ANALYSIS OF MANAGEMENT FACTOR CONTRIBUTIONS TO HIGH-YIELDING CORN PRODUCTION SYSTEMS

BY

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THESIS

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ABSTRACT

Five agricultural management factors were tested in an "omissions treatment" experiment conducted in central Illinois to assess their individual and cumulative contribution to a high-yield corn production system. The five management factors (non-nitrogen (N) fertility, N fertility, hybrid trait, plant population, and fungicide application) were evaluated by establishing 2 levels (traditional and advanced) of each factor. Twelve total treatments consisted of a High Technology (HT) treatment (all advanced factors combined), a Traditional (TRAD) treatment (all traditional factors combined), five treatments of the HT system with each factor individually replaced with its traditional-level counterpart, and five treatments of the TRAD system with each factor individually replaced with it advanced-level counterpart. During years with good season-long growth conditions, like 2009, increased plant population and additional nitrogen (N) fertilizer were the critical factors for increasing crop yield, pushing the system to produce the maximum yield of 14.5 Mg ha^{-1}. In high-stress years, like 2010, plant health factors, like strobilurin fungicide and corn rootworm-resistant hybrids, was most important by protecting crop yield potential. This data also suggests that plasticity of the corn plant provides flexibility for the plant to adjust its allocation of resources in response to environmental conditions, resulting in a lower probability that increasing plant populations will reduce yields in a bad year relative to the probability that it will increase yields in a good year. Although there were no net differences in grain quality between the HT and TRAD systems, N fertility, plant population, and fungicide application affected kernel protein and oil concentration relative to the other management factors tested. This study suggests that a system of synergies is created when these five agronomic management factors are combined. The results of this 2-year study suggest that corn yields of 13-16 Mg ha^{-1} are consistently achievable under non-irrigated conditions in the absence of drought when the high-yielding factors tested here are combined.

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INTRODUCTION

Corn (*Zea mays* L.) yield potential of the U.S. Corn Belt must increase in order to meet future domestic and global demands for food and biofuel. Of the 9.4 million metric tons of corn traded on the world market this year (as of Nov. 1, 2011), 43% was exported from the U.S., more than any other country in the world (USDA-FAS). Illinois is one of the highest yielding corn production states in the U.S. Corn Belt with average corn yields 15% above the U.S. average yield; IL produces about 18% of the U.S. corn crop and more than 7% of the corn produced in the world (Nafziger 2009). The objective of this research study is to identify and quantify the most critical components of a high-yielding corn production system for well-adapted, non-irrigated environments, like IL. A high-yielding corn production system is defined here as one with the capacity to consistently provide 250-300 bushels of corn grain per acre (13-16 Mg ha^{-1}), which is approximately twice the current average corn grain yield in the U.S. The biological potential of a corn plant with advanced genetics is about 500 bushels $acre^{-1}$ (26.5 Mg ha^{-1}) (Walsh 1982; Gilland 1985, as reported in Gilland 2002), thus there is great potential for increased corn yields through improved management and breeding for increased stress tolerance at high plant populations (Tollenaar & Lee 2002). To achieve a high-yielding corn production system, we adopted the concept of Liebig's Law of the Minimum, which states that agricultural production is controlled not by the total amount of resources present to the crop, but by the resource that is most limiting. The factors that most commonly limit yield in corn production systems are weather conditions, soil moisture, fertility deficiencies, plant population, weed and disease pressure, insect damage, unsuitable hybrids, and soil physical and chemical properties. Using this approach, we propose to maximize corn grain production by supplying adequate nutrients (nitrogen, phosphorus, sulfur, and zinc) and crop health chemicals (strobilurin fungicide) to support a high plant population (111,150 plants ha^{-1}) of advanced seed hybrids.

For the purpose of our research objectives, we do not consider pest, disease, and weed pressure high-yield factors because they can only reduce crop yield; therefore we assume that they are managed in a high-yielding system. Previous data collected by the Crop Physiology Lab at University of Illinois, Urbana-Champaign points to seven factors that are critical to high-yielding corn production:

1. Weather
2. Nitrogen fertility
3. Hybrid
4. Previous Crop
5. Plant population
6. Tillage
7. Crop health chemicals

Additional research suggests that non-nitrogen fertility (especially phosphorus, sulfur, and zinc) is also critical to increased corn yields when plant populations are increased above 98,800 plants ha^{-1}.

Weather, the greatest determinant of yield potential, cannot be managed or predicted with accuracy, thus, we must adapt to local weather patterns as much as possible. The most common **tillage** practice, fall chisel plow with spring field cultivation, was used for seedbed preparation in this study. As a management factor, **plant population** directly limits crop production potential; accordingly, we tested two plant populations: a currently common population of 79,040 plants ha^{-1} and an advanced population of 111,115 plants ha^{-1}. **Nitrogen (N) fertility** is generally the most critical nutrient management factor for corn production. We tested a currently common N rate of 202 kg N ha^{-1} applied pre-plant and an advanced N rate of 202 kg N ha^{-1} plus 112 kg N ha^{-1} side-dress. The most recent and perhaps radical advance in corn breeding, the introduction of genetically engineered insect- and herbicide-tolerant **hybrids** has resulted in the wholesale adoption of these traits in commercial corn production. However, the safety, longevity, and integrity of bioengineering technology is fervently questioned. To examine the production value of genetically engineered corn rootworm (CRW) resistance traits, we tested the currently favored “triple-stack” hybrid containing CRW resistance traits against the same corn cultivar without the CRW traits. Soybean is the most common **preceding crop** for corn production in the U.S., especially in the central Corn Belt; therefore, previous crop was maintained as soybean for all treatments throughout the experiment. The **crop health chemical** that has displayed the greatest promise for increasing crop yields in high population systems is strobilurin fungicides. We tested the value of a strobilurin fungicide (as Headline, a BASF fungicide) by either applying it at vegetative tassle (VT) or omitting it. Phosphorus (P), sulfur (S), and zinc (Zn) are also important management factors in high-yielding corn systems, especially when seasonal weather is favorable for optimum crop growth. We tested these three **non-N fertility** components, comparing them with no non-N fertilizers, to examine their benefit in the high-yielding corn production environment.

Based on these factors, we established an omissions treatment design to quantify the importance of five factors (non-nitrogen fertility, nitrogen fertility, hybrid, plant population, and fungicide) considered critical for increasing corn grain yield. An omissions treatment design selectively tests individual factors for their value to crop yield individually and cumulatively.

The objective of this research experiment was to quantify the agricultural management factors that individually and cumulatively provide the greatest yield potential for corn production, making it possible to consistently produce 13-16 Mg ha^{-1} (250-300 bushels acre^{-1}).

Hypothesis: Corn production systems will benefit most from a combination of high population and increased N fertility in a year with favorable weather; in a year with poor growing conditions, growth regulators and plant hybrid will be the most influential factors.

LITERATURE REVIEW

Corn (*Zea mays* L), like most grain crops, is a summer annual, producing flowers, filling seeds, maturing, and dying within a single growing season. As a C4 plant, corn is well-adapted for crop production in high light, high heat environments, making it more efficient at carbon capture and grain production than the world's other two staple crops, wheat and rice, under the climatic conditions of the U.S. Midwest. Corn has also proven to be receptive to breeding efforts, both traditional and transgenic, making it possible to create hybrids adapted to a range of environmental conditions and /or resistant to a variety of pests and diseases. Effective breeding efforts, increased plant populations, and improved management practice have resulted in a nearly 7-fold increase in corn yields since 1924 with approximately linear increases amounting to 65-75 kg ha^{-1} $year^{-1}$ (Duvick 2005).

Grain yield per unit area is the product of grain produced per plant and number of plants per unit area and is a parabolic function of plant density (Hashemi et al. 2005). Crop grain yield is a factor of the number of plants (ears) per unit area, rows per ear, kernels per row, and kernel weight. The number of rows multiplied by the number of kernels per row determines total kernels per ear. Typically, 750-1000 ovules (potential kernels) develop per ear shoot, but generally only 400-600 kernels are harvested per ear. Row number of a corn plant is determined early in crop development, beginning soon after the ear shoot is initiated, V5-V6, and completed by about V8; stresses resulting from weather or plant competition during this period may reduce the number of rows per ear (Hollinger and Changnon 1993). Row number is determined primarily by plant genetics, rather than by growth environment, although it can be modified by poor growing conditions. Kernel number (row length), on the other hand, is primarily controlled by environmental conditions. The potential kernel number (row length) is determined by the development of kernel primordia between V12 and V15 (Ritchie et al. 1986), thus weather conditions during this time period determine potential kernel number per row. Actual kernel number per row is determined during "grain fill," the period following pollination and ending with black layer (i.e. physiological maturity) during which the corn kernels are developing within the corn ear.

The effect of weather on crops has always been the main source of year-to-year variability in yields under non-irrigated field conditions (Hollinger and Changnon 1993). Like most grain crops, corn responds to environmental signals that regulate its developmental stages, assuring that adapted plants have sufficient time to develop mature and viable seeds before dying in the fall. Photoperiod and heat accumulation units are two common environmental signals for plants. Modern corn hybrids are not very responsive to photoperiod (Rood and Major 1980; Warrington and Kanemasu 1983), but heat accumulation units, measured as growing degree days, drive crop physiological development (Nafziger 1998) and, along with soil moisture and fertility requirements, largely determine number of rows per ear, pollination, and kernel weight, among other critical yield factors. Precipitation is also important from a developmental perspective. Grant et al. (1989) concluded that the period most sensitive to drought stress begins at silking and extends for 22 days. Eck (1986) investigated the effect of water stress at various corn growth stages and determined that water deficits during vegetative growth reduced kernel number, but had little effect on kernel weight. Temperature and water stress during the grain fill period can result in significant yield loss due to reduced kernel weight and kernel abortion. Kernel abortion during grain-fill results in "tip-back," the observation of kernels that remain undeveloped at the tip of the corn ear. The observation of tip-back is a result of grain development from the base of the corn ear to the tip, making the tip the last part of the ear to produce kernels. For a 16-row ear of corn, the loss of one kernel per row results in a yield loss of approximately five bushels per acre at conventional planting populations. A number of studies conducted by Jones et al. (1981, 1984, 1985) demonstrated that air temperatures <15° C or >25° C during grain-fill reduce corn yields by decreasing endosperm cell formation and starch granule numbers. Frosts early in the growing season are less detrimental to corn than to other crops because the growing point of the young corn plant remains underground, safe from light frosts, until about V5 (Ritchie et al. 1986). Additionally, because ear initiation does not occur until about V5, environmental stressors prior to this stage do not directly affect ear size determination unless it results in a severely weakened plant. Heat units and precipitation also affect the plant indirectly by controlling nutrient availability to the crop through decomposition and related mineralization effects on organic compounds. Nutrients such as calcium, magnesium, and sulfur reach the plant via mass flow, or movement of nutrients in the transpiration stream. When soil moisture is limiting, mass flow slows, directing less nutrients to the plant (Barber et al. 1963). Alternatively, when soil moisture is excessive and the soil is saturated with water, creating anaerobic conditions, fertilizer N can be lost through the process of denitrification, in which N is reduced from NH_4^+ and NO_3^- forms to N_2 gas and to a lesser extent (about 5-10% of total N denitrified) is converted to the potent greenhouse gas N_2O. Because of the net negative charge on soils, plant nutrients that exist in soil as cations are generally retained on the negatively charged soil and organic matter particles, resulting in relatively little leaching of nutrients like NH_4^+, Ca^{2+}, Mg^{2+}, Na^+, and K^+. From a predominantly physical perspective, strong winds and hail can have devastating effects on crop yield, resulting in partial to complete grain loss. Finally, cold, wet soils early in the growing season have a negative effect on seedling emergence, stand establishment, and early season plant vigor.

Corn plants require 17 nutrients to complete their life cycle and produce grain (Joern and Sawyer 2006). In commercial cropping systems, nutrients come primarily from the soil and fertilizers with small amounts also provided from rain water, soil minerals, and decomposition of plants, animals, and manures. Nitrogen is typically the most limiting nutrient for corn production and a high-yielding crop requires 308 kg N ha^{-1} to reach physiological maturity (Joern and Sawyer 2006). In the absence of fertilizer N, productive soils will produce corn yields that average about 55% of optimum yields in continuous corn (CC) systems and 70% of yield in corn-soy rotations (Joern and Sawyer 2006). Additionally, 6-24 kg N ha^{-1} comes from precipitation and small amounts are made available from soil minerals, crop residues, and soil organic matter (Joern and Sawyer 2006). Phosphorus (P), potassium (K), and sulfur (S) are the other major macronutrients required for corn production. A corn plant removes 78 kg P_2O_5 ha^{-1}, 56 kg K_2O ha^{-1}, and 23 kg S ha^{-1} to reach physiological maturity (Laboski 2007; Oldham 2004). The need for P or K fertilization is assessed from soil sample results taken from a depth of 0-15 cm. Sulfur is less commonly applied as a corn fertilizer, although it is becoming more commonly identified as deficient in soils of the Midwest. Other nutrients required for corn production are required in lesser amounts and, thus, are referred to as micronutrients. Zinc (Zn) is a micronutrient that is a component of various plant enzymes responsible for metabolic reactions. In corn, Zn deficiency is characterized by broad bands of light-colored striped tissue on either side of the corn leaf midrib and as stunted plants with shortened internodes along the stalk (Rehm and Schmitt 1997). Response to Zn fertilizer is most likely during cool years, when soils have high clay content, in areas with low soil organic matter, where soils are eroded, or when very high rates of P fertilizer (>112 kg P_2O_5 ha^{-1}) or manure have been applied (Rehm and Schmitt 1997).

Prior to the early 1930s, corn seeds were produced via open pollinating varieties, meaning they were largely uncontrolled and unplanned pollinations that occurred via wind and other natural mechanisms; corn yields during this period were around 1-2 Mg ha^{-1} (Cardwell 1982; Tollenaar & Lee 2002). As breeding became recognized as a means of increasing corn yields in the U.S., double-cross hybrids were developed and grown from 1930s-1960s, producing grain yields of 2-4 Mg ha^{-1} (Duvick 2005). Today's hybrids produce average grain yields of 8.2 Mg ha^{-1} (USDA NASS). Improved genetics of hybrids (pre-genetic alteration), contributed an average of 51% of on-farm yield gains (Duvick 2005). Although yields increased dramatically from the 1930s to 1990s, there was little change in individual plant grain yield when plants were grown at very low plant densities and thus it seems that increased yields displayed with new hybrids is partly attributed to an enhanced ability to tolerate, and thus exploit, higher plant populations and other biotic and abiotic stresses (Meghji et al. 1984; Carlone & Russell

1987; Duvick & Cassman 1999; Tokatlidis & Koutroubas 2004, Duvick 2005). Tollenaar and Lee (2002) suggest that most of the yield increases observed during the past six decades were the result of an improved genetic by agronomic-management interaction and note that plant population is the management factor that has changed most during this time period. The plant hybrids themselves were selected partially because they were better suited to higher populations. The trend beginning in the 1970s of phenotypes changing from large, horizontal leaves to narrower, more upright leaves suggests that higher yields are largely attributable to corn plants that create less shading and greater interception of sunlight when grown at higher population densities (Meghji et. al 1984). Advances in modern corn hybrids other than tolerance to high plant density include tolerance to stresses like drought, water saturated soils, nitrogen deficiency, root lodging, stalk rot, insects, and barrenness (Duvick 2005). In a review of factors resulting in greater stress tolerance, Tollenaar and Wu (1999) reported that newer hybrids were better able to tolerate high plant population density, weed pressure, low nighttime temperatures during grain-fill, low soil moisture content, low soil N, and a number of different herbicides. In 2000, the first commercially-available genetically-altered corn was available for planting in the U.S. In 2011, 88% of all corn seed planted in the U.S. was transgenic, representing 33 million hectares (USDA NASS) of the total U.S. land area planted to corn in 2011, 16% was planted with insect-resistant-only bioengineered crops, 23% was planted with herbicide resistant-only bioengineered crops, and 49% was planted with “stacked” gene varieties (USDA NASS). Nearly 5000 permits for the release of genetically engineered varieties of corn have been approved by USDA (Animal and Plant Health Inspection Service (Fernandez-Cornejo and Caswell 2006). Currently, there are corn hybrids with genetically engineered herbicide tolerance and insect resistance tolerance traits commercially available; other genetically engineered varieties with viral/fungal resistance and advanced agronomic properties (resistance to cold, drought, frost, salinity, more efficient N use, and increased yields) are in various stages of development and testing (Fernandez-Cornejo and Caswell 2006). From an environmental and human health perspective, genetically engineered corn, soybean, and cotton plant hybrids have resulted in a total reduction of 2.5 million pounds of pesticide application (Fernandez-Cornejo and Caswell 2006). Insecticide use was found to be 8% lower per planted hectacre for farmers who use Bt corn than for those who do not (Fernandez-Cornejo and Li 2005). Fernandez-Cornejo and McBride (2002) determined that herbicide- and insecticide-tolerant crops significantly reduce potential human exposure to toxic agricultural chemicals.

Although corn can be planted in the same field year after year, a practice called “corn after corn” when referring to 2 years of back-to-back corn production, usually with a soybean crop planted in the third year, and “continuous corn” for 3 or more years of corn grown back to back, it is widely accepted that this practice results in lower corn yields for the second and subsequent years relative to corn planted following a different crop species (Porter et al. 1997; Peterson and Varvel 1989; Wilhelm and Wortman 2004; Erickson 2008). The most common corn rotation in the U.S. Corn Belt is corn-soybean, which generally results in corn yields that are 10-25% greater than for continuous corn. The reasons for reduced yield in continuous corn culture are not well understood, but are likely to result from accumulating corn residue which immobilizes plant nutrients (Gentry et al. 2001), maintains moisture in the soil and reduces soil temperatures (Rehm et al. 1997), leads to a buildup of corn disesase, and potentially releases autotoxic chemicals that retard early season growth of the crop planted into the previous season’s residue.

Seeding rate and final plant population are direct limiting variables for corn yield determination. The relationship between grain yield per unit area and plant population is usually parabolic. At low plant densities, grain yield is limited by the small number of plants; as plant densities increase, yield declines primarily due to more aborted kernels and/or barren stalks (Hashemi et al. 2005). Seeding rates have increased dramatically and without pause over the past 75 years of corn cultivation in the

U.S. In the 1930s, corn was seeded at <30,000 seeds per ha^{-1} (Duvick 2005). Today, seeding rates range from 309,000-331,000 plants ha^{-1}. In order to increase plant yields to 250-300 bushels $acre^{-1}$ (13-16 Mg ha^{-1}) plant populations must increase. Factors limiting corn populations to current levels are primarily based on competition for resources – sunlight energy, nutrients, and water. Ultimately, maize breeding efforts should focus on combining high population-tolerance with improved per-plant yield potential (Tokatlidis and Koutroubas 2004). Widdicombe & Thelen (2002) suggest that periodic reassessment of plant population and row widths are needed as a result of continued genetic improvement in the ability of corn to withstand high plant populations.

Tillage provides four crop production services: incorporates crop residues and fertilizers, prepares a well-fractured seedbed, manages soil moisture conditions, and manages weeds. According to a survey conducted in 2011, over 40% of corn in Illinois was produced with conventional full-width tillage practices; 25% of corn was produced with a reduced tillage system, like strip tillage or ridge till, and 20% was produced using no-till production practices (Vyn, personal communication). Nationwide, results of the Conservation Tillage Information Center Crop Residue Management Survey (2000-2008) determined that no-till acres have steadily, but modestly, increased from 17.9% to 21.0% of all U.S. planted corn acres from 2000 to 2008. The use of all conservation tillage methods, defined as all systems that retain at least 30% residue cover on the soil surface, increased from 36.2% to 40.2% of U.S. planted corn acres during the same time period. Some of the increase in acreage in the survey was the result of increased corn production in non-Corn Belt states, particularly in the southeast. Despite documented benefits in soil physical, chemical, and biological properties, reduced soil erosion, and reduced greenhouse gas emissions, the adoption of conservation tillage practices has not generally increased in recent years for U.S. corn production (Boomsma et al. 2010), probably due to the increasing land area devoted to continuous corn and corn-after-corn (Werblow, 2007; USDA-NRCS 2010). Boomsma et al. (2010) cite a number of papers addressing potentially yield-reducing concerns associated with corn no-till systems: reduced early-season soil temperatures, reduced seed germination and emergence, reduced plant populations, poorer weed control, delayed plant development, increased grain moisture content, and reduced grain yields. The aforementioned tillage concerns are highly dependent on soil type, drainage, climate/latitude, and crop rotation (Griffith et al. 1973). Closely related to these tillage concerns are large amounts of previous crop biomass that hinder no-till practices, especially in a continuous corn system, unless the residue is grazed, harvested, or otherwise removed prior to no-tilling the crop the following spring. The management issues related to reduced- and no-till systems for corn production are region-specific and studies across the U.S. have proven that these systems can result in yields comparable to full-width tillage systems when grown on warmer, well-drained soils in a two-or-more year cropping rotation (Kladivko et al. 1986, Dick et al. 1991, Kapusta et al. 1996, West et al. 1996)

Some fungicides, particularly those in the strobilurin class, have been found to increase corn yields even when fungal disease is not detectable in the crop (personal communication). This has been called the strobilurin “stay-green effect” because it appears to be related to an enhanced capacity for strobilurin-treated crops to maintain the green leaf area of the canopy later in the growing season, thus prolonging the grain-filling period with the result of higher crop yields (Bartlett 2002). 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 and other plant hormones (Bartlett 2002). A related hypothesis is that strobilurin fungicides reduce crop stress, thus allowing the plant to come closer to attaining full yield potential by maximizing kernel production and grain fill and increasing kernel weight. Since the yield-enhancement effect of strobilurin fungicides independent of disease management appears to result from increased photosynthetic capacity, reduced respiration, and improved crop stress tolerance, it is reasonable to expect strobilurin fungicides to be especially effective in high-yield environments.

In addition to the previously discussed management factors, issues that result in crop loss, include planting date, disease and pest pressure, uneven plant spacing within the crop row, missing plants and uneven plant stand in the crop row constitute common problems under commercial production systems (Tokatlidis & Koutroubas 2004). Unevenness in plant stand and plant height variability often result in corn grain yield reduction (Tokatlidis & Koutroubas 2004; Boomsma et al. 2010) and can result from delayed and variable emergence (Ford and Hicks 1992; Liu et al. 2004), planter issues (Lauer and Rankin 2004; Andrade and Abbate 2005) and early season disease, weed, and pest pressures (Varvel and Peterson 1990; Katupitiya et al. 1997; Dodd and White 1999). When grain is forfeited as a result of missing plants, it is not fully compensated by the increased yields of surrounding plants, resulting in net grain loss. Although spatial variability in the crop canopy can be associated with reduced resource-use efficiency and thus reduced grain production (Nafziger 1991; Tokatlidis & Koutroubas 2004), other researchers find that remaining plants can compensate for missing plants and high spacing variability depending on the developmental stage at which stand loss occurs and the extent and pattern of spacing variability, respectively (Nafziger 2006).

MATERIALS AND METHODS

Field Notes & Experimental Design

Field trials were conducted during the 2009 and 2010 growing season at the Crop Science Research and Education Center in Champaign (40°06' N, 88°12' W) in East Central Illinois. Different fields were used each year of the study. Field sites were located within 3 km of each other and had similar soil types, fertility levels, and management histories. Both sites were non-irrigated and tile-drained. 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). Soybean was the previous crop in both years.

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 4 rows spaced 0.76 m apart. Tillage practice was chisel plow in fall with two field cultivations in spring for seedbed preparation. Planting occurred on May 26th, 2009 and May 24th, 2010. Additional planting information is provided below with the description of the population treatment. Fertilizer application details are provided with the description of the nitrogen (N) and non-N fertility (P, S, and Zn) treatments, below. The soil insecticide tefluthrin (Force 3G) was applied with the seed at planting at a rate of 0.11 kg a.i. ha^{-1}. Weeds were managed with a pre-emergent application of Lumax (S-metoachlor + atrazine + mesotrione) at a rate of 3.32 Kg a.i. ha^{-1}.

Crop grain yield and moisture were determined by harvesting the center 2 rows of each 4-row plot with a research plot combine along the entire length of each plot. In 2010, a field sampling of 6 representative plants was conducted at R6 (physiological maturity) to estimate grain, husk, cob, and stover weight per plant and per treatment. A representative subsample of grain from each plot was analyzed at 0% moisture for protein, oil concentration, and starch by near-infrared transmission spectroscopy (FOSS 1241 Grain Analyzer). Stover material was shredded in the field (Vermeer BC600 XL chipper/shredder) and a representative subsample was dried to constant weight and analyzed for N concentration by loss-on-emission. From this information, crop harvest index and N harvest index were calculated by computing the ratio of grain weight or nitrogen weight to total above ground biomass weight. The weight of grain removed during the R6 sampling was added back into the final yield calculations. Yield was calculated based on 15.5% moisture content for the bushel weight analysis as well as 0% moisture content for the metric (Mg ha^{-1}) analysis.

Treatment Structure

The individual and combined effects of five high-yield management factors - non-N fertility (P, S, and Zn), nitrogen (N), genetics, plant population, and fungicide application – were studied in this experiment (Fig. 1). Each factor consisted of two levels representing either the current agronomic practice (referred to as 'Traditional' and abbreviated 'TRAD') or a higher technological practice or input level (referred to as 'High-Technology' and abbreviated 'HT'). As described in Figure 1, the study was made up of 12 treatments, 5 factors with 2 levels each plus one treatment comprising all the 'Traditional' management factors (Treatment 7) and one treatment comprising all the 'High-Technology' management factors (Treatment 1). For each of the management factors, the 'traditional' level was tested while maintaining the other 4 factors at the 'high-technology' level and the 'high-technology' level of the treatment was tested while maintaining the other 4 factors at the 'traditional' level. In this way, the value of each management factor was tested in 4 different ways: 1) as part of the full 'traditional' system (Treatment 7), 2) as part of the full 'high-technology' system (Treatment 1), 3) with all other factors held as 'traditional' to test the individual value of the treatment (Treatments 8-12), and 4) with all other factors held as 'high-technology' to test the cumulative value of the other factors in the absence of the single factor (Treatments 2-6). This design is referred to as an "omission treatment" design.

Treatments

The 2 levels comprising the first management factor, non-N fertility, were NONE or MESZ (Fig. 1). The NONE level would be the traditional practice on the soils 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 high-technology level of this factor consisted of phosphorus (P), sulfur (S), and zinc (Zn) application with a Mosaic Company product, MESZ (12-40-0-10S-1Zn) at a rate that would supply 112 kg P_2O_5 ha^{-1}. Fertilizer was broadcast before planting and incorporated with a cultivator-harrow.

The 2 levels of the second management factor, N, were BASE and BASE+SLOW RELEASE. For the BASE rate, N was applied at V1 as 28% urea-ammonium nitrate solution at a rate of 202 kg N ha^{-1}. The BASE+SLOW RELEASE rate consisted of an additional broadcast application at V6 of 112 kg N ha^{-1} of SuperU, a slow-release urea-based N fertilizer produced by Agrotain which contains a urease inhibitor and a mineralization inhibitor to decrease losses due to volatilization, leaching, and denitrification.

The 2 levels of the third management factor, Genetics, were CORN ROOT WORM (CRW)-SUSCEPTIBLE (DKC61-22) or CRW-RESISTANT (DKC61-19). The CRW-SUSCEPTIBLE level was the same corn cultivar as CRW-RESISTANT, but without the resistance to corn rootworm. The CRW-RESISTANT level was, obviously, a corn hybrid that was resistant to CRW. Both hybrids possessed transgenic tolerance to the herbicide glyphosate.

The 2 levels of the fourth management factor, Population, were 79,040 and 111,150 plants ha^{-1}. Plots were planted with an ALMACO SeedPro 360 research plot planter with variable seeding rate capacity.

The 2 levels of the final management factor, fungicide, were NONE and PYRACLOSTROBIN. Strobilurin is a class of fungicides shown in some studies to have plant growth-enhancing properties in addition to fungicidal activity. Headline, a BASF product, was the strobilurin fungicide used in this study and was applied at VT at the maximum labeled rate of pyraclostrobin at 0.21 Kg a.i. ha^{-1}.

Measurements

In 2009, corn grain yield was measured at harvest for each of the two test rows in each plot. In 2010, total aboveground biomass, total kernels per ear, moisture content of grain, and moisture content of aboveground biomass were measured in addition to kernel mass. Additionally, a subsample of grain and stover was retained from each bulk sample to allow analysis of kernel weight, N content of aboveground biomass, and N, protein, oil, and starch concentration of grain.

Statistical Analysis

Grain yield data were analyzed with the MIXED MODEL procedure of SAS (SAS Institute, ver. 9.2). Treatments and years were treated as fixed effects and replications were treated as random effects. Means comparisons were prepared via least significant difference (LSD) analysis. The pre-planned comparisons for which individual LSDs were determined were 1) Treatments 1-6 (high technology with individual omission of treatments), 2) Treatments 7-12 (traditional with individual omission of treatments, and 3) All treatments, used exclusively to compare Treatments 1 and 7.

RESULTS AND DISCUSSION

Weather

Weather conditions (monthly average ambient temperature and precipitation) for each growing season (April through October) of 2009 and 2010 are presented in Table 1. In 2009, temperatures were above average in June and below average in July and August, while precipitation was above average for every month, except September, which received only 25% of average monthly precipitation. In 2010 ambient temperatures were above average and rainfall was below average every month except June, when rainfall was approximately 50% above the monthly average. Overall, the 2009 growing season was cool and wet and was conducive for favorable plant growth during the grain filling period, while the 2010 growing season was hot and dry which created stress and limited crop productivity.

Corn Grain Yields

In reference to our yield goal of 13-16 Mg ha^{-1} for grain production, we achieved the goal in 2009 with a yield of 14.5 Mg ha^{-1} but did not meet the goal in 2010, a drought year. The experimental control of the high technology system (HT) (Treatment 1, consisting of advanced levels of all treatments) was 3.5 and 2.1 Mg ha^{-1} greater than the experimental control of the traditional (TRAD) system (Treatment 7, consisting of lower levels of all treatments) in 2009 and 2010 (Table 2). Averaged across both years, the yield of the HT system was 13.42 Mg ha^{-1} and the yield of the traditional system was 10.62 Mg ha^{-1}, therefore the five factors combined to increase grain yields by approximately 3 Mg ha^{-1}. Average corn grain yields in Champaign county were 10.1 and 9.0 Mg ha^{-1} (190 and 169.5 bu a^{-1}) in 2009 and 2010, respectively (USDA-NASS). Grain yield of the traditional system (the treatment most similar to conventional practices in the region) were 11.0 and 10.2 Mg ha^{-1} in this study, indicating that our yields were approximately 10% higher than on-farm yields in the area. Corn grain yields were greater in 2009 than in 2010 for every experimental treatment except for Treatment 12 (TRAD + fungicide) (Table

2). In general, yield responses were more pronounced during the favorable growing season of 2009 and were muted due to the unfavorable growing conditions of 2010.

The yield response to P, S, and Zn fertilizer application varied between years. Omitting P, S, and Zn from the HT system (Treatment 2) resulted in a significant yield reduction (7%) in 2009 (Tables 2 and 3), but otherwise did not significantly affect corn yield. This data suggests that P, S, and Zn are an important part of a “high-yield package” in a high-yielding environment with high plant density under good crop growth conditions. Similarly, these data suggest that under poor growing conditions or when other high-yielding factors are not present (high plant population, nitrogen, etc.) additional P, S, and Zn provide little additional yield advantage when soil test results indicate that fertility levels are adequate.

In 2009, omitting or adding extra side-dressed, slow-release nitrogen fertilizer from either the HT or the TRAD system (Treatments 3 and 9) had a significant effect on corn grain yield. The wet conditions of 2009 (Table 1) likely resulted in substantial N loss via leaching and denitrification, resulting in a N effect for grain yield in both the HT and TRAD systems. A significant yield gain of 0.87 Mg ha^{-1}, nearly 8%, was achieved by applying the additional 11 kg of slow-release N fertilizer to the TRAD system. Similarly, yield of the HT system was significantly reduced by 1.26 Mg ha^{-1}, approximately 9%, when the slow release N fertilizer application was omitted. This data confirms the finding of Boomsma et al. (2009) stating that tolerance to high plant densities is contingent on adequate N application rates. Boomsma et al. reported low crowding tolerance and poor tolerance to low-N conditions as well as high responsiveness to side-dress applications of N fertilizers at high corn plant populations. Side-dressing N and using a slow-release formulation may also improve fertilizer recovery, particularly in a wet growing season, like 2009.

Additional N fertilizer was less critical for yield production during the 2010 growing season due to the drought conditions which limited overall growth of the crop, thus reducing N demand in both the TRAD and HT systems (Tables 2 and 4). Based on these results, it seems likely that corn yield response to increased plant population and increased N fertility will be the same, such that in years with favorable weather conditions, increased plant population is required to reach the maximum potential of the field environment and increased N fertilizer application is required to maximize growth of individual plants.

Corn N fertilizer recommendations are now calculated using the Iowa State N calculator based on the current price of corn and N fertilizer (http://extension.agron.iastate.edu/soilfertility/nrate.aspx). Until recently, however, 1.2 lb N bushel^{-1} of expected yield was a common recommendation to guide farmers when determining N fertilizer application rates for corn production in IL (Nafziger 1998). Today, with higher corn plant populations, better N management practices, and more N-efficient corn hybrids, this value is frequently less than 1 lb N bushel^{-1}. Expressed in these terms, crop N use for both the HT and TRAD systems (Treatments 1 and 7) was more efficient in 2009, than in 2010. In 2009, the HT system produced 269 bu acre^{-1} (with 280 lb of N fertilizer) resulting in apparent crop N use of 1.04 lb N bushel^{-1} while the TRAD system produced 208 bushel acre^{-1} (with 180 lb of N fertilizer) with a crop N use of 0.87 lb N bushel^{-1}. The poor growing conditions in 2010 decreased efficiency, and crop N use was 1.03 and 0.93 lb N bushel^{-1} for the HT and TRAD systems, respectively. While this method is no longer recommended as a way to guide growers when determining N fertilizer application rates, it remains a valid method to assess fertilizer N use.

Corn hybrid was an important factor determining crop yield in both years of the study. When omitting the CRW resistant trait from the HT system (Treatment 4), crop yields were significantly reduced by more than 9% each year (Tables 3 and 4). Although trending higher, adding the CRW-resistant hybrid to the TRAD system (Treatment 10) did not significantly affect yields either year (Table 2). There are at least two possible mechanisms that explain the observed yield reduction when the CRW-resistant trait was omitted from the HT system. The higher plant population in the HT system may have induced a greater CRW pressure that reduced yield in the absence of the CRW-resistant trait. Alternatively, there may have been present a sub-acute CRW pressure in the TRAD system that responded positively, but not significantly, to the CRW-resistance trait. Without CRW damage ratings, which were not conducted, this cannot be determined with certainty. The other proposed explanation is that the CRW-resistant hybrids have a more substantial and/or vigorous root system that allows for greater uptake of water and nutrients under stress induced by high plant populations. Although a number of studies reported that there was no difference on rate of decomposition of residue due to *Bt* versus non-Bt corn production (Cortet et al. 2006; Hönemann et al. 2008; Tarkalson et al. 2008), no information could be found in the scientific literature regarding biomass amounts or root activity of *Bt* vs. non-*Bt* corn hybrids.

Plant population is an interesting yield factor because crop response is highly dependent on interacting factors like spatial arrangement of plants, light interception, and nutrient and water availability (Nafziger 2006). Under the more favorable growing conditions of 2009, reducing population in the HT system (Treatment 5) decreased grain yield; however, increasing population in the TRAD system (Treatment 11) also decreased grain yield (Table 2). In 2010, Treatments 5 and 11 did not statistically differ with the control Treatments (1 and 7). In 2009, when moisture and nutrients were not limiting in the HT system, reducing plant population resulted in a statistically significant 5% yield reduction (Tables 2 and 3), indicating that yield potential of the system was greater when fertility and disease issues were managed accordingly. Specifically, these data suggest that, properly managed, high yield environments can support a 40% increase in plant population with a corresponding 26% increase in grain yield (Treatment 1 vs. Treatment 7 averaged across both years).

In 2010, neither decreasing plant population in the HT system nor increasing plant population in the TRAD system significantly affected yield (Table 2), indicating that crop response to high plant density under drought conditions is to compensate by decreasing kernel number or, to a lesser extent, kernel weight (see sections below). This data indicates that increasing plant populations is a key factor for increasing crop yields in a good year, especially when other inputs are not limiting. Furthermore, owing to the unique plasticity of the corn plant to adjust kernel weight and kernel number according to environmental conditions, it is less likely that increasing plant populations will reduce yields in a bad year relative to the probability that it will increase yields in a good year. This is, however, a generalized statement reflecting the physiological plasticity of the corn plant and does not consider the economic cost of corn seed and other inputs.

Fungicide treatments (Treatments 6 and 12) did not provide significant grain yield differences in 2009 but strongly impacted grain yields for both systems in 2010 (Table 2). Yield in the TRAD system increased 8.5% with the addition of the strobilurin fungicide in 2010 and, similarly, decreased by almost 16% with the omission of fungicide in the HT system (Table 4). Although 2010 was, overall, a drought year, the month of June had 50% above average rainfall, creating conditions favorable for fungal growth. The fungicide, applied at tasseling, protected against fungal pathogens in the treated plots that otherwise may have reduced corn grain production while moderate fungal disease levels were present in non-treated plots. Other research does not suggest that strobilurin chemistry provides greater drought tolerance to the crop (Nason et al. 2007), but the increased yield may be the result of the "stay-green" effect which can, in effect, extend the growing season of the crop by delaying plant senescence and prolonging the photosynthetic capacity of the plant (Bartlett 2002).

An important result in this study is that the yield value of each factor (percent increase or decrease in yield when the factor is omitted or added) depends on the other factors present in the system (Table 3). For example, the yield value of adding P, S, and Zn to the TRAD system is +0.37 Mg ha^{-1} (3.4% yield increase); the yield value of omitting P, S, and Zn from the high technology system is -0.94 Mg ha^{-1} (6.9% yield decrease). In general, the yield value of each factor is greater in the HT system than the TRAD system. This observation suggests that the higher yields obtained in the HT system can be regarded as a system of synergies, built upon overall better health afforded to the crop by improved hybrid, complete fertility, and fungicide application in the higher population.

Grain Yield Components

Grain yield components measured in this study were kernel number and kernel weight, displayed in Table 5. Corn has the ability to adapt to varying environmental conditions by adjusting yield components in order to maximize grain yield, a trait referred to as “plasticity” (Bonaparte and Brawn 1975). Compensation of one yield component for the other can occur when weather perturbations or nutrient limitations disrupt the life cycle of this determinant crop species (Ritchie et al. 1986). In 2010, kernel number was significantly lower in the HT system relative to the TRAD system (Treatment 1 vs. 7, Table 5) due to the greater plant density in the HT system. Only Treatment 5 (HT – Population) displayed a significantly greater kernel number than Treatment 1, indicating that the greater per-plant nutrient and water availability and reduced shading resulted in more kernels per ear at the lower plant population. Similarly, when population was increased in the TRAD system (Treatment 11), kernel number was significantly reduced. Individual corn plants in the HT system probably adjusted for higher plant population (relative to the TRAD system) by reducing the number of kernels per row (these were not measured directly); if this is the case, then the plant compensated for high populations before V15 when kernels per row is set. Nafziger (2006) reported that increasing plant population from 37,050 to 98,800 plants ha^{-1} resulted in linear decreases in both kernels per ear and kernel weight while yield increased in a curvilinear manner up to approximately 86,450 plants ha^{-1} under the given management regime.

Kernel weight, unlike kernel number which is determined prior to anthesis, is primarily affected by environmental conditions during grain-fill (the period between pollination and physiological maturity). Kernel weight (mg $kernel^{-1}$) did not significantly differ between the HT and TRAD systems, even though precipitation and heat stress occurred during grain fill. These results suggest that plants responded to high population by making adequate compensation decisions early in the 2010 growing season (before grain fill) by reducing the number of kernels per ear. This data also indicates an allometric relationship between grain yield components, allowing the plant to reallocate available resources and maximize reproductive capacity (kernel number) according to environmental stimuli without compromising kernel viability (indicated by kernel weight). Other studies have similarly shown that kernel number is the primary factor resulting in loss of kernel yield with increased plant populations (Hashemi et al. 2005).

Although kernel weight did not differ between the HT and TRAD systems, there were significant differences in kernel weight among the factors within each of the systems (Table 5). Most notably, decreasing plant population in the HT system (Treatment 5) resulted in an 8% increase in kernel weight while increasing plant population in the TRAD system (Treatment 11) resulted in a decrease in kernel weight of 7%. Both kernel weight and kernel number increased when population was decreased in the HT system, while both kernel weight and kernel number decreased when population was increased in the TRAD system (Table 5). These results suggest that treatment effects due to plant population within a system exerted a strong effect on the plant throughout the growing season, influencing both kernel number and kernel weight.

Kernel weight was significantly less when the CRW trait was omitted from the HT system (Treatment 4); adding the trait to the TRAD system, however, had no effect. This data follows the observation of decreased plant yield in the HT system with the omission of the CRW resistance trait, again suggesting that the *Bt* corn hybrid used in this study may be more effective at taking up water and/or plant nutrients (and/or uses available water more efficiently) under stresses associated with high plant populations and drought. As previously mentioned, there is little published research regarding the effect of the *Bt* trait on the size of the corn root system or its relative ability to take up water and nutrients.

It is not unexpected that kernel number was not affected by fungicide application (Table 5) since the fungicide was applied after the developmental stage at which kernel length (kernel number row^{-1}) is established. Kernel weight decreased by 13% when fungicide was omitted from the HT system (Treatments 1 vs. 6), and kernel weight increased by 10% when it was applied to the TRAD system (Treatments 7 vs. 12). These results suggest that the fungicide imparted its effect during grain fill and may support the idea that treated plants stay green longer and continue supplying photosynthate to the grain later in the season (Bartlett 2006).

Corn Grain Quality

Corn grain quality can be divided into three main components and are expressed as percent protein, oil, and starch (Table 6). These components comprise approximately 85% of the kernel composition. Despite differences in yield and kernel number, there were no significant differences for any grain quality measurements between the HT system and the TRAD system (Treatment 1 vs. Treatment 7).

Although not statistically different between the two experimental controls (Treatments 1 and 7), grain composition was greatly affected by adjusting plant population within a system, which was found to affect all three components (Table 6). When plant population was increased in the TRAD system protein and oil significantly decreased and starch significantly increased. The opposite was observed when plant population was reduced in the HT system, i.e. protein and oil significantly increased and starch significantly decreased. These results suggest that decreasing plant population in the HT system made more N available on a per-plant basis, resulting in greater grain protein concentration. In addition, decreasing plant population in a drought year may have provided more water per plant so that plants were better able to take up N (and other nutrients) to produce protein. Numerous studies show a relationship between N availability and grain protein; however, grain oil appears more difficult to alter via management (Blumenthal et al. 2008).

The omission or addition of fungicide also had a major impact on grain quality in the two systems (Table 6). Adding fungicide to the TRAD system increased grain oil, reduced starch concentration, and did not change grain protein. When fungicide was omitted from the HT system, grain protein increased while grain oil decreased, with no change in starch. Fungicide application in 2010 played a role in improving grain quality, and as noted earlier significantly increased grain yield.

The omission or addition of the slow release N fertilizer had a relatively small effect on corn grain composition and quality measures. As expected, omitting the supplemental N fertilizer in the HT system (Treatment 3) significantly decreased grain protein concentration by 5.6% relative to Treatment 1 (Table 6). Adding additional N to the TRAD system, however, did not significantly increase grain protein concentration, perhaps suggesting limited N fertilizer uptake due to the drought during grain fill in 2010. It is interesting to note that the effect of population had a stronger effect on plant protein than N availability, suggesting that in a drought year adding additional N fertilizer is less effective at making N available to the crop than reducing competition for available N (and water) by reducing plant population.

<u>Whole Plant Biomass and Harvest Index</u>

As with grain quality measurements, individual whole plant biomass was affected by plant population and fungicide application in 2010 (Table 7). Whole plant biomass, measured as aboveground biomass (g $plant^{-1}$) was significantly less for the HT system than for the TRAD system (Treatment 1 vs. 7).

The effect of plant population on whole plant biomass was confirmed by the 41% increase in whole plant biomass resulting from the 29% reduction in plant population in the HT system (Treatments 1 vs. 5, Table 7). Similarly, increasing plant population by 40% in the TRAD system reduced whole plant biomass by 26% (Treatments 7 vs. 11). Fungicide significantly increased whole plant biomass by 7% in the TRAD system (Treatments 7 vs. 12) and omission of fungicide in the HT system decreased whole plant biomass by 10%.

Harvest index (HI) did not differ significantly between the HT and TRAD systems (Treatments 1 vs. 7). Although individual plant biomass was significantly less when populations were higher, there remained a consistent allometric biomass partitioning of plant parts such that HI was unaffected. These findings agree with those of Shapiro and Wortmann (2005) who found that, in general, N fertilizer rate, row spacing, and plant population did not affect the HI. Kamprath et al. (1982) also determined that HI did not change as a result of hybrid used or, in most cases, N fertilizer application rate. The only factor that affected HI was replacement of the CRW-resistant trait with a CRW-susceptible trait in the high yield system, resulting in a significant reduction in HI. This can be attributed to one replicate of the 6-plant R6 sample that, although not an outlier, had a large total plant biomass compared with the grain weight recorded. It is not likely that CRW-susceptible hybrids consistently display lower HI than CRW-resistant hybrids and nothing in the published literature could be found to supports this, although Ma and Subedi (2005) display a table indicating statistical differences in *Bt* hybrids and their conventional near-isolines for harvest index, although no further information within the article was discussed.

Total Plant Nitrogen and Nitrogen Harvest Index

Total plant N, expressed as g N plant^{-1}, was 22% lower in the HT system than in the TRAD system (Treatments 1 vs. 7, Table 8). Consistent with results for plant biomass and HI, plant population affected total plant N accumulation but did not alter N harvest index. It is interesting to note that neither omitting additional N fertilizer in the HT system (Treatments 1 vs. 3) nor adding it to the TRAD system (Treatments 7 vs. 9) affected total plant N. As discussed earlier, this finding may be due to limited growth resulting from drought conditions in 2010. Including P, S, and Zn fertility in the TRAD system decreased the plant N content (Treatments 7 vs. 8, Table 8), but the opposite effect was not observed in the HT system. Since P, S, and Zn fertility made only a small and non-significant overall difference in crop yield in 2010, the observed difference in plant N content is probably a sampling effect or random error rather than a treatment effect. Shapiro and Wortmann (2005) observed decreased N HI with increasing N rate in 2 years and no change in N HI in one year of a three-year study; the observed differences were due to a smaller increase in the N content of harvested grain relative to accumulated stover N at higher N application rates.

SUMMARY AND CONCLUSION

Yields were 3.5 Mg ha^{-1} (66 bu acre^{-1}) greater in the HT system relative to the TRAD system in 2009 and 2.1 Mg ha^{-1} (40 bu acre^{-1}) greater in 2010. In reference to the yield goal of 13-16 Mg ha^{-1} for grain production, we achieved the goal in 2009 with a yield of 14.5 Mg ha^{-1} but did not meet the goal in 2010, a drought year. In 2009, a favorable growth year with above average rainfall and high potential for nitrate leaching, additional N, the CRW trait, and increased plant population provided the greatest yield increases. In 2010, applying strobilurin fungicide and the CRW trait provided the greatest yield increases. Increasing plant population by 41% in the HT system in 2010 resulted in a 16% reduction in kernel number (kernel ear^{-1}) and no significant change in kernel weight relative to the TRAD system, reflecting the plasticity of the crop to adapt to environmental field conditions. Grain quality measurements (protein, oil, and starch content) did not differ between the HT and TRAD systems (Treatments 1 and 7). Pyraclostrobin fungicide application increased individual plant biomass and kernel weight when applied to the TRAD system and decreased kernel weight when omitted from the HT system. When pyraclostrobin was added to the TRAD system (Treatment 12), oil concentration of the grain increased and starch concentration decreased; the same observation was made when plant population was reduced in the HT system (Treatment 5). Removing pyraclostrobin from the HT system (Treatment 6) or increasing plant population in the TRAD system (Treatment 11) had the opposite effect on grain quality, i.e. oil concentration decreased and starch concentration increased. Individual plant biomass decreased by 17% in the HT system compared to the TRAD system, but harvest index did not vary between the systems. Total plant N content was lower in the HT system relative to the TRAD system, primarily as a response to higher plant populations, but there was no difference in the N harvest index between the two systems.

This study establishes, above all, that there exists a system of synergies that begins with weather and plant population. When seasonal weather conditions are favorable for crop growth, the other agronomic management factors (non-N fertility, nitrogen, hybrid, and fungicide) act synergistically to “push” crop yield so that each plant has adequate fertility and above- and below ground biomass protection to allow the full yield potential of the crop to be achieved. In years with favorable weather, the agronomic management factors tested in this study act to “push” crop yields to their maximum level. Similarly, in a poor growing season, although yield potential is diminished in a high population system because individual plants are less likely to “set” as many ovules and/or nourish each ovule to produce a kernel, the remaining four agronomic management factors will “protect” the crop so that remaining production potential can be preserved. In years with suboptimal weather, the agronomic management factors tested in this study act to “protect” the remaining crop potential. This explains the observation that population and N fertility were the two major production factors in 2009, a good growing season, and corn rootworm resistance and fungicide contributed more to yield in a poor growing season, like 2010. The “push” factors of Population and N fertility supported plants when they were provided with all the foundational factors of adequate moisture, heat, and sunlight, resulting in high yields. The “protect” factors, i.e. Corn Rootworm Resistance and Fungicide, preserved the remaining yield potential during the hot, dry conditions of 2010.

These data also suggest that the remarkable plasticity of the corn plant provides flexibility for the plant to adjust its allocation of resources in response to environmental conditions. Kernel number and kernel weight responded to the agricultural management factors tested here and also to the weather conditions unique to each year, resulting in a flexible and favorable response to plant population, such that the potential for increased yields in a good year was greater than the expected yield reduction in a bad year, assuming that other advanced management factors are in place to support a higher plant population. This statement, however, does not take into consideration the economic cost of additional seed and other inputs.

LITERATURE CITED

Andrade, F.H.; P.E. Abbate. 2005. Response of maize and soybean to variability in stand uniformity. Agron. J. 97: 1263-1269.

Barber, S.A., J.M. Walker, E.H. Vasey. 1963. Mechanisms of movement of plant nutrients from the soil and fertilizer to the plant root. Ag. Food Chem. 11(3): 204-207.

Bartlett, D.W.; J.M. Clough, J.R. Godwin, A.A. Hall, M. Hamer, B. Parr-Dobrzanski. 2002. The Strobilurin Fungicides: A Review. Pest Manag Sci 58: 649-662.

Blumenthal, J.M.; D.D. Baltensperger, K.G. Cassman, S.C. Mason, A.D. Pavlista. 2008. Importance and effect of nitrogen on crop quality and health. *In* Nitrogen in the Environment: Sources, Problems, and Management. 2nd ed. J.L. Hatfield and R.F. Follet eds. Elsevier. Also available on-line: http://digitalcommons.unl.edu/agronomyfacpub/200. Accessed Dec. 12, 2011.

Bonaparte, E.E.N.A. and R.I. Brawn. 1975. The effect of intra-specific competition on the phenotypic plasticity of morphological and agronomic characters of four maize hybrids. Ann. Bot. 39: 863-869.

Boomsma, C.R.; J.B. Santini, T.D. West, J.C. Brewer, L.M. McIntyre, T.J. Vyn. 2010. Maize grain yield responses to plant height variability resulting from crop rotation and tillage system in a long-term experiment. Soil Till. Res. 106: 227-240.

Cardwell, V.B. 1982. Fifty years of Minnesota corn production: Sources of yield increase. Ag. J. 74: 984-990.

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.

Conservation Tillage Information Center Crop Residue Management Surveys (conducted in cooperation with USDA NRCS and local conservation partnerships). Available on-line: http://ctic.org/crm_results/. Accessed Dec. 7, 2011.

Cortet, J.; M.N. Anderson, S. Caul, B. Griffiths, R. Joffre, B. Lacroix, C. Sausse, J. Thompson, P. Henning Krogh. 2006. Decomposition processes under Bt (*Bacillus thuringiensis*) maize: Results of a multi-site experiment. Soil Biol. Biochem. 1: 195-199.

David, M.B.; L.E. Gentry, D.A. Kovacic, K.M. Smith. 1997. Nitrogen balance in and export from an agricultural watershed. J. Environ. Qual. 26: 1038-1048.

Dick, W.A.; E.L. McCoy, W.M. Edwards, R. Lal. 1991. Continuous application of no-tillage in Ohio soils. Agron. J. 83: 65-73.

Dodd, J.L.; D.G. White. 1999. Seed rot, seedling blight, and damping-off. *In* Compendium of Corn Diseases. D.G. White, ed. American Phytopathological Society Press, St. Paul, MN. pp 10-11.

Duvick, D.N. 2005. Genetic progress in yield of United States maize (*Zea mays* L.). Maydica 50 (2005): 193-202.

Duvick, D.N. and K.G. Cassman. 1999. Post-Green revolution trends in yield potential of temperate maize in the North-Central United States. Crop Sci. 39: 1622-1630.

Eck, H.V. 1986. Effects of water deficits on yield, yield components, and water use efficiency of irrigated corn. Agron. J. 78: 1035-1040.

Erickson, B. 2008. Corn/Soybean rotation literature summary. Available on-line: http://www.agecon.purdue.edu/pdf/Crop_Rotation_Lit_Review.pdf. Accessed: December 9, 2011.

Fernandez-Cornejo, J. and J. Li. 2005. The impacts of adopting genetically-engineered crops in the U.S.A.: The case of Bt corn. Paper presented at the American Agricultural Economics Association Meetings. Providence R.I.

Fernandez-Cornejo, J. and W.D. McBride. 2002. The adoption of bioengineered crops. USDA-ERS Report Number 810. May 2002.

Fernandez-Cornejo, J. and M. Caswell. 2006. The first decade of genetically engineered crops in the United States. USDA-ERS Bulletin Number 11.

Ford, J.H.; D.R. Hicks. 1992. Corn growth and yield in uneven emerging stands. J. Prod. Agric. 5: 185-188.

Gilland, B. 2002. World population and food supply: Can food production keep pace with population growth in the next half-century? Food Policy 27: 47-63.

Grant, R.F.; B.S. Jackson, J.R. Kiniry, and G.F. Arkin. 1989. Water deficit timing effects on yield components in Maize. Agron. J. 81: 61-65.

Griffith, D.R. E.J. Kladivko, J.V. Mannering, T.D. West, S.D. Parsons. 1988. Long –term tillage and rotation effects on corn growth and yield on high and low organic matter, poorly drained soils. Agron. J. 80: 599-605.

Hashemi, A.M.; S.J. Herbert, D.H. Putnam. 2005. Yield response of corn to crowding stress. Agron. J. 97: 839-846.

Hönemann, L.; C. Zurbrügg, W. Nentwig. 2008. Effects of Bt-corn decomposition on the composition of the soil meso- and macrofauna. App. Soil Eco. 40: 203-209.

Hollinger, S.E. and S.A. Changnon. 1993. Response of corn and soybean yields to precipitation augmentation, and implications for weather modification in Illinois. Bulletin 73 Illinois State Water Survey, Champaign, Illinois 61820.

Joern, B. and J. Sawyer. 2006. Nitrogen and Corn Use. *In* Concepts and rationale for regional nitrogen rate guidelines for corn. M. Loukianenko and J. McGuire, eds. Iowa State University Extension. Available on-line at: www.extension.iastate.edu/Publications/2015.pdf. Accessed Nov. 11, 2011.

Jones, R. J.; B.G. Gengenback and V.B. Cardwell. 1981. Temperature effects on in-vitro development of Maize. Crop Sci. 25: 761-766.

Jones, R.J.; S. Ouattar, R.K. Crookston. 1984. Thermal environment during endosperm cell division and grain filling in maize: Effects on kernel growth and development in vitro. Crop Sci. 24: 133-137.

Jones, R.J.; J. Roessler, and S. Ouattar. 1985. Thermal environment during endosperm cell division in maize: Effects on endosperm cells and starch granules. Crop Sci. 25: 830-834.

Kamprath, E.J.; R.H. Moll, N. Rodriguez. 1982. Effects of nitrogen fertilization and recurrent selection on performance of hybrid populations of corn. Ag. J. 74: 955-958.

Katupitiya, A.; D.E. Eisenhauer, R.B. Ferguson, R.F. Spalding, F.W. Roeth, M.W. Bobier. 1997. Long-term tillage and crop rotation effects on residual nitrate in crop root zone and nitrate accumulation in the intermediate vadose zone. Trans. ASAE 40: 1321-1327.

Kladivko, E.J.; D.R. Griffith, J.V. Mannering. 1986. Conservation tillage effects on soil properties and yield of corn and soya beans in Indiana. Soil Tillage Res. 8: 277-287.

Laboski, C. 2007. Phosphorus and potassium management for corn. University of Wisconsin Integrated Pest and Crop Management. Available on-line: http://ipcm.wisc.edu/WCMNews/tabid/53/EntryId/215/Phosphorus-and-Potassium-Management-for-Corn.aspx. Accessed November 20, 2011.

Lauer, J.G.; M. Rankin. 2004. Corn response to within row plant spacing variation. Agron. J. 96: 1464-1468.

Liu, W.; M. Tollenaar, G. Stewart, W. Deen. 2004. Response of corn grain yield to spatial and temporal variability in emergence. Crop Sci. 847-854.

Ma, B.L. and K.D. Subedi. 2005. Development, yield, grain moisture, and nitrogen uptake of Bt corn hybrids and their conventional near-isolines. Fields Crop Res. 93: 199-211.

Meghji, M.R.; J.W. Dudley, R.J. Lambert, G.F. Sprague. 1984. Inbreeding depression, inbred and hybrid grain yields, and other traits of maize genotypes representing three eras. Crop Sci. 24: 545-549.

Nafziger, E.D.; P.R. Carter, E.E. Graham. 1991. Response of corn to uneven emergence. Crop Sci. 31: 811-815.

Nafziger, E.D. 1998. Corn. *In* Illinois Agronomy Handbook 1999-2000. University of Illinois at Urbana-Champaign, Department of Crop Sciences, University of Illinois Extension, Circular 1360.

Nafziger, E.D. 1999. Corn. *In* Illinois Agronomy Handbook, 24th edition. University of Illinois at Urbana-Champaign, Department of Crop Sciences, University of Illinois Extension, Circular 1394.

Nafziger, E.D. 2006. Inter- and Intraplant Competition in Corn. Proceedings of the Symposium *Plant Arrangement in Fields to Maximize Productivity*. Crop Management doi: 10.1094/CM-200600227-05-RV.

Nason, M.A.; J. Farrar, D. Bartlett. 2007. Strobilurin fungicides induce changes in photosynthetic gas exchange that do not improve water use efficiency of plants grown under conditions of water stress. Pest Manag Sci 63: 1191-1200.

Oldham, L. 2004. Crops require sulfur. Mississippi State University Extension Service. Available online: http://msucares.com/crops/fertilizer/sulfur_required.html. Accessed Nov. 20, 2011.

Peterson, T.A. and G.E. Varvel. 1989. Crop yield as affected by rotation and nitrogen rate. III. Corn. Agron. J. 81: 735-738

Porter, P.M.; J.G. Lauer, W.E. Lueschen, J. H. Ford, T.R. Hoverstad, E.S. Oplinger, R.K. Crookston. 1997. Environment affects the corn and soybean rotation effect. Ag. J. 89: 441-448.

Rehm, G. and M. Schmitt. 1997. Zinc for crop production. University of Minnesota Extension. Available online: http://www.extension.umn.edu/distribution/cropsystems/DC0720.html. Accessed Nov. 20, 2011.

Ritchie, S.W.; J.J. Hanway, G.O.Benson. 1986. How a Corn Plant Develops. Special Report No. 48. Iowa State Univ.

Rood, S.B. and D.J. Major. 1980. Response of early corn inbreds to photoperiod. Crop Sci. 20: 679-682.

Shapiro, C.A. and C.S. Wortmann. 2006. Corn response to nitrogen rate, row spacing, and plant density in Eastern Nebraska. Agron. J. 98: 529-535.

Tarkalson, D.D.; S.D. Kachman, J.M.N. Knops, J.E. Thies, C.S. Wortmann. 2008. Decomposition of Bt and Non-Bt corn hybrid residues in the field. Nut. Cycling in Agroecosys. 80: 211-222.

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

United States Department of Agriculture Foreign Agricultural Service. 2011. Current world production, markets, and trade report. Grains: World markets and trade. Available online: http://www.fas.usda.gov/report.asp. (Accessed Dec. 7, 2011).

United States Department of Agriculture National Agricultural Statistics Service. 2011. Acreage. ISSN: 1949:1522.

United States Department of Agriculture Ohio. 2010. Western Lake Erie Basin Conservation Tillage Study Results. Available on-line: http://www.oh.nrcs.usda.gov/technical/tillage_results.html. (Accessed Dec. 8, 2011)Varvel, G.E.; T.A. Peterson. 1990. Residual soil nitrogen as affected by continuous, two-year, and four-year crop rotation systems. Agron. J. 82: 958-962.

Vitosh, M.L.; J.W. Johnson, D.B. Mengel. 2007. Tri-State Fertilizer Recommendations for Corn, Soybeans, Wheat and Alfalfa. Available on-line: http://ohioline.osu.edu/e2567/index.html (Accessed November 20, 2011).

Warrington, I.J. and E.T. Kanemasu. 1983. Corn growth response to temperature and photoperiod I. Seedling emergence, tassel initation, and anthesis. Ag. J. 75: 749-754.

Werblow, S. 2007. More corn: Is conservation tillage at risk? Partners – A quarterly publication of the Conservation Tillage Information Center. April 2007, feature story. Available online: http://partnersarchive.ctic.org/partners/040107/feature.asp. (Accessed Dec. 8, 2011.)

West, T.D.; D.R. Griffith, G.C. Steinhardt, E.J. Kladivko, S.D. Parsons. 1996. Effect of tillage and rotation on agronomic performance of corn and soybean: Twenty-year study on dark silty clay loam soil. J. Prod. Agric. 9: 241-248.

Widdicombe, W.D. and K.D. Thelen. 2002. Row width and plant density effects on corn grain production in the northern corn belt. Agron. J. 94: 1020-1023.

Wilhelm, W.W. and C.S. Wortman. 2004. Tillage and rotation interactions for corn and soybean grain yield as affected by precipitation and air temperature. Agron. J. 96: 425-432.

APPENDIX

Figure A1. Omission treatment design consists of 5 agricultural management factors with two levels per factor. Treatments 1 and 7 are the experimental controls for the 5 treatments following them in the design. Treatment 1, the experimental control for the High Technology system, consists of the advanced level of all five factors (Non-N fertility, Nitrogen, Genetics, Population, and Fungicide). Treatments 2-6 were created by changing one factor in the High Technology system from the advanced level to the traditional level. Treatments 8-12 were created by changing one factor in the Traditional system from the traditional level to the advanced level.

		FACTORS				
	TREATMENT	Non-N Fertility	Nitrogen	Genetics	Population	Fungicide
	1. HIGH TECH	MESZ	Base + Slow release	CRW-resistant	111,150	Strobilurin
Remove Technology	2. Non-N Fertility	None	Base + Slow release	CRW-resistant	111,150	Strobilurin
	3. Nitrogen	MESZ	Base	CRW-resistant	111,150	Strobilurin
	4. Genetics	MESZ	Base + Slow release	CRW-susceptible	111,150	Strobilurin
	5. Population	MESZ	Base + Slow release	CRW-resistant	79,040	Strobilurin
	6. Fungicide	MESZ	Base + Slow release	CRW-resistant	111,150	none
	7. STANDARD	None	Base	CRW-susceptible	79,040	none
Add Technology	8. Non-N Fertility	MESZ	Base	CRW-susceptible	79,040	none
	9. Nitrogen	None	Base + Slow release	CRW-susceptible	79,040	none
	10. Genetics	None	Base	CRW-resistant	79,040	none
	11. Population	None	Base	CRW-susceptible	111,150	none
	12. Fungicide	None	Base	CRW-susceptible	79,040	Strobilurin

Table A1. Average monthly temperature (TEMP) and precipitation (PRECIP), 2009-2010 growing seasons; values in parentheses represent departure from average monthly temperature or precipitation. Values obtained from NOAA National Weather Service Forecast Office for Central Illinois (Urbana weather station 118740, Lat: 40:05; Long: -88:14, Elev: 220m).

YEAR	**MONTH**	**TEMP, °C**	**PRECIP, mm**
2009	APRIL	10.7 (0.1)	176 (84)
	MAY	17.4 (0.5)	145 (23)
	JUNE	23.7 (1.7)	112 (5)
	JULY	21.1 (-2.7)	160 (41)
	AUGUST	21.4 (-1.3)	143 (32)
	SEPTEMBER	19.3 (0.4)	20 (-61)
	OCTOBER	9.9 (-2.3)	223 (152)
2010	APRIL	14.5 (3.9)	53 (-40)
	MAY	18.1 (1.2)	87 (-35)
	JUNE	23.8 (1.8)	212 (105)
	JULY	25.0 (1.2)	95 (-23)
	AUGUST	25.1 (2.4)	42 (-69)
	SEPTEMBER	19.7 (0.8)	81 (-1)
	OCTOBER	13.6 (1.3)	28 (-43)

Table A2. Omission treatment corn yield results with associated standard error in parentheses for 2009 and 2010. Yield calculations based on target plant population; average of six replications. The omission treatment design provides two sets of comparisons: omission of treatments from the High Technology system (Treatments 1-6) and addition of treatments to the Traditional system (Treatments 7-12). Treatments 1 and 7 are considered the experimental controls (i.e. the basis for comparison) for treatments 2-6 and 8-12, respectively. Least significant difference values (LSD, P<0.10) are provided for each of the major systems for means comparisons within that system. A third LSD ("Overall LSD, P<0.10) is also provided for comparison of the two experimental controls, High Technology and Traditional.

Treatment	**2009 Yield (Mg ha^{-1})**	**2010 Yield (Mg ha^{-1})**
1. High Technology (HT)	14.529 (0.100)	12.321 (0.157)
2. HT – P, S, Zn	13.590 (0.294)	12.120 (0.184)
3. HT – N	13.271 (0.370)	12.231 (0.188)
4. HT – Hybrid Trait	13.128 (0.406)	11.202 (0.236)
5. HT – Population	13.818 (0.065)	12.406 (0.091)
6. HT – Fungicide	13.929 (0.141)	10.379 (0.088)
TREATMENTS 1-6 LSD (P<0.10)	**0.64**	**0.40**
7. Traditional (TRAD)	11.032 (0.287)	10.204 (0.186)
8. TRAD + P, S, Zn	11.398 (0.419)	10.294 (0.275)
9. TRAD + N	11.897 (0.385)	10.321 (0.203)
10. TRAD + Hybrid Trait	11.456 (0.333)	10.528 (0.158)
11. TRAD + Population	10.263 (0.426)	9.923 (0.104)
12. TRAD + Fungicide	10.809 (0.561)	11.069 (0.305)
TREATMENTS 7-12 LSD (p<0.10)	**0.83**	**0.48**
OVERALL LSD (P<0.10)	**0.77**	**0.44**

Table A3. 2009 Omission Treatment – Value of Factors. The result of adding each factor to the traditional package or removing each factor from the high tech package is displayed as the percent difference relative to the traditional treatment (treatment 7) or the high tech treatment (treatment 1).

Factor	Traditional		High Tech	
	Yield (Mg ha^{-1})	% Difference	Yield (Mg ha^{-1})	% Difference
None or All	11.03	-	14.53	-
P, S, Zn	11.40	+3.4	13.59	-6.9
Nitrogen	11.90	+7.9	13.27	-8.7
Hybrid	11.46	+3.9	13.13	-9.6
Population	10.26	-7.0	13.82	-4.9
Fungicide	10.81	-2.0	13.93	-4.1

Table A4. 2010 Omission Treatment (30-inch rows) – Value of Factors. The result of adding each factor to the traditional package or removing each factor from the high tech package is displayed as the percent difference relative to the traditional treatment (treatment 7) or the high tech treatment (treatment 1).

Factor	Traditional		High Tech	
	Yield (Mg ha^{-1})	% Difference	Yield (Mg ha^{-1})	% Difference
None or All	10.20	-	12.32	-
P, S, Zn	10.29	+0.9	12.12	-1.6
Nitrogen	10.32	+1.2	12.23	-0.7
Hybrid	10.53	+3.2	11.20	-9.1
Population	9.92	-2.7	12.41	+0.7
Fungicide	11.07	+8.5	10.38	-15.7

Table A5. Corn yield components, 2010 growing season. Kernel number and kernel weight expressed as average of 6 replications, 6 plants replication^{-1}. Standard error provided in parentheses.

Treatment	**2010**	
	Kernel number (kernel ear^{-1})	**Kernel Weight (mg kernel^{-1})**
1. High Technology (HT)	490 (18)	238 (5)
2. HT – P, S, Zn	502 (25)	231 (7)
3. HT – N	527 (16)	235 (4)
4. HT – Hybrid Trait	511 (31)	225 (2)
5. HT – Population	631 (14)	257 (2)
6. HT – Fungicide	508 (24)	208 (3)
TREATMENTS 1-6 LSD (P<0.10)	**51**	**10**
7. Traditional (TRAD)	585 (23)	233 (3)
8. TRAD + P, S, Zn	571 (12)	235 (5)
9. TRAD + N	623 (14)	231 (2)
10. TRAD + Hybrid Trait	587 (17)	234 (3)
11. TRAD + Population	467 (17)	214 (3)
12. TRAD + Fungicide	590 (20)	257 (2)
TREATMENTS 7-12 LSD (p<0.10)	**41**	**7**
OVERALL LSD (P<0.10)	**46**	**9**

Table A6. Corn grain quality measurements, 2010 growing season. Protein, oil, and starch content of grain expressed as average of 6 replications, 6 plants replication^{-1}. Standard error provided in parentheses.

Treatment	2010		
	Protein (%)	**Oil (%)**	**Starch (%)**
1. High Technology (HT)	8.27 (0.13)	3.45 (0.09)	73.27 (0.16)
2. HT – P, S, Zn	8.32 (0.17)	3.47 (0.07)	73.23 (0.21)
3. HT – N	7.80 (0.19)	3.46 (0.09)	73.65 (0.18)
4. HT – Hybrid Trait	8.42 (0.15)	3.45 (0.16)	73.22 (0.37)
5. HT – Population	8.73 (0.09)	4.01 (0.05)	71.87 (0.18)
6. HT – Fungicide	8.78 (0.12)	2.95 (0.08)	73.77 (0.11)
TREATMENTS 1-6 LSD (P<0.10)	**0.31**	**0.23**	**0.50**
7. Traditional (TRAD)	8.47 (0.11)	3.50 (0.10)	73.02 (0.18)
8. TRAD + P, S, Zn	8.28 (0.11)	3.45 (0.10)	73.27 (0.15)
9. TRAD + N	8.65 (0.08)	3.36 (0.07)	73.23 (0.10)
10. TRAD + Hybrid Trait	8.22 (0.05)	3.41 (0.10)	73.35 (0.19)
11. TRAD + Population	8.02 (0.21)	2.88 (0.09)	74.62 (0.09)
12. TRAD + Fungicide	8.52 (0.14)	3.75 (0.06)	72.57 (0.15)
TREATMENTS 7-12 LSD (p<0.10)	**0.31**	**0.21**	**0.35**
OVERALL LSD (P<0.10)	**0.31**	**0.22**	**0.44**

Table A7. Corn biomass (whole plant) and harvest index. Biomass represents all aboveground plant material, vegetative and reproductive as an average of 6 plants per replication, 6 replications per treatment. Harvest index is a measure of grain biomass as a fraction of total aboveground biomass. Associated standard errors are displayed in parentheses.

Treatment	**2010**	
	Biomass (g plant^{-1})	**Harvest Index**
1. High Technology (HT)	222 (6.2)	0.523 (0.015)
2. HT – P, S, Zn	228 (10)	0.506 (0.007)
3. HT – N	242 (11)	0.514 (0.011)
4. HT – Hybrid Trait	239 (17)	0.484 (0.015)
5. HT – Population	314 (7.2)	0.516 (0.010)
6. HT – Fungicide	199 (5.3)	0.530 (0.011)
TREATMENTS 1-6 LSD (P<0.10)	**24**	**0.0290**
7. Traditional (TRAD)	269 (9.6)	0.510 (0.019)
8. TRAD + P, S, Zn	263 (7.6)	0.512 (0.006)
9. TRAD + N	279 (6.6)	0.516 (0.010)
10. TRAD + Hybrid Trait	267 (4.9)	0.515 (0.011)
11. TRAD + Population	199 (6.5)	0.503 (0.008)
12. TRAD + Fungicide	288 (7.3)	0.526 (0.007)
TREATMENTS 7-12 LSD (p<0.10)	**17**	**0.0270**
OVERALL LSD (P<0.10)	**21**	**0.0276**

Table A8. Nitrogen uptake (whole plant) and N partitioning. Nitrogen (N) uptake (total N) is expressed as total N uptake harvested in the aboveground plant material. Nitrogen harvest index is a measure of N removed in grain as a fraction of total aboveground plant (vegetative + reproductive) tissues.

Treatment	**2010**	
	Total N (g plant^{-1})	**N Harvest Index**
1. High Technology (HT)	2.55 (0.10)	0.606 (0.03)
2. HT – P, S, Zn	2.57 (0.19)	0.604 (0.02)
3. HT – N	2.50 (0.11)	0.621 (0.02)
4. HT – Hybrid Trait	2.79 (0.25)	0.567 (0.04)
5. HT – Population	3.81 (0.10)	0.595 (0.01)
6. HT – Fungicide	2.31 (0.09)	0.642 (0.02)
TREATMENTS 1-6 LSD (P<0.10)	**0.34**	**0.058**
7. Traditional (TRAD)	3.10 (0.15)	0.601 (0.03)
8. TRAD + P, S, Zn	2.78 (0.11)	0.643 (0.02)
9. TRAD + N	3.11 (0.09)	0.642 (0.02)
10. TRAD + Hybrid Trait	2.89 (0.10)	0.626 (0.01)
11. TRAD + Population	2.12 (0.08)	0.606 (0.02)
12. TRAD + Fungicide	3.33 (0.18)	0.625 (0.02)
TREATMENTS 7-12 LSD (p<0.10)	**0.30**	**0.044**
OVERALL LSD (P<0.10)	**0.32**	**0.052**