Yield Gaps and Input-Use Efficiency of High-Yield Irrigated Corn in Nebraska

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Actual On-Farm Irrigated Corn Yield and Input Efficiency in Nebraska

> **What's Your Yield Gap?**
>
> *This publication includes a worksheet where you can record actual yields and applied inputs and quantify yield gaps and production efficiencies for your corn fields. (See page 12).*

Irrigated corn accounts for 74 percent of Nebraska's total annual corn production of 1,260 million bushels. Rising demand for food, livestock feed, and biofuel coupled with limited irrigation water supplies require greater yields on existing irrigated acreage without using more water. At the same time there are concerns about water quality and greenhouse gas emissions from the relatively large amounts of nitrogen (N) fertilizer and irrigation water being applied to irrigated corn. However, neither the gap between actual yields and yield potential, which determines the opportunity for future yield increases, nor the input-use efficiency of existing high-yield irrigated corn systems has been well documented in Nebraska or elsewhere in the U.S. Corn Belt. Using irrigated corn in the Tri-Basin Natural Resources District (NRD) in central Nebraska as a case study, this publication provides a means for corn producers to:

1) estimate the exploitable yield gap in their corn production operations — the difference between current yield and potential yield — and quantify water- and fertilizer N-use efficiency, and

2) identify management practices that contribute to increased yields and improved water and N fertilizer efficiencies.

Background

The Tri-Basin NRD

Nebraska is divided 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 its boundaries (*www.nrdnet.org/*). Each NRD sets its own priorities and develops its own programs to best serve local needs. The Tri-Basin NRD (*www.tribasinnrd.org/*) includes Gosper, Phelps, and Kearney counties in central Nebraska (*Figure 1*). Crop production in this

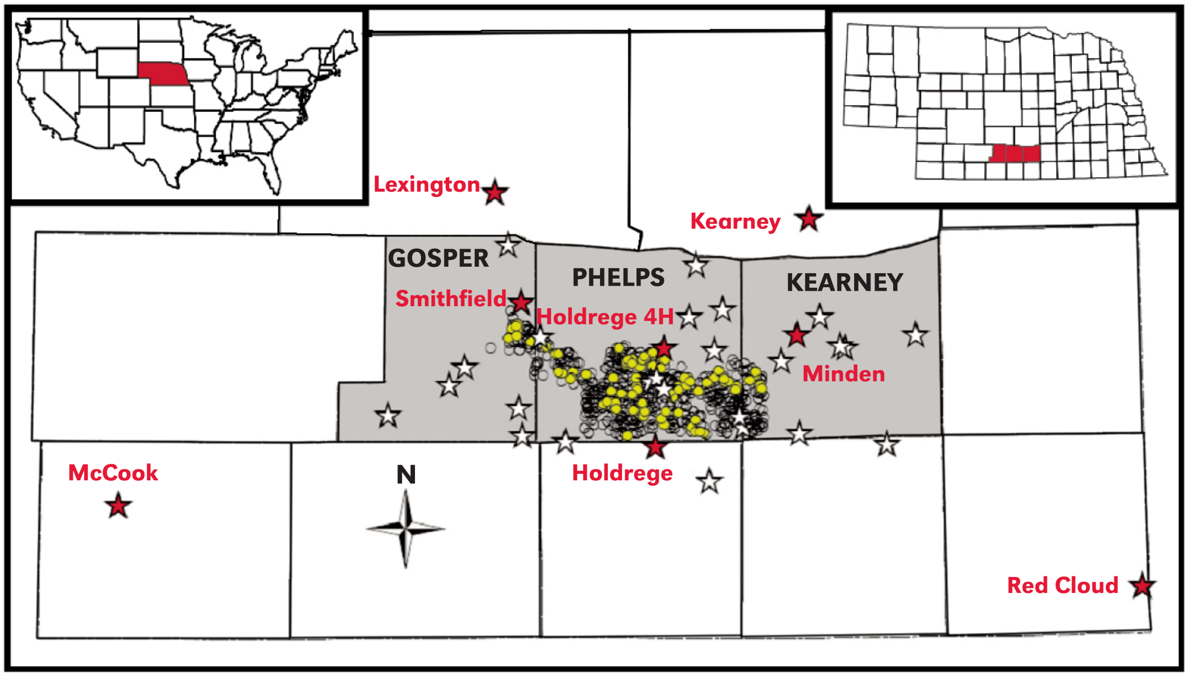

Figure 1. Map of south central Nebraska showing the location of the Tri-Basin NRD (shaded area). Empty circles indicate locations of the fields included in the database (n = 777 field-year combinations), while solid yellow circles show locations of those fields with additional crop management data (n = 123 field-year combinations). White stars indicate locations of rain gauges (n = 33); red stars indicate locations of weather stations used for interpolation of solar radiation and temperature (n = 8; names in italic).

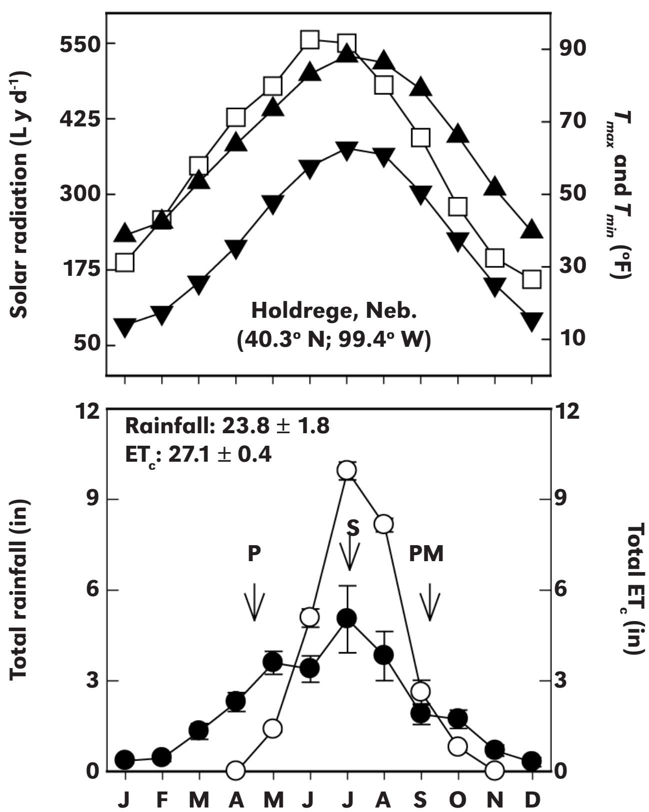

Figure 2. Monthly average of incident solar radiation (□), maximum and minimum temperature (T_{max} [▲] and T_{min} [▼], respectively), and monthly total rainfall (●) and estimated crop evapotranspiration under non-limiting water supply (ET_C [○]) in the Tri-Basin NRD based on 21 years (1988-2008) of weather records from Holdrege (see *Figure 1*). Vertical arrows in the bottom panel point to the average dates of planting (P), silking (S), and physiological maturity (PM). Average annual total rainfall and ET_C are also shown in the bottom panel.

NRD is largely dependent on irrigation with irrigated acreage accounting for 87 percent and 90 percent of corn and soybean production, respectively. There are 6,244 active registered groundwater wells for agricultural use in the NRD. Average (2001-2008) corn yield was 193 and 83 bu/ac in irrigated and rainfed fields, respectively. Comparable average soybean yields were 58 and 33 bu/ac, with and without irrigation. The average irrigated corn yield in the Tri-Basin NRD is similar to the Nebraska state irrigated average yield of 190 bu/ac.

The Tri-Basin NRD has flat to rolling terrain comprised of silt loam soils with available soil water-holding capacity in the root zone (0-5 feet) ranging from 9.1 to 12.6 inches. Annual patterns of solar radiation, temperature, rainfall, and crop evapotranspiration (ET_C) are shown in *Figure 2*. Crop ET (ET_C) peaks in July and August, which is coincident with silking and grain-filling crop stages. Total water deficit, estimated as the difference between rainfall and ET_C during the growing season, is 10 inches, significantly higher than for wetter areas in the U.S. Corn Belt such as Ames, Iowa (1.3 inches). Hence, corn grown in the Tri-Basin NRD depends strongly on irrigation water and stored soil water that accumulates from snow melt and spring rains.

Farmer-Reported Data from the Tri-Basin NRD

Farmer-reported data for irrigation pumping from a total of 777 field-year combinations during 2005-2007 seasons included:

- field GPS coordinates,
- grain yield,
- N fertilizer rate,
- applied irrigation water,
- crop rotation,
- type of irrigation, and
- energy source.

Additional information on crop management practices was collected for a subset of 123 field-year observations and included:

- planting date,
- hybrid maturity,
- seeding rate, and
- tillage method.

Statistical analysis indicated no difference in grain yield, N fertilizer rate, and applied irrigation water between the 777-field-year database and the subset of 123 observations. Therefore, the 123 field-year subset can be considered representative of the larger database.

Grain Yield and Management Practices in Irrigated Corn Fields

Farm grain yields were very high and remarkably stable (i.e., having small year-to-year variation) for production-scale data. This attests to both good management and the favorable environment for irrigated corn production (*Table 1*). The three-year mean yield of 207 bu/ac was well above the U.S. average (2005-2007) corn yield of 149 bu/ac and world average of 75 bu/ac. Average applied irrigation decreased from 2005 to 2007 because of higher rainfall in 2006 and 2007 than in 2005. Analysis of farmer-applied irrigation amounts indicated that 15 percent to 20 percent of the fields in each year received a much larger amount of applied water than other fields. Irrigation was applied by center pivot sprinklers, surface gravity (mostly gated-pipe and furrows), or a mix of both pivot and surface irrigation (49 percent, 33 percent, and 18 percent of the total fields, respectively) (*Figure 3*). The latter category involves a center pivot that typically covers more than 85 percent of total field area coupled with surface irrigation in corners. Main energy sources for irrigation pumping are natural gas, diesel, and electricity (49 percent, 26 percent, and 21 percent, respectively).

Average rates of N fertilizer did not differ among years or irrigation systems (*Table 1*). Most N fertilizer was applied before planting (70-90 percent); the rest was applied as a side-dress or through the irrigation system (fertigation) during the 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 percent of total N fertilizer applied in the Tri-Basin NRD (USDA-NASS, 1999-2008). Phosphorus (P) fertilizer is typically applied before planting at a rate of about 22 lb/ac while potassium (K) fertilizer is rarely applied because soil tests usually indicate an adequate supply of this nutrient. Soils typically have neutral to slightly alkaline pH, which means lime is not widely used.

Table 1. Average grain yield and management practices in irrigated corn fields in Tri-Basin NRD during the 2005-2007 seasons.

	2005	2006	2007	Average
Grain yield (bu/ac) *	218	199	205	207
Applied irrigation (inches) *	14	10	8	11
N rate (lb N/ac) *	161	163	160	161
Planting date **	Apr 24	Apr 25	May 3	Apr 27
Hybrid maturity (days) **	113	113	113	113
Seeding rate (per acre) **	30k	30k	30k	30k

*Based on 777 site-years (2005-2007)
** Based on a subset of 123 site-years.

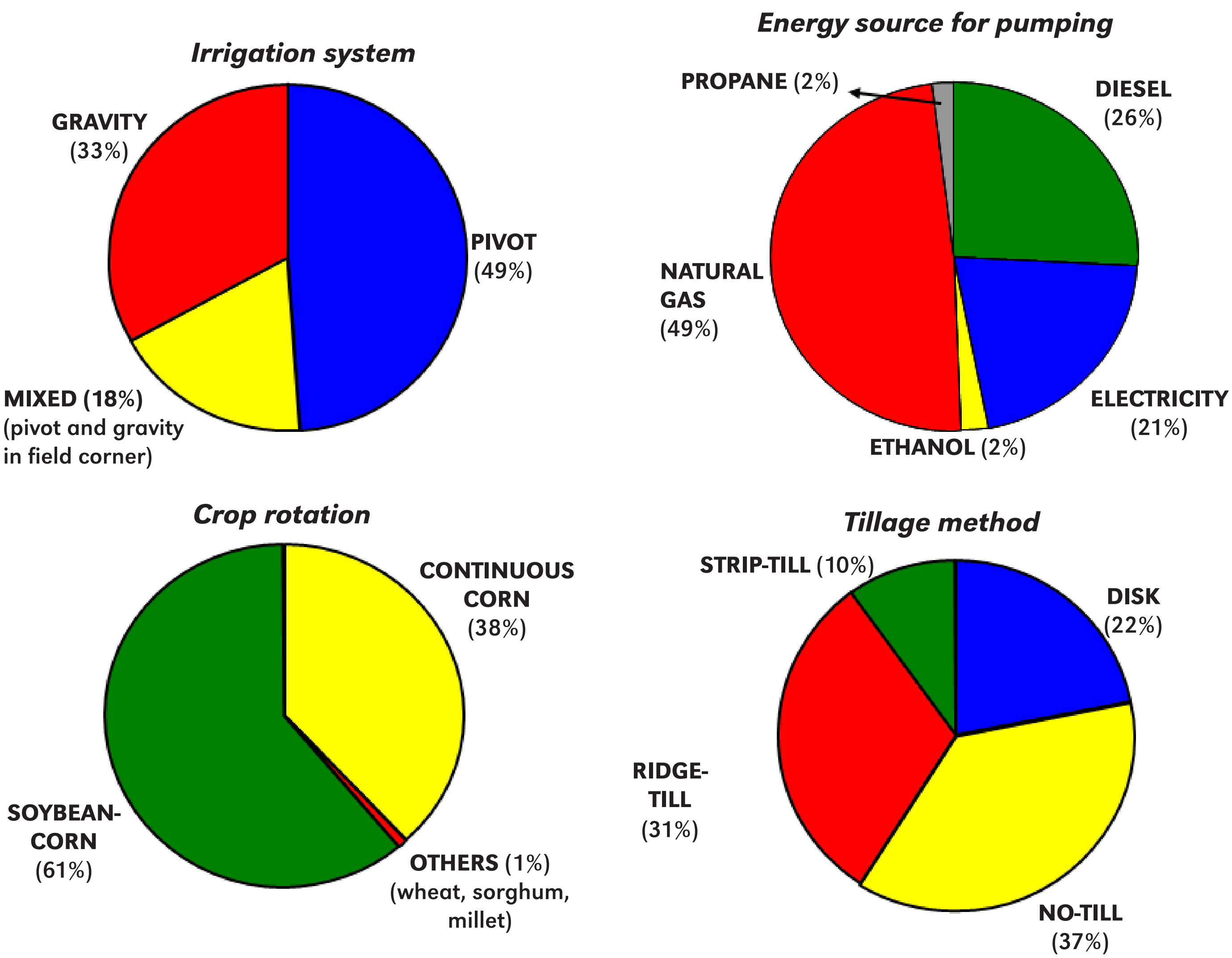

Figure 3. Characteristics of the fields in the Tri-Basin NRD included in this study, including frequency of fields under different types of irrigation systems, energy source for pumping, crop rotation, and tillage method.

The most common crop rotations were corn after soybean and continuous corn (61 percent and 38 percent, respectively) (*Figure 3*). A small proportion of corn (1 percent) was planted after wheat. No-till, ridge-till, disk, and strip-till accounted for 37 percent, 31 percent, 22 percent, and 10 percent of all the fields, respectively (*Figure 3*). Hybrid maturity and seeding rates were similar across years (*Table 1*). Corn planting in 2007 was later than 2005 and 2006 due to intense rainfall around the end of April. Interestingly, average seeding rate in this area (30,000 seeds per acre) is below the level that produces highest yields in the region (33,000-40,000 seeds per acre), as reported by Haishun Yang and his coauthors in 2004. We suspect that the economic optimum for plant population is significantly below the biophysical optimum for highest yield because seed costs in irrigated corn systems represent about 25 percent of total variable production costs in Nebraska. About 75 percent of the corn fields during the 2005-2007 seasons were planted with hybrids possessing one or more transgenic traits, including Bt insect control, herbicide tolerance, or both. Therefore, insecticide application was 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.

Yield Gaps of Irrigated Corn in the Tri-Basin NRD

By comparing the actual yields against the simulated yield potential, you can quantify the yield gaps of your corn fields. (See worksheet on page 12).

Yield gap is the difference between current yield and the yield potential of that field. Yield potential (Y_P) is defined as the yield of a well adapted hybrid when grown with optimal management that eliminates yield reduction from water deficit, nutrient deficiencies, or losses from insect pests, diseases, and weeds. Hybrid maturity, planting date, and plant population have a large impact on Y_P, but even with the same hybrid planted on the same date with the same plant population, Y_P varies across years in the same field, and across locations in the same year due to differences in weather. Crop simulation models can be used to estimate Y_P for individual fields when weather and management data are available (see *page 6*).

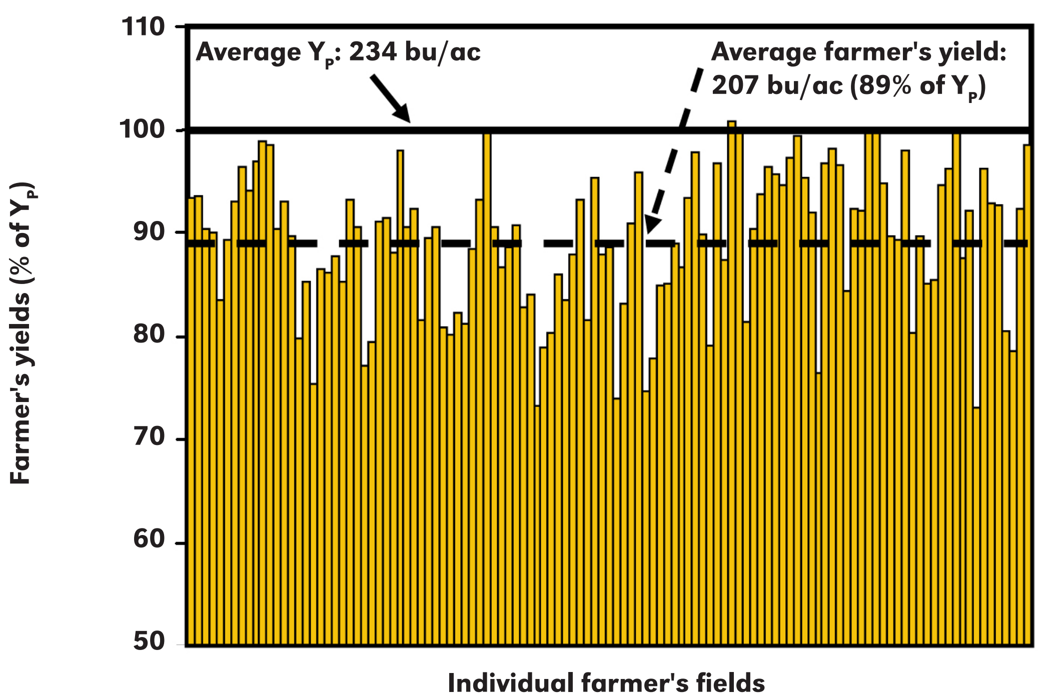

Figure 4. Farmer's yield expressed as percentage of corresponding simulated yield potential (Y_P) in 123 irrigated corn fields in the Tri-Basin NRD (2005-2007). Y_P was simulated based on actual weather data, soil properties, and farmer-reported management practices. Average Y_P and farmer's yield were 234 and 207 bu/ac, respectively.

How to Estimate Yield Potential Using the Hybrid-Maize Model

Hybrid-Maize (*hybridmaize.unl.edu*) is a computer program that simulates corn growth and yield when the crop is grown without being limited by nutrient deficiencies or toxicities, or by insect pests, diseases, or weeds. The model contains mathematical equations that describe the key physiological processes that ultimately determine grain yield, including phenology, photosynthesis, respiration, and dry matter partitioning (see below). Yield predicted by the Hybrid-Maize model assumes optimal management. Compared with other corn simulation models, Hybrid-Maize is relatively easy to use and requires few input settings. Perhaps more important, Hybrid-Maize is robust and reasonably accurate in estimating corn yield in field studies across a wide range of environments in the U.S. Corn Belt where crops were managed under near optimal conditions.

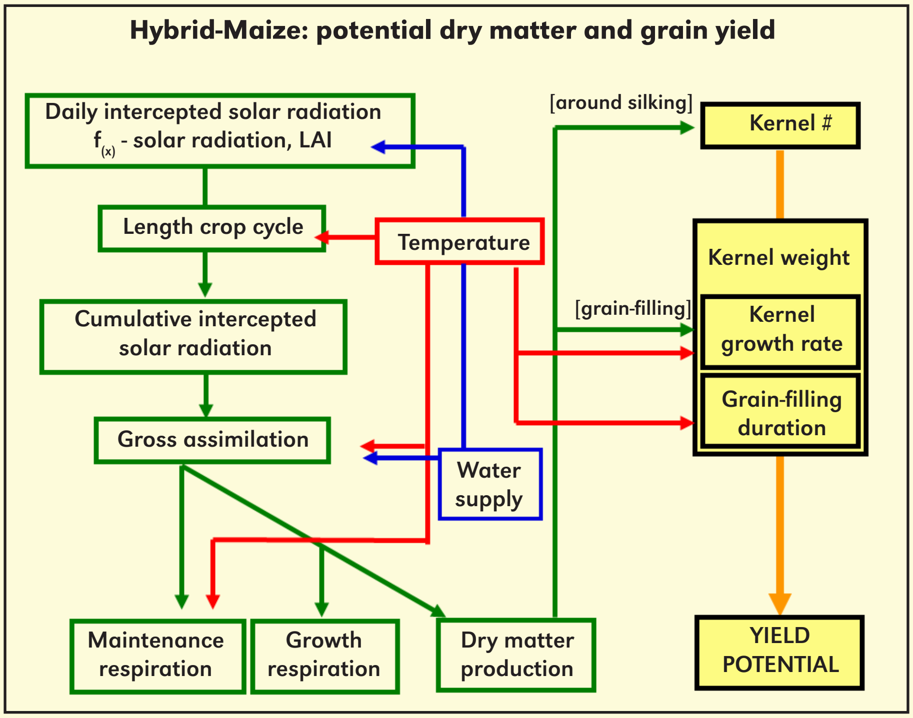

Figure 5. Potential dry matter and grain yield as estimated by the Hybrid-Maize model.

Minimum data required to simulate yield potential (Y_P) using Hybrid-Maize are:

1. daily weather including solar radiation, maximum and minimum temperature;
2. planting or emergence date;
3. hybrid maturity; and
4. plant population density.

To simulate water-limited Y_P (i.e., rainfed conditions), additional data are required:

(i) daily relative humidity, precipitation, and ET_O;
(ii) applied irrigation amount and timing (if any);
(iii) soil texture; and
(iv) soil water content at planting.

All of this information is readily available from public sources, and a seed dealer can provide information about the relative maturity of the selected hybrid. A step-by-step explanation about how to run a simulation is available at: *hybridmaize.unl.edu/howtorun.shtml.*

Potential applications of Hybrid-Maize include:

- to understand the effect of past, present, and future weather conditions on crop growth and yields, which ultimately determine yield potential;
- to quantify the impact of different combinations of hybrid maturity, planting date, and plant population on long-term Y_P and risk of early frost during grain filling based on historical weather data;
- to estimate impact of different irrigation tactics, such as limited irrigation, on yield and water requirements;
- to estimate reasonable yield goals for N fertilizer recommendations (see Maize-N Model, *hybridmaize.unl.edu/maizeN.shtml*);
- to perform in-season yield forecasting based on real-time weather data and historical weather data.

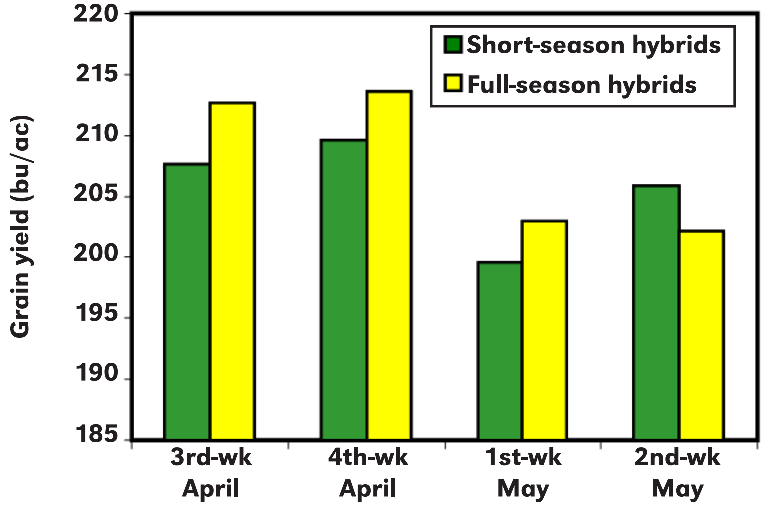

Figure 6. Actual corn yields in response to planting date and hybrid maturity based on data collected from 123 field-years in the Tri-Basin NRD. Short-season hybrid category includes relative maturities from 106 to 112 days while the full-season hybrid category includes maturities from 113 to 118 days.

Yield potential (Y_p) estimated by the Hybrid-Maize model was based on actual weather records, soil properties, and detailed data on crop management collected from the subset of 123 field-year observations. Average yields were quite high, ranging from 199 to 218 bu/ac across years (*Table 1*). A comparison of actual yield and simulated Y_p for each of the 123 fields showed that irrigated corn producers in this region achieve yields, on average, 11 percent below simulated Y_p of 234 bu/ac (*Figure 2*). Given the relatively narrow gap between Y_p and farmer yields, a significant yield increase seems difficult to achieve. This is reflected in the lack of increase in average irrigated corn yield in the Tri-Basin NRD during the last 10-year period (see page 11). Increases in average yields can still be achieved by optimizing management practices, including the use of longer maturity hybrids and early planting dates (*Figure 6*). Likewise, slightly higher yields can be achieved with seeding rates greater than 30,000 seeds per acre. There are trade-offs, however, associated with adopting longer maturity hybrids and higher plant density in some years due to:

1) frost incidence during the grain-filling phase,
2) difficulty in harvest operations due to snow,
3) lodging with higher plant density, and
4) higher seed and grain drying costs.

Producers appear to choose management practices that reduce risk and lower costs rather than striving to maximize potential yields.

Crop management differed by field with regard to irrigation system (center-pivot or surface gravity), rotation (corn after corn or corn after soybean), and tillage (disk, hereafter called conventional till, and ridge-, strip-, or no-till, hereafter called reduced till). Rotation and tillage were the factors most affecting yields while type of irrigation had no impact on yield (*Figure 7*).

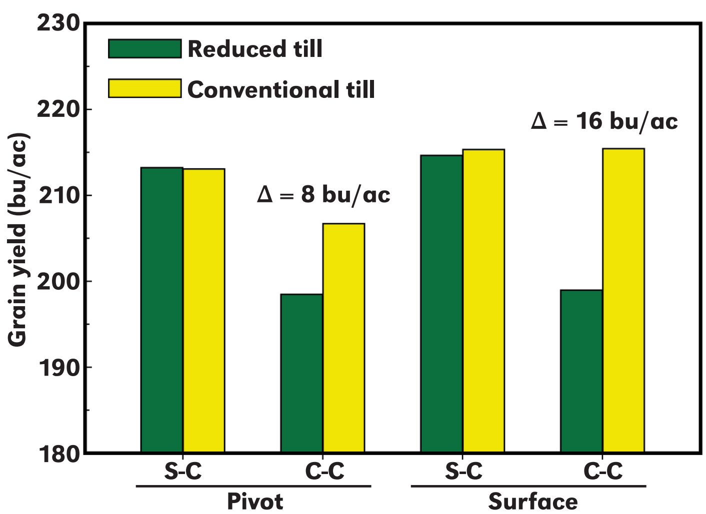

Figure 7. Corn yields as influenced by irrigation system, rotation (soybean-corn [S-C] and corn-corn [C-C]), and tillage method based on data collected from 123 field-years in Tri-Basin NRD. Also shown are yield differences (Δ) between tillage methods under continuous corn.

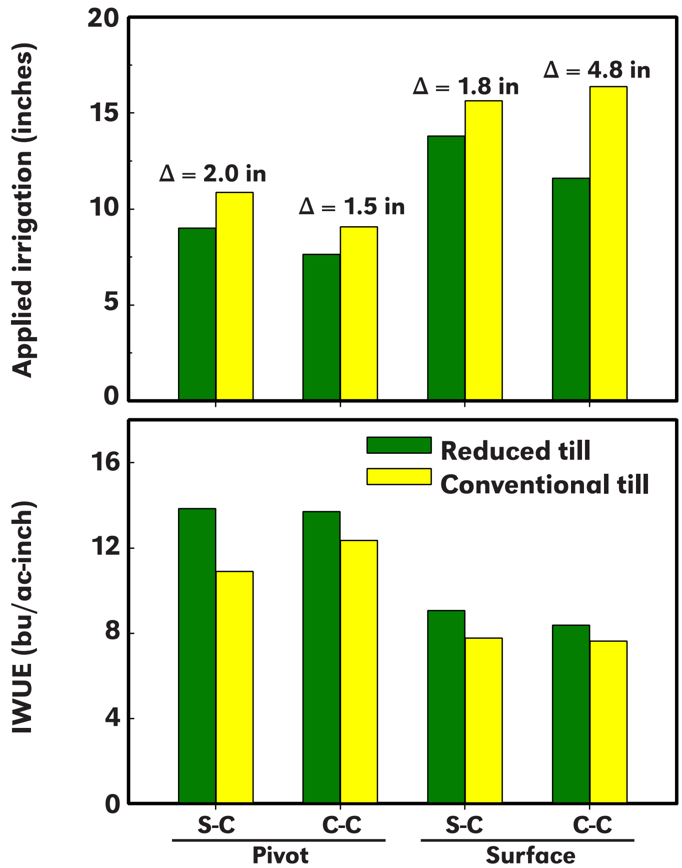

Figure 8. Applied irrigation and corresponding efficiency in relation to irrigation system, rotation, and tillage based on data collected from 123 field-years in the Tri-Basin NRD. Irrigation water use efficiency was calculated as the ratio of irrigated yield minus average rainfed yield to the amount of applied irrigation. Also shown are irrigation differences (Δ) between tillage methods.

Although yield was not affected by tillage method when corn followed soybean, in continuous corn systems, yield with reduced tillage was, on average, 5 percent less than that of conventional till. Lower yields with reduced tillage in continuous corn may result from greater disease pressure and difficulties in crop establishment that result in uneven stands and greater plant-to-plant variability. However, the yield penalty observed with reduced-tillage under continuous corn can be offset by benefits from reduced soil erosion, increased snowmelt capture, and reduced evaporative water loss from the soil surface — all of which contribute to a reduction in irrigation water requirements (*Figure 8*). The fact that more than 80 percent of the irrigated corn fields in central Nebraska are currently under reduced-tillage indicate that farmers are aware of the benefits associated with reduced tillage.

Irrigation Water Use Efficiency (IWUE) and N Fertilizer Use Efficiency (NUE)

Irrigation water use efficiency and nitrogen use efficiency were calculated for different management practices applied in the 123-field subset. For each year, irrigation water use efficiency was calculated as the ratio of:

[1] (irrigated yield - rainfed yield) / irrigation amount

in units of bushels per acre-inch of applied water. Rainfed yield was assumed to be equal to the USDA-NASS reported rainfed yield for the Tri-Basin NRD counties. Nitrogen use efficiency of irrigated corn was calculated as the ratio of:

[2] yield / applied fertilizer N

in unit of bushels per pound of applied N. Note that, by recording actual field yields and applied inputs, you also can quantify production efficiencies in your corn fields by using the worksheet on page 12.

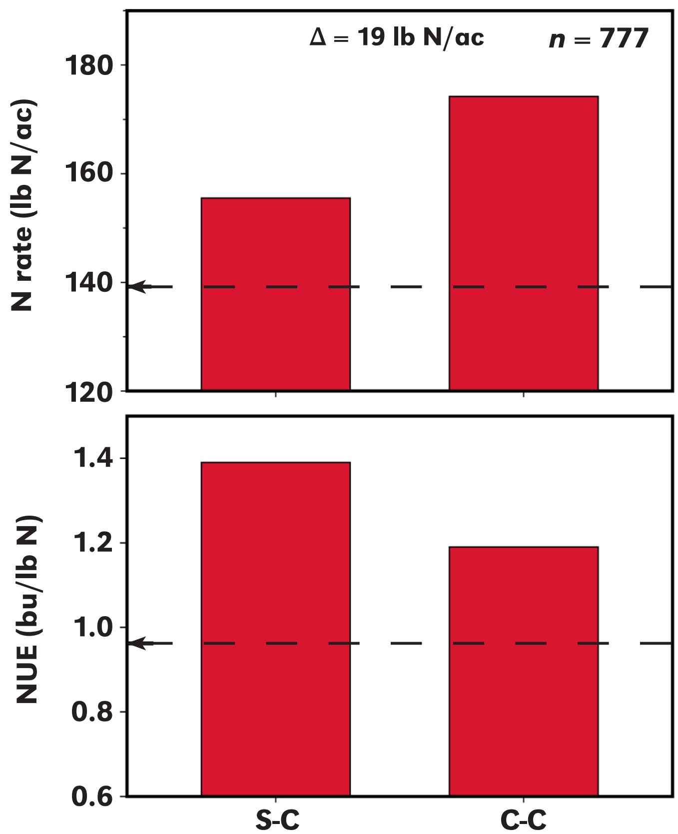

Figure 9. Applied N fertilizer and its corresponding efficiency as influenced by rotation (soybean-corn and corn-corn). Nitrogen use efficiency (NUE) was calculated as the ratio of grain yield to fertilizer-N rate. Effect of irrigation and tillage method on N rate or nitrogen use efficiency was not significant. Horizontal dashed arrows indicate U.S. average N fertilizer rate and nitrogen use efficiency. Also shown are N fertilizer differences between crop rotations.

Crop rotation, tillage, and irrigation system were the most sensitive factors affecting input rates and efficiencies (*Figures* 8 and 9). Remarkably, results derived from analysis of farmer-reported data in the Tri-Basin NRD indicated that achieving high yields with high-input use efficiencies are not conflicting objectives in intensive cropping systems. (Also see page 11.)

- Highest grain yield with the highest input-use efficiencies (IWUE and NUE) were achieved with pivot irrigation when corn followed soybean under reduced till.

Average applied irrigation water and irrigation water use efficiency were 11 inches and 10.6 bu/ac-in, respectively (*Figure* 8).

- Applied irrigation under surface irrigation was 41 percent higher than that under pivot, with no difference in grain yield. As a result, pivot-irrigated fields exhibit higher irrigation water use efficiency than surface-irrigated fields (13 and 8 bu/ac-inch, respectively).
- Applied irrigation water in reduced-till fields was 20 percent less than in conventional-till fields. Crop residues left in reduced-till fields may reduce irrigation requirements by increasing snow capture and rainfall infiltration due to reduced runoff during heavy rainfall events, as well as by reducing water loss from evaporation and runoff at the soil surface.
- There was no significant effect of irrigation or tillage method on N fertilizer rate and nitrogen use efficiency. Thus, the analysis focused on the rotation effect based on the entire 777-field database (*Figure* 9). Despite the relatively high average N fertilizer rate on corn in the Tri-Basin NRD (161 lb/ac), nitrogen use efficiency was high (1.3 bu/lb N) compared to the U.S. national average for corn. When corn followed soybean, the average N fertilizer rate was 19 lb/ac less, nitrogen use efficiency was 17 percent higher (*Figure* 9), and grain yields were greater (*Figure* 7) than those in corn after corn. The reduced N fertilizer requirement of corn after soybean is associated with greater N mineralization from soybean residue than when corn follows corn.

Key Findings

- High quality, farmer-provided data are valuable for
  - diagnosing current cropping systems,
  - conducting "field-based research" without the much higher cost of formal field experiments to evaluate impact of crop management practices on productivity and resource use efficiencies, and
  - exploring topics of global importance such as food security and greenhouse gas emissions (see page 11).
- Irrigated corn producers in the Tri-Basin NRD, on average, achieve relatively high yields (only 11 percent below the yield-potential ceiling) with a nitrogen use efficiency much greater than the national average.
- Substantial opportunities remain to improve yields and input efficiencies by adopting 1) pivot irrigation (instead of surface irrigation), 2) reduced tillage, 3) corn in rotation with soybean, and 4) better N fertilizer and irrigation management practices.
- Highest grain yield with the highest input-use efficiencies (irrigation water use efficiency and nitrogen use efficiency) were achieved in fields with pivot irrigation when corn followed soybean under reduced tillage using no-till, strip-till, or ridge-till systems.
- By recording data on actual yield and applied N fertilizer and irrigation water and using the Hybrid-Maize model, you can quantify yield gaps and input-use efficiencies of your corn fields. (See Page 12.)

Acknowledgments

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On-farm Data, Cropping System Intensification, and Exploitable Yield Gap

Irrigated systems accounted for 40 percent of world cereal production while using only 18 percent of total arable land. Hence, research directed toward achieving higher yields and input-use efficiencies in irrigated systems is crucial to ensure future food security while conserving natural resources. Farmer-reported data offer a tremendous opportunity to answer questions of global relevance and establish benchmarks for productivity, input-use efficiency, and environmental impact. To take advantage of this opportunity, however, requires high quality data from a large population of farmers over several (3+) seasons. Below are two practical examples on how farmer-reported data can be used to test hypothesis of global importance.

Hypothesis 1: Intensive cropping systems have lower input-use efficiency than low-input systems. This hypothesis is not supported by analysis of on-farm data from the Tri-Basin NRD. High-input irrigated corn in the Tri-Basin NRD exhibited stable and much higher yields with higher nitrogen use efficiency and water productivity than low-input dryland corn in the same region (*Table 1*). If there is no overuse of applied inputs, yields and input-use efficiencies are expected to increase together with cropping-system intensification due to optimization of growing conditions.

You can quantify the production efficiency of your corn fields by using the worksheet on page 12.

Table 2. Applied inputs, efficiencies, and yield of rainfed and irrigated corn in the Tri-Basin NRD.

	Dryland	Irrigated	Difference[††] (percent)
Applied N fertilizer (lb N/ac)	98	163	+66
N Fertilizer use efficiency (bu/lb N)	1.0	1.3	+32
Total water supply (inches)[†]	26	36	+38
Water productivity (bu/ac-inch)	3.6	5.8	+59
Grain yield (bu/ac)	94	207	+220
Grain yield inter-annual variation (CV, percent)	23	3	

[†] Includes plant-available soil water at planting, in-season rainfall, and applied irrigation
[††] On the basis of rainfed values

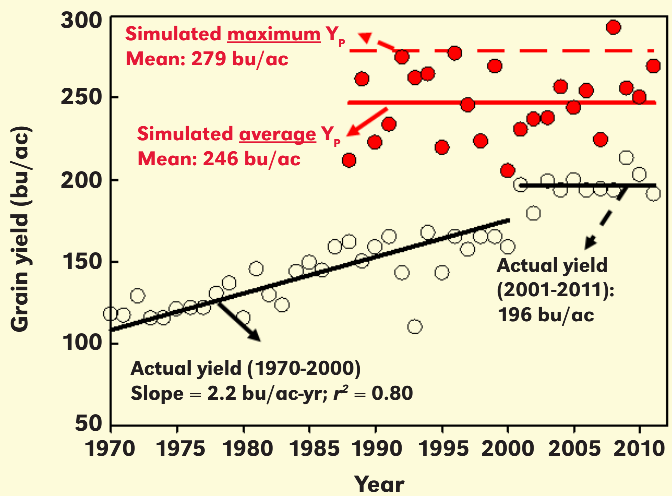

Figure 10. Trends in simulated average yield potential (YP) and average actual irrigated corn yield in the Tri-Basin NRD (solid and open circles, respectively). Note the lack of increase in actual yield during the last 11-year (2001-2011) period. The red dashed line indicates maximum simulated Y_P obtained with best combination of planting date, hybrid maturity, and plant density (Source: Grassini et al., 2011a).

Hypothesis 2: A large exploitable gap (i.e., the difference between yield potential [Y_P] and average farmer's yield) is necessary to sustain further increases in grain yields. Irrigated corn fields in the present study achieved, on average 89 percent of simulated Y_P based on actual field-year specific weather and management data (*Figure 4*). Average irrigated corn yield in the three-county Tri-Basin NRD has not increased during the past 11-year (2001-2011) period, remaining at 193 bu/ac. This represents 79 percent and 70 percent of simulated Y_P using average and best-possible management practices, respectively (*Figure 10*). Hence, the apparent stagnation in irrigated corn yield is consistent with the hypothesis that a large gap between farmer's yield and Y_P is needed to sustain further yield gains.

You can quantify the yield gaps of your corn fields by using the table on page 12.

Quantify Yield Gaps and Input-Use Efficiency for Your Farm

Use this table to record yields and applied inputs in your corn fields and quantify your production efficiency. For each field, enter data on nitrogen (N) fertilizer and water supply on a single row. You can include as many corn fields as you wish but keep one table per year. An example is provided on the first row in bold text. Detailed instructions are provided below.

Year	Field Name	Actual Corn Yield (bu/ac)	Simulated Yield Potential (bu/ac)	Yield Gap (bu/ac)	Applied N Fertilizer (lb N/ac)	Nitrogen Use Efficiency (bu grain/lb N)	Soil Water at Planting (inches)	In-season Rain (inches)	In-season Irrigation (inches)	Total Water (inches)	Corn Water Productivity (bu/ac-inch)
A	B	C	D	E (D – C)	F	G (C/F)	H	I	J	K (H + I + J)	L (C/K)
2010	**EXAMPLE**	**185**	**230**	**45**	**230**	**0.80**	**10**	**15**	**12**	**37**	**5.00**
AVERAGE PER YEAR											

How to Input Yield and Applied Inputs to Estimate Efficiencies

COLUMN A: Year in which the corn crop was planted. **COLUMN B:** Name of the field planted with corn. **COLUMN C:** Actual corn yield (bu/ac) on that field. **COLUMN D:** Simulated corn yield potential for the particular field-year (see Page 6 to see how to simulate yield potential using Hybrid-Maize corn simulation model. **COLUMN E:** Yield gap (bushels/ acre), calculated as: Simulated corn yield potential (column D) – actual corn yield (column C). **COLUMN F:** Total nitrogen fertilizer (lb/ac) applied on that particular corn field-year. **COLUMN G:** Fertilizer nitrogen use efficiency (bushels per lb of N fertilizer), calculated as: Actual corn yield (column C) / total applied N fertilizer (column F). **COLUMN H:** Inches of plant available soil water around planting date on the top 5 feet of the soil profile. A fully recharged soil profile can be assumed, except in years or locations in which total precipitation (snow plus rain) during non-growing season (roughly, from October 1 of previous year until planting date) is insufficient to ensure full recharge. (See EC105, *Evaluation of Water Productivity and Irrigation Efficiency in Nebraska Corn Production*, for information on how to estimate plant available water by planting in Nebraska soils.) **COLUMN I:** Total inches of in-season rainfall (from planting to maturity). **COLUMN J:** Total inches of in-season irrigation applied on that particular corn field-year (from planting to maturity). **COLUMN K:** Total inches of water, calculated as: available soil water at planting (column H) plus in-season rain (column I) plus in-season irrigation (column J). **COLUMN L:** Corn water productivity (bushels per acre-inch of total water), calculated as: actual corn yield (column C) / total water inches (column K). See EC105 for values of attainable water productivity of dryland and irrigated corn in Nebraska.