2011

High-yield irrigated maize in the Western U.S. Corn Belt: I. On-farm yield, yield potential, and impact of agronomic practices

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Published in *Field Crops Research* 120 (2011), pp. 142–150; doi: 10.1016/j.fcr.2010.09.012

Submitted July 6, 2010; revised September 14, 2010; accepted September 18, 2010.

High-yield irrigated maize in the Western U.S. Corn Belt: I. On-farm yield, yield potential, and impact of agronomic practices

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Abstract

Quantifying the exploitable gap between average farmer yields and yield potential (Y_p) is essential to prioritize research and formulate policies for food security at national and international levels. While irrigated maize accounts for 58% of total annual maize production in the Western U.S. Corn Belt, current yield gap in these systems has not been quantified. Our objectives were to quantify Y_p, yield gaps, and the impact of agronomic practices on both parameters in irrigated maize systems of central Nebraska. The analysis was based on a 3-y database with field-specific values for yield, applied irrigation, and N fertilizer rate (n = 777). Y_p was estimated using a maize simulation model in combination with actual and interpolated weather records and detailed data on crop management collected from a subset of fields (n = 123). Yield gaps were estimated as the difference between actual yields and simulated Y_p for each field-year observation. Long-term simulation analysis was performed to evaluate the sensitivity of Y_p to changes in selected management practices. Results showed that current irrigated maize systems are operating near the Y_p ceiling. Average actual yield ranged from 12.5 to 13.6 Mg ha^{-1} across years. Mean N fertilizer efficiency (kg grain per kg applied N) was 23% greater than average efficiency in the USA. Rotation, tillage system, sowing date, and plant population density were the most sensitive factors affecting actual yields. Average yield gap was 11% of simulated Y_p (14.9 Mg ha^{-1}). Time trends in average farm yields from 1970 to 2008 show that yields have not increased during the past 8 years. Average yield during this period represented ~80% of Y_p ceiling estimated for this region based on current crop management practices. Simulation analysis showed that Y_p can be increased by higher plant population densities and by hybrids with longer maturity. Adoption of these practices, however, may be constrained by other factors such as difficulty in planting and harvest operations due to wet weather and snow, additional seed and grain drying costs, and greater risk of frost and lodging. Two key points can be made: (i) irrigated maize producers in this region are operating close to the Y_p ceiling and achieve high levels of N use efficiency and (ii) small increases in yield (<13%) can be achieved through fine tuning current management practices that require increased production costs and higher risk.

Keywords: *Zea mays* L., maize, yield potential, on-farm yield, exploitable yield gap, simulation model

1. Introduction

Yield potential (Y_p) is defined as the yield of a crop cultivar when grown in an environment to which it is adapted, with nutrient and water non-limiting and pests and diseases effectively controlled (Loomis and Connor, 1992; Evans, 1993). Thus, Y_p is determined by genotype, plant population density and uniformity, and location-specific solar radiation and temperature regimes. The difference between on-farm yield and Y_p represents the exploitable yield gap (Cassman et al., 2003; Lobell et al., 2009). As farmer's yields approach Y_p (i.e., diminishing exploitable yield gap), it becomes more difficult for farmers to sustain yield increases because further gains require the elimination of small imperfections in management of the crop system which is usually not economically viable. Hence, plateaus in yield time trends typically occur when average farm yields reach about 80% of Y_p as was first observed in irrigated rice systems in Asia, although this value may change across regions due to differences in the ratio of grain to input prices and access to cost-effective technologies (Cassman, 1999; Lobell et al., 2009). Accurate estimation of current exploitable gaps in major cropping systems of the world is therefore essential to estimate future food production capacity and help to formulate policies and research to ensure local and global food security.

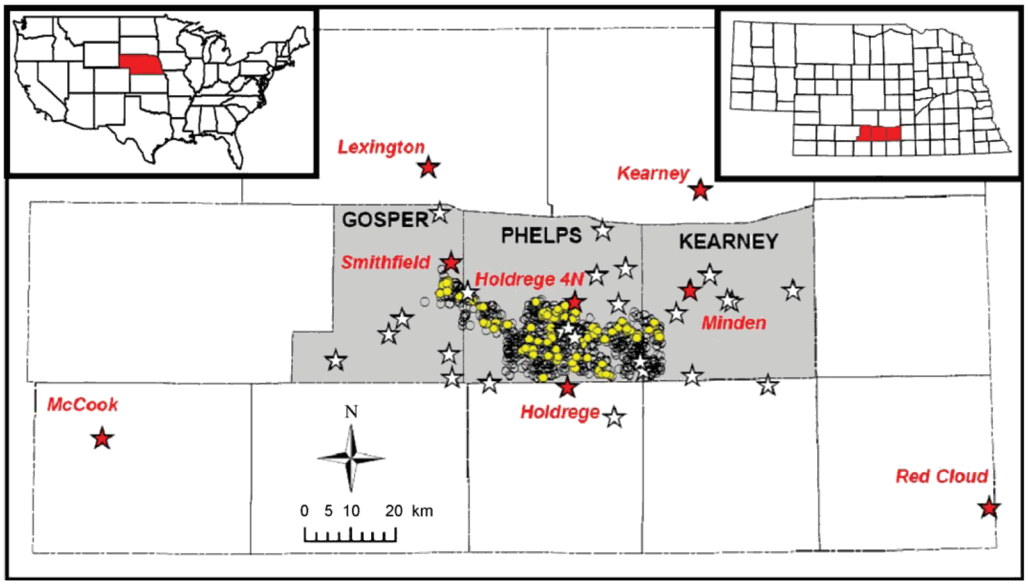

Figure 1. Map of south-central Nebraska showing the location of the Tri-Basin Natural Resources District (NRD; shaded area). Empty circles indicate location of the 521 fields included on the database; solid circles show location of those fields with additional data on crop management. Stars indicate location of rain gauges (n = 33); solid stars indicate location of meteorological stations used for interpolation of daily incident solar radiation, temperature, relative humidity, and reference evapotranspiration (n = 8; names are shown in italic). Lines show county boundaries; Tri-Basin NRD counties are named. Location of Tri-Basin NRD within Nebraska and Nebraska within contiguous U.S. is shown (right and left insets, respectively).

Although maize production must increase substantially to meet the rapidly increasing demand for food, livestock feed, and biofuel at a global scale (Cassman et al., 2003; Cassman and Liska, 2007), little increase in maize Y_p has been observed during the last 30 years (Duvick and Cassman, 1999; Tollenaar and Lee, 2002). The Western U.S. Corn Belt (37°N–45°N; 92°W–105°W) includes one of the largest irrigated areas cultivated with maize in the world (3.2 million ha) mostly located in Kansas, Nebraska, and South Dakota states (USDA-NASS, 2003–2008). Irrigated maize represents 43% of the total maize area (70% of the total irrigated cropland in the Western Corn Belt) and accounts for 58% of the total annual maize production of 60 million Mg in this region. Duvick and Cassman (1999) reported Nebraska state-level yield to be approximately 50% below the Y_p estimated from reported contest-winning yield levels (18.2 Mg ha^{-1}). Farmers who win these contests, however, use practices that are not likely to be economically viable or environmentally sustainable when practiced on a commercial scale. Likewise, average Y_p may be smaller than contest-winning yields because winning yields come from the most favorable combination of soil, weather, and crop management over a large geographic area. For example, Grassini et al. (2009) estimated average Y_p to range between 11.4 and 16.1 Mg ha^{-1} across 18 locations in the Western U.S. Corn Belt based on simulation modelling using 20 years of weather records and site-specific management. Hence, the magnitude of the exploitable yield gap has not been accurately quantified based on the current management of maize systems.

Lack of data from well-designed experiments in which yield-limiting factors have been effectively controlled makes it difficult to obtain reliable quantifications of Y_p based on actual measurements (Duvick and Cassman, 1999). Simulation models can provide reasonable estimates of Y_p when soil and historical daily weather data are available (Abeledo et al., 2008; Lobell et al., 2009). Data collected from farmer's fields can be used to evaluate actual productivity and identify major limitations in crop systems (e.g., Mercau et al., 2001; Sadras et al., 2002; Lobell et al., 2005). Because these studies lack an explicit experimental design and specific hypotheses, it is difficult to establish causal relationships although sensitive factors associated with productivity can be identified (Wiese, 1982; Sadras et al., 2002).

Given the paucity of measured data that can benchmark average farm yields against Y_p, we explored the use of on-farm crop yield and management data with simulation modelling to assess actual and potential productivity of high-yield irrigated maize systems. Specific objectives of the present study were to: (i) provide a description of current management practices in irrigated maize systems using a large database collected from farmer's fields in central Nebraska (USA), (ii) quantify the existing gap between actual yield and Y_p using on-farm data and simulation analysis, and (iii) assess the impact of agronomic practices on on-farm yield and Y_p.

2. Materials and methods

2.1. Tri-Basin Natural Resources District (NRD)

State law divides Nebraska into 23 natural resources districts (NRDs), each serving as a local government entity with authority to establish regulations and incentives to protect and conserve natural resources within the district (Nebraska Association of Resources Districts, 2010). Each NRD sets its own priorities and develops its own programs to best serve local needs. The Tri-Basin NRD (Tri-Basin Natural Resources District, 2010) includes Gosper, Phelps, and Kearney counties in central Nebraska (Figure 1). Total cropland area (excluding crops for silage and forages) in these three counties is approximately 250,000 ha (USDA-NASS, 2001–2008). Major crops are maize and soybean (61 and 33% of total cropland area, respectively) with 87 and 90% of the land area planted with these crops under irrigation. There are 6244 active registered groundwater wells for agricultural use in the area (Nebraska DNR, 2010). Average well and pumping depths are 58 and 34 m, respectively. Average rainfed yields for maize and soybean in the Tri-Basin NRD three-county region are 5.2 and 2.2 Mg ha^{-1}, respectively, and 12.1 and 3.9 Mg ha^{-1} with irrigation (USDA-NASS, 2001–2008). Average maize yield with irrigation is similar to the Nebraska state-level irrigated average yield (11.9 Mg ha^{-1}). Maize production in the Tri-Basin NRD (≈1.7 million Mg) is highly dependant on irrigated maize, which represents 94% of total production.

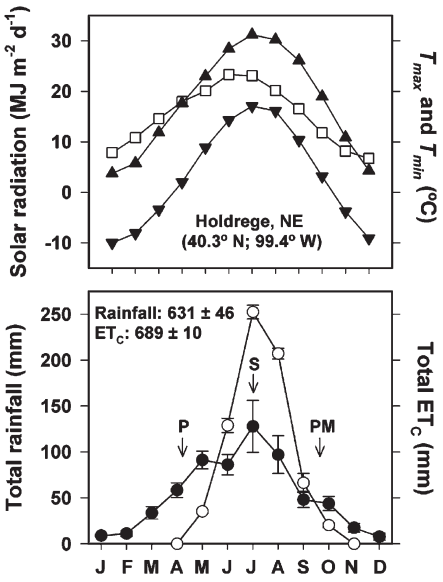

Figure 2. Monthly values for average total incoming solar radiation (□), maximum and minimum temperature (T_{max} [▲] and T_{min} [▼], respectively), total rainfall (●), and crop evapotranspiration under non-limiting water supply (ET_C [○]) in Tri-Basin Natural Resources District based on 20-year (1988–2008) weather records from Holdrege (see Figure 1). ET_C simulated using Hybrid-Maize model for maize crops with average management practices (sowing date: DOY 117, relative maturity: 113 d; 7.2 plants m^{-2}). Error bars indicate ±SE of the mean. Arrows in bottom panel indicate average dates of planting (P), silking (S), and physiological maturity (PM). Annual average (±SE) total rainfall and ET_C are shown.

The area inside the Tri-Basin NRD has flat to rolling terrain. Soils suitable for maize production are mapped in the Holdrege and, to a lesser extent, the Coly, Detroit, Hobbs, Kenesaw, and Uly series (USDA-NRCS). All series have silt loam texture. Available soil water-holding capacity in the root zone (0–1.5 m) ranges from 230 to 320 mm. None of the soils have physical impediments to root growth under typical production conditions. Annual patterns of radiation, temperature, rainfall, and crop evapotranspiration (ET_C) in Tri-Basin NRD are shown in Figure 2. Rainfall distribution follows a monsoonal pattern: 70% is concentrated in the maize growing season. ET_C peaks in July and August, which is coincident with silking and early grain-filling crop stages. Total water deficit, estimated as difference between rainfall and ET_C during growing season is 253 ± 47 mm, well above water deficit estimated for other more favorable locations in U.S. Corn Belt such as Ames, Iowa (32 ± 44 mm). Hence, maize crops grown in Tri-Basin NRD depend strongly on irrigation water and stored soil moisture that accumulates from snow melt and spring rains.

2.2. Database description and analysis

Farmers in the Tri-Basin NRD must report data on certain management practices used on each of their irrigated fields. Included in this NRD databases are geographic coordinates, grain yield (at standard moisture content of 0.155 kg H_2O kg^{-1} grain), previous crop, and amount of nitrogen (N) fertilizer applied. There are three basins within the Tri-Basin NRD: Little Blue, Platte, and Republican. Farmers in the Republican Basin must also report type of irrigation system and amount of irrigation water applied during crop growing-season based on flow meter readings. For the current study, we used data from 521 commercial irrigated maize fields (mean size: 46 ha) in the Republican Basin from 2005 to 2007 (Figure 1). Some fields were included in more than one year, so our analysis included a total of 777 field-year observations. Each field was planted, managed, and (mechanically) harvested as a unit.

Data on crop management (sowing date, seeding rate, hybrid name and relative maturity [RM][1], and tillage system) and adversities (incidence of insects, pests, diseases, hail, lodging, green snap, and lack of stand uniformity) were collected from a subset of 123 field-years through mail survey, phone, and personal interviews (Figure 1). Incidence of crop adversities was based on farmer's visual inspection and records. Two-tailed *t*-tests were performed separately for each year and showed no difference in grain yield, applied irrigation, or rate of N fertilizer between the 777 field-year database and the subset of 123 field-years ($p > 0.20$), except in 2006 when yield in the subset was slightly higher (3%, $p = 0.04$) than in the complete database. Thus, similarity in yield and applied inputs indicate the 123 field-year subset is representative of the larger database.

A variety of analytical methods are available to describe and analyze on-farm data as reviewed by Wiese (1982). In the present study, frequency distributions were calculated to illustrate the range of variation and probabilities associated with actual yield and crop management practices. Two approaches were used to assess causes of yield variation due to management factors: (i) regression analysis and (ii) comparison of factors means measured in the highest- *vs*. lowest-yielding field classes (determined from the upper and lower yield terciles, respectively, on each year) using a two-tailed *t*-test or Wilcoxon test when distribution of observed values deviated from normality. To investigate interactions between sowing date and hybrid maturity, crops were classified into four sowing date interval categories (day of year [DOY] 105–113, 114–120, 121–127, and 128–135) and two RM categories ("short"-[RM 106–112 d] and "full-season" hybrids [RM 113–118 d). Short- and full-season hybrids were equally represented across the four sowing intervals.

2.3. Simulation analysis

The Hybrid-Maize model (Yang et al., 2004, 2006) was used to simulate Y_P for the subset of crops that included data on actual sowing date, hybrid brand and RM, and seeding rate ($n = 123$). Hybrid-Maize is a process-oriented model that simulates maize development and growth on a daily time-step under growth conditions without limitations from nutrient deficiencies or toxicities, or from insect pests, diseases, and weeds. It features temperature-driven maize development, vertical canopy integration of photosynthesis, organ-specific growth respiration, and temperature-sensitive maintenance respiration. Validation of Hybrid-Maize has shown to be robust and reasonably accurate in estimating maize yields in field studies across a wide range of environments in the U.S. Corn Belt where the crop was managed under near optimal conditions (Yang et al., 2004; Grassini et al., 2009). Daily values of radiation and maximum and minimum temperature are required to simulate Y_P with this model. Thus, synthetic weather files were assembled for each of the 123 field-years with data on crop management. A modified inverse distance weight method proposed by Franke and Nielson (1980) was used to interpolate daily values of incident solar radiation and maximum and minimum temperature from meteorological stations located inside or near the Tri-Basin NRD ($n = 8$; Figure 1). Density and distribution of meteorological stations were adequate to describe geospatial patterns of radiation and temperature (Hubbard, 1994). Simulations used actual sowing date, hybrid brand and RM, and plant population reported for each field-year observation. Hybrid-Maize requires effective plant population density, thus, the latter was assumed to be 94% of actual seeding rate as suggested by Yang et al. (2006). Yield gap for each field-year was calculated as the difference between actual reported yield from the NRD database and simulated Y_P.

1. Relative maturity values are reported by seed companies for each hybrid on the market.

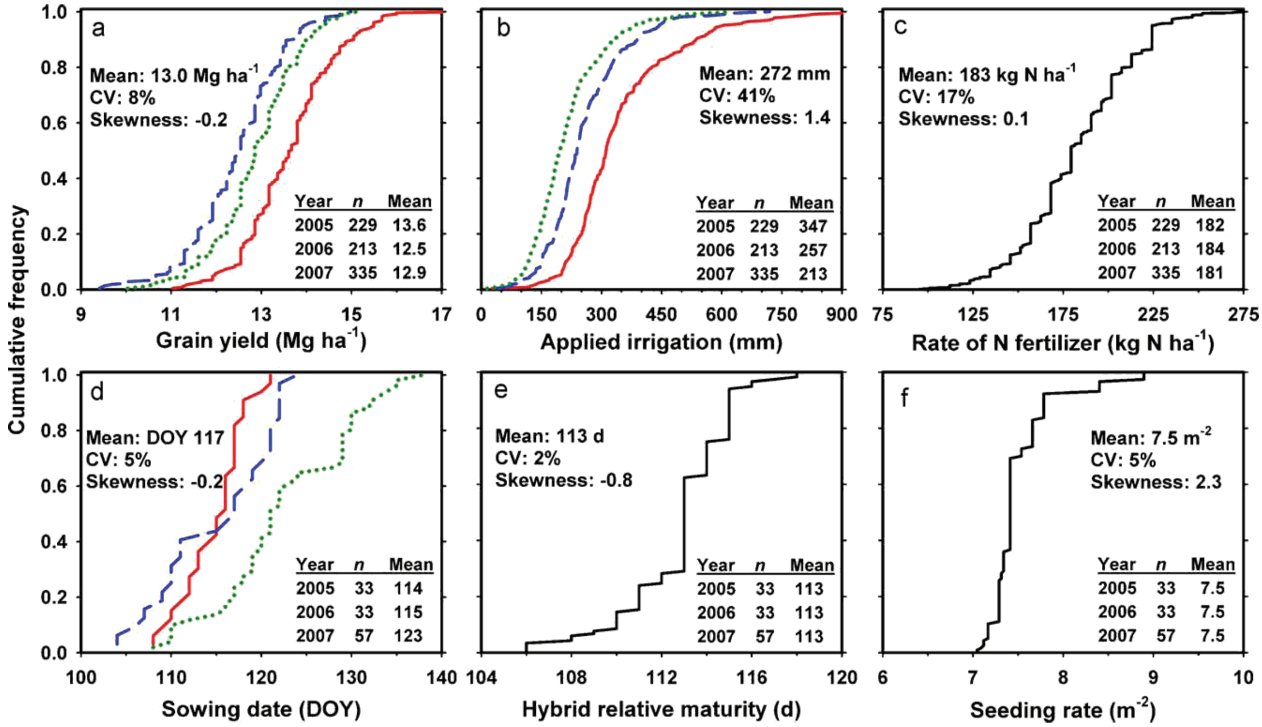

Figure 3. Cumulative frequency distributions of actual (a) grain yield, (b) applied irrigation, (c) rate of N fertilizer, (d) sowing date, (e) hybrid relative maturity, and (f) seeding rate collected from irrigated maize fields in the Tri-Basin Natural Resources District (NRD) during 2005 (—), 2006 (– –), and 2007 (- - -) seasons. Effect of year on rate of N fertilizer, hybrid maturity, and seeding rate was not significant ($p > 0.65$); thus, data were pooled across years. Mean values for each year are shown. Data for yield, irrigation, and N fertilizer rate came from the Tri-Basin NRD database with 777 field-year observations. Data for sowing date, hybrid maturity, and seeding rate were obtained from a subset of 123 field-year observations.

Opportunities to increase Y_p by changing current crop management were investigated using Hybrid-Maize in combination with daily radiation and temperature records from four meteorological stations inside or near the Tri-Basin NRD. One weather station (Holdrege) had weather records from 1988 to 2008 period; the other three weather stations (Holdrege 4N, Minden and Smithfield) had records from 1996 to 2008 period (Figure 1). Change in mean Y_p at Holdrege when simulations used weather records from 1988 to 2008 instead of 1996–2008 interval was negligible (<0.5%); thus, Y_p at Holdrege was estimated using 1988–2008 weather record series. A representative combination of current average farmer management practices from the subset of 123 field-year observations (sowing date: DOY 117, RM 113 d, 7.2 plants m^{-2}) was taken as a baseline to evaluate Y_p response to changes in sowing date (–7, +7, and +14 d), RM (–4 and +4 d), and plant population (+0.7, +1.4 plants m^{-2}) resulting in 36 sowing date × RM × plant population combinations. Sign and magnitude of these changes were representative of the actual range of management practices used by farmers in the 123 field-year subset. Average Y_p for each of the 36 combinations was calculated by averaging the mean Y_p calculated using weather records from the four weather stations. Additionally, time trends

Table 1. Average (±SE) total incoming solar radiation, maximum (T_{max}) and minimum (T_{min}) temperatures, total rainfall, and total reference evapotranspiration (ET_O; FAO-Penman-Monteith) computed for the entire crop cycle (ECC), or the pre-silking (Pre-S), around-silking (S), and post-silking (Post-S) phases of maize crops grown in the Tri-Basin Natural Resources District (NRD) during the 2005–2007 seasons. 12-y means for the ECC are also shown.

Season	Crop phase[a]	Solar radiation (MJ m^{-2} d^{-1})	T_{max} (°C)	T_{min} (°C)	Rainfall (mm)	ET_O (mm)
2005	Pre-S	20.7 ± 0.3[b]	24.0 ± 0.2	10.5 ± 0.3	227 ± 6	448 ± 4
	S	23.2 ± 0.6	32.1 ± 0.5	17.9 ± 0.1	26 ± 4	198 ± 9
	Post-S	20.1 ± 0.4	29.2 ± 0.3	15.6 ± 0.1	113 ± 9	259 ± 9
	ECC	21.0 ± 0.4	27.2 ± 0.3	13.6 ± 0.2	366 ± 13	906 ± 22
2006	Pre-S	23.4 ± 0.3	26.5 ± 0.1	11.2 ± 0.1	179 ± 14	510 ± 3
	S	24.2 ± 0.4	31.0 ± 0.2	17.1 ± 0.1	59 ± 9	189 ± 5
	Post-S	20.3 ± 0.5	29.1 ± 0.3	16.3 ± 0.1	148 ± 29	252 ± 9
	ECC	22.5 ± 0.4	28.2 ± 0.2	14.0 ± 0.1	386 ± 31	952 ± 15
2007	Pre-S	22.1 ± 0.5	25.2 ± 0.1	13.0 ± 0.2	225 ± 23	377 ± 1
	S	23.8 ± 0.4	30.8 ± 0.4	17.6 ± 0.2	53 ± 13	175 ± 7
	Post-S	19.2 ± 0.4	30.1 ± 0.3	18.2 ± 0.1	153 ± 12	227 ± 11
	ECC	21.5 ± 0.4	28.0 ± 0.2	15.7 ± 0.2	431 ± 27	779 ± 17
12-y mean	ECC	20.8 ± 0.2	27.4 ± 0.3	13.9 ± 0.1	392 ± 12	907 ± 16

a. Crop phases for each year were determined based on average actual sowing date and simulated dates of silking and maturity for a 113-d RM hybrid using Hybrid-Maize model. Silking (S) phase includes the interval from –14 to 7d around silking
b. Each value is the average of four weather stations inside or near the Tri-Basin NRD (Holdrege, Holdrege 4N, Minden, and Smithfield).

in Tri-Basin NRD (3-county average) irrigated yields reported by USDA-NASS were compared against average Y_p simulated for the 1988–2008 period using current average farmer management practices (sowing date: DOY 117, RM 113 d, 7.2 plants m^{-2}).

3. Results

3.1. Actual productivity and management of irrigated maize systems in central Nebraska

Farmer's grain yields were normally distributed and had a relatively small degree of variation for production-scale data, which attest to both the high degree of farmer management skills and the favorable environment for irrigated maize production (Figure 3a). Mean 3-y yield was slightly above (≈5%) the Tri-Basin 3-county irrigated average yield (12.3 Mg ha^{-1}; USDA-NASS, 2005–2007). The effect of year on grain yield was significant ($p < 0.001$): average and maximum yields were lower in 2006 and 2007 compared with those reported in 2005. This reduction in yield was presumably due to an episode of very high temperature and low relative humidity immediately after silking in 2006 (data not shown) and higher night temperatures combined with low radiation during the post-silking phase in 2007 (Table 1; see also Section 3.3). No geospatial pattern in grain yield was observed in any of the years (data not shown).

Frequency distribution of applied irrigation deviated from normality because 15–20% of the fields in each year received a much larger amount of applied water than other fields (Figure 3b). Effect of year on irrigation was significant ($p < 0.001$). Average applied irrigation decreased from 2005 to 2007, and this trend was associated with higher rainfall and lower evaporative demand during the silking and post-silking phases (Table 1). Irrigation was applied by center pivot sprinklers, surface gravity (mostly gated-piped furrows), or a combination of both irrigation systems (49, 33, and 18% of the total fields, respectively). The latter category involves a center pivot that typically covers >85% of total field area coupled with surface irrigation in field corners. Main energy sources for irrigation systems are natural gas, diesel, and electricity (49, 26, and 21%, respectively). Most farmers (≈70–75%) rely on crop consultants to determine amount and timing of irrigation events. Irrigations are typically scheduled based on soil water content, water balance computations, and type of irrigation system. A thorough analysis of irrigation management and efficiency is discussed in a separate paper (Grassini et al., 2011).

Average rates of N fertilizer in the Tri-Basin NRD dataset did not differ among years or irrigation system ($p = 0.66$; Figure 3c). Mean N fertilizer rate in maize grown after soybean was 21 kg N ha^{-1} less than when maize followed maize ($p < 0.001$) while N rates were similar across tillage systems ($p > 0.40$). Most N fertilizer was incorporated before sowing (70–90%); the rest was applied as a side-dressing or fertigation during the crop growing season. Over the last 10 years, anhydrous ammonia has been gradually replaced by urea–ammonium–nitrate solution (UAN), and these two forms account for approximately 70–80% of total N fertilizer applied in commercial maize fields in the Tri-Basin NRD (USDA-NASS, 1999–2008). Although mean N rate on irrigated maize in the Tri-Basin was considerably greater than the Nebraska state average (182 *vs*. 152 kg N ha^{-1}), N fertilizer use efficiency (kg grain per kg N fertilizer applied) was also much higher than Nebraska state average (71 *vs*. 64 kg grain kg^{-1} N fertilizer).

Sources of indigenous N supply include residual soil inorganic N, net N mineralization from soil organic matter and residues, and N inputs from atmospheric deposition and irrigation water. Based on measured plant N accumulation in replicated on-farm plots that did not receive N fertilizer, the contribution of indigenous N supply to irrigated maize in Tri-Basin NRD is about 145 kg N ha^{-1}, as measured in the study of Dobermann et al. (2006), which is consistent with values of indigenous N supply reported for U.S. Corn Belt (Cassman et al., 2002). Average N fertilizer uptake efficiency, calculated as the ratio of (N accumulation at farmers average yield level minus N uptake in non-fertilized plots) to applied N fertilizer, is 0.40 kg N uptake per kg N supply. In the previous calculation, N accumulation in aboveground biomass for average yield reported by farmers in this study (13.0 Mg ha^{-1}) was derived from the generic relationship between maize grain yield and N uptake following Cassman et al. (2002). Phosphorus (P) fertilizer is typically applied before planting at a rate of about 25 kg P ha^{-1}. Potassium fertilizer is rarely applied to maize in the Tri-Basin NRD because soil tests usually indicate adequate supply of this nutrient.

Most common crop sequences were maize after soybean and continuous maize (61 and 38%, respectively). A small proportion of maize (1%) was sown after wheat. No-till, ridge-till, disk, and strip-till accounted for 37, 31, 22, and 10% of the crops, respectively. Crop sequences and tillage systems were equally represented across years. Data on sowing date, RM and seeding rate collected from a subset of 123 field-years are summarized in Figures 3d–f. Frequency distributions for these parameters did not deviate from normality except for seeding rate. While RM and seeding rates were not different across years ($p > 0.80$), maize sowing in 2007 was later than in 2005 and 2006 (DOY 123 *vs*. 114 and 115, respectively) due to intense rainfall between DOY 112 and DOY 115. Average farmer's seeding rate in the Tri-Basin NRD (7.5 seeds m^{-2}) is below the range of plant population densities that gives highest yields in the region (8–10 plants m^{-2}) as reported in several studies (Yang et al., 2004; Verma et al., 2005; Grassini et al., 2009). We suspect that economic optimum for plant population density is significantly below the biophysical optimum for highest yield because seed costs in irrigated maize systems represent ~25% of total variable production costs in Nebraska (Klein and Wilson, 2010).

About 75% of the maize fields during the 2005–2007 seasons were planted with hybrids possessing one or more transgenic trait, including Bt insect control, herbicide tolerance, or both (36, 22, and 17% of the total maize land area, respectively; USDA-ERS). Therefore, insecticide application was very low on transgenic hybrids and most applications were made to fields and refuge areas planted with non-transgenic hybrids. Weed control was performed with herbicides and/or cultivation. Fungicides are rarely applied to maize in the relatively dry Western U.S. Corn Belt because incidence and severity of diseases rarely justify treatment.

3.2. Impact of management practices on actual yield

Crop sequence and tillage system have significant effects on grain yield ($p < 0.001$). Data contained in the 777 field-year database revealed that maize after soybean produced 0.5 ± 0.1 Mg ha^{-1} more than maize after maize, which was consistent across years (Figure 4a). The subset of fields with more detailed management indicated a significant crop sequence × tillage interaction on grain yield ($p < 0.005$): while yield was not affected by tillage when maize followed soybean, maize yield following maize was smaller in ridge- and no-till compared to disk (Figure 4b). Yield advantage of maize/soybean rotation over continuous maize was only significant in no-tilled crops.

Regression analysis and two-tailed *t*-test comparison of highest- and lowest-yield field classes showed a significant effect of sowing date, seeding rate, and in a lesser degree, RM on actual yields (Table 2). In general, highest-yield fields were observed with early sowing (DOY 107–120) and high seeding rates (>7.5 seeds m^{-2}). A small advantage of full- over short-season hybrids (≈0.3 Mg ha^{-1}) was consistent in the first three sowing intervals (DOY 105–127). This trend reversed (–0.2 Mg ha^{-1}) in the last interval (DOY 128–135) probably due to greater incidence of a

Table 2. Coefficients (±SE) of linear regressions between actual yield (Mg ha^{-1}) and a series of management factors. Data were pooled across years. Quadratic effects were not significant. Factors means for lowest- (LY) and highest-yield fields (HY) are also shown (average yield: 12.1 and 13.9 Mg ha^{-1}, respectively); the difference (Δ) was tested by a two-tailed *t*-test or Wilcoxon test when distribution deviated from normality.

Management factor	Intercept (Mg ha^{-1})	Slope	Pearson *r*	Factors means		
				LY[a]	HY[a]	Δ
Planting date (day of year)	17.1 ± 1.3	−0.03 ± 0.01 Mg per day	−0.32**	119	115	4**
Hybrid relative maturity (days)	5.9 ± 3.8	0.06 ± 0.03 Mg per day	0.17*	112	114	2*
Seeding rate (m^{-2})	8.2 ± 1.6	0.65 ± 0.21 Mg per seed	0.32**	7.4	7.7	0.3***
N fertilizer rate (kg N ha^{-1})	14.1 ± 0.5	−0.005 ± 0.003 Mg per kg N	0.15	187	182	5
Applied irrigation (mm)	12.7 ± 0.2	0.001 ± 0.001 Mg per mm	0.26*	224	271	47

a. Lowest- and highest-yield categories based on pooling fields in the lower and upper tercile of the yield frequency distribution across years, respectively.
* Significance at $p < 0.05$; ** Significance at $p < 0.01$; *** Significance at $p < 0.001$

frost event before physiological maturity in full-season hybrids. Data analysis also revealed that yield was poorly related to the rate of N fertilizer and amount of applied irrigation. Although frequency of fields reported by farmers to have been affected by diseases, weeds, insects, hail damage, lodging, green snap or lack of stand uniformity was not negligible (10, 15, and 25% in 2005, 2006, and 2007 seasons, respectively), there was no correlation between incidence of these constraints and yield. We suspect that farmers reported these occurrences even when a relatively small portion of the field was affected.

3.3. Yield gaps and opportunities for increasing yield potential through crop management

There was a significant effect of year ($p < 0.001$) on simulated Y_p, yield gap, and the ratio of actual yield to Y_p (Figure 5a–c). Average Y_p in 2007 (14.2 Mg ha^{-1}) was lower than in 2005 and 2006 (15.3 and 15.1 Mg ha^{-1}, respectively). The late sowing date in 2007 exposed crops to low solar radiation during the post-silking phase which, combined with high night temperatures that shortened the grain-filling period, reduced Y_p (Table 1). Reduced post-silking cumulative solar radiation and concomitant effect on Y_p with late sowing dates has been previously documented for temperate maize by Cirilo and Andrade (1994) and Otegui et al. (1995).

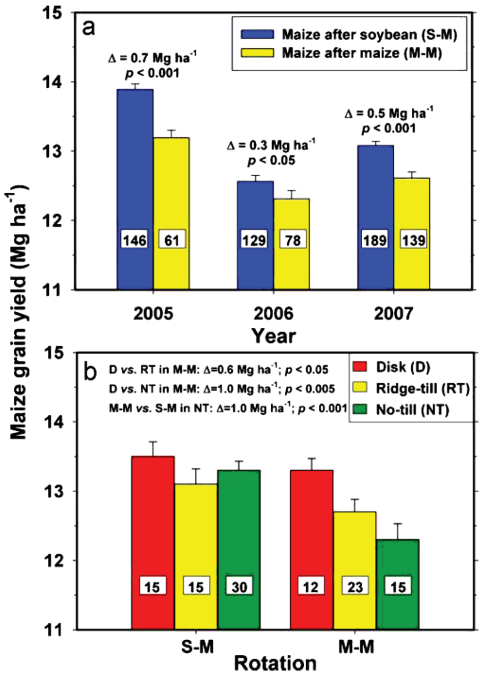

Figure 4. Average (±SE) maize yield in fields (a) under different rotation (maize after maize and maize after soybean) during the 2005–2007 seasons and (b) under disk, ridge-, and no-till systems. Tillage systems were equally represented across years, thus, data were pooled across years in (b). Rotation × tillage interaction was significant ($p < 0.005$). Difference (Δ) and *t*-test significance for selected comparisons between rotations or tillage systems are shown. Numbers inside bars indicate number of observations. A small proportion of crops under strip-till or sown after wheat was not include in this analysis.

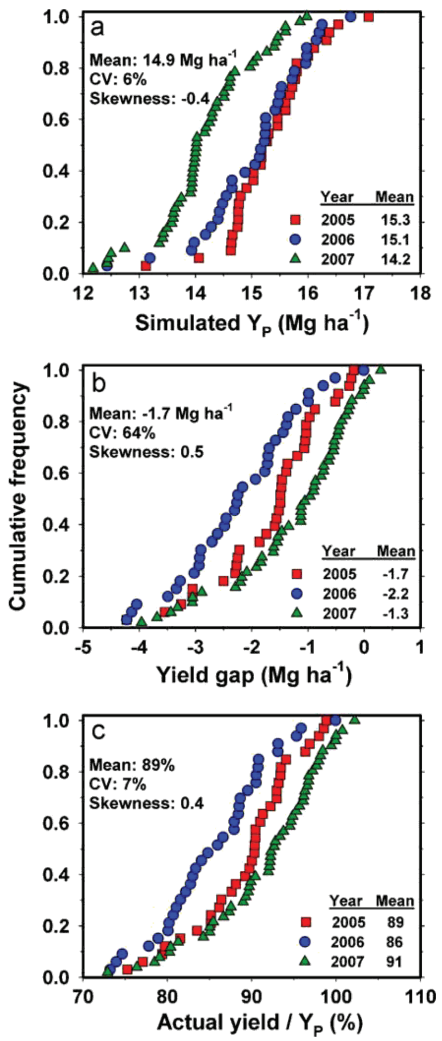

Figure 5. Cumulative frequency distributions of (a) yield potential [Y_p], (b) yield gap, and (c) actual yield as percentage of Y_p for a subset of maize crops grown in the Tri-Basin Natural Resources District (NRD) in 2005, 2006, and 2007 (n = 33, 33, and 57, respectively, representing a subset of 123 field-year observations for which detailed crop management data were obtained). Y_p was estimated using the Hybrid-Maize model in combination with actual weather records and management practices for each field. Yield gap was computed as the difference between actual yield and corresponding simulated Y_p. Mean values for each year are shown.

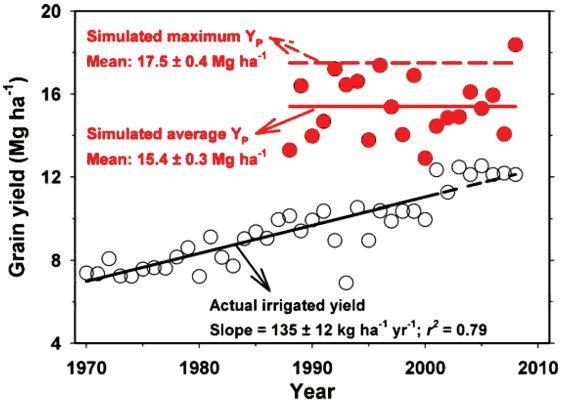

Figure 6. Trends in Tri-Basin NRD (3-county average) irrigated yields (○) and yield potential (Y_P, ●) simulated using Hybrid-Maize model based on average management practices and weather records (1988–2008). Dashed regression line for actual yield trend corresponds to lack of yield improvement in the last 8-y period. Upper dashed line is maximum simulated Y_P estimated based on the combination of practices that gives highest Y_P as given in Table 3. The slopes of the linear regressions for Y_P were undistinguishable from zero (p = 0.60).

Management practices identified to affect Y_P were sowing date, RM, and seeding rate, which as independent variables in a multiple regression model explained 57, 81, and 54% of the variation on Y_P in 2005, 2006, and 2007, respectively (data not shown). Sensitivity of simulated Y_P to these factors highlights the need for accurate specification of planting date, plant population, and cultivar maturity to arrive at Y_P estimates that reflect current crop management.

Yield gaps averaged –1.7 Mg ha^{-1} across years. Interestingly, yield gaps (expressed either as absolute values or percentage of Y_P) were more closely correlated to Y_P than actual yields (p < 0.001, r^2 = 0.46 and 0.26, respectively). Average on-farm yield in the Tri-Basin NRD was 89% of the Y_P simulated using current management practices. Yield potential simulated for the 1986–2008 period using current average farmer management practices and actual weather records in each year averaged 15.4 ± 0.3 Mg ha^{-1} (Figure 6). No time trend in simulated Y_P was detected. Actual mean irrigated yield in the Tri-Basin NRD increased at 135 kg ha^{-1} y^{-1} during 1970–2008 period. However, no increase in actual yield has occurred during the last 8-y period of the time series, a period in which farmer's yields have remained relatively stable at 21% below simulated Y_P (mean: 12.1 ± 0.1 Mg ha^{-1}). This estimate of yield gap contrasts with the value derived from simulation analysis using field-year specific data (21 *vs.* 11%, respectively). We speculate the reasons for this difference were due to: (i) specific management practices were used to determine Y_P for the subset of 123 field-years while average management practices were used to estimate Tri-Basin NRD 3-county average Y_P; (ii) 100 out of the 123 field-years included in our subset were located in Phelps County, which has a higher average irrigated yield (+0.4 Mg ha^{-1}) than reported for Gosper and Kearney Counties; and (iii) average yield gap derived from Figure 6 for the 2005–2007 period was slightly smaller than the 2001–2008 average (18 *vs.* 21% of Y_P, respectively).

Changes in current management practices were explored as an option to increase the Y_P ceiling. Simulations using long-term weather records from four meteorological stations inside or near the area of study showed increases in Y_P with higher plant population and longer hybrid RM (Table 3). Compared to average current management practices (sowing date: DOY 117, RM 113 d, 7.2 plants m^{-2}), Y_P increased by 6 and 8% when RM was extended to 117 d and plant population increased to 8.6 plants m^{-2}, respectively, and by 13% when both RM and plant population were increased (mean: 17.5 ± 0.4 Mg ha^{-1}; see dashed horizontal line in Figure 6). Using 117 d RM and 8.6 plants m^{-2} as the reference scenario for simulated maximum Y_P, Tri-Basin NRD 3-county average irrigated yields (2001–2008) are 70% of this benchmark. However, trade-offs associated with adoption of later-maturing hybrids and greater plant population may limit their adoption by farmers, at least under current grain to input price ratios. While extending growth duration through use of a longer maturity hybrid gives higher simulated Y_P, it also substantially increases the risk of frost occurrence before physiological maturity and difficulties in harvest operations due to wet weather and snow (Table 3). Likewise, yield and economic benefits from higher plant populations can be reduced, or even eliminated, as a result of higher seed costs, higher plant-to-plant variability if intra-row spacing is not uniform, greater incidence of lodging and green snap, and higher susceptibility to heat stress as reported by Yang et al. (2004).

Finally, sowing date effect on simulated Y_P was negligible (Table 3) although actual field data indicated decreasing yields with later planting (Table 2). Based on information provided by local crop consultants, this inconsistency may result from factors not simulated in the Hybrid-Maize model. For example, higher soil temperatures in late plantings may cause rapid soil drying resulting in surface crust formation and higher impedance to root growth which can make more difficult to achieve uniform crop stands. Likewise, late-planted crops are more frequently subjected to weed and disease problems, heat stress episodes during the silking and pollen shed period, and difficulties in harvest operations due to wet weather and early snow.

Table 3. Simulated yield potential (Y_P) using long-term weather records under different combinations of hybrid relative maturity, plant population density, and sowing date. Average Y_P for current average farmer management practices in the Tri-Basin Natural Resources District (NRD) is in italics. Percentage of years in which frost occurs before physiological maturity is indicated between brackets for each of the relative maturity × sowing date combinations.

Relative maturity (d)	Plant population (m^{-2})	Sowing date (day of year)			
		110	117	124	131
109	7.2	14.3[a] (5)	14.4 (5)	14.5 (5)	14.5 (14)
	7.9	14.9	14.9	15.1	15.1
	8.6	15.4	15.4	15.6	15.7
113	7.2	15.3 (10)	*15.4 (14)*	15.4 (14)	15.5 (19)
	7.9	15.9	16.0	16.1	16.2
	8.6	16.5	16.6	16.6	16.7
117	7.2	16.3 (14)	16.3 (24)	16.4 (29)	16.4 (33)
	7.9	16.9	16.9	17.0	17.0
	8.6	17.4	17.4	17.5	17.5

a. Each value is the average of Y_P simulated in four locations inside or near the Tri-Basin NRD.

4. Discussion

The use of on-farm data to identify major management constraints to actual productivity has strengths and weaknesses. A major weakness is that uncontrolled factors across farms can confound effects of management practices on yield. Such confounding can be minimized or avoided if data used in the analysis are of sufficient detail and quality, and include a representative population of farmers over several cropping seasons. These requirements appear to be met by the Tri-Basin NRD database used in the present study. As both federal and state governments increase regulatory pressures on environmental performance of agriculture (e.g., water quality, endangered species, and greenhouse gas emissions), farm reporting requirements for factors affecting environmental performance will likely increase. The result will be greater availability of high quality on-farm data, which provides opportunities to quantify the impact of management practices on yield and efficiencies of water and fertilizer as a compliment to high-cost, multi-year, multi-site field studies.

This study evaluated the impact of current management practices on yield in high-yield irrigated maize systems where actual yields approach Y_P. Rotation, tillage system, sowing date, and plant population density were identified as most sensitive factors affecting current yields. The effect of rotation and tillage system on yield of irrigated maize reported here are consistent with published data from long-term rainfed field experiments (Porter et al., 1997; Fischer et al., 2002; Boomsma et al., 2010). While yield of maize after soybean had an overall advantage compared to maize after maize, the benefit of rotation was greater in fields under conservation tillage. Whereas rotation and tillage effects on rainfed yields have multiple causes, including residual N, soil water storage, and disease pressure (Kirkegaard et al., 2008), the explanation for such effects on yield of irrigated maize with generally adequate supply of water and nutrients, and with most other yield-reducing factors effectively controlled, may result from difficulties in crop establishment coupled with greater plant-to-plant variability, N immobilization in maize residue, and changes in soil biota (Johnson et al., 1992; Gentry et al., 2001; Boomsma et al., 2010).

Farmers in the Tri-Basin NRD had grain yields that were ~35% greater than Nebraska state average yield, which includes both irrigated and rainfed production. Although they used 20% higher N fertilizer rates, N-fertilizer efficiency was 11% greater than the state average. Extension education in the Tri-Basin NRD encourages use of N "credits" for manure, legume rotations, nitrates applied in irrigation water, and residual soil nitrate as determined by soil testing. As a result, 66% of reported N-fertilizer rates were within ±20% recommended values (data not shown). The results also suggest that Tri-Basin farmers can further improve N fertilizer efficiency by achieving better congruence between nitrogen supply and crop N demand. For example, shifting N application from fall to spring or at planting and greater use of split N-fertilizer or fertigation applications during the growing season, rather than a single large N application, represent options to achieve better congruence (Cassman et al., 2002).

Time trends in Y_P and actual yield in the Tri-Basin NRD suggest that size of exploitable yield gap for irrigated maize has decreased markedly as average yields are now about 80% of the Y_P ceiling. Moreover, lack of increase in actual yield since 2001 may represent first indications of a plateau in actual yields as it has been reported for irrigated rice systems in Asia (Cassman et al., 2003). The fact that magnitude of the yield gap in a given year was more closely correlated with Y_P than actual yield suggests that current management practices, focused on maximizing net return, may limit productivity in years when weather conditions support Y_P levels above the long-term average.

The average yield gap reported in this study for irrigated maize in the Tri-Basin NRD based on field-specific management is smaller than Nebraska state-level gap estimated by Duvick and Cassman (1999). This apparent discrepancy is due to differences in the method used to estimate current average Y_P. Whereas Duvick and Cassman used contest-winning yields as the Y_P reference, the current study used simulations based on actual weather and management data for a large number of field-year observations. The latter accounts for a more representative spectrum of current management practices, soil quality, and weather conditions in estimates of Y_P for farmer's who seek to maximize net return. In contrast, contest-winning yields provide an estimate of the single best combination of management and environment amongst a large number of competing farmers and environments, which is not representative of average Y_P at regional, state, or national scales. Consistent with this discrepancy is the observation that Nebraska contest-winning average irrigated yield reported by Duvick and Cassman (1999) compares well with maximum simulated Y_P estimated in our study using a combination of practices that gives highest Y_P (18.2 *vs.* 17.5 Mg ha^{-1}).

Results from this study suggest limited potential for further increases in irrigated maize yields without a substantial increase in the current Y_P ceiling. While some of the yield constraints are not amenable to improved management (e.g., excessive heat, terminal frost, warm nighttime temperatures), actual yields may be increased through incremental changes in crop management (e.g., earlier planting dates, soybean–maize rotation instead of continuous maize). Other options might increase Y_P but are operationally difficult or economically risky to adopt with the current grain to input price ratio (e.g., higher plant population and longer maturity). While improving irrigation and nutrient management may reduce excessive inputs amounts and protect environmental quality by enhancing input efficiency, they will have little impact on yield. The same applies to transgenic approaches for higher nitrogen- or water-use efficiencies. Instead, improvement in maize yielding ability is most likely to occur by continued brute-force breeding for grain yield and yield stability across a wide range of environments to produce a continuous stream of improved hybrids, complemented by agronomic research to more fully exploit crop community-level relations and genotype by environment interactions in high-yield environments (Duvick and Cassman, 1999; Denison, 2007).

Acknowledgments — We are grateful to the Tri-Basin NRD board and staff, especially to Tammy Fahrenbruch for providing access to the crop and water use reports and helping with the survey and the many farmers who collaborated in this study. We also thank Drs Albert Weiss, James Specht, and Shashi Verma for useful comments on an earlier version of the paper. Support for this project comes from the Water, Energy and Agriculture Initiative, made possible with funding from the Nebraska Corn Board, the Nebraska Soybean Board, the Agricultural Research Division (ARD) at the University of Nebraska-Lincoln (UNL) and Nebraska Public Power District through the Nebraska Center for Energy Sciences Research at UNL. The senior author wishes also to acknowledge financial support from the Fulbright Program, UNL, and the ARD for his graduate assistantship.

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