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EC105

Evaluation of Water Productivity and Irrigation Efficiency in Nebraska Corn Production

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Corn Yield and Water Supply in Nebraska

In Nebraska, agriculture is the largest user of fresh water, accounting for about 72 percent of current withdrawals. Irrigated corn accounts for 74 percent of the state's total annual corn production of about 1,260 million bushels. With approximately 70,000 center pivots and more than 100,000 active irrigation wells in Nebraska, irrigation provides stability for corn yield, especially in years with below-average precipitation. Increasing corn water productivity — the amount of corn yield achieved for a given amount of water supply — is crucial to optimize farmers' net economic return from irrigation and to sustain future corn production while protecting water resources. This publication presents a post-harvest method for diagnosis and improvement of water productivity for Nebraska corn fields.

Developing a Benchmark for Corn Water Productivity

A key question for irrigated crop production is how to estimate the attainable corn yield for a certain water supply. To answer this question, a benchmark for corn water productivity was developed using the Hybrid-Maize model (*www.hybridmaize.unl.edu*). Hybrid-Maize simulates corn yield potential, assuming optimal crop management practices with no nutrient deficiencies or yield losses due to weeds, diseases, or insect pests. Corn yield potential was simulated at 18 locations across the western Corn Belt for a period of 20 years (1986-2005), using location-specific actual weather data, soil properties, and common cropping practices such as planting date, choice of hybrid maturity, and plant population. Simulations encompassed a wide range of environments, from the western semiarid High Plains (Akron, Colo.) to the more humid and higher rainfall central Corn Belt (Ames, Iowa). At each location, separate simulations were conducted for rainfed and irrigated conditions, except for locations where either rainfed or irrigated corn production was negligible. Moreover, rainfed yield potential was simulated for two levels of plant available soil water at planting: a fully recharged soil profile and a partially recharged soil profile to reflect year-to-year variations in soil water recharge from non-growing season precipitation.

The simulated yield potential was plotted against the total water supply at each location (*Figure 1*). Total water supply includes:

- plant available soil water at planting (rooting depth for corn assumed to be 5 feet),

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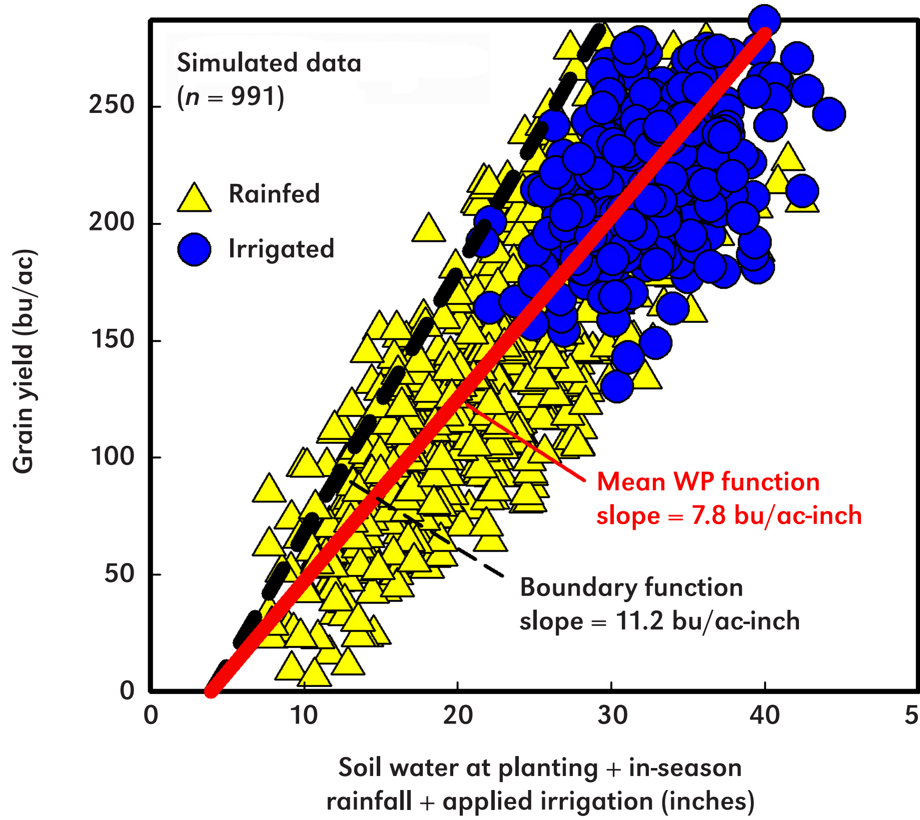

Figure 1. Simulated corn yield potential plotted against total water supply which includes available soil water at planting (0-5 feet), in-season rainfall, and applied irrigation. The water productivity *boundary function* indicates the maximum yield possible over the range of water supplies (dashed black line) while the *mean water productivity function* defines a targeted water productivity that farmers could achieve with good crop management and irrigation practices in an average year (solid red line). Simulations included rainfed and irrigated conditions at 18 locations across the western Corn Belt and central Great Plains over a period of 20 years and assumed optimal management with no yield losses due to nutrient deficiencies or pests.

- total rainfall from planting to maturity, and
- applied irrigation.

Each data point in *Figure 1* corresponds to a particular location-year-water regime combination. Two water productivity benchmarks were defined to describe the relationship between simulated yield potential and total water supply: the water productivity boundary function and the mean water productivity function.

Water Productivity Boundary Function

The water productivity boundary function is the maximum yield achievable over the range of water supplies (*Figure 1*; dashed upper line) when the crop is not limited by nutrient deficiencies, weeds, insect pests, or disease. There was considerable variation in simulated yield at any level of water supply due to variability in solar radiation and temperature under irrigated conditions, and also the distribution of rainfall in rainfed systems, across site-year combinations. For example, data points that approach the boundary function correspond to site-years when there were cool temperatures after silking that extended the grain-filling period and maximized grain yield.

Mean Water Productivity Function

To account for water productivity variation across site-years, a second benchmark was defined, the mean water productivity function. It defines the average attainable yield over the range of total water supply (*Figure 1*; solid line). The mean water productivity function can be taken as a reasonable target that producers can achieve with good crop management and irrigation practices in an average year. The further the farmer's actual yields are from the mean water productivity function for the same level of water supply, the greater the likelihood that non-water related factors or inadequate irrigation water management contributed to reduced water productivity.

The mean water productivity function has an x-intercept of 4 inches. This represents the minimum amount of total water supply lost by soil evaporation or deep percolation, or left in the soil profile at crop

How to Estimate Plant Available Soil Water at Planting Time

In eastern Nebraska, precipitation during the non-growing season ensures full soil-water recharge prior to corn planting in most years. Soil water content at planting is typically very close to field capacity, which is the maximum water content that the particular soil can hold in the root zone. However, as you move west across Nebraska, rainfall decreases such that rainfall between harvest of one year's crop and planting of the next crop is insufficient for full soil-water recharge in many years. It is essential to have a good estimate of initial soil water to quantify water productivity for both rainfed and irrigated crops.

Plant available soil water (PAW) is the portion of water in the soil that a plant can extract before soil water content reaches permanent wilting point, the lower limit of soil water for crop survival. Direct measurement of plant available water requires

- soil sampling in the active crop rooting zone (5 feet),
- subsequent determination of actual total soil water content, the difference between wet and dry soil weight, and
- subtraction of soil water content at permanent wilting point as determined through soil moisture release curves or estimated based on soil texture classification.

Alternatively, plant available water (PAW) at planting date can be estimated as:

PAW = AWHC x [-14.07 + 7.24 x PPT + 1.04 x RPAW (percent) - 0.07 x RPAW (percent) x PPT] x 0.01

where

- AWHC (in inches) is the plant available soil water holding capacity in the rooting zone (see *Table 1*),
- PPT (in inches, obtained from on-farm rain gauges or nearby weather stations) is total non-growing season precipitation from maturity of previous crop to planting date of next-season crop including rain, snow, and sleet, and
- RPAW (percent) is the residual plant available water left at maturity by previous crop, expressed as percentage of AWHC. (When RPAW (percent) is unknown, it can be roughly assumed to be 50-60 percent and 30-40 percent of AWHC under irrigated and rainfed conditions, respectively.)

This model can be used as a first approximation to estimate plant available water at planting date of summer crops although it is most suitable for silt loam and silty clay loam soils, and may be less suitable for sandy or heavy soil textures, sloping terrain, and conventional tillage. In eastern Nebraska, PAW by time of planting can be assumed to be equal to AWHC, except in years with exceptionally low non-growing season precipitation.

Table 1. Plant available soil water holding capacity (AWHC) in the rooting zone (0-5 feet) reported by USDA-NRCS for representative soil series in Nebraska.

Soil series name	*inches*	*Soil series name*	*inches*
Kennebec silt loam	12.6	Crete silt loam	10.9
Holdrege silt loam	12.2	Aksarben silty clay loam	10.7
Hord silt loam	12.1	Tomek silt loam	10.7
Holder silt loam	11.9	Hastings silt loam	10.4
Moody silty clay loam	11.6	Wymore silty clay loam	10.1
Nora silty clay loam	11.3	Woodly sandy loam	9.1
Yutan silty clay loam	11.1	Jansen loam	6.4

Another option is to consult real-time maps of plant available water for 51 sites across Nebraska on the High Plains Regional Climate Center website at *www.hprcc.unl.edu/awdn/soilm/*. Online PAW is reported as percent of AWHC, hence, inches of PAW by time of planting for a given field can be calculated as: PAW = Percent AWHC x 0.01 x AWHC from *Table 1*.

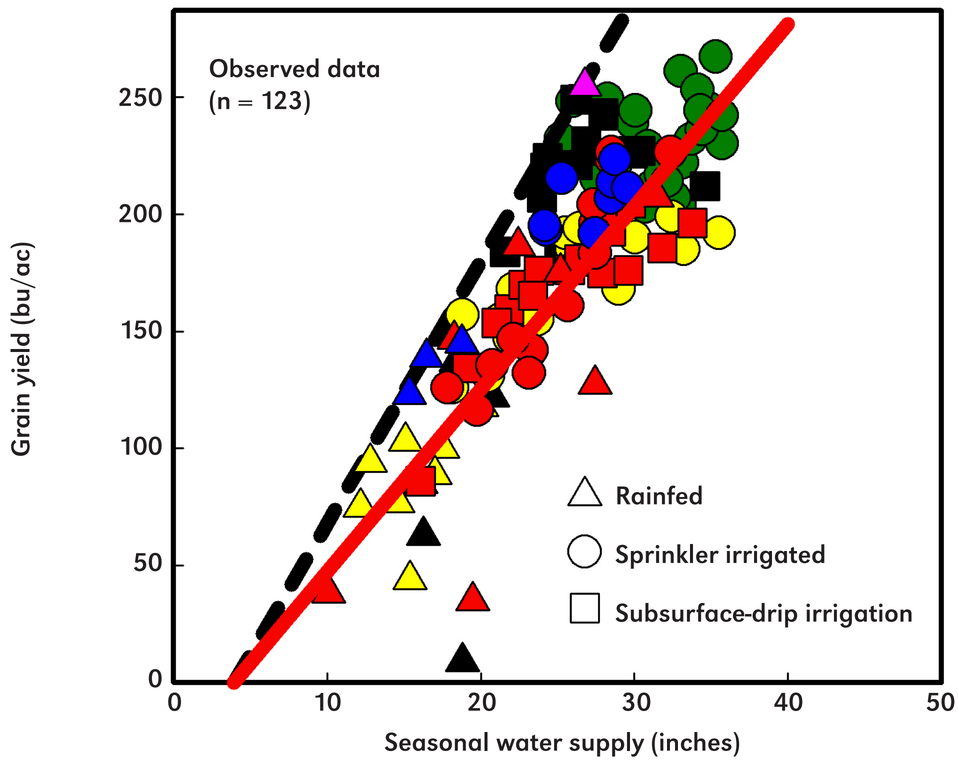

Figure 2. Actual corn yield plotted against total water supply. Data were collected from field experiments in Nebraska (except one data point from Iowa) where crops were grown with adequate nutrient supply and kept free of diseases, insect pests, and weeds. Data included rainfed and irrigated crops and a wide range of irrigation systems and schedules. The dashed black line represents the water productivity boundary function and the solid red line represents the mean water productivity function as defined in *Figure 1*.

maturity. To estimate the attainable yield for a given water supply, subtract 4 inches from the water supply estimate as follows:

Grain yield (bu/ac) =
7.8 bu/ac-inch x (water supply – 4 inches)

The relationship can be used in water supplies ranging from 0 to 38 inches. Beyond this range, there is no further yield response to increasing levels of water supply. This does not mean that maximum grain yields can be achieved at any site in any year with 38 inches of water because attainable yields also depend on the particular site-year specific weather, soil, and management conditions. Also, maximum yields are not congruent with a farmer's target of maximum net financial return. Hence, the boundary and mean water productivity functions should be used as post-season tools to diagnose and detect inefficiencies in current crop and water management practices, but not to estimate irrigation water requirements before or during the crop growing season. Attainable yield also can be estimated by a robust crop simulation model such as Hybrid-Maize (*hybridmaize.unl.edu*).

Previous water productivity benchmarks were compared against actual data collected from field experiments under optimal management, where crops were grown with adequate nutrient supply and kept free of diseases, insect pests, and weeds (*Figure 2*). Even when actual data were collected from rainfed and irrigated crops, including a wide range of irrigation systems and irrigation scheduling practices, no data point fell above the water productivity boundary function. Most data were distributed around the mean water productivity function, except in a few cases where rainfed crops were exposed to severe water stress around the silking period. Some site-year observations exhibited very high water productivity at high yield and water supply levels, especially with limited-irrigation techniques and subsurface drip irrigation.

- Comparison of previous benchmarks against actual data indicated that the mean water productivity function provides a relevant estimate of water productivity for irrigated and rainfed corn in Nebraska.

The mean water productivity function can be used to diagnose and improve water productivity in crop fields (*Figure 3*). For a given field-year combination (indicated in the example with a yellow star), the larger the distance is to the right of the mean water productivity function, the lower the water productivity. (A spreadsheet to calculate and record field-specific water productivity is in EC106, *Yield Gaps and Input Use Efficiency of High-Yield Irrigated Corn in Nebraska*). This allows users to identify opportunities to increase water productivity, which would shift the water productivity attained for a given field toward the mean water productivity function line. There are three ways corn producers can increase water productivity on their fields and move closer to the mean water productivity function:

- by increasing grain yield through better crop and soil management with the same amount of water;
- by reducing water supply through better irrigation management (for example, timing) while maintaining the same grain yield;
- by both increasing grain yield and reducing water supply.

The value of this water productivity method is:

1) It is easy to use.
2) It is easy to obtain the data for estimating water productivity (that is, yield and initial stored soil moisture, rainfall, and irrigation amounts).
3) It allows scaling up estimates of water productivity and irrigation water requirements from the field to the watershed or state levels. This can aid the development and implementation of regulations or incentives and adoption of yield-increasing and/or water- and energy-saving management practices.

An important distinction of the present approach, compared to other methods of evaluating water productivity, is that it relies on total water supply (plant available soil water at planting plus in-season rainfall and applied irrigation) instead of only crop evapotranspiration (ET_C) or applied irrigation water. We believe that expressing water productivity in terms of total water supply is more relevant to crop management when the objective is to diagnose the overall efficiency of the cropping system with regard to total water inputs. This emphasizes efficient use of both indigenous water sources (stored soil water and rainfall) and irrigation water.

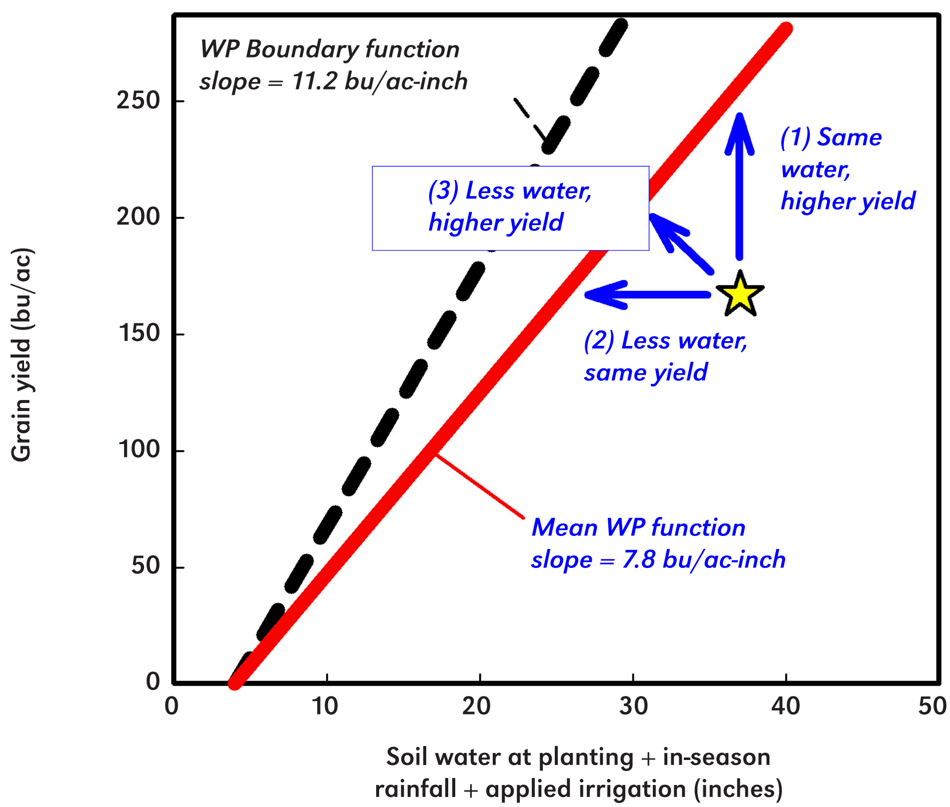

Figure 3. Method to diagnose and improve water productivity in crop fields. For a given field-year combination (indicated in the figure with a yellow star), the larger the distance to the mean water productivity function, the lower the water productivity. There are three ways farmers can increase water productivity on their fields by moving closer to the mean *WP function*: 1) increase yield with the same amount of water supply; 2) reduce water supply while maintaining the same yield; or 3) increase yield while reducing water supply.

Application of the Water Productivity Benchmark in Irrigated Corn Fields in Central Nebraska

The use of mean water productivity function for diagnosis and improvement of on-farm water productivity was evaluated using grain yield and management data collected from 777 geo-referenced irrigated fields in the Tri-Basin Natural Resources District (NRD) in central Nebraska during the 2005-2007 seasons. Farmers reported grain yield and applied irrigation amounts for each field-year combination. For each field-year, plant available soil water at planting date was estimated based on non-growing season rainfall and field-specific soil properties (see page 3), while in-season rainfall was interpolated from nearby rain gauges (*Figure 4*). Records from at least three nearby rain gauges were used to estimate in-season rainfall in each field-year to account for the large spatial variability in rainfall. Total water supply ranged from 35 to 38 inches across years. Plant available soil water at planting, planting-to-maturity rainfall, and applied irrigation represented 25, 45, and 30 percent, respectively, of total water supply.

Average on-farm water productivity — estimated as the ratio between yield and total water supply — was 5.7 bu/ac-inch, exhibiting large variation across field-year combinations (*Figure 5*). Although most field-year combinations exhibited high grain yields (average: 207 bu/ac), only 5 percent of them approached or exceeded the mean water productivity function. Fields under pivot systems were closer to the mean while those under surface irrigation were more likely to have received excess water. This observation became more evident when data were segregated by irrigation system type. The corresponding water productivity was 6.0 and 5.3 bu/ac-inch for fields under pivot and surface irrigation, respectively. The difference was explained by applied irrigation water that was 41 percent higher in fields under surface irrigation than those under pivot while showing no yield difference.

These benchmarks indicate that irrigation amounts can be reduced through better irrigation scheduling with little risk of yield reduction. For example, according to the mean water productivity function, to achieve the average yield of 207 bu/ac in this region would require no more than 31 inches of water (available soil water

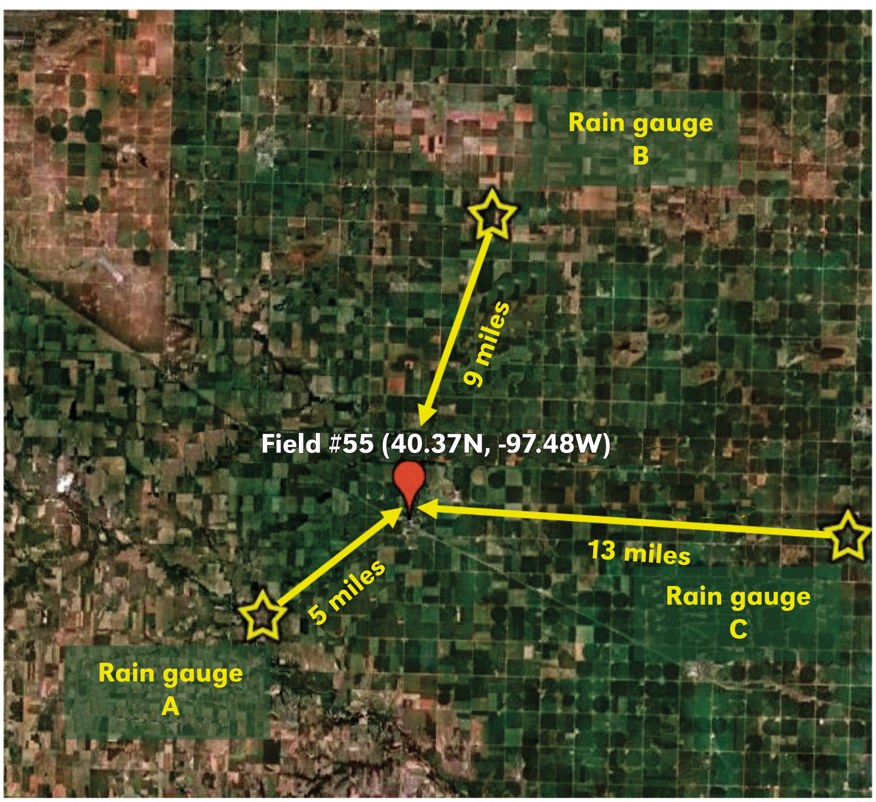

Figure 4. Schematic representation of the interpolation method used for determining in-season rainfall in each of the 777 field-year combinations in the Tri-Basin NRD. On-farm rainfall was calculated by averaging daily rainfall recorded at nearby rain gauges weighted according to the field-to-rain gauge distance. Readings from closer sites were weighted more heavily than those from greater distances.

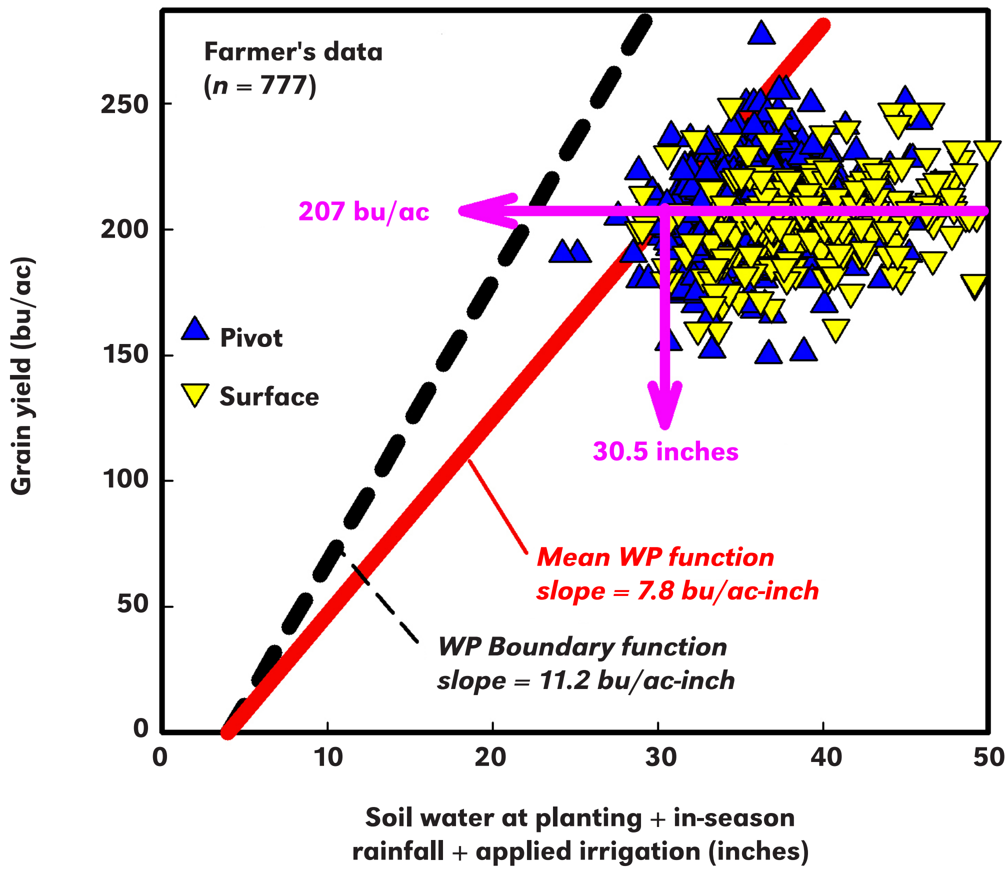

Figure 5. Farmer-reported grain yield plotted against estimated total water supply in 777 field-year combinations of irrigated corn fields in the Tri-Basin NRD. Solid arrows represent current average yields in this region (207 bu/ac) and the associated total water supply requirement of about 31 inches as estimated from the mean water productivity function. Data are distinguished by type of irrigation system (center pivot and surface gravity). Solid lines are the water productivity benchmarks as defined in *Figure 1.*

at planting plus in-season rainfall and applied water). In contrast, farmer data revealed that 95 percent of the field-year combinations had a water supply greater than this amount. These findings highlight the large room for improvement in water-related technologies and management practices that can help reduce irrigation amounts and increase water productivity.

Analysis of farmer-reported management practices in a representative subset of 123 field-year combinations (out of the total 777 observations) allowed further identification of yield-increasing and water-saving opportunities. These opportunities for increasing water productivity, derived from adjusting current crop management practices including planting date, hybrid maturity, plant population density, crop rotation, and tillage method, are discussed in detail in the companion publication. (See *Yield Gaps and Input-Use Efficiency of High-Yield Irrigated Corn in Nebraska*, EC106.) This publication focuses on the irrigation system and schedule as a means to improve water productivity by reducing applied irrigation amounts and energy use while maintaining the same grain yield level. This analysis identified the following opportunities for Tri-Basin corn producers (*Figure 6*):

- Average yields could be increased by up to 13 percent by adopting full-season hybrids, earlier planting dates, and a higher plant population.
- Switching from continuous corn with conventional tillage to reduced tillage (either no-till, strip-till, or ridge-till) with a corn-soybean rotation could increase corn yield by 8 percent while reducing applied irrigation water by 20 percent.

It should be noted, however, that it makes sense to spread the risk of yield loss from a high temperature spike at pollination by planting several hybrid maturities. Similarly, adopting longer maturity hybrids may lead to higher frost incidence during the grain-filling period and increased grain drying costs. Also, there is additional seed cost from using higher plant populations, and in many cases the additional yield does not pay for the added cost.

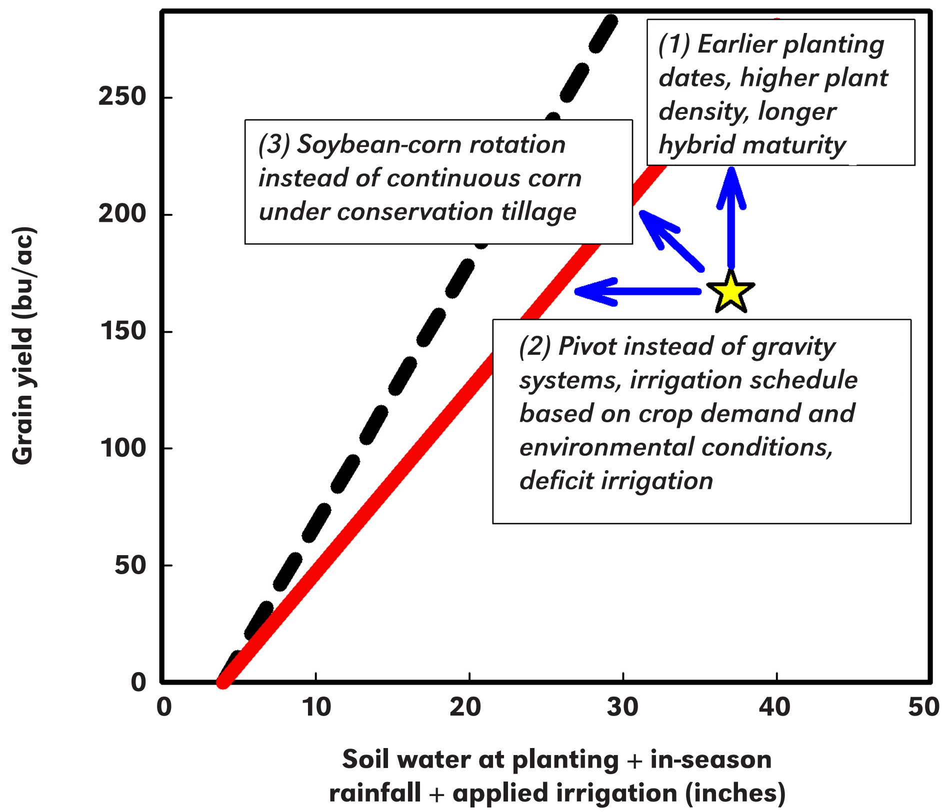

Figure 6. Yield-increasing and water-saving alternatives that increase water productivity in the Tri-Basin NRD, as identified through analysis of farmer-reported data. While this article focuses on irrigation water management as a means of achieving higher water productivity (2), detailed information about the other options (1, 3) are reported in Yield Gaps and Input-Use Efficiency of High-Yield Irrigated Corn in Nebraska (EC106). Dashed and solid lines are the water productivity benchmarks defined in *Figure 1.*

Impact of Irrigation System and Scheduling

Field and regional (the three-county Tri-Basin NRD area) impact of replacing current surface irrigation systems with center pivots was quantified based on the average applied irrigation and corn land area under each type of irrigation system. The Hybrid-Maize model was used to simulate irrigation water requirements for each of the 123 fields in the Tri-Basin NRD database subset using actual weather records, soil properties, and detailed crop management data. The purpose of these simulations was to quantify potential water savings from more timely irrigation scheduling. “Full” and “limited” irrigation management scenarios were simulated. Under the full irrigation simulation, irrigation was applied whenever crop growth rate was limited by soil water supply. Thus, full irrigation ensured crop growth without water-stress over the entire growing season, providing 100 percent of ET replacement. In the limited irrigation scenario, the amount of water applied with optimal irrigation was reduced by 25 percent throughout the cropping period except for the interval from 14 days before to seven days after silking. During this period the crop was kept fully irrigated (see Page 10).

Results showed that, on average, the amount of applied irrigation under center pivot and surface irrigation systems exceeded simulated full water requirements by 8 and 46 percent, respectively (*Table 2*). Under the limited irrigation simulation, the irrigation requirement was 15 percent less than under full irrigation with only a small yield penalty (-4 percent). For the Tri-Basin NRD, simulated results estimated:

- Converting corn fields from surface to pivot irrigation systems would result in 37,819 acre-feet of irrigation savings.
- Optimizing irrigation scheduling according to crop water needs would save an additional 20,639 acre-feet of water.
- Using center pivot irrigation and limited-irrigation scheduling practices would result in an additional potential water savings of 33,281 acre-feet and a small yield penalty of about 4 percent.
- Adopting these three practices (converting surface irrigation systems to pivot systems and fine-tuning irrigation scheduling) could result in a total savings of 91,738 acre-feet of water, 32 percent of the water volume allocated to irrigated corn in the Tri-Basin NRD.

Table 2. Actual amount of irrigation applied in comparison with simulated full and limited irrigation amounts for a subset of 123 fields in the Tri-Basin NRD. (For details see *Yield Gaps and Input-Use Efficiency of High-Yield Irrigated Corn in Nebraska,* EC106.) Total planting-to-maturity rainfall was 14, 15, and 17 inches in 2005, 2006, and 2007, respectively. Estimated total annual water volume allocated to irrigated corn land in the entire three-county Tri-Basin NRD is shown for actual and simulated irrigation scenarios (right column). Total water volume was calculated by extrapolating the irrigation water use in the subset of 123 fields to the entire irrigated corn land area within the Tri-Basin NRD, based on the proportion of land under different irrigation systems.

	2005	*2006*	*2007*	*Mean*	*Tri-Basin NRD*
			inches		*ac-ft*
Actual irrigation					
Surface	19.4	14.2	12.3	15.3	92,173
Pivot	12.3	8.2	6.5	9.0	192,708
					Total actual: 284,881
Simulated full irrigation	10.4	9.5	4.9	8.3	226,424
Simulated limited irrigation	8.9	8.1	4.2	7.0	193,143

Key Points

- The mean water productivity function is a post-season tool to evaluate corn water productivity. It is based on the relationship between grain yield and total water supply, including plant available soil water at planting and in-season rainfall plus applied irrigation. The mean water productivity function represents the yield that a farmer should achieve for a given amount of water, with good crop and irrigation management, in an average year. It can be estimated as:

  Grain yield (bu/ac) = 7.8 bu/ac-inch x (water supply – 4 inches)

- The mean water productivity function can be used post-season to diagnose and improve water productivity in crop fields. Water productivity can be increased by

  1) achieving higher yields with the same amount of water supply;

  2) applying less irrigation water without reducing yield; or

  3) achieving a combination of 1 and 2.

- This tool is not suitable for estimating irrigation water requirement before or during the crop growing season. A spreadsheet to calculate and record field-specific water productivity is in *Yield Gaps and Input-Use Efficiency of High-Yield Irrigated Corn in Nebraska*, EC106.

- When compared with the mean water productivity function, irrigation in these central Nebraska fields exceeded crop water requirements to achieve yield levels typical for this region. This overage was especially common in fields under surface irrigation.

- Results clearly document considerable opportunity to improve water productivity in irrigated fields by replacing surface irrigation with pivots to reduce applied irrigation, improving irrigation scheduling according to crop water demand and phenology, and adopting limited-irrigation techniques. A previous study also identified adoption of reduced tillage as a means to reduce irrigation water requirements (see EC106).

Scheduling Limited Irrigation in Corn

Recent field studies conducted in high-yielding irrigated corn fields in eastern and central Nebraska (16 site-year combinations from 2007-2008) indicate it is possible to reduce irrigation water amounts with minimum yield penalty. In each site-year, two adjacent center-pivot irrigated corn fields received two irrigation managements: current practice based on the farm manager's experience and a soil moisture-based, limited irrigation approach. (In the following, these will be labeled as "current practice irrigation" and "limited irrigation," respectively). In some cases a pivot field was split between current practice and limited irrigation. Current practice irrigation was based on farmer observation and personal experience. Under limited irrigation, irrigation amounts and timing were based on pre-determined soil water depletion thresholds for different crop stages.

Under the limited irrigation approach, irrigation water was applied when plant available soil water (PAW) reached 60-65 percent of its maximum in the rooting zone during the entire growing season, except during the -10 to +7 day window around silking when the threshold for plant available soil water (PAW) was raised to about 70 percent (*Figure 7*). The rationale for this irrigation scheduling is to ensure stress-free growth during the silking, pollination, and kernel-setting period while allowing greater depletion of soil water during the early-vegetative and grain-filling phases when the corn plant is less sensitive to mild water stress. Managing a limited irrigation system requires continuous monitoring of soil water content with soil-moisture sensors and real-time prediction of crop phenology using the Hybrid-Maize model.

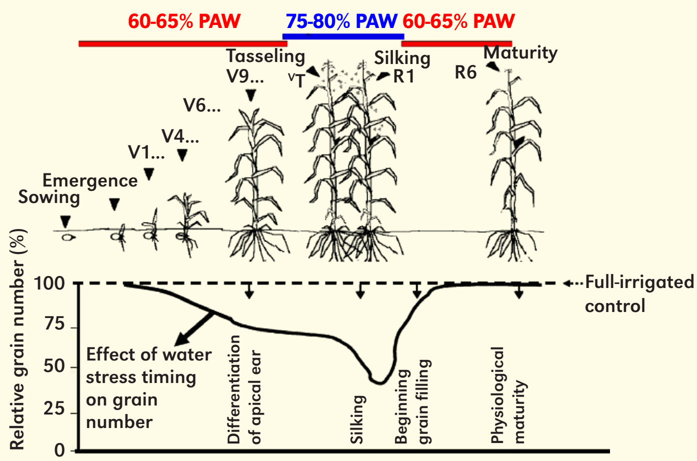

Figure 7. Illustration of limited-irrigation scheduling in corn. Plant available soil water (PAW) thresholds for irrigation application are shown. Sensitivity of grain number to water stress at different growth stages is shown. (*Figure 7* by Dr. Maria Otegui.)

Grain yields ranged from 230 to 268 bu/ac across site-year combinations. Applied irrigation water under limited irrigation was, on average, 34 percent lower than that under current irrigation practices while no difference in grain yield was observed between the two irrigation management regimes (*Figure 8*). Irrigation water use efficiency, defined as the ratio of grain yield to total applied irrigation, was 34 percent higher in fields under limited irrigation than those under current practice irrigation. Interestingly, no difference in crop water uptake was detected between irrigation management regimes. This suggests that fields under limited irrigation compensated by increasing soil water depletion. Results were consistent across all site-year combinations despite variations in weather, soil, and management practices. It appears that achieving high yields and high water productivity are not conflicting objectives for irrigated corn systems in the western U.S. Corn Belt; however, this strategy requires careful monitoring of soil water status, prediction of silking date using the Hybrid-Maize model, and fine-tuning of irrigation scheduling.

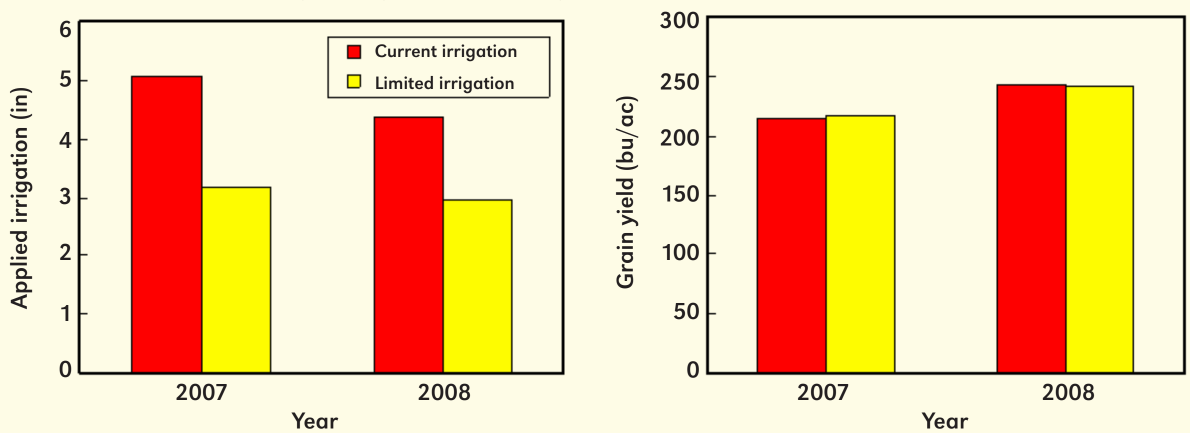

Figure 8. Average applied irrigation and yield under current practice- and limited-irrigation management. Total in-season rainfall was 11 and 13 inches in 2007 and 2008, respectively.

Acknowledgments

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Related Resources

Yield Gaps and Input-Use Efficiency of High-Yield Irrigated Corn in Nebraska, EC106, by Patricio Grassini, Haishun Yang, Jennifer M. Rees, Charles A. Burr, and Kenneth G. Cassman, 2012, University of Nebraska–Lincoln Extension. (*www.ianrpubs.unl.edu/sendIt/ec106.pdf*)

Hybrid Maize is a computer program developed at the University of Nebraska–Lincoln to simulate corn growth under non-limiting or water-limited (irrigated or rainfed) conditions based on daily weather data. See more at *hybridmaize.unl.edu/*

SoyWater is an online, irrigation decision aid to help Nebraska farmers determine the most efficient irrigation scheduling for soybeans. Using local field information input by the farmer and current and long-term historical weather data available through the software, SoyWater predicts soybean growth stages and the next irrigation date. While irrigation management is a key feature of this tool, the crop growth stage information can be helpful in determining a herbicide or fungicide program. See more at *soywater.unl.edu*.

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