

WATER PRODUCTION FUNCTIONS FOR CENTRAL PLAINS CROPS

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Abstract. *Sustaining irrigated agriculture with limited water supplies requires maximizing productivity per unit of water. Relationships between crop production and water consumed are basic information required to maximize productivity. This information can be used to determine if deficit irrigation is economically desirable and how to best manage limited water supplies. Field trials of corn, sunflower, dry bean, and wheat production with six levels of water application were used to develop water production functions based on consumptive use and to better understand water timing effects and crop responses to stress. Initial results indicate linear relationships between yield and crop ET. The field data are being used to improve and validate crop models so they can be used to generalize the field results for other climate and soil characteristics.*

INTRODUCTION

Irrigation water supplies in the Central Plains and much of the western U.S. are declining. Supplies originally developed for irrigated agriculture are being diverted to growing urban areas and for ecosystem restoration. Groundwater use in many areas must decrease if we are to reduce depletion of this valuable resource. Temperature increases due to climate change will likely reduce the mountain snowpack accumulation that is critical to surface water supplies. Irrigated agriculture will very likely have less water available in the future than it had in the past. Sustaining irrigated agriculture will require increasing the economic productivity per unit of water.

Past studies have shown that the reduction in yield is often less than the reduction in irrigation water applied - for example, a 30% reduction in irrigation may result in only a 10% reduction in yield (Zang, 2003). This means the marginal productivity of irrigation water applied tends to be low when water application is near full irrigation. However, as the water deficit increases, higher marginal productivity may result either from higher efficiency of water applications (less deep percolation, runoff, and evaporation losses from irrigation and better use of precipitation), or from a physiological response in plants that

increases productivity per unit water consumed when water is limited. Increasing marginal productivity of water with deficit irrigation indicates that deficit irrigation may be a way to maximize economic returns per unit irrigation water.

Past studies have also shown that yield relationships based on water consumption or evapotranspiration are often linear (Doorenbos et al., 1986). This implies that the marginal productivity of the water is constant and deficit irrigation may be no more productive per unit water consumed than full irrigation. If this is the case, where deep percolation and runoff losses can be reused and have value, full irrigation on a reduced irrigated area may provide higher economic returns for the watershed. In many western watersheds, water is effectively reused, and in fact, reuse of irrigation water return flows is the legal water right of downstream users. For example, Colorado water law allows transfers to other uses only of the estimated consumptively used portion of a water supply; the return flows must be maintained for downstream users.

Thus, it is critical to understand the water balance and water law in a watershed to establish the value of water for crop production and means to maximize irrigation productivity. Improved irrigation efficiency is not likely to produce much “new” water because it results primarily in a reduction of return flows rather than a reduction in ET, and even deficit irrigation is economically viable only if the marginal productivity of consumed water increases substantially.

Although many limited irrigation studies have been carried out in the Central Plains and around the world, we feel there continues to be a need for more information on crop responses to deficit irrigation. So, in 2008, USDA-ARS began a field study of the water productivity of 4 common Central Plains crops under a wide range of irrigation levels from fully irrigated to about 40% of full irrigation. We are measuring ET of the crops under each of these conditions and seeking ways to maximize productivity per unit water consumed. We also strive to better understand and predict the responses of the crops to deficit irrigation so that limited irrigation water can be scheduled and managed to maximize yields.

METHODS

A 50 acre research farm northeast of Greeley, CO – the Limited Irrigation Research Farm, or LIRF - was developed to enable the precision water control and field measurements required to accurately measure ET of field crops. The predominately sandy-loam soils and good groundwater well are ideal for irrigation research.

Four crops – field corn, sunflower (oil), dry beans (pinto), and winter wheat were rotated through research fields on the farm. Crops are planted, fertilized, and managed for maximum production under fully-irrigated conditions, but are irrigated at 6 levels that range from fully irrigated to 40% of the fully irrigated

amount. Deficit irrigations are timed to maximize production – usually by allowing relatively higher stress during mid-to-late vegetative and late maturity stages and applying extra water to reduce stress during reproductive stages.

Each crop field was divided into 4 replications in which the 6 irrigation treatments were randomized. Water was regulated, measured, and delivered to each 12 row (30 ft) x 140 ft plot. We applied irrigation water with drip irrigation tubes placed on the soil surface in each crop row to insure that the water was applied uniformly. This was essential to be able to complete the water balance. Figure 1 shows an aerial view of the research fields in 2008.

A CoAgMet (Colorado Agricultural Meteorological Network) automated weather station was installed on the farm in a 1 acre grass plot. Hourly weather data from the station were used to calculate ASCE Standardized Penman-Monteith alfalfa reference evapotranspiration (ET_r). Soil water content between 6 inch and 7 ft depth was measured by a neutron probe from an access tube in the center of each plot. Soil water content in the surface 6 inches was measured with a portable TDR system (MiniTrase, SoilMoisture, Inc., Santa Barbara, CA)*. Soil evaporation was estimated based on techniques described in Allen et al. (1998). Basal crop coefficients were adapted from Table 8.8 in Allen et al. (2007) based on full cover date. Irrigations were scheduled using both predicted soil water depletions based on ET_r measurements, and measured soil water depletion.



Figure 1. Aerial view of the water productivity plots at LIRF in 2008. Crops from left to right are beans, wheat, sunflower, and corn. Lower fields contain Bowen Ratio instrumentation.

* Equipment brand names are provided for the benefit of the reader and do not imply endorsement of the product by USDA.

Plant measurements were taken periodically to determine crop responses to the water levels. We recorded plant growth stage and measured canopy cover with digital cameras. The digital camera along with spectral radiometers and an infrared thermometer were mounted on a “high boy” mobile platform and driven through the plots weekly (Figure 2). Indicators of crop water stress such as stomatal conductance and leaf water potential were measured periodically. Canopy temperature was measured continuously with stationary infrared thermometers and periodically with the mobile platform (Bausch et al., 2010). At the end of the season, seed yield and quality as well as total biomass were measured in each plot. On two fields on the farm, crop ET was measured with energy balance instruments (Bowen Ratio method) for well-watered crops. These measurements allow crop coefficients to be estimated for the crops.

An important part of the research is to extend the results beyond the climate and soils at LIRF. We are working with the ARS Agricultural Systems Research group to use this field data to improve and validate crop models. Once we have confidence in the models, we can estimate crop water use and yields over a wide range of conditions.



Figure 2. High Boy reflectance tractor measuring canopy reflectance and temperature.

RESULTS

We will summarize the four years of corn (Dekalb DKC52-59 (VT3)) results in this paper. Figure 3 shows the seasonal water balance for the 2011 corn crop for the 6 irrigation treatments. The irrigation applications varied from 6 to 19". Of the 8" of seasonal precipitation, about 1.2" was lost by deep percolation from the 100% treatment and none was lost from the lowest two irrigation treatments. All treatments ended the season with slightly increased soil water storage due to late season rainfall. With deep percolation and storage changes, the ET varied only between 13 to 24". In all years, ET of the fully-irrigated crop averaged 23" and of the most stressed crop, 14". Irrigations were timed such that plant water stress for the deficit irrigation levels was least between tasseling and soft dough (growth stages VT to R4).

The wide range of irrigation applications resulted in substantial differences in crop growth. Figures 4 and 5 show a comparison of plant height and ground cover in early August, 2008 as the corn was beginning to tassel.

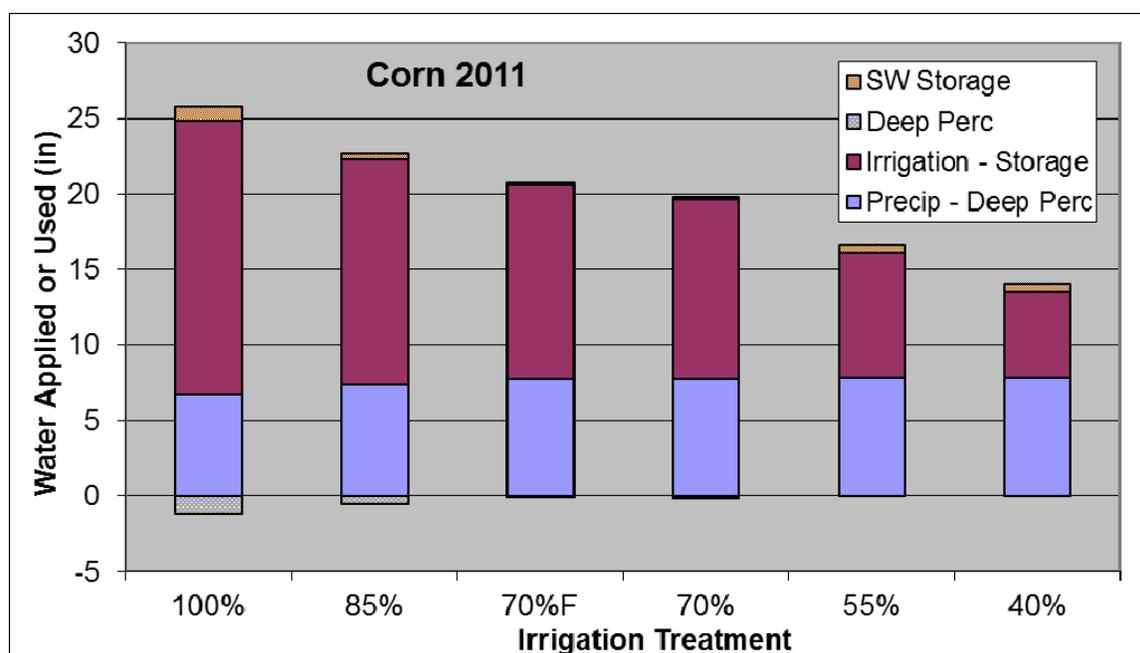


Figure 3. Water balance for the 2011 corn crop showing precipitation, irrigation, and seasonal soil water storage changes. Bars below zero represent deep percolation losses.



Figure 4. Comparison of corn growth condition on Aug 4, 2008 just before tasseling. Rows at the left and background were fully irrigated; rows at right were the lowest irrigation level.



(a) Full irrigation: 91% ground cover (b) Low irrigation: 63% ground cover

Figure 5. Overhead photos showing corn canopy on Aug 1, 2008.

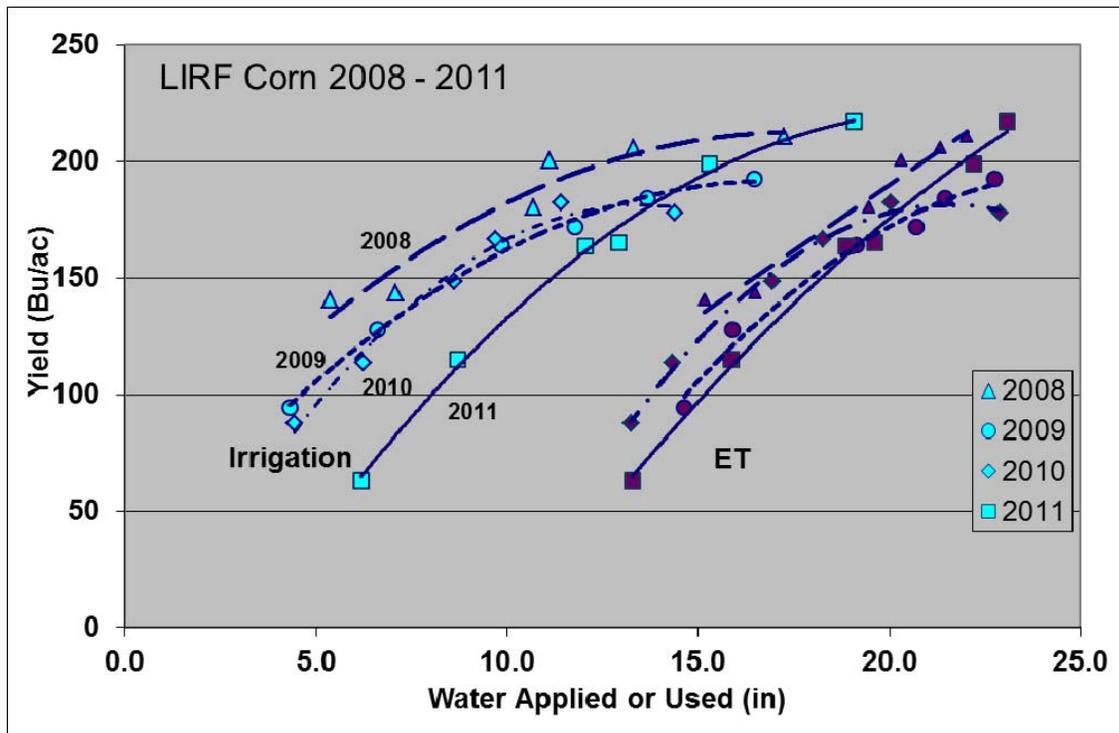


Figure 6. Water production functions for 2008 - 2011 corn at LIRF. Left curves are yield vs. irrigation water applied; right curves are yield vs ET.

Figure 6 shows the yield:water relationship for corn for each year. Grain yields varied from over 200 bu/ac at full irrigation to under 100 bu/ac at low irrigation. Hail damage in 2009 resulted in about 15% lower grain yields. The reason for the relatively low yield with full irrigation in 2010 is not known. Harvest index (the portion of total above-ground biomass that is grain) ranged from 50 – 60% and did not vary with irrigation level.

The water production function curves based on applied irrigation water tends to flatten (get horizontal) as the water application increases because the increase in yield for each unit increase in water applied tends to decrease as irrigation increases. This means that the marginal productivity of irrigation water (additional yield per unit additional water) is relatively low near full irrigation, showing the potential benefit to the farmer of deficit irrigating and using the water for higher-valued uses. The marginal value of water decreases from about 15 bu/ac-in. of irrigation water applied at the lowest irrigation level to less than 4 bu/ac-in. near full irrigation. The marginal value of irrigation above full irrigation requirements would be zero. Likewise, the water use efficiency (absolute yield per unit water applied), tends to increase with deficit irrigation. This shows a possible economic benefit to deficit irrigation.

However, the water production function for grain yield based on ET is relatively linear (straight line). This implies that, once sufficient water is available from rainfall or irrigation to produce grain (about 10 in.), the corn is equally efficient in its use of every additional unit of water consumed and the marginal value of the consumptively used water is fairly constant over the wide range of applications – about 15 bu/ac-in. Beyond full irrigation, the yield would not increase and line would be expected to be horizontal. Because of the initial water requirement to produce yield, the water use efficiency decreases with deficit irrigation from about 9 bu/ac-in. at full irrigation to about 8 bu/ac-in. at 16 in. of consumptive use and eventually to zero at about 10 in. of consumptive use.

For our highly uniform drip irrigation system, most of the increase in the marginal value of applied water with deficit irrigation results from more effective use of precipitation and increased use of stored soil water, or conversely, the lower marginal value of water near full irrigation is due to inefficient use of rainfall and irrigation water. The marginal value of applied water near full irrigation would be even smaller with less efficient irrigation systems since more of the applied water would be lost to runoff, deep percolation, and possibly surface evaporation.

These results imply that, based on consumptive use, there would be no yield benefit to deficit irrigation compared to fully irrigating only a portion of the land. Fully irrigating less land would likely provide higher economic return due to lower production costs of fallowed land compared to cropped land.

These results demonstrate the importance of developing water production functions based on the relevant unit of water. If water value is based on cost of the water supply (eg. pumping costs from a well), then productivity based on applied water is important and deficit irrigation might be a good economic practice. However, if water costs or value is based on consumptive use (eg. for the purpose of transferring consumptive use savings), the productivity would be based on water consumed and deficit irrigation based on consumptive use savings may not be beneficial. If the crop is efficient at converting increased consumptive use to yield, as was corn in these trials, there may be no economic benefit to limited irrigation. In areas with declining groundwater, if water that is not evapotranspired percolates to the groundwater and can be repumped, consumptive use, rather than amount pumped, may be the more important unit of water to consider.

CONCLUSION

Although the yield per unit of applied water will generally increase with deficit irrigation, the yield per unit of consumptive use for corn tends to decrease with deficit irrigation. Thus, in watersheds where return flows are effectively used downstream, deficit irrigation may not increase overall irrigated production in the watershed and may not be economically viable for farmers.

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