planting density of 108,600 plants ha^{-1} (Table 12). Multiple concurrent applications of foliar B and Zn tended to produce the greatest reduction in yield of about 0.5 Mg ha^{-1} when averaged over both hybrids and all populations (Table 9). This result contradicts the findings of Aref (2010) who showed an interaction between Zn and B in other crops, and that in some instances Zn reduced the toxicity of B. We speculate that the efficiently applied foliar B and

Zn could have elevated these micronutrient concentrations within the plant to inhibitory or toxic levels. Micronutrients have a very narrow range of optimal concentration within the plant between deficient and toxic levels. Applying too little of a particular micronutrient can be ineffective, while applying too much can be harmful to the crop. The optimal range between deficient and toxic concentrations in the plant is much narrower for the micronutrients than the macronutrients, due to their overall lesser quantities (Chapman, 1967). Also, the optimal range of micronutrient amount changes throughout the growing season as the plant continues to progress through the vegetative and reproductive stages (Campbell, 2000). Finding the right application rate for the right time is critical to optimize the effectiveness of micronutrient applications and to maximize yield.

SUMMARY AND CONCLUSIONS

The two years of research focusing on innovative foliar micronutrient sources in high-yielding corn production systems experienced very similar growing conditions. Abundant amounts of rain early in the growing season likely caused N loss through leaching and denitrification causing N to be limiting and as a result plants were unable to reach their full yield potential. In 2015, the additional 67 kg ha^{-1} of N applied mitigated this N limiting effect, producing higher yields. Soil test levels for both B and Zn were considered low. Despite these soil test levels, no B or Zn deficiencies were observed within the trials for the untreated controls at any population, as concluded by foliar supplementations having no effect.

In no instance, in either year, did foliar micronutrient applications significantly affect grain yield. In this study, the amino-acid chelated micronutrient technology allowed the plant to absorb the nutrients through the leaves as evident by the 16% Zn concentration increase in the stover with foliar Zn applied at the R2 growth stage. This notable intake of nutrients suggests that the use of foliar micronutrients would be beneficial to a grower experiencing deficiencies and looking for corrective solutions.

The results from this trial document the impact that foliar B and Zn can have on corn grain yield along with the role of hybrid and planting density and their interaction in determining grain yield. All hybrids are different, with different responses to management practices. For example, the ‘workhorse’ hybrid, DKC63-33 had no or decreased yield response to the foliar B and Zn additions, suggesting that foliar micronutrient supplementation may not be appropriate for this hybrid-type. However, the use of supplemental B and Zn on a ‘racehorse-type’ hybrid was more effective and evident by the 0.5 Mg ha^{-1} yield increase with foliar B applied at VT on hybrid DKC64-87 at 108,600 plants ha^{-1}.

Further research on foliar micronutrients in high-yield production systems and their interactive effects with plant density, hybrids, application timings, application rates, and tank mixed with pesticides may help to identify management practices that increase the value of incorporating these nutrient sources. A better understanding of these interactions could provide producers with management guidelines to maximize the grain yield benefits from foliar micronutrient applications.

TABLES

Table 1. Amount of water supplied (cm) using a subsurface drip irrigation system when soil water levels dropped below 50 % field capacity for Champaign, IL in 2015. All plots received equal amounts of water. Timing of water supplied is expressed by calendar date and corn growth stage.

Date	Growth Stage	Water (cm)
July 21	R2	.7
August 4	R3	1.0
August 18	R5	1.1
August 26	R5	1.0

Table 2. Treatment schedule to evaluate applications of foliar Metalosate B and Metalosate Zn on corn growth and productivity at Champaign, IL in 2014. Plants were grown with 202 kg N ha^{-1} with six replications.

Foliar Metalosate	Population	Growth Stage	Nutrient Rate
	plants ha^{-1}		g ha^{-1}
Control	79,000	-	-
Control	93,800	-	-
Control	108,600	-	-
Metalosate Boron	79,000	VT	72
Metalosate Boron	93,800	VT	72
Metalosate Boron	108,600	VT	72
Metalosate Zinc	79,000	R2	202
Metalosate Zinc	93,800	R2	202
Metalosate Zinc	108,600	R2	202

Table 3. Treatments to evaluate applications of foliar Metalosate B and Metalosate Zn on corn growth and productivity at Champaign, IL in 2015. Plants were grown with 202 kg N ha^{-1} preplant with an additional 67 kg N ha^{-1} sidedressed at V4 with five replications. All foliar treatments and planting densities were evaluated across two hybrids, DKC63-33 and DKC64-87.

Foliar Metalosate	**Population**	**Growth Stage**	**Nutrient Rate**	
			B	**Zn**
	(plants ha^{-1})		(g ha^{-1})	
Control	79,000	-	-	-
Control	93,800	-	-	-
Control	108,600	-	-	-
Metalosate Boron	79,000	V6	72	
Metalosate Boron	93,800	V6	72	
Metalosate Boron	108,600	V6	72	
Metalosate Zinc	79,000	V6	-	202
Metalosate Zinc	93,800	V6	-	202
Metalosate Zinc	108,600	V6	-	202
Metalosate Boron + Zinc	79,000	V6	72	202
Metalosate Boron + Zinc	93,800	V6	72	202
Metalosate Boron + Zinc	108,600	V6	72	202
Metalosate Boron	79,000	VT	72	-
Metalosate Boron	93,800	VT	72	-
Metalosate Boron	108,600	VT	72	-
Metalosate Zinc	79,000	VT	-	202
Metalosate Zinc	93,800	VT	-	202
Metalosate Zinc	108,600	VT	-	202
Metalosate Boron + Zinc	79,000	VT	72	202
Metalosate Boron + Zinc	93,800	VT	72	202
Metalosate Boron + Zinc	108,600	VT	72	202
Metalosate Boron + Zinc	79,000	V6, VT	72	202
Metalosate Boron + Zinc	93,800	V6, VT	72	202
Metalosate Boron + Zinc	108,600	V6, VT	72	202

Table 4. Monthly weather data between 1 April and 30 September for Champaign, IL in 2014 and 2015. Temperature (°C) is the average daily temperature and precipitation (cm) is the average monthly accumulated rainfall. Values were obtained from Illinois State Water Survey (2015) and values in parentheses are the deviations from the 20-year average (1981-2010).

	Month					
Year	**April**	**May**	**June**	**July**	**August**	**September**
2014						
Temperature, °C	11.7 (+0.6)	17.9 (+1.0)	23.0 (+0.7)	21.1 (-2.8)	23.1 (+0.1)	18.3 (-0.7)
Precipitation, cm	10.0 (+0.7)	11.1 (-1.3)	20.9 (+9.9)	22.1 (+10.2)	3.9 (-6.1)	8.7 (+0.7)
2015						
Temperature, °C	12.2 (+1.1)	18.7 (+1.8)	22.3 (+0.0)	23.1 (-0.8)	22.3 (-0.7)	21.1 (+2.1)
Precipitation, cm	9.2 (-0.1)	15.4 (+3.0)	23.3 (+12.3)	10.7 (-1.2)	8.0 (-2.0)	16.4 (+8.4)

Table 5. Effect of planting population, foliar treatment, and source of variation on grain yield, yield component, and grain quality for corn grown at Champaign, IL in 2014 averaged over six replications. Grain yield is presented at 0% moisture concentration.

		Yield Components		Grain Quality		
Treatment factor	**Yield**	**Kernel Number**	**Kernel Weight**	**Protein**	**Oil**	**Starch**
	Mg ha^{-1}	seed m^{-2}	mg $seed^{-1}$		%	
Population						
plants ha^{-1}						
79,000	12.7	4880	259.8	7.5	3.8	73.5
93,800	12.5	5135	244.5	7.4	3.7	73.7
108,600	12.4	5319	233.5	7.4	3.7	73.9
LSD (α = 0.10)	ns	132	4.7	0.1	0.1	0.3
Foliar Treatment						
Control	12.5	5104	245.4	7.5	3.8	73.6
Foliar B at VT	12.5	5077	247.0	7.4	3.7	73.7
Foliar Zn at R2	12.6	5154	245.5	7.4	3.7	73.9
LSD (α = 0.10)	ns	ns	ns	ns	ns	ns
Source of variation				$P > F$		
Treatment (T)	0.502	0.605	0.819	0.922	0.116	0.214
Population (P)	0.106	<.001	<.001	0.060	0.003	0.024
T x P	0.835	0.684	0.556	0.818	0.230	0.629

Table 6. Interaction of population and foliar nutrient applications on grain yield, yield component, and grain quality for corn grown at Champaign, IL during 2014 averaged over six replications. Grain yield is presented at 0% moisture concentration.

			Yield Components		Grain Quality		
Population	Foliar Treatment	Yield	Kernel Number	Kernel Weight	Protein	Oil	Starch
plants ha^{-1}		Mg ha^{-1}	seed m^{-2}	mg $seed^{-1}$	——	%	——
79,000	Control	12.7	4926	258.7	7.5	3.9	73.4
79,000	Foliar B at VT	12.6	4815	261.4	7.5	3.7	73.6
79,000	Foliar Zn at R2	12.7	4900	259.5	7.6	3.9	73.5
93,800	Control	12.4	5162	241.9	7.4	3.8	73.5
93,800	Foliar B at VT	12.5	5110	244.3	7.5	3.7	73.8
93,800	Foliar Zn at R2	12.7	5135	247.3	7.4	3.6	74.0
108,600	Control	12.3	5224	235.6	7.4	3.7	73.8
108,600	Foliar B at VT	12.4	5306	235.2	7.4	3.7	73.8
108,600	Foliar Zn at R2	12.5	5428	229.7	7.3	3.6	74.1
	LSD ($\alpha = 0.10$)	ns	ns	ns	ns	ns	ns

Table 7. Effect of foliar treatment and source of variation on plant biomass, Zn and B tissue concentration, and Zn and B uptake at R2 + 7 days growth stage for corn grown at Champaign, IL in 2014 averaged over all planting densities and six replications. Biomass and nutrient accumulation are presented at 0% moisture concentration.

Treatment factor	**Biomass**	**Zn Concentration**	**B Concentration**	**Zn Uptake**	**B Uptake**
	Mg ha^{-1}	mg kg^{-1}	mg kg^{-1}	g ha^{-1}	g ha^{-1}
Foliar Treatment					
Control	17.1	17.7	3.5	304.2	60.2
Foliar B at VT	17.4	18.0	3.4	324.9	57.9
Foliar Zn at R2	16.8	20.5	3.1	344.0	51.7
LSD (α = 0.10)	ns	1.4	ns	29.7	ns
Source of variation			*P > F*		
Treatment (T)	0.535	0.002	0.553	0.092	0.361
Population (P)	0.495	0.511	0.808	0.171	0.574
T x P	0.623	0.532	0.377	0.142	0.283

Table 8. Plant biomass, Zn and B tissue concentration, and Zn and B nutrient uptake at R2 + 7 days growth stage in response to micronutrient foliar treatments and three planting densities for corn grown at Champaign, IL during 2014 averaged across six replications. Biomass and nutrient accumulation are presented at 0% moisture concentration.

Population	**Foliar Treatment**	**Biomass**	**Zn Concentration**	**B Concentration**	**Zn Uptake**	**B Uptake**
plants ha^{-1}		Mg ha^{-1}	mg kg^{-1}	mg kg^{-1}	g ha^{-1}	g ha^{-1}
79,000	Control	16.6	16.3	3.1	269.3	50.2
79,000	Foliar B at VT	16.5	17.5	3.5	288.8	57.1
79,000	Foliar Zn at R2	17.0	21.1	3.1	357.6	53.3
93,600	Control	17.2	18.0	3.9	312.0	67.8
93,600	Foliar B at VT	18.0	18.4	3.7	364.0	66.5
93,600	Foliar Zn at R2	17.0	19.9	2.7	336.5	45.7
108,600	Control	17.6	18.8	3.6	331.4	62.5
108,600	Foliar B at VT	17.7	18.2	2.9	321.9	50.2
108,600	Foliar Zn at R2	16.3	20.6	3.5	337.9	56.1
	LSD ($\alpha = 0.10$)	ns	ns	ns	ns	ns

Table 9. Effect of hybrid, planting population, foliar treatment, and source of variation on grain yield, yield components, and grain quality for corn grown at Champaign, IL in 2015 averaged over five replications. Grain yield is presented at 0% moisture concentration.

		Yield Components		Grain Quality		
Treatment factor	**Yield**	**Kernel Number**	**Kernel Weight**	**Protein**	**Oil**	**Starch**
	Mg ha^{-1}	seed m^{-2}	mg $seed^{-1}$		%	
Hybrid						
DKC63-33	12.9	5330	244.0	7.2	3.9	73.1
DKC64-87	13.5	5463	246.7	6.6	3.9	73.6
LSD (α = 0.10)	0.2	81	ns	0.1	ns	0.1
Population						
plants ha^{-1}						
79,000	12.9	4966	258.8	7.2	4.1	73.0
93,800	13.3	5509	242.3	6.8	3.9	73.4
108,600	13.4	5714	235.0	6.7	3.7	73.7
LSD (α = 0.10)	0.3	99	2.6	0.1	0.1	0.2
Foliar Treatment						
Control	13.4	5474	245.6	7.0	3.9	73.2
B @ V6	13.1	5406	244.4	6.9	3.9	73.3
Zn @ V6	13.3	5447	245.1	7.0	4.0	73.2
B + Zn @ V6	13.3	5422	246.0	6.9	3.9	73.4
B @ VT	13.2	5431	244.3	6.9	4.0	73.3
Zn @ VT	13.2	5390	246.3	6.9	3.9	73.4
B + Zn @ VT	13.1	5321	246.4	6.9	3.9	73.5
B + Zn @ V6 and VT	12.9	5281	244.6	6.9	3.9	73.4
LSD (α = 0.10)	ns	ns	ns	ns	ns	ns
Source of variation			*P > F*			
Hybrid (H)	0.0008	0.0100	0.2646	0.0001	0.3439	<.0001
Population (P)	0.0085	<.0001	<.0001	<.0001	<.0001	<.0001
Foliar Treatment (T)	0.2353	0.3102	0.9511	0.6176	0.4201	0.4867
H x P	0.6815	0.3258	0.5542	0.6214	0.0573	0.4276
H x T	0.3735	0.9304	0.2984	0.7042	0.2756	0.4319
P x T	0.4798	0.3006	0.1999	0.6403	0.5296	0.4962
H x P x T	0.1351	0.2543	0.4417	0.4792	0.2831	0.2713

Table 10. Effect of hybrid and foliar treatment applications on grain yield, yield components, and grain quality for corn grown at Champaign, IL during 2015 averaged over all three populations and five replications. Grain yield is presented at 0% moisture.

			Yield Components		Grain Quality		
Hybrid	**Foliar Treatment**	**Yield**	**Kernel Number**	**Kernel Weight**	**Protein**	**Oil**	**Starch**
		Mg ha^{-1}	seed m^{-2}	mg seed $^{-1}$		%	
DKC63-33	Control	13.4	5457	245.7	7.4	3.9	73.0
	B @ V6	12.7	5335	242.6	7.2	3.9	73.1
	Zn @ V6	13.2	5375	246.0	7.3	3.9	73.2
	B + Zn @ V6	13.2	5386	245.3	7.2	3.9	73.0
	B @ VT	12.8	5293	242.3	7.2	4.0	73.0
	Zn @ VT	12.9	5328	246.1	7.2	3.9	73.2
	B + Zn @ VT	12.7	5258	242.9	7.2	3.9	73.3
	B + Zn @ V6 and VT	12.5	5208	240.8	7.2	3.9	73.0
DKC64-87	Control	13.5	5491	245.4	6.6	3.9	73.5
	B @ V6	13.5	5477	246.3	6.6	3.9	73.6
	Zn @ V6	13.5	5519	244.2	6.7	4.0	73.2
	B + Zn @ V6	13.4	5458	246.7	6.6	3.9	73.7
	B @ VT	13.7	5569	246.2	6.6	3.9	73.6
	Zn @ VT	13.4	5452	246.5	6.6	3.9	73.7
	B + Zn @ VT	13.4	5385	249.9	6.6	3.8	73.6
	B + Zn @ V6 and VT	13.3	5353	248.4	6.6	3.8	73.7
	LSD ($\alpha = 0.10$)	ns	ns	ns	ns	ns	ns

Table 11. Effect of planting population and foliar treatment applications on grain yield, yield components, and grain quality for corn grown at Champaign, IL during 2015 averaged over both hybrids and five replications. Grain yield is presented at 0% moisture.

			Yield Components		Grain Quality		
Population	**Foliar Treatment**	**Yield**	**Kernel Number**	**Kernel Weight**	**Protein**	**Oil**	**Starch**
plants ha^{-1}		Mg ha^{-1}	seed m^{-2}	mg seed $^{-1}$		%	
79,000	Control	13.0	5002	259.2	7.2	4.1	72.8
	B @ V6	12.6	4943	254.1	7.1	4.0	73.0
	Zn @ V6	12.9	5018	257.9	7.3	4.1	72.9
	B + Zn @ V6	13.3	5138	258.3	7.3	4.1	73.0
	B @ VT	13.2	5089	259.9	7.3	4.2	72.6
	Zn @ VT	12.8	4882	261.0	7.2	4.0	73.1
	B + Zn @ VT	12.7	4773	265.5	7.2	4.0	73.2
	B + Zn @ V6 and VT	12.5	4887	254.6	7.1	4.0	73.1
93,800	Control	13.4	5535	242.5	6.8	3.9	73.3
	B @ V6	13.2	5498	240.2	6.9	3.8	73.5
	Zn @ V6	13.5	5576	241.6	6.9	3.9	73.2
	B + Zn @ V6	13.5	5501	244.7	6.8	3.8	73.4
	B @ VT	13.0	5415	241.0	6.8	3.8	73.6
	Zn @ VT	13.7	5724	244.2	6.9	3.9	73.3
	B + Zn @ VT	13.2	5481	240.2	6.8	3.9	73.4
	B + Zn @ V6 and VT	13.0	5341	243.6	6.8	4.0	73.2
108,600	Control	13.8	5884	235.0	6.8	3.8	73.6
	B @ V6	13.5	5778	239.0	6.8	3.8	73.5
	Zn @ V6	13.6	5748	235.7	6.9	3.8	73.5
	B + Zn @ V6	13.2	5627	235.1	6.6	3.8	73.6
	B @ VT	13.4	5788	232.0	6.6	3.8	73.6
	Zn @ VT	13.0	5563	233.7	6.6	3.7	73.8
	B + Zn @ VT	13.3	5711	233.4	6.7	3.7	73.9
	B + Zn @ V6 and VT	13.2	5614	235.7	6.8	3.6	73.7
	LSD (α = 0.10)	ns	ns	ns	ns	ns	ns

Table 12. Interaction of hybrid, planting population and foliar treatment applications on grain yield, yield components (kernel number and kernel weight), and grain quality for corn grown at Champaign, IL during 2015 averaged over five replications. Grain yield is presented at 0% moisture.

Population	Foliar Treatment	Yield		Kernel Number		Kernel Weight		Oil		Protein		Starch	
		DKC 63-33	DKC 64-87	DKC 63-33	DKC 64-87	DKC 63-33	DKC 64-87	DKC 63-33	DKC 64-87	DKC 63-33	DKC 64-87	DKC 63-33	DKC 64-87
plants ha^{-1}		— Mg ha^{-1} —		— seed m^{-2} —		— mg seed^{-1} —		%					
79,000	Control	12.8	13.1	4888	5117	263	256	4.1	4.0	7.5	6.9	72.6	73.1
	B @ V6	12.3	12.9	5085	5191	253	255	4.0	4.0	7.3	6.9	72.9	73.2
	Zn @ V6	12.7	13.2	4579	5196	260	256	4.2	4.1	7.5	7.0	72.6	73.1
	B + Zn @ V6	12.9	13.6	4652	4893	255	262	4.1	4.0	7.5	7.0	72.7	73.3
	B @ VT	12.9	13.5	4852	5033	261	259	4.4	4.0	7.7	6.8	72.0	73.1
	Zn @ VT	12.7	12.8	4962	5216	259	263	4.1	3.9	7.5	6.9	72.6	73.6
	B + Zn @ VT	12.3	13.0	4887	5149	264	267	4.0	3.9	7.5	6.9	73.1	73.2
	B + Zn @ V6 and VT	11.5	13.5	4888	4876	250	259	4.2	3.8	7.4	6.9	72.7	73.5
93,800	Control	13.4	13.5	5572	5498	240	246	3.9	3.9	7.3	6.4	73.2	73.4
	B @ V6	12.9	13.5	5518	5484	241	240	3.9	3.7	7.1	6.6	73.1	73.9
	Zn @ V6	13.6	13.4	5252	5430	243	241	3.9	4.0	7.2	6.5	73.1	73.3
	B + Zn @ V6	13.5	13.4	5387	5574	245	244	3.8	3.9	7.1	6.5	73.1	73.6
	B @ VT	12.8	13.3	5357	5639	241	241	3.9	3.8	7.2	6.5	73.2	74.1
	Zn @ VT	13.6	13.9	5330	5500	246	243	3.9	3.9	7.2	6.5	73.2	73.4
	B + Zn @ VT	12.6	13.8	5595	5557	233	247	3.8	4.0	7.0	6.6	73.4	73.4
	B + Zn @ V6 and VT	12.7	13.4	5742	5706	241	246	4.0	4.0	7.1	6.5	73.0	73.5
108,600	Control	13.9	13.8	5910	5857	235	235	3.8	3.7	7.2	6.4	73.2	74.0
	B @ V6	13.0	14.1	5556	5698	234	244	3.8	3.8	7.1	6.5	73.3	73.7
	Zn @ V6	13.3	13.8	5793	5435	235	236	3.6	4.0	7.2	6.6	73.7	73.2
	B + Zn @ V6	13.1	13.4	5735	5687	236	234	3.9	3.7	6.8	6.3	73.3	74.0
	B @ VT	12.6	14.3	5796	5760	226	238	3.7	3.9	6.8	6.4	73.7	73.6
	Zn @ VT	12.5	13.5	5585	5990	233	234	3.7	3.8	6.9	6.4	73.6	74.0
	B + Zn @ VT	13.3	13.4	5644	5852	231	236	3.7	3.6	7.2	6.2	73.5	74.3
	B + Zn @ V6 and VT	13.4	13.1	5354	5773	231	240	3.6	3.6	7.2	6.3	73.5	74.1
	LSD (α = 0.10)	ns		ns		ns		ns		ns		ns	

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