This is not a peer-reviewed article.
5th National Decennial Irrigation CD-ROM Proceedings
Phoenix Convention Center, 5 - 8 December 2010, Phoenix, AZ USA
M. Dukes ed. St Joseph Mich: ASABE
ASABE Publication Number 711P0810cd

2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Conference Presentation

Paper Number: IRR10-9277

Advances in Deficit Irrigation Management

Derrel L Martin, Irrigation and Water Resources Engineer
University of Nebraska-Lincoln, Lincoln, NE 68583-0726, dlmartin@unlnotes.unl.edu
Raymond J. Supalla, Natural Resources Economist
University of Nebraska-Lincoln, Lincoln, NE 68583-0922, rsupalla1@unl.edu
Christopher L. Thompson, Research Economist
University of Nebraska-Lincoln, Lincoln, NE 68583-0922, cthompson2@unl.edu
Brian P. McMullen, Research Water Scientist
University of Nebraska-Lincoln, Lincoln, NE 68583-0922
Gary W Hergert, Agronomist and
University of Nebraska–Lincoln, Scottsbluff, NE 69361-4939, ghergert1@unl.edu
Paul A Burgener, Agricultural Economist
University of Nebraska–Lincoln, Scottsbluff, 69361-4939, pburgener2@unl.edu

Written for presentation at the
5th National Decennial Irrigation Conference
Sponsored jointly by ASABE and the Irrigation Association
Phoenix Convention Center
Phoenix, Arizona
December 5 - 8, 2010

Abstract. *Scarcity of irrigation water supplies is leading to the need to consider deficit irrigation which is the intentional under-irrigation of crops resulting in evapotranspiration and yield reduction. We present analytical tools that can be used to assist irrigators and water managers in assessing the water balance and economic consequences of various alternatives. We combine a water balance model of an irrigated field with crop production functions and nonlinear optimization to identify optimal cropping choices and irrigation water allotments to crops. The methodology has been developed for planning for deficit irrigation management for conditions ranging from one field for a single year to allocation programs that focus on farms with multiple fields and multiannual water supply constraints. Example applications are presented to illustrate the methodology for some typical conditions in the Central Great Plains of the United States.*

Keywords. Deficit irrigation, water use efficiency, irrigation uniformity, irrigation water balance

No. 126 Orig.
Ex. K92

Introduction

Water supplies for agriculture, especially irrigated agriculture, are becoming more scarce, expensive and regulated. Downstream and instream demands for environmental and municipal purposes are leading to severe changes in many irrigated regions. Controlling or reducing consumptive use of irrigation water is seen as essential for sustaining ecosystems and agricultural production for many watersheds. Deficit irrigation has been defined as "the deliberate under-irrigation of the crop" by English (1990) or as "the application of water below full crop-water requirement" by Fereres and Soriano (2007). Deficit irrigation has been identified as a mechanism to assist in managing the water balance of a watershed. Fereres and Soriano (2007) suggest that "irrigation management will shift from emphasizing production per unit area towards maximizing the production per unit of water and that deficit irrigation can play a role in achieving that goal". Many view deficit irrigation as the reduction of current irrigation water applications. However, cutting back current applications may not lead to substantial consumptive use reduction, especially for systems that are inefficient or where excessive irrigation has historically been applied. It is important to develop analytical methods that will assess the change in consumptive use for changing irrigation supplies.

The climate of the Central Great Plains in the USA varies from semiarid to subhumid. Irrigation water supplies are becoming limited in the area and agricultural producers are being required to deficit irrigate primarily cereal crops. Water scarcity is occurring in response to droughts, regulatory policies and dwindling capacities of irrigation wells. Producers worldwide are facing similar management issues. While many see deficit irrigation as an alternative for water conservation, it must be remembered that the practice will lead to reductions in crop yields which can have varying impacts on producer, local and regional economies. The economic consequences of deficit irrigation may be exaggerated when people face change and it is essential to develop analytical methods to quantify the impact to producers and associated economies. Regulators need to know the long-term impact of alternative policies.

Ultimately irrigators will be faced with managing deficit irrigation. Their management choices include: (1) amount of land irrigated, (2) crops irrigated, (3) allotment of water to the crops selected for irrigation and (4) selection of the rainfed crop to substitute for irrigated lands if area reductions occur. The water supply may be constrained for a single season or regulatory agencies may implement multiyear allocations that can be applied to a single field or that may be shared across more than one field on a farm. Markets are also emerging where producers may purchase or sell water through a transfer program. In such cases, producers need to know how much water to buy or sell, and what value to expect for the water.

Deficit irrigation can be a planning problem and a management problem. Planning involves the selection of irrigated and rainfed crops for the irrigable land and the allotment of water to those parcels before the irrigation season. Planning can range from a single field for one year to multiple fields over several years. Once the irrigation season begins, producers must manage the deficit strategy for actual conditions, deciding how to deviate from the planned allotment and timing as evapotranspiration (ET), precipitation and water availability vary during the season.

We have developed a series of spreadsheet based analytical tools that assist producers and water managers in evaluating the economic and water balance consequences of deficit irrigation. The principles for the tools are briefly described here along with some example results to illustrate the outcome of planning decisions. We are currently working on tools for the management dimension of the problem but those developments are not discussed here.

Analytic Framework

Production Function

Analysis of annual planning decisions requires a relationship between irrigation water application and crop yield. Simulation models are available to simulate crop response to irrigation. While these models are very useful in understanding crop response to water stress they do not lend themselves well to analyzing water distribution alternatives for multiple crops and for optimization of alternatives. We have instead used a crop production approach to represent the impact of water stress on crop yield. Our method builds on the procedures of Stewart and Hagan (1973) and Martin et al. (1984). We begin with a linear relationship of crop yield to seasonal evapotranspiration (ET):

$$Y = Y_n + b\,(ET - ET_n) \tag{1}$$

where Y is the marketable yield, Y_n is the rainfed yield without irrigation, b is the slope of the yield-ET relationship, ET is the crop evapotranspiration at a specified irrigation level and ET_n is the evapotranspiration for the rainfed crop. Numerous researchers have shown that a linear relationship exists between yield and ET for many irrigated crops grown in the Great Plains (Doorenbos and Kassam, 1979; Hergert et al., 1993; Klocke et al., 2004; Nielsen, 1995; Payero et al., 2006; Schneekloth et al., 1991; Stegman, 1982 and Stegman et al., 1990).

Martin et al. (1984) developed production functions relating crop yield to the depth of irrigation water applied. The method is based on a linear yield-ET relationship and other parameters that can be readily defined. The function depends on three conditions:

- The rainfed yield and ET of the irrigated crop (Y_n, ET_n),
- The yield and ET when the crop is fully irrigated (Y_f, ET_f) along with the amount of gross irrigation required to produce the full yield (D_f), and
- The slope of the yield-ET relationship (b).

Martin et al. (1984) used the assumption suggested by Stewart and Hagan (1975) that the slope of the production function should equal the slope of the yield-ET relationship when the production function is evaluated at zero irrigation. This assumes that if a very small annual irrigation was applied that all of the water would be used for ET. Martin et al. (1984) evaluated three mathematical formulations for the production function as used by economists (Hexem and Heady, 1978). Each function contained three unknown coefficients, thus the conditions above can be used to define the production function. This allows the coefficients to be based on physically defined parameters rather than empirical results.

We primarily use the Cobb-Douglas equation which with the above assumptions gives:

$$Y = Y_n + (Y_f - Y_n)\left[1 - (1 - D/D_f)^{1/\beta}\right] \qquad \text{where } \beta = (ET_f - ET_n)/D_f \tag{2}$$

The parameter β represents the fraction of the irrigation application for full yield that is used for ET. We refer to the parameter as the water use efficiency at full irrigation. We stress that the definition of the parameter results from mathematical solution for the three conditions and thus the production function is based on physical parameters that could be measured or estimated.

Water Balance Model

It is essential to incorporate the water distribution across the field to analyze alternatives. Clemmens (1991) developed a procedure to partition infiltration into net irrigation and deep percolation based on a normal distribution. When the method is combined with an estimate of the amount of water lost at the soil surface (S_L), *i.e.* did not infiltrate, the mean depth of application required to produce the full yield for a prescribed portion of the field can be predicted (Figure 1). The remainder of the field would not receive enough water to produce the full yield and would suffer varying levels of stress. The mean depth of application can be used as the full irrigation requirement (D_f). We define the adequacy as that portion of the field that that receives enough infiltration to equal the increase in ET from irrigating for the full yield ($ET_{inc} = ET_f - ET_n$). For the portion of the field that is adequately irrigated the ET equals ET_f. To the right of the adequacy point in Figure 1 the amount of ET equals the depth infiltrated plus the ET for rainfed conditions. The adequacy (A_d) is computed as:

$$A_d = \int_{-\infty}^{D_r} \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{1}{2}\left(\frac{D-D_f}{\sigma}\right)^2\right] dD \qquad \text{where } D_r = \left(\frac{ET_{inc}}{1-S_L}\right) \tag{3}$$

The inverse normal distribution function can be used to determine the full infiltration depth (D_f) for a selected adequacy and the standard deviation (σ) of the irrigation depth. James (1993) showed that for a normal distribution the coefficient of variation ($C_v = \sigma / D_f$) is given by $C_v = (1 - C_u) / 0.798$ where C_U is the coefficient of uniformity that is typically used to describe the uniformity of water application, thus

$$\sigma = D_f\ (1-C_u)/0.798 \tag{4}$$

Combining equations 3 and 4 provides a relationship for the adequacy based on the full irrigation depth, uniformity coefficient, surface loss and the ET increase when irrigating for the full yield. Conversely, if the adequacy is selected then the required depth for full irrigation (D_f) can be determined from the inverse normal distribution function.

Application of the production function requires determination of the water use efficiency when irrigating for full yield. The average ET for the field when irrigating so that the portion of the field represented by the adequacy is fully irrigated is computed by integrating the upper portion of the curve shown in Figure 1. The portion of the field receiving more infiltration than ET_{inc} is represented by the adequacy. For this region the ET equals that for full yield (ET_f). To the right of the adequacy the ET equals the infiltrated depth plus ET_n. Thus the average ET for the field (FET) is given by:

$$FET = A_d * ET_f + (1-A_d)ET_n + \int_{-\infty}^{D_r} \frac{D\,(1-S_L)}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{1}{2}\left(\frac{D-D_f}{\sigma}\right)^2\right] dD \tag{5}$$

and the water use efficiency that corresponds to the specified adequacy is given by:

$$\beta = (FET - ET_{inc})/D_f \tag{6}$$

Combining the linear yield-ET relationship with the normal distribution model allows for prediction of the average yield for the field. Mathematically that is equivalent to using the field average ET in the linear yield-ET model:

$$Y_a = Y_n + b\,(FET - ET_n) \tag{7}$$

The average field yield can be compared to the predicted yield from the production function for varying irrigation levels.

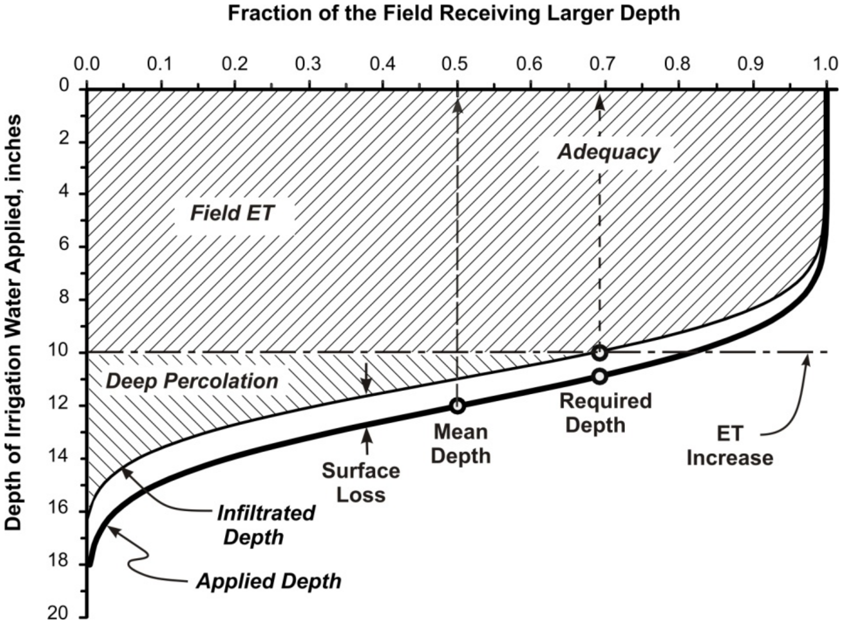


Figure 1. Partitioning of irrigation infiltration using the normal distribution.

The uniformity model has been built-in into an Excel spreadsheet model. We included the ability of the user to estimate components of the water balance of irrigation systems as illustrated in Figure 2. The uniformity of infiltration can be adjusted from the uniformity of application from center pivots to account for conditions where water runs off hillslopes and infiltrates in lower areas. The user can also enter estimates of various components of the water lost from the surface, *i.e.*, does not infiltrate, or for water that leaves the field and is either used by vegetation adjacent to the field or that flows into streams or that recharges the ground water aquifer. We total the return flow and recharge components of the water balance to summarize the fraction of the irrigation application that is not consumptively used. We also total the amount of consumptive use including the ET from the field as well as the evaporation and transpiration from the adjacent areas and present that sum as a fraction of the irrigation application. These summaries provide the user the ability to evaluate irrigation system changes and to include system changes into assessing the management of deficit irrigation.

Estimates are needed for the evapotranspiration for the irrigated crop for full production and rainfed conditions. We predict ET_f and ET_n for the crops of interest using a simple water balance model (CROPSIM) which was originally described by Martin et al. (1984). We have enhanced the model to broaden and improve accuracy. We simulate a series of years to average conditions for selected soils across the region for which the model is to be applied. Rainfed ET is more difficult to predict than ET_f, but the value is constrained by the amount of annual precipitation and over prolonged periods errors tend to be small for semiarid regions.

Optimization

We have integrated the production function into a series of optimization programs to predict the optimal cropping choices and irrigation water allocation when water supplies are limited. The suite of optimization models is referred to as *Water Optimizer.* The single-field single-year model seeks to maximize the average annual net return subject to water supply constraints and user specified cropping limitations (allowable crops and acreage limitations).

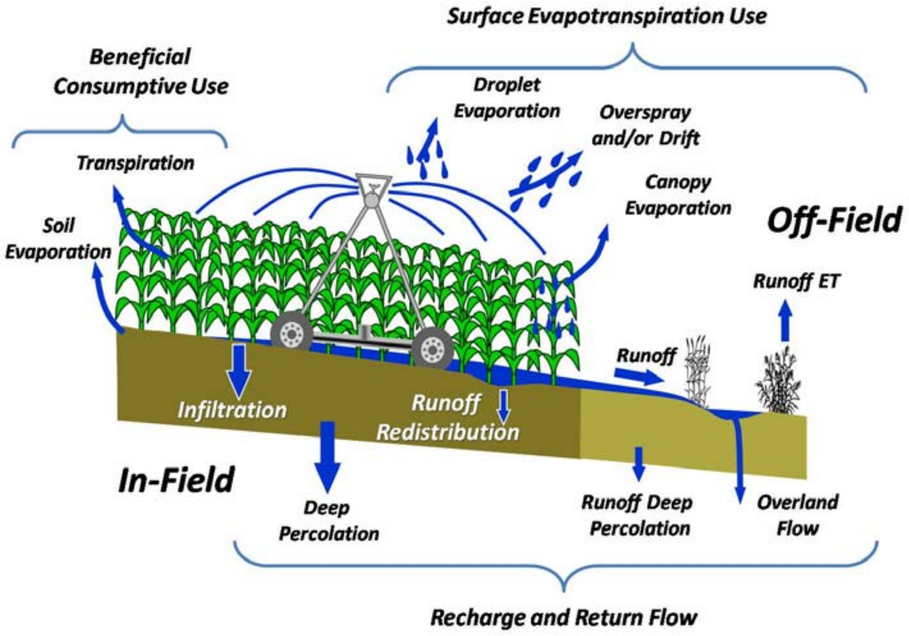


Figure 2. Components of water balance model.

The objective function, net return, water supply constraint and the land constraints for the single-season model are given by:

$$
\begin{array}{lll}
\text{Max } N_r = & \displaystyle\sum_{i=1}^{n_c} \left\{ A_i \left[V_i \, Y_i(D_i) - C_i \right] - C_w D_i \right\} + A_n \left[V_n \, Y_n - C_n \right] - C_s & \\
\text{subject to:} & \displaystyle\sum_{i=1}^{n_c} \left\{ A_i D_i \right\} \le W_s & \text{water supply constraint} \\
 & \displaystyle\sum_{i=1}^{n_c} \left\{ A_i \right\} + A_n \le A_t & \text{irrigable area constraint} \\
 & AL_i \le A_i \le AU_i \quad \forall \; i & \text{irrigated crop constraint}
\end{array}
\tag{8}
$$

where N_r is the net return, n_c is the number of irrigated crops of concern, A is the area of a crop, V is the value of the crop adjusted for costs that depend on the yield such as for nitrogen and trucking, Y is the yield of the crop, D is the irrigation application depth for the crop, C is the production cost per unit area of the crop, C_w is the cost of irrigation water per unit volume, C_s is the fixed cost of deciding to irrigate (such as for electrical connect costs or irrigation district fees), W_s is the volume of water available for the field for the year, A_t is the amount of irrigable land in the field, and AL and AU represent the upper and lower area constraints for a crop. Subscript i denotes the irrigated crop and n is for the rainfed crop. The crop area and the irrigation application depth are also subject to nonnegativity constraints.

We have developed additional components to optimize the net return when the annual water supply can be allocated to a group of fields rather than a specific allocation to each individual field. We refer to that as the multiple-field single-year model. We also have water allocation programs that provide a quantity of water to a single field for a multi-year period. We refer to that version as the single-field multiyear model. Finally, we also have a multifield – multiyear model for distributing water in the most general case. Space limitations do not allow for detailed description of each version of the *Water Optimizer.* We have manuals that can be downloaded from our web site to obtain more information on building and using the models.

We developed the optimization programs into an Excel model where we use the nonlinear version of the “Solver” add-in to determine the optimal mixture of crops and to distribute the water. We have found this to be robust and relatively easy for user operation. Many of the required functions for modeling the response have been built into Visual Basic functions in Excel such that they are easily called and better documented than many spreadsheet applications.

Crop Yields and Budgets

Reliable results depend on accurate crop yield representation and development of crop budgets that depict relationships between commodities. While users are free to enter their own values for crop yields and costs, we have found that using default values is desirable. The default values minimize the time required for users to set up the program and maintains important ratios between commodities. We have developed a stand-alone spreadsheet to update the default budgets in the program. We periodically provide those updates in the versions of the programs that can be downloaded from the web site. Users can update commodity prices and production costs on their own by using the budgeting spreadsheet. We ignore fixed costs not related to annual irrigation and thus do not provide income estimates for cash flow analysis.

Rainfed and fully irrigated yields vary considerably between years and locations due to the strong east-west precipitation gradient in the Great Plains. The expected value of yield over a period is the most appropriate value for planning the upcoming production season. While growers have a good feel for yields, we have found that biases between crops are frequent and maintaining a balance between commodities is challenging. Thus, while we allow users to enter their own estimates for the upcoming season for yields, we have conducted extensive work to build a database of representative yields and associated ET requirements for rainfed and irrigated crops across the Great Plains. We have relied heavily on the National Agricultural Statistical Service database for county-level yields. We have smoothed the data across county lines when necessary. We simulate ET for three soil types (coarse ← loamy sands, medium ← fine sandy loam, and fine ← silt loam). We have built county-level estimates for the Central Great Plains for the yields and ETs.

We do not include data for crops that are not typically grown in the area. Users are free to enter their own data for such cases but should do so carefully. It is very important to accurately represent the rainfed options which can vary considerably across the region - not just the types of crops grown, but also the cropping rotations that may or may not include a fallow period for rainfed conditions.

Results

The suite of models has been developed for use in the Central Great Plains of the USA and thus is based on English units which we use in this paper.

An example application of the water balance model is illustrated in Table 1 for a location where the annual ET for fully irrigated corn is 30 inches and the ET for rainfed corn is 20 inches. Coefficients of uniformity that are typical for the designated irrigation systems are listed as the base coefficients. The uniformity reduction for runoff represents how the distribution of infiltration varies from the uniformity of water application. Estimates of in-field and off-field surface losses are listed along with the slope of the yield-ET relationship and the rainfed yield of corn. The desired adequacy for determining the full irrigation depth is listed as the last parameter.

The first two lines of the results are information needed for the crop production function while the remaining information describes the fate of the irrigation water when irrigating corn for full yields.

The yield predicted with the production function closely matches the yield predicted from integrating the yield across the field (Figure 3) for varying levels of irrigation. Clearly the production function represents the response of the field to limited irrigation amounts. Other tests show that the function generally works well for the uniformities that are appropriate for the normal distribution assumption. Situations with large surface losses are less reliable than when water not used for ET occurs as deep percolation in the field. Details are provided for alternatives to address the amount of consumptive use, ground water recharge and return flow for varying irrigation levels.

Table 1. System Performance Chart

	Alternative				
Item	***1***	***2***	***3***	***4***	***5***
Alternative Description	Center Pivot Very Good	Center Pivot Average	Center Pivot Poor	Furrow Irrigation Good	Furrow Irrigation Poor
Parameter Input:					
Base Coefficient of Uniformity	0.92	0.90	0.88	0.80	0.75
Uniformity Reduction for Runoff	0.02	0.04	0.05	0.00	0.00
ET Required for Full Yield, inches	30	30	30	30	30
Rainfed (Non-Irrigated) ET , inches	20	20	20	20	20
Spray Evap. and Drift Loss, % of application	3%	3%	3%	0%	0%
Net Canopy Evaporation, % of application	6%	6%	8%	0%	0%
Runoff ET, % of application	0%	1%	2%	5%	8%
Runoff Deep Percolation, % of application	0%	2%	2%	12%	24%
Overland Flow, % of application	0%	0%	0%	0%	0%
Rainfed (Non-Irrigated) Yield, bushel/acre	100	100	100	100	100
Slope of Yield-ET, bushel/acre-inch	12	12	12	12	12
Desired Adequacy, percent	84%	80%	80%	80%	80%
Results when Irrigating for Full Yield					
Irrigation Depth for Full Yield, inches	12.55	13.33	14.33	15.27	19.97
Water Use Efficiency	0.80	0.75	0.70	0.65	0.50
Surface Loss, percent of application	9%	12%	15%	17%	32%
Distribution Uniformity (DU)	0.84	0.78	0.73	0.68	0.60
Percent of Irrigation to Field ET, %	79%	73%	68%	63%	48%
Consumptive Use,% of application	88%	83%	81%	68%	56%
Return Flow & Recharge, % of application	12%	17%	19%	32%	44%

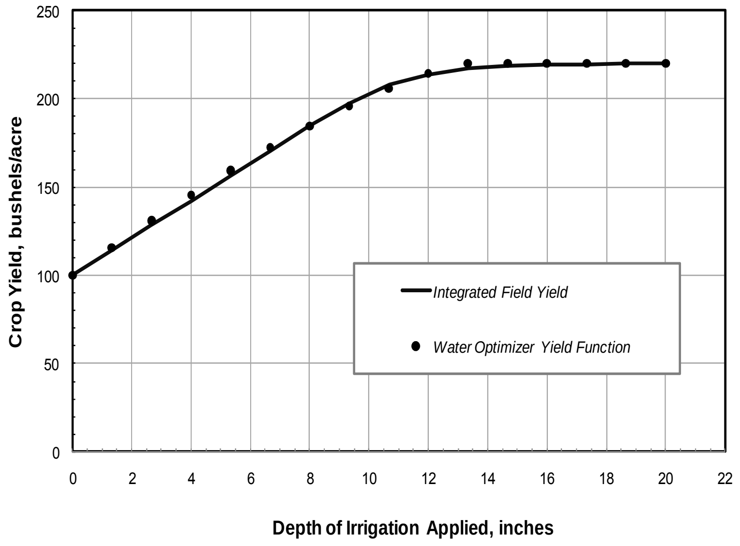
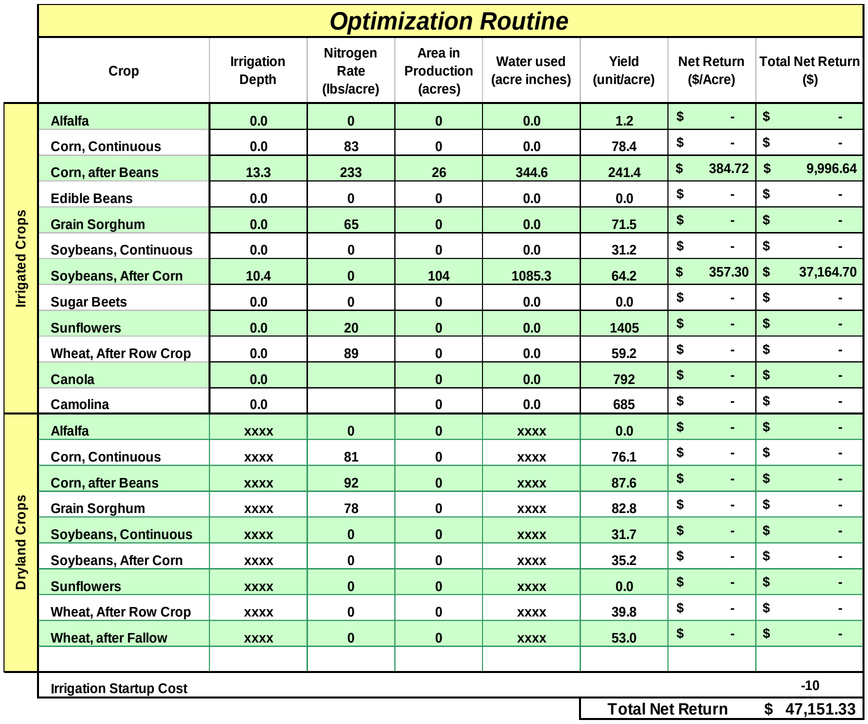


Figure 3. Comparison of corn yield predictions for an average pivot.

An example of an optimization for a field in west central Nebraska for an allocation of 11 inches of water for a center pivot irrigated field of 130 acres is illustrated in Figure 4. In this case the optimal result is a mixture of irrigated corn (26 acres) and soybeans (104 acres) with 13.3 inches of irrigation on the corn and 10.4 inches on the soybeans. The user would likely want to revise the area constraints to evaluate the net return for equal areas of 65 acres for each crop. That mixture produced a net return of $46,916 for the same water constraints. Thus, there is a reduction of net return for a more convenient cropping pattern. The user can also compare the net return to what would be achieved if a smaller area was fully irrigated and a rainfed crop wa



Optimization Routine

	Crop	Irrigation Depth	Nitrogen Rate (lbs/acre)	Area in Production (acres)	Water used (acre inches)	Yield (unit/acre)	Net Return ($/Acre)	Total Net Return ($)
Irrigated Crops	Alfalfa	0.0	0	0	0.0	1.2	$ -	$ -
	Corn, Continuous	0.0	83	0	0.0	78.4	$ -	$ -
	Corn, after Beans	13.3	233	26	344.6	241.4	$ 384.72	$ 9,996.64
	Edible Beans	0.0	0	0	0.0	0.0	$ -	$ -
	Grain Sorghum	0.0	65	0	0.0	71.5	$ -	$ -
	Soybeans, Continuous	0.0	0	0	0.0	31.2	$ -	$ -
	Soybeans, After Corn	10.4	0	104	1085.3	64.2	$ 357.30	$ 37,164.70
	Sugar Beets	0.0	0	0	0.0	0.0	$ -	$ -
	Sunflowers	0.0	20	0	0.0	1405	$ -	$ -
	Wheat, After Row Crop	0.0	89	0	0.0	59.2	$ -	$ -
	Canola	0.0		0	0.0	792	$ -	$ -
	Camolina	0.0		0	0.0	685	$ -	$ -
Dryland Crops	Alfalfa	xxxx	0	0	xxxx	0.0	$ -	$ -
	Corn, Continuous	xxxx	81	0	xxxx	76.1	$ -	$ -
	Corn, after Beans	xxxx	92	0	xxxx	87.6	$ -	$ -
	Grain Sorghum	xxxx	78	0	xxxx	82.8	$ -	$ -
	Soybeans, Continuous	xxxx	0	0	xxxx	31.7	$ -	$ -
	Soybeans, After Corn	xxxx	0	0	xxxx	35.2	$ -	$ -
	Sunflowers	xxxx	0	0	xxxx	0.0	$ -	$ -
	Wheat, After Row Crop	xxxx	0	0	xxxx	39.8	$ -	$ -
	Wheat, after Fallow	xxxx	0	0	xxxx	53.0	$ -	$ -
	Irrigation Startup Cost							-10
							Total Net Return	$ 47,151.33

Figure 4. Sample results from optimization for west central Nebraska.

Several other worksheets included in the optimization workbook provide additional information to the user; however, space limitations do not allow presentation of those results. A sensitivity sheet compares the stability of cropping and water distribution decisions for a range of commodity prices. Prices vary substantially and cannot be predicted. The sensitivity sheet allows the user to determine how commodity prices need to change before the user would alter from the corn-soybean rotation given above.

Conclusion

We present a suite of analytical tools based on crop production functions and irrigation water balance estimates that can help producers identify optimal cropping choices and irrigation water allotment for deficit irrigation. The methodology is based on parameters that can be relatively easily estimated for local conditions. Results also provide estimates of consumptive use, return flow and ground water recharge that may occur for alternative management strategies for deficit irrigation. The tools have been built into Excel spreadsheets and associated databases for the Central Great Plains have been developed to assist in producer and water manager adoption.

Acknowledgement

We acknowledge the financial support from the USDA-RMA and the University of Nebraska Extension for this work.

References

Clemmens, A. J. 1991. Irrigation uniformity relationships for irrigation system management. *J. Irrig. Drain. Eng.* 117(5): 682-699.

Doorenbos, J., and A. H. Kassam. 1979. *Yield Response to Water*, FAO Irrigation and Drainage Paper 33, 193. Rome, Italy: FAO.

English, M. 1990. Deficit Irrigation. I: Analytical Framework*. J. Irrig. Drain. Eng*. 116: 399-412.

Fereres, E., and M. A. Soriano. 2007. Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.* 58: 147-158.

Hergert, G. W., N. L. Klocke, J. L. Petersen, P. T. Nordquist, R. T. Clark, and G. A. Wicks. 1993. Cropping systems for stretching limited irrigation supplies. *J. Prod. Agric*. 6: 520–528.

Hexem, R. W., and E. O. Heady. 1978. Water production functions for irrigated agriculture. Ames, Iowa: Iowa State University Press.

James, L. G. 1993. *Principles of Farm Irrigation System Design* , 543. Malabar, Fla.: Krieger Publishing Co.

Klocke, N. L., J. P. Schneekloth, S. Melvin, R. T. Clark, and J. O. Payero. 2004. Field scale limited irrigation scenarios for water policy strategies. *Applied Eng. In Agric.* 20: 623–631.

Martin, D. L., D. G. Watts, and J. R. Gilley. 1984. Model and production function for irrigation management. *J. Irrig. Drain. Eng*. 110(2): 149-164.

Nielsen, D. C. 1995. Conservation Tillage Fact Sheet #2-95. Water use/yield relationships for central Great Plains corps. Akron, Colo.: Colorado Conservation Tillage Association.

Payero, J. O., S. R. Melvin, S. Irmak, and D. Tarkalson. 2006. Yield response of corn to deficit irrigation in a semiarid climate. *Agric. Water Manage*. 84: 101–112.

Pereira, L. S., T. Oweis, and A. Zairi. 2002. Irrigation management under water scarcity. *Agric. Water Manage.* 57: 175-206.

Schneekloth, J. P., N. L. Klocke, G. W. Hergert, D. L. Martin, and R. T. Clark. 1991. Crop rotations with full and limited irrigation and dryland management. *Trans. ASAE* 34: 2372–2380.

Stegman, E. C. 1982. Corn grain yield as influenced by timing of evapotranspiration deficits. *Irrig. Sci.* 3(2): 75-87.

Stegman, E. C., B. G. Schatz, and J. C. Gardner. 1990. Yield sensitivities of short season soybeans to irrigation management. *Irrig. Sci*. 11(2): 111-119.

Stewart, J. I., and R. M. Hagan. 1973. Functions to predict effects of crop water deficits*. J. Irrig. Drain.* 99(4): 421-439.