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Evaluating management factor contributions to reduce corn yield gaps

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ABSTRACT

The need to intensify agricultural production due to a growing human population requires closing yield gaps. In 2009 and 2010, five agronomic management factors were assessed for their individual and cumulative contributions to reducing the corn (*Zea mays* L.) yield gap as well as yield components in a corn-soybean rotation. Five management factors (plant population, transgenic insect resistance, strobilurin-containing fungicide, P-S-Zn fertility, and N fertility) were evaluated. An incomplete factorial design with these factors resulted in twelve total treatments, including two control treatments, High and Standard Technology, comprised of all five factors applied at the supplemental level or the standard level, respectively. The High Technology control yielded 2.9 Mg ha^{-1} (ranged across sites and years from 2.12 to 3.50 Mg ha^{-1}) (28%) more grain than the all Standard Technology control, demonstrating the yield gap between traditional farmer practice and attainable yield using available and proven technologies. All management factors except plant population were necessary for reducing the yield gap. Fungicide and Bt traits provided the greatest yield increases to the Standard Technology system. Averaged over the sites and years, when each factor was withheld from the High Technology system, yield decreased by decreasing kernel number. Increased plant population reduced the yield gap when all other inputs were applied at the supplemental level. Kernel number was more significant for increasing yield than kernel weight. Yield contribution of each factor was greater when applied as part of a full complement of supplemental-level inputs rather than when added individually to the standard-input system.

Numerous recent papers have established that agricultural production must increase substantially in order to meet the increasing per capita demand for food, feed, fuel, and fiber of a burgeoning human population (Keyzer et al., 2005, FAO, 2009, Tilman et al., 2011). From a global perspective, it is generally agreed that agricultural intensification (increasing agricultural production per unit area) is preferable to extensification (expanding agriculture onto new areas) as a means of increasing crop production (Cassman et al., 2003; Burney et al., 2010; McLaughlin, 2011; Tilman et al., 2011; Foley et al., 2011). In contrast to the question of *whether* yield increases are needed, the more practical issue of *how* to increase crop yields has received considerably less attention and research investments into this critical area have, to date, been inadequate.

Meeting demand for agricultural commodity crops requires increasing crop yields and closing yield gaps (the difference between farmer's actual yield and potential yield) (Cassman et al., 2003; Licker et al., 2010; Tilman et al., 2011; Mueller et al., 2012). Mueller et al. (2012) determined that 60% to 80% of global yield variability for most major crops was explained by climate, fertilizer application, and irrigation area. According to an analysis by Lobell et al. (2009), among the three staple grain crops grown worldwide: wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), and corn (*Zea mays* L.), wheat and rice yields generally exceed 70% of yield potential, but corn yields do not exceed 70% of potential in any of

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the major corn-producing regions. Such yield gaps can be minimized by improving our understanding of those management factors that are most influential in achieving crop yield potential on a consistent basis (Dobermann et al., 2003).

Plant population directly limits crop yield potential of a given environment; maximum yield occurs when the spatial plant density allows rapid development of the leaf canopy to provide maximum leaf area index and, thus, maximum interception of solar radiation as early as possible in the growing season (Lobell et al., 2009). A number of papers have demonstrated that modern corn hybrids have greater yield potential as a direct result of greater tolerance to the stresses associated with higher plant population (Carlone and Russell, 1987; Duvick, 1997; Sangoi et al., 2002; Tokatlidis and Koutroubas, 2004; Hammer et al., 2009). Furthermore, because of corn's limited ability to efficiently use inputs at suboptimal plant populations, there is reason to believe that future corn yield advancement will focus on improving stress tolerance specifically to support higher plant populations (Tollenaar and Lee, 2002). However, others have demonstrated that increased plant population can be detrimental under drought conditions and that increased planting rates have resulted in more sensitivity to drought and greater yield variability across years (Lobell et al., 2014).

Nutrient deficiencies are the most common and manageable abiotic stress and corn yield limiting factor worldwide (Mueller et al., 2012); and logical crop nutrition is needed to reduce the yield gap. Of all the nutrients required for corn grain production, nitrogen is accumulated in the largest quantity (Bender et al., 2013) and is also the most commonly and severely limiting for grain production worldwide and in the U.S. Corn Belt (Ciampitti and Vyn (2012). However, over-application of N leads to lower profitability and potential negative environmental impact (Dinnes et al., 2002). In order to improve N use and profitability, nutrient availability must be synchronized with crop need, which can be managed by split application of N fertilizer and the use of urease and nitrification inhibitors, among other management practices (Dinnes et al., 2002; Fageria and Baligar, 2005). The phosphorus (P) harvest index is the highest harvest index among all nutrients for corn (Bender et al., 2013); it is the least soil available of the major plant nutrients (Kovar and Claasen, 2005) and is the second most yield limiting nutrient after nitrogen (Andraski and Bundy, 2008). Fixen et al. (2010) reported a 10 mg kg^{-1} decline in the median soil P test between 2005 and 2010 in Illinois and that 39% of the soil samples analyzed were below critical levels in 2010, indicating a sharp decline in soil phosphorus fertility and widespread deficiency in this state. Among the secondary nutrients (calcium, magnesium and sulfur), sulfur deficiency has been reported more frequently in the U.S. Corn Belt as a result of reduced atmospheric deposition, increased yields and a reduction in tillage intensity (Camberato and Casteel, 2010; Sawyer et al., 2012). Sulfur demonstrates the largest harvest index among the secondary nutrients for corn and a season long uptake (Bender et al., 2013). It has been demonstrated that zinc is the micronutrient that most commonly and severely limits corn yield in the world (Bell and Dell, 2008) and in North America (Alloway, 2009). Among all micronutrients, the harvest index for zinc is greatest (Bender et al., 2013).

Weed competition, along with insect and disease pressure, are key biotic stresses responsible for reduction in corn grain yields. New corn hybrids with transgenic traits conferring greater tolerance to insect feeding and herbicides create potential for greater yields, increased yield stability, and reduced yield gaps. Introduction of transgenic insect- and herbicide-tolerant hybrids has resulted in near-wholesale adoption of these traits in U.S. commercial corn production. In 2013, 90% of all U.S. corn acres were planted with some type of transgenic corn hybrid (USDA-NASS 2013). Transgenic insect resistance traits have been demonstrated to increase corn yields by an average of 0.5 Mg ha^{-1} compared to non-traited isolines, a value which increases under conditions of stress (Edgerton et al., 2012). There are two general types of transgenic insect resistance traits available in corn hybrids; both are obtained from soilborne bacteria called *Bacillius thuringiensis* and are referred to as "Bt" genes (Nielsen, 2010). One type of Bt trait confers resistance to rootworm species (Coleoptora, Diabrotica sp.) and the other type of Bt trait confers resistance to European corn borer and similar "moth" type insects (Nielsen

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2010). Corn rootworm larvae feed on corn roots, thereby limiting plant uptake of water and nutrients (Kahler et al., 1985; Riedell, 1990; Spike and Tollefson, 1991), increasing incidence of corn lodging, and reducing CO_2 assimilation, biomass accumulation, and carbohydrate partitioning (Dunn and Frommelt, 1998a, 1998b; Riedell and Reese, 1999). European corn borer damage includes leaf feeding and tunneling of the stalk and ear shank (Rice, 2006) resulting in yield reductions from disruption of water and nutrient translocation to the ear, stalk rot, and pre-harvest losses due to stalk lodging and dropped ears (Steffey and Gray, 2002). Cultural, chemical, or genetic strategies for control of insect pests are likely to improve yield and input-use efficiency of corn. Hybrid corn is susceptible to a number of foliar fungal diseases including gray leaf spot (*Cercospora zeae-maydis*), northern leaf blight (*Exserohilum turcicum*), southern rust (*Puccinia polysora*), and eyespot (*Aureobasidium zeae*) (Bradley, 2012). Foliar fungal diseases can reduce corn yields by reducing photosynthetic area of the plant and, in turn, lessen stalk strength (Dodd, 1977), resulting in lodging and reduced harvestability of grain. Management factors that increase the risk of corn yield reductions resulting from foliar diseases include planting hybrids that are susceptible to foliar disease, planting corn continuously, using no-tillage or minimum-tillage practices, irrigation, planting corn late, and planting corn at higher plant populations (Wise and Mueller, 2011). Systemic foliar fungicides have been labeled for corn use since the 1990s and a class of fungicides called quinone-outside inhibitors (QoI), more commonly referred to as strobilurin fungicides, were labeled for corn in the mid-2000s. Strobilurin-containing fungicides are known to be effective against a broad spectrum of fungal pathogens (Grossman & Retzlaff, 1997), but they have also been reported to increase corn yields even when fungal disease is not detectable in the crop (Jeschke and Doerge, 2010). A number of hypotheses have been suggested for the greening effect of strobilurin, primarily increased photosynthetic capacity and reduced respiration due to a variety of physiological effects on stomatal aperture, chlorophyll content, water use, and endogenous levels of abscisic acid, ethylene, and other plant hormones (Grossmann et al., 1999; Bartlett et al., 2002).

The objectives of this research were to 1) demonstrate and quantify the corn yield gap in Illinois, 2) quantify the impact of different management technologies on the reduction of the corn yield gap, 3) determine the impact of these technologies combined, and 4) assess the effect of these technologies on yield components (kernel weight and number) as a means to understand the mechanism behind the yield response.

To accomplish our objectives, we evaluated five factors for their individual and cumulative contributions to corn yield and yield components: 1) plant population, 2) Bt hybrid trait, 3) strobilurin-containing fungicide, 4) phosphorus, sulfur, and zinc (P-S-Zn) fertility, and 5) N fertility.

Factorial arrangements of treatments are commonly used for agronomic experimental designs when it is suspected that one factor may have significant influence on the effect of another factor or factors. However, there are several limitations to traditional full-factorial designs in agronomic field experiments when a large number of factors are to be evaluated. The most significant limitations of full factorial designs are their large size (and the accompanying issue of increased experimental error), the time and labor requirements for managing such studies and analyzing the data produced, and, above all, the inclusion of treatments and interactions that are frequently neither interesting nor practical. An unfortunate consequence of many studies established with a full factorial arrangement is that the treatment structure is limited to three or fewer factors in order to maintain a manageable number of treatments, experimental area, and fieldwork. To avoid the practical issues associated with complete-factorial experiments, we implemented a straightforward treatment structure that included two control treatments (Standard and High Technology) to which we compared five “Supplemented” or “Withheld” treatments, respectively, in an incomplete factorial design. This treatment structure was explicitly designed to allow three important comparisons, each necessary for answering the objectives of this project: 1) Standard to High Technology controls, 2) individual “Supplemented” treatments to their

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counterpart Standard Technology control, 3) individual "Withheld" treatments to their counterpart High Technology control.

MATERIALS AND METHODS

Field trials were conducted during the 2009 and 2010 growing seasons at two sites: the Crop Sciences Research and Education Center in Champaign-Urbana (CU) (40°06' N, 88°12' W) in east-central Illinois and the Dixon Springs Research Center (DS) (37°26' N, 88°40' W) in southern Illinois. Different fields were used for each year of the study. Fields in each site were within 3 km of each other and had similar soil types, fertility levels, and management histories. Both sites were non-irrigated and tile-drained. In CU, soils were level (0-2% slope) and classified as Drummer silty clay loam (fine-silty, mixed, superactive, mesic typic endoaquoll) and Flanagan silt loam (fine, smectitic, mesic aquic argiudoll) and, in DS, soils were 2-5% slopes classified as Grantsburg silt loam (fine-silty, mixed, active, mesic oxyaquic fragiudalf). At CU, the preplanting soil properties at the 0-15 cm depth for 2009 and 2010 included, respectively, 44 and 41 g kg^{-1} organic matter, pH 5.8 and 6.1, 40 and 44 mg kg^{-1} P, and 153 and 160 mg kg^{-1} K. At DS, the preplanting soil properties at the 0-15 cm depth for 2009 and 2010 included, respectively, 39 and 35 g kg^{-1} organic matter, pH 6.3 and 6.6, 39 and 45 mg kg^{-1} P, and 146 and 157 mg kg^{-1} K. The minerals P and K were extracted using Mehlich III solution. We did not measure nitrate levels at these sites because soil nitrate concentration can change considerably, due to the unpredictable Illinois weather, from the time of preplanting soil testing to the time the plant needs it (Fernandez et al., 2012). Soybean (*Glycine max*) was the previous crop in both years in both locations. Weather values for CU were obtained from the National Weather Service Forecast Office for Central Illinois (NOAA Urbana weather station 118740, 40°05' N, 88°14' W, Elevation: 220m); reported departures from average are compared to the 30-year monthly averages (1981-2010). Dixon Springs weather values were obtained from the Illinois Climate Network (Dixon Springs weather station, 37°44' N, 88°67' W, Elevation: 50m); departures from average reflect the 20-year monthly averages (1990-2010) available from that station.

The study was designed as a randomized complete block with six replications of each treatment. Plots were 5.3 m long by 3.0 m wide and consisted of four rows spaced 0.76 m apart. Plots were planted with an ALMACO SeedPro 360 research plot planter (Nevada, IA) with variable seeding rate capacity. Tillage included chisel plow in fall with two field cultivations in spring for seedbed preparation. Planting occurred on 26 May 2009 and 24 May 2010 in CU and 8 June 2009 and 18 May 2010 in DS. The soil insecticide tefluthrin [2,3,5,6-tetrafluoro-4-methylphenyl)methyl-(1a,3a)-(*Z*)-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropane-carboxylate] was applied with seed at planting at a rate of 0.11 kg a.i. ha^{-1}. Weeds were managed with a pre-emergent application of S-metolachlor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide), atrazine (6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine), and mesotrione (2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione), at a rate of 3.32 kg a.i. ha^{-1}.

Crop grain yield and moisture were determined by harvesting the center two rows of each four-row plot with a research plot combine along the entire length of each plot. Yield was calculated based on 0% moisture content. Average individual kernel weight was estimated by weighing 300 randomly selected kernels from each plot and expressed at 0% moisture. Kernel number was estimated by dividing grain yield by the average individual kernel weight of each plot.

Treatments

The five agronomic management factors considered were: 1) plant population, 2) transgenic insect resistance by Bt trait, 3) strobilurin-containing fungicide, 4) P-S-Zn fertility and 5) N fertility (Table 1). Each factor consisted of two levels representing either the current or lesser agronomic practice (referred to as 'Standard Technology') or a supplemental level (referred to as 'High Technology'). The

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population levels used were 79,000 and 111,000 plants ha^{-1}, representing an average and high population; and denoted as –Pop or +Pop, respectively. For determination of the effect of transgenic insect resistance, a non-Bt (refuge) (DeKalb hybrid DKC61-22 with glyphosate resistance) and its near-isoline containing Bt (DeKalb hybrid DKC61-19 with resistance to European corn borer [*Ostrinia nubilalis*] and corn rootworm [*Diabrotica* spp.]) were used, and denoted as –Bt or +Bt, respectively. Both hybrids were 111-day relative maturity rated and possessed transgenic tolerance to the herbicide glyphosate. For determination of the influence of Strobilurin fungicide application on yield, the treatment levels were either None or with Fungicide, and denoted as –Fung or +Fung respectively. Headline (BASF, Florham Park, NJ), a product containing pyraclostrobin (a foliar fungicide in the strobilurin chemical class) was the fungicide used in this study and was applied at VT at the maximum-labeled rate of 0.21 kg a.i. ha^{-1}. The two levels comprising the fourth management factor, P-S-Zn nutrition, were None or P-S-Zn and denoted as –P-S-Zn or +P-S-Zn respectively. The intensified level of the fourth factor consisted of P, S, and Zn application using MicroEssentials SZ (12-40-0-10[S]-1[Zn]) at a rate of 280 kg ha^{-1} (The Mosaic Company, Plymouth, MN). The MicroEssentials SZ was broadcast immediately prior to planting and incorporated with a cultivator-harrow. The None level would be the normal practice on the fields of this study, since soil test results for P and K were above the critical threshold determined by Vitosh et al. (2007) for corn production. The two levels of the fifth management factor, N, were Base and Base + Side-dress and denoted as –N or +N respectively. For the Base rate, N was applied at the V1 growth stage as 28% urea-ammonium nitrate solution at a rate of 202 kg N ha^{-1}. The Base + Side-dress rate consisted of a supplemental broadcast application at the V5 growth stage of 112 kg N ha^{-1} of SuperU (Koch Agronomic Services, Wichita, KS), a stabilized urea N fertilizer (46-0-0) containing a urease inhibitor (N-(n-butyl) thiophosphoric triamide) and a nitrification inhibitor (dicyandiamide) to decrease losses due to volatilization, leaching, and denitrification.

Supplemented/Withheld Treatment Structure

The Supplemented/Withheld treatment structure used in this study assessed individual and combined effects of the five management factors resulting in 12 treatments (Table 1). Five 'Supplemented treatments' (+Pop, +Bt, +Fung, +P-S-Zn, and +N) were established by individually substituting the high level for each management factor while all other management factors were maintained at the Standard level (Table 1). For example, the +Pop treatment was created by substituting the higher plant population (111,000 plants ha^{-1}) for the standard level (79,000 plants ha^{-1}) while all other management factors were maintained at the lower, standard level. Similarly, five 'Withheld treatments' (-Pop, -Bt, -Fung, -P-S-Zn, and -N) were established by individually substituting the lower level of the factor while maintaining all other factors at the High Technology level. Thus, the –Pop treatment was created by substituting the lower plant population (79,000 plants ha^{-1}) for the higher plant population (111,000 plants ha^{-1}) while all other management factors were maintained at the advanced level. In this way, the value of each management factor was tested at the Standard Technology level of agronomic management while in an intensified management system (High Technology).

Data Analysis

Treatment effects were evaluated for yield and yield components (kernel number and kernel weight) with a linear mixed model using the MIXED procedure of SAS, version 9.2 (SAS Institute, 2009). Treatments, years, and locations were considered fixed effects and blocks were declared random and nested within locations and years. Normality and homogeneity of residuals were tested using the Shapiro-Wilks test and Brown and Forsythe test. Homogeneity of variances was confirmed with the folded F test (P<0.05). A pre-planned set of t-tests was used to evaluate significance of difference in least square means estimates between specific treatments at the 0.1 or 0.05 probability level. The pre-

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planned comparisons were comprised of the differences between the High and Standard Technology controls, the five ‘Supplemented treatments’ (+Pop, +Bt, +Fung, +P-S-Zn, and +N) against the Standard Technology control, and the five ‘Withheld treatments’ (-Pop, -Bt, -Fung, -P-S-Zn, and -N) against the High Technology control. A 95% confidence interval was calculated for the differences between the High and Standard Technology controls across all sites and years and in each site-year. These confidence intervals were compared against the sum of the yield difference between the ‘Supplemented treatments’ (+Pop, +Bt, +Fung, +P-S-Zn, and +N), if statistically significant, and the Standard Technology control. Pearson’s correlation coefficient was used to evaluate the linear association between grain yield and yield components across all locations and years and within each location-year, using the CORR procedure of SAS.

RESULTS & DISCUSSION

Weather

Weather data for each growing season (April through October) of 2009 and 2010 at both locations are presented in Table 2. In 2009, temperatures in CU were above average in June and below average in July and August; precipitation was above average for every month, except September. In 2010 in CU, temperatures were above average and rainfall was below average during every month except June, when rainfall was 50% above the monthly average. Overall, CU weather in 2009 was cool and wet and conducive for favorable plant growth; the 2010 growing season was hot and dry, especially during pollination and grain-fill, creating stress conditions that limited crop productivity. At DS, average air temperatures in 2009 were generally cool with the exception of June and precipitation was above average. In 2010 in DS, monthly temperatures were generally above average; precipitation was near normal April through June, but substantially below average in July, which likely decreased yield potential.

Corn Yields

Summary of Treatment and Site by Year Effects

There was a significant effect of Treatment, Site, Year and Site x Year, and treatment x site x year interaction on corn grain yield (P<0.0001).

The greatest yield at any site in any given year was obtained with the High Technology control. Furthermore, yields were larger in CU 2009 than in the other three site-years (P<0.01), which did not differ (Table 3). This result indicates that CU 2009 was an environment conducive to greater yields than the other three site-years.

We estimated the corn yield gap as the difference between the Standard Technology control, representing traditional farmer practice, and the High Technology control, representing the attainable yield using the high level of the technologies. The average corn yield gap across all sites and years was 2.9 Mg ha^{-1} (28%) and ranged from 2.1 to 3.5 Mg ha^{-1} (21-32%) (P <0.0001) (Tables 3 and 4). The yield gap was positively correlated with both the yield of the High Technology (r=0.87, p=0.13) and Standard controls (r=0.51, p=0.48) but more strongly so with the High Technology control yield. This finding indicates that the gap is greatest in environments capable of supporting higher yields, but which are limited to lower yields due to management practices.

Plant Population Effect

Comparison of the High and Standard Technology control treatments indicated that the environments tested in this study were capable of supporting plant populations greater than 79,000 plants ha^{-1}, because there was a significant yield difference between the Standard and High Technology controls (Table 4). In terms of yield effects resulting from the population (Pop) treatment, only one significant instance was identified across the four site-years; in 2009 at CU, +Pop (increasing plant

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population of the Standard system) reduced grain yield by 0.77 Mg ha^{-1} (7%) relative to the Standard Technology control (Tables 3 and 4) indicating a negative response to increased plant population. These data indicate that increasing the plant population of a non-Bt hybrid without supplying additional fertilizer or fungicide may reduce corn yield, especially when the yield potential of a given year or environment is high. Conversely, reducing plant population in the High Technology system (-Pop) did not significantly affect corn yield in any site-year, which suggests that the standard planting rate of 79,000 plants ha^{-1} was enough to maximize yield; but, at the same time, the higher population did not have a detrimental effect on corn yield when the other technologies were applied. Also, having a reduced plant population while supplying adequate supporting inputs did not increase (or decrease) yield, even in a moderate drought year like 2010.

Bt Trait Effect

Substituting the Bt-traited hybrid into the Standard Technology control system did not affect crop yield for any individual site-year tested, although the yield increase averaged over site-years (0.46 Mg ha^{-1} or 4.5%) was statistically significant (*P*=0.04, Table 4). In all site-years tested, replacing the Bt-traited hybrid from the High Technology control system with a non-traited near-isoline significantly reduced grain yield between 0.85 Mg ha^{-1} and 1.4 Mg ha^{-1} (Table 4) with an average reduction of 1.13 Mg ha^{-1} (8.7%), relative to the High Technology control (Tables 3 and 4).

A number of recent studies have demonstrated that Bt corn hybrids tolerate a greater plant population density than non-Bt hybrids, due largely to a superior resistance to stem lodging and ear dropping (Singer et al., 2003; Coulter et al., 2010; Stanger and Lauer, 2006). For example, Stanger and Lauer (2006) determined that Bt corn hybrids yielded 6.6% greater grain yield and demonstrated 22% less lodging than non-Bt hybrids when planted at a plant population of 104,500 plants ha^{-1}. They also determined that the plant population for maximizing grain yield was 5700 plants ha^{-1} (5.8%) greater for Bt hybrids than for non-Bt hybrids. In the present study, the observation of yield reductions when the Bt trait was omitted from the High Technology control system (averaging 8.7% less yield than High Technology control) relative to the more modest increase measured when the Bt trait was added to the Standard Technology control system (averaging 4.5% greater yield than Standard Technology control) demonstrates that the Bt trait provided greater value in the High Technology system. By overcoming the most pressing causes of yield reduction at high plant populations, i.e. stem lodging (Stringfield and Thatcher, 1947; Crosbie, 1982) and greater pest pressure, the Bt trait may improve yields.

Strobilurin Fungicide Effect

The strongly positive effect of applying a strobilurin-containing fungicide at VT was unexpected, as we did not observe measurable leaf fungal infection in any of the site-years (data not shown). Also, particularly in 2010 there was hot, dry weather that should have deterred fungal growth. Adding fungicide to the Standard Technology control was the strongest factor for yield increase in 2010, a moderate drought year, increasing yield by 8.5% and 9.4% at CU and DS, respectively (Table 4). Adding fungicide to the Standard Technology control did not affect yield at either site in 2009. Omitting strobilurin fungicide from the High Technology control significantly reduced yield for three of four site-years relative to the High Technology control (Table 3); reductions ranged from 9.5% to 18% (Table 4). Averaged over site-years, omitting fungicide from the High Technology system reduced grain yields by 11.6%. Fungicide was the single factor that had the largest impact on corn yield under the High Technology system.

The results, considered within the context of yearly weather conditions suggest that the strongly positive effect of the strobilurin fungicide in 2010 is related to its effect as a plant growth regulator

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rather than its fungicidal properties. Strobilurin has been shown to extend the growing season of the crop by delaying plant senescence and prolonging the photosynthetic capacity of the plant, a side-effect of strobilurin referred to as the "stay green" effect (Bartlett et al., 2002; Holmes and Rueber, 2006). By delaying leaf senescence, strobilurin appears to provide an extended window of time during which the corn plant can potentially offset the negative consequences of drought and higher plant populations which involve abbreviated grain-filling period (Westgate 1994), reduced leaf area (Denmead and Shaw, 1960; NeSmith and Ritchie, 1992; Albrecht and Carberry, 1993), and decreased vegetative dry matter (Claassen and Shaw, 1970). Our data suggest that, by prolonging the duration for photosynthesis to occur, strobilurin fungicide application provides an opportunity for plants to take advantage of favorable weather later in the growing season. Grossmann and Retzlaff (1997) determined that intact wheat plants, leaf discs, and shoots subjected to drought stress demonstrated substantial reductions in ethylene formation with the application of the strobilurin kresoxim-methyl as well as an increase in endogenous cytokinins, potentially explaining delay of senescence and intensification of green leaf pigmentation of wheat exposed to strobilurin.

The fungicide factor contributed two valuable pieces of information to future research in agricultural intensification efforts: 1) plant growth regulators may play a role in high-yielding, intensively managed agricultural systems and 2) strobilurin chemicals can substantially increase crop yields, even under environmental conditions non-conducive to fungal pathogens. More work should be done to better understand the mode of action and cause of the strobilurin yield advantage, investigating, specifically, the interaction between the grain-filling period, photosynthetic capacity, and soil moisture conditions observed in newer crop hybrids and strobilurin-treated plants.

Fertility Effect

As found for the other factors, yield response to P-S-Zn fertilization varied between site-years. Adding P-S-Zn to the Standard Technology control increased yields by almost 9% at DS in 2010, but did not affect yields for other site-years (Tables 3 and 4). Omitting P-S-Zn from the High Technology control reduced yields in two of four site-years, and when averaged over all site-years reduced yields by 0.66 Mg ha^{-1} (5.1%). The influence of P-S-Zn nutrition was most notable in the high-population, high-input system, which requires the greatest availability of P-S-Zn for maximum yield.

The side-dress application of 112 kg N ha^{-1} to the base application of 202 kg N ha^{-1} of the Standard Technology control affected yield in one of four site-years (7.9% yield increase in 2009 in CU, Table 4). Omitting the side-dress application from the High Technology control reduced yield in the same two site-years where we found a similar effect to the application of P-S-Zn, and also reduced overall yields by 0.75 Mg ha^{-1} (5.7%) (Table 4). Similar to the effect of P-S-Zn application, these data suggest that a side-dress N fertilizer application benefits an intensively managed (high-population and high-input) cropping system more than the Standard Technology (lower-population and lower-input) system. Side-dressing N with a stabilized N source may have improved N fertilizer recovery during the wet growing season of 2009, potentially explaining the significant N effects observed. These results support the findings of Boomsma et al. (2009) who reported that high plant density systems demonstrated reduced tolerance to inter-plant competition under low-N conditions as well as high responsiveness to side-dress N applications.

Systems Effects

The experimental design allows evaluation of the single and combined value of factors on corn yield, and assessment if their combined effect is either additive or synergistic. The individual yield value of any single management factor alone can be estimated as the yield difference between the Standard Technology +factor and the Standard Technology control treatments. The resulting individual yield value of each supplemented factor (averaged across sites and years) was significant for hybrid trait and

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fungicide, 0.46 and 0.45, respectively (Table 4). Summing the individual yield values for these supplemented factors gives an additive yield value of 0.91 Mg ha^{-1} (Table 5); this value estimates the yield increase if combinations of the significant yield factors acted additively. However, the actual yield response to all factors combined, obtained by calculating the difference between the High and Standard Technology control treatments, was 2.87 Mg ha^{-1} (across sites and years) with a 95% confidence interval of 2.2-3.27 Mg ha^{-1}. The lower limit of 2.2 Mg ha^{-1}, a value substantially greater than the average yield value for the summation of all individual supplemented factor contributions, 1.52 Mg ha^{-1} (Table 5), demonstrates the significance of the synergistic nature of the yield increase resulting from the combination of intensified management factors. Moreover, this synergistic effect was observed in three of four site-years, as indicated by summation of the factors being smaller than the lower limit of the 95% confidence interval for the difference between the High Technology and Standard Technology controls. The same conclusion is reached even if all factors are considered, regardless if they had a statistically significant effect or not.

Another important result of this work is the observation that the yield contribution provided by an individual factor depends on the other factors present in the system (Table 4). This is demonstrated by noting that the yield reduction resulting from omitting a factor from the High Technology control is greater than the yield increase occurring when that factor is added to the Standard Technology control. Thus, the yield contribution of a factor is generally greater when included as part of a full complement of other intensive-level inputs rather than when added individually to the lower-input system.

Yield Components – Kernel Number and Kernel Weight

General Effects

The Treatment, Site, and Year effects strongly affected kernel number and kernel weight (P<0.0001 for effects on both variables). The Year x Site interaction was also significant for kernel number (P=0.0018) and kernel weight (P<0.0001). There was a significant difference (P<0.0001) in kernel number for the High Technology control relative to the Standard Technology control (26% averaged across years) but no difference for kernel weight, indicating that kernel number was the more important yield component (data not shown).

Averaged across site-years, kernel number declined significantly in response to each of the Withheld treatments (-Pop, -Bt, -Fung, -P-S-Zn, and -N) relative to the High Technology control (Table 6). In contrast, kernel number was not affected by any of the management factors when each factor was added singly to the Standard Technology control (+Pop, +Bt, +Fung, +P-S-Zn, and +N). Plant population and fungicide application were the only two factors that affected kernel weight, either relative to the Standard Technology or High Technology controls. Kernel weight responded positively to fungicide application and negatively to increased plant population.

Correlations between Yield and Yield Components

Linear correlations between yield and kernel number were highly significant (P < 0.001) for all site-years and across years (Table 7). Kernel weight, however, was not correlated with yield for both sites in 2009, and weakly correlated in 2010 and across site-years (Table 7). The positive relationship between yield and kernel number has been demonstrated in a number of studies (Haegele et al., 2014; Strieder et al., 2008). A non-significant or weakly significant relationship between kernel weight and yield has been noted by other researchers (Borras, et al., 2004). These results demonstrate that kernel number is more directly responsible for changes in corn grain yield than kernel weight, suggesting that increasing corn yields and, thus, reducing the yield gap for corn should continue to focus on maximizing ovule number and reducing kernel abortion to increase kernel number per unit area.

Plant Population Effects

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Yield component data (Table 6) demonstrated that increasing plant population without increasing crop inputs (+Pop) resulted in reduced kernel weight and had no effect on kernel number. Generally, these contrasting effects cancelled each other out, resulting in no effect on crop yield (Table 3). The one exception (2009 CU, 7% yield reduction; Table 3) resulted from a 9.6% reduction in kernel weight and a more modest 2.7% increase in kernel number. These results reflect the unique plasticity characteristic of individual corn plants responding to stresses. Stress induced by weather and intraspecific competition prompts the plant to make adjustments in kernel number (via kernel abortion) and/or kernel weight to assure viability of remaining kernels, a developmental response referred to as "yield component compensation" (Adams, 1967; Ritchie, et al. 1986). The net result, on an area basis, is a less-than-expected grain yield reduction due to population stress. The average yield reduction for the +Pop treatment was a modest and non-significant 0.24 Mg ha^{-1} (2.4%; Table 4) relative to the Standard Technology control; the yield components resulting in the measured yield reduction were the product of a non-significant 3.6% average increase in kernel number and a significant 5.5% average decrease in kernel weight relative to the Standard Technology control (P<0.10). In addition, owing to yield component compensation, these results support other studies concluding that it is less likely that increasing plant population will reduce yields in a bad year relative to the probability that it will increase yields in a good year (Carmer and Jackobs, 1965; Cox, 1997).

In the High Technology system, reducing plant population (-Pop), resulted in a significant decrease in kernel number and increase in kernel weight in CU in both years (Table 6). Decreasing the plant population from 111,000 to 79,000 pl ha^{-1} resulted in an a priori decrease in potential kernel number per area of 29%. However, in the High Technology system in CU across the years, we observed only a 12% decrease in kernel number with -Pop, indicating that more kernels per ear developed using the additional factors included in the High Technology system with the lower population (Table 6).

Bt Effects

Adding the Bt trait to the Standard Technology control did not affect kernel number or kernel weight for any site-year and across all site-years (Table 6). Omitting the trait from the High Technology control reduced kernel number in three of four site-years and reduced kernel weight in one site-year (Table 6). Averaged across site-years, omitting the trait from the High Technology control reduced kernel number by 7.2%, but had no effect on kernel weight. This positive effect on kernel number and lack of effect on kernel weight may be due to transgenic insect resistance preventing damage to corn silks from corn rootworm feeding (as reported by Nielsen, 2001) improving ovule pollination.

Strobilurin Effects

Kernel number was affected by adding a strobilurin application to the Standard Technology control (+Fung) in just one of four site-years (a 6% reduction in kernel number relative to the Standard technology control at CU in 2009). However, omitting strobilurin from the High Technology control reduced kernel number in three out of four site-years by an average of 7% (Table 6). Since fungicide was applied after the developmental stage at which row number (rows ear^{-1}) and row length (kernels row^{-1}) are established, we conclude that fungicide reduced kernel abortion in the High Technology system in the drought of 2010. The fungicide application at VT was during the period when photoassimilates are crucial for kernel set (Cantarero et al., 1999). Strobilurin fungicide application also positively affected kernel weight in 2010, indicating leaf protection extending into the grain- filling stage. On average, kernel weight increased by 8% when strobilurin fungicide was added to the Standard Technology control and decreased by 12% when it was omitted from the High Technology control. Further, fungicide was the only management factor that consistently affected kernel weight for both sites in 2010. Fungicide application did not affect kernel weight in 2009.

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Yield component results (Table 6) support the idea that strobilurin fungicide is capable of reducing the impact of stress and either prolongs the grain-filling period or increases the grain filling rate, resulting in both more kernels (per unit area) and heavier kernels. Correspondingly, strobilurin was most effective under increased stress conditions (i.e. drought and/or high plant population) in this study.

Fertility Effects

The effect of P-S-Zn fertility on yield components varied between years and sites. In DS in 2010, adding P-S-Zn to the Standard Technology control resulted in an 8% increase in kernel number, corresponding closely to the observed 9% increase in yield (relative to the Standard Technology control) (Table 6). Omitting P-S-Zn from the High Technology control reduced kernel number, but not kernel weight, at two of four site-years: kernel number declined by 6.3% at CU in 2009 and 8.3% at DS in 2010. The influence of P-S-Zn application was most evident in the High Technology system, where omission of these nutrients reduced kernel number by an average of 3% (averaged across sites), corresponding to an average yield reduction of 5%. Kernel weight was not affected by P-S-Zn. All three of these nutrients, P, S, and Zn, have relatively high harvest indices, indicating their importance to kernel development (Bender et al., 2013).

The only instance of a yield increase resulting from applying a side-dress N application to the Standard Technology control was primarily the result of increasing kernel weight, not kernel number. In 2009 at CU, kernel weight increased by 5% for the +N treatment relative to the Standard Technology control. Conversely, the 8.7% yield reduction when N was omitted from the High Technology control in 2009 at CU was primarily the result of a 6.9% reduction in kernel number (Tables 3 & 6). Boomsma et al. (2009) found that high populations (104,000 pl ha $^{-1}$) receiving less side-dress N fertilizer (165 versus 330 kg N ha^{-1}) yielded less in two out of three years, with reductions in both kernel number and weight.

CONCLUSIONS

This study provides the first estimate of the corn yield gap under field conditions for the U.S Corn Belt. Averaged across site-years, the intensified system (High Technology control) combining increased plant population, transgenic insect resistance, strobilurin-containing fungicide, and balanced crop nutrition yielded 28% (ranging from 21% to 32%) greater corn grain (2.87 Mg ha^{-1}, ranging from 2.12 to 3.50 Mg ha^{-1}) than the standard system (Standard Technology control).

Furthermore, this study showed that no single factor or technology could account for this yield gap. All the factors except plant population were necessary for the greater corn yield of the High Technology system; demonstrated by decreased yield when they were removed from the system. Even though plant population did not show a positive effect on grain yield, we found evidence that the environments tested in this study were capable of supporting plant populations of 111,000 plants ha^{-1}, when fertility and pest control technologies were adjusted to minimize nutritional and biotic stresses. Increasing plant population without adjusting the other components of the cropping system can result in a significant yield decrease. Withholding an intensified factor from the High Technology system decreased yield, primarily by decreasing kernel number. Plant population was negatively correlated with kernel weight, while fungicide was positively correlated with kernel weight.

This study also demonstrated that combining intensified management factors resulted in a greater-than-additive yield increase relative to the combined value provided by each factor applied individually, suggesting a synergy among the technologies.

Finally, the absolute and relative effect of each factor was greater under the intensified system (High Technology) than the Standard Technology system. This finding has important economic implications, as the benefit of each technology will be more favorable under a system rather than when they are evaluated as a single technology. We believe that more rapid advancements in closing yield

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gaps and increasing grain production will be achieved if agronomists and scientist evaluate new technologies under more intensive management systems.

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REFERENCES

Albrecht D.G., and P.S. Carberry. 1993. The influence of water deficit prior to tassel initiation on maize growth, development and yield. Field Crops Res. 31:55–69.

Adams, M.W. 1967. Basis of yield component compensation of crop plants with special reference to the field bean, *Phaseolus vulgaris*. Crop Sci. 7:505-510.

Alloway, B.J. 2009. Soil factors associated with zinc deficiency in crops and humans. Env. Geochemistry Health 31:537-548.

Andraski, T.W., and L.G. Bundy. 2008. Corn residue and nitrogen source effects on nitrogen availability in no-till corn. Agron J. 100:1274-1279.

Bartlett, D.W., J.M. Clough, J.R. Godwin, A.A. Hall, M. Hamer, and B. Parr-Dobrzanski. 2002. The strobilurin fungicides. Pest Manage. Sci. 58:649-662.

Bell, R.W. and B. Dell. 2008. Micronutrients in sustainable food, feed, fibre and bioenergy production. Int. Fertilizer industry Assn., Paris.

Bender, R.R., J.W. Haegele, M.L.Ruffo, and F.E. Below. 2013. Nutrient uptake, partitioning, and remobilization in modern, transgenic insect-protected maize hybrids. Agron. J 105:161-170.

Boomsma, C.R., J.B. Santini, M. Tollenaar, and T.J. Vyn. 2009. Maize morpho-physiological responses to intense crowding and low nitrogen availability: An analysis and review. Agron. J. 101:1426-1452.

Borras, L., G.A. Slafer, M.E. Otegui. 2004. Seed dry weight response to source-sink manipulations in wheat, maize and soybean: A quantitative reappraisal. Field Crops Res. 86:131-146.

Bradley, C.A. 2012. Managing Diseases. In: Illinois Agronomy Handbook. Univ. of Illinois Ext. Urbana, IL. p. 197-207. (available online at http://extension.cropsci.illinois.edu/handbook/) (accessed 29 May 2014).

Burney, J.A., S.J. Davis, and D.B. Lobell. 2010. Greenhouse gas mitigation by agricultural intensification. Proc. Nat. Acad. Sci. 107:12052-12057.

Camberato, J. and S. Casteel. 2010. Keep an eye open for sulfur deficiency in wheat. Purdue Univ. Dep. of Agronomy, Soil Fertility Update. Available at: http://www.agry.purdue.edu/ext/soybean/Arrivals/04-13-10_JC_SC_Sulfur_deficiency.pdf. (accessed 17 June 2014).

Cantarero, M.G., A.G. Cirilio, and F.H. Andrade. 1999. Night temperature at silking affects kernel set in maize. Crop Sci. 39:703-710.

Carlone, M.R., and W.A. Russell. 1987. Response to plant densities and nitrogen levels for four maize cultivars from different eras of breeding. Crop Sci. 27:465-470.

Carmer, S.G., and J.A. Jackobs. 1965. An exponential model for predicting optimum plant density and maximum corn yield. Agron. J. 57:241-244.

Cassman, K.G., A. Dobermann, D.T. Walters, and H. Yang. 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Annu. Rev. Environ. Resour. 28:315-358.

Agronomy Journal Accepted paper, posted 11/11/2014. doi:10.2134/agronj14.0355

Ciampitti, I.A., and T.J. Vyn. 2012. Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review. Field Crops Res. 133:48-67.

Ciampitti, I.A., and T.J. Vyn. 2013. Maize nutrient accumulation and partitioning in response to plant density and nitrogen rate: II. Calcium, magnesium, and micronutrients. Agron J. 105:1645-1657 doi:10.2134/agronj2013.0126

Claassen, M. M., and R.H. Shaw. 1970. Water deficit effects on corn. I. Grain components. Agron. J. 62:652-655.

Coulter, J.A., E.D. Nafziger, M.R. Janssen, and P. Pedersen. 2010. Response of Bt and near-isoline corn hybrids to plant density. Agron. J. 102:103-111.

Cox, W.J. 1997. Corn silage and grain yield responses to plant densities. J. Prod. Agric. 10:405-410.

Crosbie, T.M. 1982. Changes in physiological traits associated with long-term breeding efforts to improve grain yield of maize. In: H.D. Loden, D. Wilkinson, editors, Proceedings of the 37th Annual Corn and Sorghum Research Conference. Chicago, IL, 5–9 Dec., 1982 Am. Seed Trade Assoc., Washington, DC, pp. 206–223.

Denmead, O.T., and Shaw, R.H. 1960. Effects of soil moisture stress at different stages of growth on development and yield of corn. Agron. J. 52:272-274.

Dinnes, D.L., D.L. Karlen, D.B. Jaynes, T.C. Kaspar, J.L. Hatfield, T.S. Colvin, and C.A. Cambardella. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agron J. 94:153-171.

Dobermann, A.R., T.J. Arkebauer, K.G. Cassman, R.A. Dribjer, and J.L. Lindquist. 2003. Understanding corn yield potential in different environments. Agronomy—Faculty Publications. Paper 524. http://digital commons.unl.edu/agronomyfacpub/524.

Dodd, J.L. 1977 A photosynthetic stress-translocation balance of corn stalk rot. In: H.D. Loden, D. Wilkinson, editors, Proceedings of the 32nd Corn and Sorghum Research Conference. Chicago, IL, 6-8 Dec., 1977. Am. Seed Trade Assoc., Washington, DC, p. 122-130.

Dunn, J.P., and K. Frommelt. 1998a. Effects of below-ground herbivory by *Diabrotica virgifera virgifera* (*Coleoptera*) on biomass allocation and carbohydrate storage of maize. Appl. Soil Ecol. 7:213-218.

Dunn, J.P., and K. Frommelt. 1998b. Effects of below-ground herbivory by *Diabrotica virgifera virgifera* (Col., Chrysomelidea) and soil moisture on leaf gas exchange of maize. J. Appl. Ent. 122:179-183.

Duvick, D.N. 1997. What is yield? In: G.O. Edmeades, M. Bänziger, H.R. Mickelson, and C.B. Peña–Valdivia, editors, Developing drought- and low N-tolerant maize. Proceedings of a Symposium. El Batan, Mexico. 25–29 March, 1996. CIMMYT, México, D.F. p. 332–335.

Edgerton, M.D., J. Fridgen, J.R. Anderson Jr., J. Ahlgrim, M. Criswell, P. Dhungana, T. Gocken, Z. Li, S. Mariappan, C.D. Pilcher, A. Rosielle, and S.B. Stark. 2012. Transgenic insect resistance traits increase corn yield and yield stability. Nature Biotechnol. 30:493-496.

Fageria, N.K., and V.C. Baligar. 2005. Enhancing nitrogen use efficiency in crop plants. Advances in Agronomy. 88:97-185.

FAO. 2009. How to Feed the World in 2050. Proceedings of the expert meeting on how to feed the world in 2050. Rome, Italy. 24-26 June 2009. Food and Agriculture Organization, Rome, Italy http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf (accessed 17 June 2014).

Fernandez, F.G., S.A. Ebelhar, E.D. Nafziger, and R.G. Hoeft. 2012. Chapter 9: Managing nitrogen. In: Illinois Agronomy Handbook. Online edition. University of Illinois Crop Science Extension and Outreach. Urbana, IL. http://extension.cropsci.illinois.edu/handbook/ (accessed 6 October 2014).

Agronomy Journal Accepted paper, posted 11/11/2014. doi:10.2134/agronj14.0355

Fixen, P.E., T.W. Bruulsema, T.L. Jensen, R.L. Mikkelsen, T.S. Murrell, S.B. Philips, Q. Rund, and W.M. Steward. 2010. The fertility of North American soils, 2010. Better Crops Plant Food 94(4):6-8.

Foley, J.A., N. Ramankutty, K.A. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C. O'Connell, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockstrom, J. Sheehan, S. Siebert, D. Tilman, and D.P.M. Zaks. 2011. Solutions for a cultivated planet. Nature 478:337-342. doi:10.1038/nature10452

Grossman, K., J. Kwiatkowski, and G. Caspar. 1999. Regulation of phytohormone levels, leaf senescence and transpiration by the strobilurin kresoxim-methyl in wheat (*Triticum aestivum*). J. Plant Physiol. 154:805-808.

Grossman, K., and G. Retzlaff. 1997. Bioregulatory effects of the fungicidal strobilurin kresoxim-methyl in wheat (*Triticum aestivum*). Pestic. Sci. 50:11-20.

Haegele, J.W., R.J. Becker, A.S. Henninger, and F.E. Below. 2014. Row arrangement, phosphorus fertility, and hybrid contributions to managing increased plant density of maize. Agron. J. 106:1-9. doi: 10.2134/agronj2013.0382

Hammer, G.L., Z. Dong, G. McLean, A. Doherty, C. Messina, J. Schussler, C. Zinselmeier, S. Paszkiewicz, and M. Cooper. 2009. Can changes in canopy and/or root system architecture explain historical maize yield trends in the U.S. Corn Belt? Crop Sci. 49:299-312.

Holmes, J., and D. Rueber. 2006. Soybean yield response to headline fungicide applications. Iowa State University Extension Report ISRF05-22. http://www.ag.iastate.edu/farms/05reports/n/SoybeanYield.pdf (accessed 17 June 2014).

Jeschke, M. and T. Doerge. 2010. Management of foliar diseases in corn with fungicides. Crop Insights 18:1-4.

Kahler, A.L., A.E. Olness, G.R. Sutter, C.D. Dybing, and O.J. Devine. 1985. Root damage by western corn rootworm and nutrient content in maize. Agron. J. 77:769-774.

Keyzer, M.A., M.D. Merbis, I.F.P.W. Pavel, and C.F.A. van Wesenbeeck. 2005. Diet shifts towards meat and the effects on cereal use: can we feed the animals in 2030? Ecological Economics 55:187-202.

Kovar, L.K., and N. Claasen. 2005. Soil-root interactions and phosphorus nutrition of plants. In: J.T. Sims and A.N. Sharpley, editors, Phosphorus: Agriculture and the Environment. Agron. Monogr. 46. ASA-CSSA-SSSA, Madison, WI. p. 379-414.

Licker, R., M. Johnston, J.A. Foley, C. Barford, C.J. Kucharik, C. Monfreda, and N. Ramankutty. 2010. Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world? Global Ecol. Biogeogr. 19:769-782.

Lobell, D.B., K.G. Cassman, and C.B. Field. 2009. Crop yield gaps: Their importance, magnitudes, and causes. Ann. Rev.of Environ. and Resour. 34:179-204. doi:10.1146/annurev.environ.041008.093740

Lobell, D.B., M.J. Roberts, W. Schlenker, N. Braun, B.B. Little, R.M. Rejesus, and G.L. Hammer. 2014. Greater sensitivity to drought accompanies maize yield increase in the US Midwest. Science 344(6183):516-519.

McLaughlin, D.W. 2011. Land, Food, and Biodiversity. Conserv. Biol. 25:1117-1120.

Mueller, N.D., J.S. Gerber, M. Johnston, D.K. Ray, N. Ramankutty, and J.A. Foley. 2012. Closing yield gaps through nutrient and water management. Nature 490:254-257.

NeSmith, D.S., and J.T. Ritchie. 1992. Short-term and long-term responses of corn to a preanthesis soil-water deficit. Agron. J. 84:107-113.

Nielsen, R.L. 2001. Sexual dysfunction in the corn field. Purdue University Extension. http://www.agry.purdue.edu/ext/corn/news/articles.01/index.html. (accessed 17 June 2014).

Agronomy Journal Accepted paper, posted 11/11/2014. doi:10.2134/agronj14.0355

Nielsen, R.L. 2010. A Compendium of biotech corn traits. Purdue Corny News Network Articles. Purdue Univ. Dept. of Agronomy. http://www.kingcorn.org/news/timeless/BiotechTraits.html (accessed 17 June 2014).

Rice, M.E. 2006. European corn borer. Iowa State Univ. Dep. of Entomology. http://www.ent.iastate.edu/pest/cornborer/insect/damage (accessed 17 June 2014).

Riedell, W.E. 1990. Rootworm and mechanical damage effects on root morphology and water relations in maize. Crop Sci. 30:628-631.

Riedell, W.E., and R.N. Reese. 1999. Maize morphology and shoot CO_2 assimilation after root damage by western corn rootworm larvae. Crop Sci. 39:1332-1340.

Ritchie, S.W., J.J. Hanway, G.O. Benson. 1986 How a corn plant develops. Special Report No. 48. Iowa State Univ., Ames.

Sangoi, L., M.A. Gracietti, C. Rampazzo, and P. Bianchetti. 2002. Response of Brazilian maize hybrids from different eras to changes in plant population. Field Crops Res. 79:39-51.

SAS Institute. 2009. SAS 9.2 user's guide. SAS Inst. Cary, NC.

Sawyer, J.E., B. Lang, and D.W. Barker. 2012. Sulfur fertilization response in Iowa corn and soybean production. In: M.D. Ruark and S. Conley, editors, Proceedings of the 2012 Wisconsin Crop Management Conference, Madison, WI, 10-12 Jan 2012. Univ. WI Ext and Univ. WI. 51:39-48.

Singer, J.W., R.W. Taylor, and W.J. Bamka. 2003. Corn yield response of Bt and near-isolines to plant density. doi:10.1094/CM-2003-0829-01-RS (accessed 17 June 2014).

Spike, B.P., and J.J. Tollefson. 1991. Response of western corn rootworm-infested corn to nitrogen fertilization and plant density. Crop Sci. 31:776-785.

Stanger, T.F., and J.G. Lauer. 2006. Optimum plant density of Bt and non-Bt corn in Wisconsin. Agron. J. 98:914-921.

Steffey, K.L., and M.E. Gray. 2002. Management of field crop insect pests. In: R.G. Hoeft and E.D. Nafziger, editors, Illinois Agronomy Handbook. 23rd edition. Univ. of Illinois, Urbana. p. 275-293.

Strieder, M.L., P.R.F. da Silva, L. Rambo, L. Sangoi, A.A. da Silva, P.C. Endrigo, and D.B. Jandrey. 2008. Crop management systems and maize grain yield under narrow row spacing. Soc. Agric. (Piracicaba, Braz.) 65:346-353.

Stringfield, G.H., and L.E. Thatcher. 1947. Stands and methods of planting corn hybrids. Agron. J. 39:995–1010.

Tilman, D., C. Balzer, J. Hill, and B.L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. Proc. Nat. Acad. Sci. 108:20260-20264.

Tokatlidis, I.S., and S.D. Koutroubas. 2004. A review of maize hybrids' dependence on high plant populations and its implications for crop yield stability. Field Crops Res. 88:103-114.

Tollenaar, M., and E.A. Lee. 2002. Yield potential, yield stability, and stress tolerance in maize. Field Crops Res. 75:161-169.

USDA-NASS. 2013. Adoption of genetically engineered crops in the U.S. United States Department of Agriculture National Agricultural Statistics Service. http://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us.aspx (accessed 25 September 2013).

Vitosh, M.L., J.W. Johnson, and D.B. Mengel. 2007. Tri-State Fertilizer Recommendations for Corn, Soybeans, Wheat and Alfalfa. http://ohioline.osu.edu/e2567/index.html (accessed 17 June 2014).

Westgate, ME. 1994. Seed formation in maize during drought. In: K.J. Boote, J.M. Bennett, T.R. Sinclair, G.M. Paulsen, editors, Proceedings of the International Symposium on Physiology and Determination of Crop Yield. Gainesville, FL, 10-14 June 1991. Univ Florida, Gainesville, Fl. p. 361-364.

Agronomy Journal Accepted paper, posted 11/11/2014. doi:10.2134/agronj14.0355

Wise, K. and Mueller, D. 2011. Are fungicides no longer just for fungi? An analysis of foliar fungicide use in corn. APS*net* Features. The American Phytopathological Society. doi:10.1094/APSnetFeature-2011-0531

Agronomy Journal Accepted paper, posted 11/11/2014. doi:10.2134/agronj14.0355

Table 1. Supplemented/ Withheld treatment structure. The treatment exceptions are either supplemented (+ factor) to the Standard Technology control, or withheld (- factor) from the High Technology control. Specific details are found in the Materials and Methods section. Controls are indicated by exception none.

Treatment		------------------------- Factor -------------------------				
Primary Technology	Exception	Pop	Bt Trait	Fungicide	P-S-Zn	N
Standard	None	Average	Refuge	None	None	Base
Standard	+Pop	High	Refuge	None	None	Base
Standard	+ Bt	Average	Bt	None	None	Base
Standard	+ Fung	Average	Refuge	With	None	Base
Standard	+ P-S-Zn	Average	Refuge	None	P-S-Zn	Base
Standard	+ N	Average	Refuge	None	None	Base+ Side-dress
High	None	High	Bt	With	P-S-Zn	Base+ Side-dress
High	– Pop	Average	Bt	With	P-S-Zn	Base+ Side-dress
High	– Bt	High	Refuge	With	P-S-Zn	Base+ Side-dress
High	– Fung	High	Bt	None	P-S-Zn	Base+ Side-dress
High	– P-S-Zn	High	Bt	With	None	Base+ Side-dress
High	– N	High	Bt	With	P-S-Zn	Base

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Table 2. Average monthly temperature (TEMP) and precipitation (PRECIP) for two sites (Champaign-Urbana, CU, and Dixon Springs, DS) and two growing seasons. Values in parentheses represent departure from average monthly temperature or precipitation.

		Champaign-Urbana		Dixon Springs	
Year	Month	TEMP	PRECIP	TEMP	PRECIP
		°C	mm	°C	mm
2009	Apr.	10.7 (0.1)	176 (84)	13.7 (-0.6)	168 (62)
	May	17.4 (0.5)	145 (23)	18.3 (-2.8)	156 (46)
	June	23.7 (1.7)	112 (5)	24.1 (1.1)	92 (6)
	July	21.1 (-2.7)	160 (41)	22.4 (-2.4)	241 (136)
	Aug.	21.4 (-1.3)	143 (32)	22.8 (-2.2)	72 (6)
	Sept.	19.3 (0.4)	20 (-61)	20.4 (0.2)	115 (28)
	Oct.	9.9 (-2.3)	223 (152)	12.0 (-2.7)	251 (162)
2010	Apr.	14.5 (3.9)	53 (-40)	16.3 (2.1)	101 (-5)
	May	18.1 (1.2)	87 (-35)	19.9 (-1.3)	121 (11)
	June	23.8 (1.8)	212 (105)	25.4 (2.4)	100 (14)
	July	25.0 (1.2)	95 (-23)	26.1 (1.3)	54 (-51)
	Aug.	25.1 (2.4)	42 (-69)	26.1 (1.1)	68 (2)
	Sept.	19.7 (0.8)	81 (-1)	20.9 (0.7)	63 (-24)
	Oct.	13.6 (1.3)	28 (-43)	14.7 (0.0)	24 (-65)

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Table 3. Corn yield (at 0% moisture content) response to 12 management treatments for two years (2009 and 2010) at two sites (CU or DS) and the average of sites and years.

Treatment		2009		2010		Across Sites &
Primary Technology	Exception	CU	DS	CU	DS	Years
		Mg ha^{-1}				
Standard	None	11.03	9.97	10.20	9.69	10.22
Standard	+ Pop	10.26†	9.38	9.92	10.35	9.98
Standard	+ Bt	11.46	10.56	10.53	10.16	10.68*
Standard	+ Fung	10.81	10.21	11.07*	10.60*	10.67*
Standard	+ P-S-Zn	11.40	9.95	10.30	10.54*	10.55
Standard	+ N	11.90*	9.94	10.32	9.88	10.51
High	None	14.53	13.00	12.32	12.51	13.09
High	– Pop	13.82	12.81	12.41	12.13	12.79
High	– Bt	13.13†	11.84*	11.20*	11.66*	11.96*
High	– Fung	13.93	11.77*	10.38*	10.23*	11.58*
High	– P-S-Zn	13.59†	12.69	12.12	11.31*	12.43*
High	– N	13.27†	12.22	12.23	11.64*	12.34*

* Significant at the 0.05 probability level compared to the respective control treatment

† Significant at the 0.10 probability level compared to the respective control treatment

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Table 4. Differences in yield in absolute terms and percentage-wise (in parentheses) for supplemented or withheld treatments relative to the Standard or High Technology controls when grown at two sites (CU or DS) over two years (2009 and 2010). The percentage difference between the Standard and High Technology controls is expressed relative to the Standard Technology control.

Treatment		2009		2010		Across Sites
Primary Technology	Exception	CU	DS	CU	DS	& Years
		Mg ha^{-1}				
		Compared with Standard Technology control				
Standard	+ Pop	-0.77 (-7.0%)†	-0.59 (-5.9%)	-0.28 (-2.7%)	0.66 (6.8%)	-0.24 (-2.4%)
Standard	+ Bt	0.43 (3.9%)	0.59 (5.9%)	0.33 (3.2%)	0.47 (4.9%)	0.46 (4.5%)†
Standard	+ Fung	-0.22 (-2.0%)	0.24 (2.4%)	0.87 (8.5%)†	0.91 (9.4%)†	0.45 (4.4%)†
Standard	+ P-S-Zn	0.37 (3.4%)	-0.02 (-0.2%)	0.10 (1.0%)	0.85 (8.8%)†	0.33 (3.2%)
Standard	+ N	0.87 (7.9%)†	-0.03 (-0.3%)	0.12 (1.2%)	0.19 (2.0%)	0.29 (2.8%)
		Compared with High Technology control				
High	– Pop	-0.71 (-4.9%)	-0.19 (-1.5%)	0.09 (0.7%)	-0.38 (-3.0%)	-0.30 (-2.3%)
High	– Bt	-1.4 (-9.6%)†	-1.16 (-8.9%)†	-1.12 (-9.1%)†	-0.85 (-6.8%)†	-1.13 (-8.7%)†
High	– Fung	-0.6 (-4.1%)	-1.23 (-9.5%)†	-1.94 (-15.7%)†	-2.28 (-18.2)†	-1.51 (-11.6%)†
High	– P-S-Zn	-0.94 (-6.5%)†	-0.31 (-2.4%)	-0.2 (-1.6%)	-1.20 (-9.6%)†	-0.66 (-5.1%)†
High	– N	-1.26 (-8.7%)†	-0.78 (-6.0%)	-0.09 (-0.7%)	-0.87 (-6.9%)†	-0.75 (-5.7%)†
High vs. Standard		3.50 (31.7%)†	3.03 (30.4%)†	2.12 (20.8%)†	2.82 (29.1%)†	2.87 (28.1%)†

† Significant at the 0.10 probability level compared to the respective control treatment, or the control treatments compared to each other

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Table 5. Comparisons between the overall yield differences between the High and Standard Technology control treatments (shown as 95% confidence intervals; $\mu_{High} - \mu_{Std}$) and the summation of the additional yield values provided by each supplemental (+factor) treatment to the Standard Technology control (i.e. Standard+Pop, Standard+Bt, Standard +Fung, Standard +P-S-Zn, Standard +N). The additional yield value provided by each +factor treatment was calculated as the difference between the +factor yield and the Standard Technology control yield when significant. All values shown are Mg ha^{-1}.

	2009		2010		All
Treatment	CU	DS	CU	DS	Site-Years
$\mu_{High} - \mu_{Std}$	2.75-4.23	2.10-3.47	1.57-2.66	1.70-3.07	2.20-3.27
$\sum\left(Y_{+FACTOR} - Y_{Std}\right)^{\dagger}$	0.10	0	0.87	1.76	0.91

† $\sum\left[\left(Y_{+BT} - Y_{Std}\right) + \left(Y_{+FUNG} - Y_{Std}\right) + \left(Y_{+P-S-Zn} - Y_{Std}\right) + \left(Y_{+N} - Y_{Std}\right)\right]$

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Table 6. Influence of 12 management designs on yield components measured at two sites (CU and DS) and two years (2009 and 2010).

Treatment		Kernel Number					Kernel Weight				
		2009		2010		All	2009		2010		All
Primary Technology	Exception	CU	DS	CU	DS	site-years	CU	DS	CU	DS	Site-years
		---------------- kernels m^{-2} ----------------					----------------mg $kernel^{-1}$ ----------------				
Standard	None	3952	3754	4373	4023	4026	280	268	233	241	255
Standard	+ Pop	4057	3659	4637*	4330	4171	253*	258	214*	239	241*
Standard	+ Bt	3972	4006	4501	4241	4180	289	264	234	240	256
Standard	+ Fung	3712†	3992	4302	4186	4048	290	258	257*	253*	265*
Standard	+ P-S-Zn	3962	3794	4373	4336†	4116	288	263	236	243	258
Standard	+ N	4047	3793	4464	4006	4077	294*	263	231	247	259
High	None	5140	4911	5202	4981	5059	283	266	237	251	259
High	– Pop	4282*	4911	4830*	4741	4691†	323*	261	257*	256	274*
High	– Bt	4636*	4499	4979†	4665†	4695†	283	263	225*	250	255
High	– Fung	5037	4426†	4993†	4624†	4770†	277	267	208*	221*	243*
High	– P-S-Zn	4818*	4897	5263	4566*	4886†	282	260	231	248	255
High	– N	4786*	4560	5202	4754	4826†	278	268	235	245	256

* Significant at the 0.05 probability level compared to the respective control treatment

† Significant at the 0.10 probability level compared to the respective control treatment

Table 7. Pearson correlation coefficients and associated significance levels between yield and yield components over all treatments.

	2009		2010		Across sites &
Yield Component	CU	DS	CU	DS	Years
Kernel Number	0.89***	0.99***	0.72***	0.90***	0.65***
Kernel Weight	0.33	0.24	0.50†	0.56†	0.51***

† Significant at the 0.10 probability level

*** Significant at the 0.001 probability level