Published January 16, 2015

Evaluating Management Factor Contributions to Reduce Corn Yield Gaps

Matias L. Ruffo, Laura F. Gentry, Adam S. Henninger, Juliann R. Seebauer, and Frederick E. Below*

ABSTRACT

The need to intensify agricultural production due to a growing human population requires yield gaps to be closed. In 2009 and 2010, five management factors were assessed for their individual and cumulative contributions to reducing the corn (*Zea mays* L.) yield gap and yield components in a corn–soybean [*Glycine max* (L.) Merr.] rotation. Five management factors (plant population, transgenic insect resistance, fungicide containing strobilurin, P–S–Zn fertility, and N fertility) were evaluated. An incomplete factorial design with these factors resulted in 12 treatments, including two controls: high technology (HT) and standard technology (ST), comprising all five factors applied at the supplemental or the standard level, respectively. The HT control yielded 2.9 Mg ha^{-1} (2.12–3.50 Mg ha^{-1} across sites and years) more grain (28%) than the ST control, demonstrating the yield gap between traditional farm practice and attainable yield using available technologies. All management factors except plant population were necessary for reducing the yield gap. Fungicide and *Bacillius thuringiensis* gene (Bt) traits provided the greatest yield increases compared to the ST system. Averaged over sites and years, if each factor was withheld from the HT 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. The yield contribution of each factor was greater when applied as part of a full complement of supplemental inputs than when added individually to the standard input system.

Numerous recent papers have established that agricultural production must increase substantially to meet the increasing per capita demand for food, feed, fuel, and fiber of a burgeoning human population (Keyzer et al., 2005, Food and Agriculture Organization, 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; research investment into this critical area has, to date, been inadequate.

Meeting the demand for agricultural commodity crops requires us to increase crop yields and close yield gaps (the difference between a 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, wheat and rice yields generally exceed 70% of yield potential but corn yields do not exceed 70% of potential in any of the major corn-producing regions. Such yield gaps can be minimized by improving our understanding of the management factors that are the most influential in achieving crop yield potential on a consistent basis (Dobermann et al., 2003).

Plant population directly limits the 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 a higher plant population (Carlone and Russell, 1987; Duvick, 1997; Sangoi et al., 2002; Tokatlidis and Koutroubas, 2004; Hammer et al.,

M.L. Ruffo, Bioceres Semillas, Santa Fe, Argentina; L.F. Gentry, Illinois Corn Growers Assn., Urbana, IL; A.H. Henninger, Monsanto, Rushville, IL; J.R. Seebauer and F.E. Below, Crop Sciences Dep., Univ. of Illinois, Urbana, IL 61801-4730. Received 10 July 2014. Accepted 25 Oct. 2014. *Corresponding author (fbelow@illinois.edu).

Published in Agron. J. 107:495–505 (2015)
doi:10.2134/agronj14.0355

Abbreviations: Bt, *Bacillius thuringiensis* gene; –Bt, HT control system with non-Bt variety; +Bt, ST control with Bt-containing variety added; CU, Champaign-Urbana study site; DS, Dixon Springs Research Center site; –Fung, HT control treatment without fungicide; +Fung, ST control treatment with added fungicide; HT, high technology level; +N, additional side-dress N to ST control; –N, HT control without side-dress application; +Pop, high population treatment added to ST control; –Pop, decreased population treatment within HT control; +P–S–Zn, P, S, and Zn combination fertilizer added to ST control; –P–S–Zn, HT control treatment without P–S–Zn combination fertilizer; ST, standard technology level; VT, tasseling.

2009). Furthermore, because of corn's limited ability to use inputs efficiently at suboptimal plant population levels, 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); proper crop nutrition is therefore needed to reduce the yield gap. Of all the nutrients required for corn grain production, N 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, overapplication of N leads to lower profitability and has a potential negative environmental impact (Dinnes et al., 2002). 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 P harvest index is the highest harvest index among all nutrients for corn (Bender et al., 2013); P is the least soil-available of the major plant nutrients (Kovar and Claasen, 2005) and is the second most yield-limiting nutrient after N (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 found that 39% of the soil samples analyzed were below critical levels in 2010, indicating a sharp decline in soil P fertility and widespread deficiency in this state. Among the secondary nutrients (Ca, Mg, and S), S 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 has a season-long uptake (Bender et al., 2013). It has been demonstrated that Zn is the micronutrient that most commonly and severely limits corn yield in the world (Bell and Dell, 2008) and in North America in particular (Alloway, 2009). Among all micronutrients, the harvest index for Zn is the greatest (Bender et al., 2013).

Weed competition, along with insect and disease pressure, are the 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 commercial corn production in the United States. In 2013, 90% of all corn acres in the United States 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 (*Coleoptera*, *Diabrotica* spp.) and the other type of Bt trait confers resistance to European corn borer (*Ostrinia nubilalis*) and similar "moth" type insects (Nielsen, 2010). Corn rootworm larvae (*Diabrotica* spp.) feed on corn roots, thereby limiting plant uptake of water and nutrients (Kahler et al., 1985; Riedell, 1990; Spike and Tollefson, 1991), increasing the 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 the photosynthetic area of the plant and, in turn, lessening 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, more commonly referred to as strobilurin fungicides, were labeled for corn in the mid-2000s. Fungicides containing strobilurin are known to be effective against a broad spectrum of fungal pathogens (Grossman and 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 (i) demonstrate and quantify the corn yield gap in Illinois, (ii) quantify the impact of different management technologies on the reduction of the corn yield gap, (iii) determine the impact of these technologies combined, and (iv) assess the effect of these technologies on yield components (kernel weight and number) as a means to understanding 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: (i) plant population, (ii) Bt hybrid trait, (iii) strobilurin-containing fungicide, (iv) P–S–Zn fertility, and (v) N fertility.

Factorial arrangements of treatments are commonly used for agronomic experimental designs when it is suspected that one factor may have a 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 to keep the number of treatments, experimental area, and fieldwork manageable. To avoid the practical issues associated with complete factorial experiments, we implemented a straightforward treatment structure that included two control treatments (ST and HT) 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: (i) ST versus HT controls, (ii) individual supplemented treatments versus their counterpart ST control, and (ii) individual withheld treatments versus their counterpart HT 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. The fields in each site were within 3 km of each other and had similar soil types, fertility levels, and management histories. Both sites were nonirrigated 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 to 5% slopes and were classified as Grantsburg silt loam (fine-silty, mixed, active, mesic Oxyaquic Fragiudalf). At CU, the preplanting soil properties at the 0- to 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- to 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 from the time of preplanting soil testing to the time the plant needs it due to the unpredictable Illinois weather (Fernandez et al., 2012). Soybean 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 (National Oceanic and Atmospheric Administration Urbana weather station 118740, 40°05′ N, 88°14′ W, elevation: 220 m above sea level); reported departures from average are compared to the 30-yr 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: 50 m above sea level); departures from average reflect the 20-yr 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 a 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-methylbenzyl (1RS)-cis-3-([Z]-2-chloro-3,3,3-trifluoroprop-1-enyl)-2,2-dimethylcyclopropanecarboxylate] 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*-([1*S*]-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: (i) plant population, (ii) transgenic insect resistance conferred by the Bt trait, (iii) strobilurin-containing fungicide, (iv) P–S–Zn fertility, and (v) N fertility (Table 1). Each factor consisted of two levels representing either the current or lesser agronomic practice (referred to as ST) or a supplemental level (referred to as HT). The 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 and corn rootworm) were used, denoted as –Bt or +Bt, respectively. Both hybrids had a 111-d relative maturity rating 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, 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 the tasseling stage (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 with added P, S, and Zn, 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

Table 1. Supplemented and withheld treatment structure: The treatment exceptions are either supplemented (+ factor) to the standard technology control, or withheld (–factor) from the high technology control. 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

† Specific details are found in the Materials and Methods section.
‡ "None" in the exception column indicates the control.
§ Bt, *Bacillius thuringiensis* gene; Fung, treatment with strobilurin fungicide; Pop, plant population; Base, application of N fertilizer at the base rate.

Mosaic Company, Plymouth, MN). The MicroEssentials SZ was broadcast immediately before planting and incorporated with a cultivator-harrow. The –P–S–Zn level would be the normal practice in 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 application at the base rate and base application plus side-dressing, denoted as –N or +N, respectively. For the –N 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 +N 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 Versus Withheld Treatment Structure

The supplemented versus withheld treatment structure used in this study assessed the 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 HT level of each management factor while all other management factors were maintained at the ST 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 HT 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 ST level of agronomic management in an intensified management system (HT).

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 as fixed effects and blocks were declared to be random and nested within locations and years. The normality and homogeneity of the residuals were tested using the Shapiro–Wilks test and the Brown and Forsythe test. The homogeneity of variances was confirmed with the folded F-test ($P < 0.05$). A preplanned set of *t*-tests was used to evaluate the significance of the difference in least square means estimates between specific treatments at the 0.1 or 0.05 probability level. The preplanned comparisons were comprised of the differences between the HT and ST controls, between the five supplemented treatments (+Pop, +Bt, +Fung, +P–S–Zn, and +N) and the ST control, and between the five withheld treatments (–Pop, –Bt, –Fung, –P–S–Zn, and –N) and the HT control. A 95% confidence interval was calculated for the differences between the HT and ST 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 ST 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 AND DISCUSSION

Weather

Weather data for each growing season (April–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

Table 2. Average monthly temperature and precipitation for two sites [Champaign-Urbana (CU) and Dixon Springs (DS)] and two growing seasons.

Year	Month	Champaign–Urbana		Dixon Springs	
		Temperature†	Precipitation†	Temperature	Precipitation
		°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)

† Values in parentheses represent the departure from average monthly temperature or precipitation.

growing season was hot and dry, especially during pollination and grain-filling, 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 probably decreased yield potential.

Corn Yields

Summary of Treatment and Site by Year Effects

There was a significant effect of treatment, site, year and site × year, and treatment × site × year interaction on corn grain yield ($P < 0.0001$).

The greatest yield at any site in any given year was obtained with the HT 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 that was conducive to greater yields than the other three site-years.

We estimated the corn yield gap as the difference between the ST control, representing traditional farming practice, and the HT 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%) ($P < 0.0001$) (Table 3 and 4). The yield gap was positively correlated with the yield of the HT ($r = 0.87, p = 0.13$) and ST controls ($r = 0.51, p = 0.48$) but more strongly so with the HT control yield. This finding indicates that the gap is greatest in environments capable of supporting higher yields but which are limited to lower yields by management practices.

Table 3. Corn yield (at 0% moisture content) response to 12 management treatments for 2 yr (2009 and 2010) at two sites [Champaign-Urbana (CU) or Dixon Springs (DS)] and the average of sites and years.

Treatment		2009		2010		Across sites and years
Primary technology	Exception	CU	DS	CU	DS	
		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.
† "None" in the exception column indicates the control.
‡ Significant at the 0.10 probability level compared to the respective control treatment.
§ Bt, *Bacillius thuringiensis* gene; Fung, treatment with strobilurin fungicide; Pop, plant population.

Plant Population Effect

Comparison of the HT and ST 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 ST and HT controls (Table 4). In terms of yield effects resulting from the population treatment, only one significant instance was identified across the four site-years: in 2009 at CU, +Pop (increasing the plant population of the ST system) reduced grain yield by 0.77 Mg ha^{-1} (7%) relative to the ST 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 HT 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. Furthermore, 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 ST 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 HT control system with a non-traited near-isoline significantly reduced grain yield by 0.85 to 1.4 Mg ha^{-1} (Table 4), with an average reduction of 1.13 Mg ha^{-1} (8.7%) relative to the HT control (Table 3 and 4).

A number of recent studies have demonstrated that Bt corn hybrids tolerate a greater plant population density than non-Bt hybrids, largely because of 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 HT control system (averaging 8.7% less yield than the HT control) relative to the more modest increase measured when the Bt trait was added to the ST control system (averaging 4.5% greater yield than the ST control) demonstrates that the Bt trait provided greater value in the HT system. By overcoming the most pressing causes of yield reduction at high plant populations, namely 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 fungicide containing strobilurin at VT was unexpected, as we did not observe measurable leaf fungal infection in any of the site-years (data not shown). Furthermore, particularly in 2010, there was hot, dry weather that should have deterred fungal growth. Adding fungicide to the ST 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 ST control did not affect yield at either site in 2009. Omitting strobilurin fungicide from the HT control significantly reduced yield for three of four site-years relative to the HT control (Table 3); reductions ranged from 9.5 to 18% (Table 4). Averaged

Table 4. Differences in yield in absolute terms and as a percentage-wise (in parentheses) for supplemented or withheld treatments relative to the standard technology (ST) or high technology (HT) controls when grown at two sites [Champaign-Urbana (CU) or Dixon Springs (DS)] over 2 yr (2009 and 2010). The percentage difference between the ST and HT controls is expressed relative to the ST control.

Treatment		2009		2010		Across sites and years
Primary technology	Exception	CU	DS	CU	DS	
		Mg ha^{-1}				
		Compared with the ST 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 the HT 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.

‡ Bt, *Bacillius thuringiensis* gene; Fung, treatment with strobilurin fungicide; Pop, plant population.

§ The percentage difference between the standard and high technology controls is expressed relative to the standard technology control.

over site-years, omitting fungicide from the HT system reduced grain yields by 11.6%. Fungicide was the single factor that had the largest impact on corn yield under the HT system.

The results, considered within the context of yearly weather conditions, suggest that the strongly positive effect of the strobilurin fungicide in 2010 was related to its effect as a plant growth regulator 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 that involve an abbreviated grain-filling period (Westgate 1994), reduced leaf area (Denmead and Shaw, 1960; NeSmith and Ritchie, 1992; Abrecht and Carberry, 1993), and decreased vegetative dry matter (Claassen and Shaw, 1970). Our data suggest that by prolonging the time period when photosynthesis can 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 application of strobilurin kresoxim-methyl as well as an increase in endogenous cytokinins, potentially explaining the 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: (i) plant growth regulators may play a role in high-yielding, intensively managed agricultural systems and (ii) 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, specifically investigating 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, and Zn to the ST control increased yields by almost 9% at DS in 2010 but did not affect yields for other site-years (Table 3 and 4). Omitting P, S, and Zn from the HT 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 required the greatest availability of P, S, and Zn for maximum yield.

The side-dressed application of 112 kg N ha^{-1} alongside the base application of 202 kg N ha^{-1} of the ST control affected yield in one of four site-years (a 7.9% yield increase in 2009 in CU, Table 4). Omitting the side-dressed application from the HT control reduced yield in the same two site-years, where we found a similar effect to the application of P, S, and 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 side-dressed N fertilizer application benefits an intensively managed (high population and high input) cropping system more than the ST (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 interplant competition under low-N conditions as well as high responsiveness to side-dressed N applications.

System Effects

The experimental design allows evaluation of the single and combined value of factors on corn yield and assessment of whether 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 ST supplemented and the ST control treatments. The resulting individual yield value of each supplemented factor (averaged across sites and years) was significant for the Bt hybrid trait and fungicide, 0.46 and 0.45 Mg ha^{-1}, 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 HT and ST control treatments, was 2.87 Mg ha^{-1} (across sites and years) with a 95% confidence interval of 2.2 to 3.27 Mg ha^{-1}. The lower limit of 2.2 Mg ha^{-1} was substantially greater than the average yield value for the summation of all individual supplemented factor contributions, 1.52 Mg ha^{-1} (Table 5), which demonstrates the significance of the synergistic nature of the yield increase resulting from the combination of intensified

Table 5. Comparisons between the overall yield differences between the high technology (HT) and the standard technology (ST) control treatments (shown as 95% confidence intervals; $\mu_{High} - \mu_{Std}$) and the summation of the additional yield values provided by each supplemental treatment to the ST control (i.e. ST +Pop, ST +Bt, ST +Fung, ST +P–S–Zn, and ST +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.

Treatment	2009 CU †	2009 DS	2010 CU	2010 DS	All site-years
	Mg ha^{-1}				
$\mu_{High} - \mu_{Std}$	2.75–4.23	2.10–3.47	1.57–2.66	1.70–3.07	2.20–3.27
$\sum(Y_{+FACTOR} - Y_{Std})$ ‡	0.10	0	0.87	1.76	0.91

† CU, Champaign-Urbana study site; DS, Dixon Spring study site; Bt, *Bacillius thuringiensis* gene; Fung, treatment with strobilurin fungicide; Pop, plant population.

‡ $\sum\left[(Y_{+Bt} - Y_{Std}) + (Y_{+Fung} - Y_{Std}) + (Y_{+P\text{-}S\text{-}Zn} - Y_{Std}) + (Y_{+N} - Y_{Std})\right]$.

Table 6. Influence of 12 management designs on yield components measured at two sites [Champaign-Urbana (CU) and Dixon Springs (DS)] and 2 yr (2009 and 2010).

Treatment		Kernel number					Kernel weight				
		2009		2010			2009		2010		
Primary technology	Exception	CU	DS	CU	DS	All site- years	CU	DS	CU	DS	All 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.

† "None" in the exception column indicates the control.

‡ Significant at the 0.10 probability level compared to the respective control treatment.

§ Bt, *Bacillius thuringiensis* gene; Fung, treatment with strobilurin fungicide; Pop, plant population.

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 HT and ST controls. The same conclusion is reached even if all factors are considered, regardless of whether 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 HT control was greater than the yield increase occurring when that factor was added to the ST control. Thus, the yield contribution of a factor was generally greater when it was 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 × 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 HT control relative to the ST 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 HT control (Table 6). In contrast, kernel number was not affected by any of the management factors when each factor was added singly to the ST 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 ST or HT 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 either site in 2009 and was 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 nonsignificant 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 efforts to increase corn yields and thus reduce 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

Yield component data (Table 6) demonstrated that increasing the plant population without increasing crop inputs (+Pop) resulted in a 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 in 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 ensure the viability of the 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 that the grain yield reduction caused by population stress is less than expected. The average

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

Yield component	2009		2010		
	CU†	DS	CU	DS	Across sites and 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 0.001 probability level.

† CU, Champaign-Urbana study site; DS, Dixon Springs study site.

‡ Significant at the 0.10 probability level.

yield reduction for the +Pop treatment was a modest and nonsignificant 0.24 Mg ha^{-1} (2.4%; Table 4) relative to the ST control; the yield components resulting in the measured yield reduction were the product of a nonsignificant 3.6% average increase in kernel number and a significant 5.5% average decrease in kernel weight relative to the ST control ($P < 0.10$). In addition, owing to yield component compensation, these results support other studies that conclude 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 HT system, reducing the 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 plants ha^{-1} resulted in an a priori decrease in potential kernel number per area of 29%. However, in the HT 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 HT system with the lower population (Table 6).

Bt Effects

Adding the Bt trait to the ST control did not affect kernel number or kernel weight for any site-year or across all site-years (Table 6). Omitting the trait from the HT 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 HT 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 incurred by corn rootworm feeding (as reported by Nielsen, 2001) improving ovule pollination.

Strobilurin Effects

Kernel number was affected by adding a strobilurin application to the ST control (+Fung) in just one of four site-years (a 6% reduction in kernel number relative to the ST control at CU in 2009). However, omitting strobilurin from the HT 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 per ear) and row length (kernels per row) are established, we concluded that fungicide reduced kernel abortion in the HT system during 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 that leaf protection extended into the grain-filling stage. On average, kernel weight increased by 8% when strobilurin fungicide was added to the ST control and decreased by 12% when it was omitted from the HT 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.

The 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 more kernels (per unit area) and heavier kernels. Correspondingly, strobilurin was most effective under increased stress conditions (i.e., drought and/or a 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, and Zn to the ST control resulted in an 8% increase in kernel number, corresponding closely to the observed 9% increase in yield (relative to the ST control) (Table 6). Omitting P, S, and Zn from the HT 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 HT 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, and 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-dressed N application to the ST 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 ST control. Conversely, the 8.7% yield reduction when N was omitted from the HT control in 2009 at CU was primarily the result of a 6.9% reduction in kernel number (Table 3 and 6). Boomsma et al. (2009) found that high populations (104,000 plants ha $^{-1}$) receiving less side-dressed N fertilizer (165 versus 330 kg N ha^{-1}) yielded less in 2 out of 3 yr, 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 (HT control) combining increased plant population, transgenic insect resistance, strobilurin fungicide, and balanced crop nutrition yielded 28% (ranging from 21 to 32%) more corn grain (2.87 Mg ha^{-1}, ranging from 2.12 to 3.50 Mg ha^{-1}) than the standard system (ST 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 HT 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 the plant population without adjusting the other components of the cropping system can result in a significant yield decrease. Withholding an intensified factor from the HT system decreased yield, primarily by decreasing kernel number. Plant population was negatively correlated with kernel weight; 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 (HT) than the ST system. This finding has important economic implications, as the benefit of each technology will be more favorable under a system similar to that used in this experiment rather than when they are evaluated as a single technology. We believe that more rapid advancements in closing yield gaps and increasing grain production will be achieved if agronomists and scientist evaluate new technologies under more intensive management systems.

ACKNOWLEDGMENTS

This research was made possible with partial funding from the multistate Agricultural Experiment Station project NC-1168 and NC-1200 "Regulation of Photosynthetic Processes" and the Illinois AES project 802-908. Funding and in-kind support for this project were provided by BASF, Koch Industries Inc., Monsanto, and The Mosaic Company. We would like to thank Brad Bandy and Jim Kleiss for their assistance in trial implementation and analyses.

REFERENCES

Abrecht, 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. doi:10.1016/0378-4290(93)90050-W

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. doi:10.2135/cropsci1967.0011183X000700050030x

Alloway, B.J. 2009. Soil factors associated with zinc deficiency in crops and humans. Environ. Geochem. Health 31:537–548. doi:10.1007/s10653-009-9255-4

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. doi:10.2134/agronj2008.0039

Bartlett, D.W., J.M. Clough, J.R. Godwin, A.A. Hall, M. Hamer, and B. Parr-Dobrzanski. 2002. The strobilurin fungicides. Pest Manag. Sci. 58:649–662. doi:10.1002/ps.520

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. doi:10.2134/agronj2012.0352

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. doi:10.2134/agronj2009.0082

Borras, L., G.A. Slafer, and 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. doi:10.1016/j.fcr.2003.08.002

Bradley, C.A. 2012. Managing diseases In: Illinois Agronomy Handbook. Univ. of Illinois Ext, Urbana, IL. p. 197–207. 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. Natl. Acad. Sci. USA 107:12052–12057. doi:10.1073/pnas.0914216107

Camberato, J., and S. Casteel. 2010. Keep an eye open for sulfur deficiency in wheat. Purdue Univ. Dep. of Agronomy, Soil Fertility Update. http://www.agry.purdue.edu/ext/soybean/Arrivals/04-13-10_JC_SC_Sulfur_deficiency.pdf. (accessed 8 Dec. 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. doi:10.2135/cropsci1999.0011183X003900020017x

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. doi:10.2135/cropsci1987.0011183X002700030008x

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. doi:10.2134/agronj1965.00021962005700030003x

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. doi:10.1146/annurev.energy.28.040202.122858

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. doi:10.1016/j.fcr.2012.03.008

Claassen, M.M., and R.H. Shaw. 1970. Water deficit effects on corn. I. Grain components. Agron. J. 62:652–655. doi:10.2134/agronj1970.00021962006200050032x

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. doi:10.2134/agronj2009.0217

Cox, W.J. 1997. Corn silage and grain yield responses to plant densities. J. Prod. Agric. 10:405–410. doi:10.2134/jpa1997.0405

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. p. 206–223.

Denmead, O.T., and R.H. Shaw. 1960. Effects of soil moisture stress at different stages of growth on development and yield of corn. Agron. J. 52:272–274. doi:10.2134/agronj1960.00021962005200050010x

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. doi:10.2134/agronj2002.0153

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 and Horticulture Dep., Univ. Nebraska–Lincoln. http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1524&context=agronomyfacpub (accessed 27 Nov. 2014).

Dodd, J.L. 1977. A photosynthetic stress-translocation balance of corn stalk rot. In: H.D. Loden and 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. doi:10.1016/S0929-1393(97)00044-9

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. Entomol. 122:179–183. doi:10.1111/j.1439-0418.1998.tb01481.x

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 Mar., 1996. CIMMYT, Mexico City. 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. Nat. Biotechnol. 30:493–496. doi:10.1038/nbt.2259

Fageria, N.K., and V.C. Baligar. 2005. Enhancing nitrogen use efficiency in crop plants. Adv. Agron. 88:97–185. doi:10.1016/S0065-2113(05)88004-6

Food and Agriculture Organization (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. FAO, Rome, Italy. http://www.fao.org/docrep/012/ak542e/ak542e00.htm (accessed 8 Dec. 2014).

Fernandez, F.G., S.A. Ebelhar, E.D. Nafziger, and R.G. Hoeft. 2012. Chapter 9: Managing nitrogen. In: Illinois agronomy handbook. Univ. Illinois Crop Science Extension and Outreach. http://extension.cropsci.illinois.edu/handbook/ (accessed 6 Oct. 2014).

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 94:6–8.

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 10.1038/nature10452. doi:10.1038/nature10452

Grossmann, 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. doi:10.1016/S0176-1617(99)80262-4

Grossmann, K., and G. Retzlaff. 1997. Bioregulatory effects of the fungicidal strobilurin kresoxim-methyl in wheat (*Triticum aestivum*). Pestic. Sci. 50:11–20. doi:10.1002/(SICI)1096-9063(199705)50:13.0.CO;2-8

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. 106:1838–1846. 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. doi:10.2135/cropsci2008.03.0152

Holmes, J., and D. Rueber. 2006. Soybean yield response to headline fungicide applications. Iowa State Univ. 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. doi:10.2134/agronj1985.00021962007700050023x

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? Ecol. Econ. 55:187–202. doi:10.1016/j.ecolecon.2004.12.002

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? Glob. Ecol. Biogeogr. 19:769–782. doi:10.1111/j.1466-8238.2010.00563.x

Lobell, D.B., K.G. Cassman, and C.B. Field. 2009. Crop yield gaps: Their importance, magnitudes, and causes. Annu. Rev. Environ. Resour. 34:179–204 10.1146/annurev.environ.041008.093740. 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. doi:10.1126/science.1251423

McLaughlin, D.W. 2011. Land, food, and biodiversity. Conserv. Biol. 25:1117–1120. doi:10.1111/j.1523-1739.2011.01768.x

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. doi:10.1038/nature11420

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. doi:10.2134/agronj1992.00021962008400010021x

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

Nielsen, R.L. 2010. A compendium of biotech corn traits. Purdue Corny News Network Articles. Purdue Univ. Dep. of Agronomy. http://www.agry.purdue.edu/ext/corn/news/timeless/BiotechTraits.html (accessed 27 Nov. 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. doi:10.2135/cropsci1990.0011183X003000030031x

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. doi:10.2135/cropsci1999.3951332x

Ritchie, S.W., J.J. Hanway, and 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. doi:10.1016/S0378-4290(02)00124-7

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., Madison, WI. p. 39–48.

Singer, J.W., R.W. Taylor, and W.J. Bamka. 2003. Corn yield response of Bt and near-isolines to plant density. Crop Manage. 2. doi:10.1094/CM-2003-0829-01-RS.

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. doi:10.2135/cropsci1991.0011183X003100030048x

Stanger, T.F., and J.G. Lauer. 2006. Optimum plant density of Bt and non-Bt corn in Wisconsin. Agron. J. 98:914–921. doi:10.2134/agronj2005.0144

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 ed. 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. Sci. Agric. 65:346–353.

Stringfield, G.H., and L.E. Thatcher. 1947. Stands and methods of planting corn hybrids. Agron. J. 39:995–1010. doi:10.2134/agronj1947.00021962003900110006x

Tilman, D., C. Balzer, J. Hill, and B.L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. USA 108:20260–20264. doi:10.1073/pnas.1116437108

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. doi:10.1016/j.fcr.2003.11.013

Tollenaar, M., and E.A. Lee. 2002. Yield potential, yield stability, and stress tolerance in maize. Field Crops Res. 75:161–169. doi:10.1016/S0378-4290(02)00024-2

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

Vitosh, M.L., J.W. Johnson, and D.B. Mengel. 2007. Tri-State fertilizer recommendations for corn, soybeans, wheat and alfalfa. Ohio State Univ. http://ohioline.osu.edu/e2567/index.html (accessed 17 June 2014).

Westgate, M.E. 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.

Wise, K., and D. Mueller. 2011. Are fungicides no longer just for fungi? An analysis of foliar fungicide use in corn. Am. Phytopathological Soc., St Paul, MN. doi:10.1094/APSnetFeature-2011-0531.