

SCHEDULING FOR DEFICIT IRRIGATION— CROP YIELD PREDICTOR

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ABSTRACT. *Irrigators in many countries with dwindling water supplies face the prospect that they will not be able to fully irrigate their crops. In these cases, they still need to schedule their water applications to make the best economic use of available water. Major scheduling questions for deficit irrigation include: (1) will pre-season irrigation be beneficial; and (2) when should irrigation be started and stopped during the growing season. Traditional irrigation scheduling estimates crop evapotranspiration (ET_c) to predict the amount and timing of irrigation events for the next several days. Usually these schedules assume that the water supply will provide irrigation to fully irrigate the crop to produce maximum crop yields. Irrigators practicing deficit irrigation need to predict irrigation schedules in advance of the growing season and make appropriate adjustments based on potential crop yields and economic returns. A computerized decision tool, the Crop Yield Predictor (CYP), has been developed to forecast yields from alternative irrigation schedules and designed for management decisions by irrigators, crop consultants, and extension personnel. Users of CYP determine soil water status before or during the cropping season and formulate potential schedules of irrigation dates and amounts. Soil water holding capacity and irrigation system water delivery capacity are constraints on the ability to supply water to the crop. CYP uses a daily soil water balance coupled with computations of effective evapotranspiration (ET_e) to predict crop yields from regional yield-ET relationships. Multiple executions of CYP with alternative irrigation schedules lead to the schedules that project optimum net economic returns from the management scenarios. CYP is an example of adapting a crop simulation model into a tool for those who need to make irrigation management decisions.*

Keywords. *Irrigation scheduling, Deficit irrigation, Limited irrigation, Irrigation, Decision tool.*

Maximum net economic returns for irrigators with adequate water supplies usually have corresponded to irrigation management that is geared to obtain maximum crop yields. Irrigation in excess of crop water needs reduces net economic return, but the marginal increases in crop yields usually are more than marginal production costs. When water supplies cannot match crop needs and deficit irrigation management is anticipated, optimum net economic return from irrigation is the appropriate measure of best management (English, 2002). Crop selection for optimum net return may involve multiple crops in rotation, a single crop with reduced irrigation, or irrigation on a smaller area (Martin et al., 1989). In addition to crop selections, irrigation needs to be allocated among crops, using crop production functions and

production costs for optimum economic return (English, 1981, Klocke et al., 2006).

Scheduling irrigation events during the growing season for crops that have a non-limited water supply has involved the estimation of non-stressed crop ET (ET_c) from a reference ET (ET_r) that is modified with a crop coefficient (K_c) as the crop grows and matures (Doorenbos and Pruitt, 1977; Allen et al., 1998). A soil water balance of ET_c, effective precipitation, net irrigation, drainage, runoff, and run-on produces daily values for the available soil water (ASW). For irrigation schedules with the goal of producing crops with no significant water stress, irrigation requirements are calculated to keep ASW between field capacity and an ASW content that does not cause stress, usually with 50% to 60% of the ASW remaining in the active root zone. The starting dates for irrigation events are established by calculating the days until the crop will experience stress at the point of the end of the irrigation cycle (no later than starting date) and when there is room to store the irrigation event amount at the point of the beginning of the irrigation cycle (no sooner than date) (Kansas State University, 2007).

When the water supply for irrigation is less than the water required for non-stressed crops, water deficits can be anticipated. Irrigation schedules for deficit irrigation need to anticipate the potential crop yields and net economic returns prior to and during the growing season. The major irrigation scheduling decisions for deficit irrigation are: (1) whether or not pre-season irrigation is needed (Stone et al., 2008), (2) when should the first irrigation event start, and (3) when should the last irrigation event be applied. Between the start

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date and stop date, irrigation systems often operate on a fixed frequency depending on the water supplied by surface or ground water.

The objectives for this study were (1) to develop an interactive decision tool that would help users to predict optimum irrigation schedules for crops that are expected to experience water stress and (2) to illustrate the use of the decision tool to predict irrigation schedules for a range of annual precipitation, application amounts, and pre-season irrigation. Irrigators, water managers, crop consultants, extension specialists, and educators are the intended users of the decision tool.

CROP YIELD PREDICTOR DESCRIPTION AND OPERATION

The CYP was designed as an interactive decision tool to predict crop yields and economic returns for deficit irrigated crops. CYP uses the Kansas Water Budget (KSWB) simulation model to predict crop yields, ETr, ETc, and daily ASW (Stone et al., 1995; Stone and Schlegel, 2006; Khan et al., 1996; Klocke et al., 2010). The KSWB was designed to use average daily values from 30 years of weather data (maximum and minimum air temperature, solar radiation, and precipitation) for each location to calculate ETr, ETc, daily ASW, and crop yields. Klocke et al. (2010) described the technical background and operation of the KSWB and

furthermore compared the results from KSWB simulations with data from a field study conducted at Garden City, Kansas during 2005-2008. The KSWB was executed with daily weather data and irrigation events from the field study. They showed that (1) field and KSWB yield-ET relationships were almost identical; (2) soil water contents from field data compared well with KSWB results; (3) KSWB tended to underestimate crop yields relative to fully irrigated yields and ETc as irrigation declined. These differences were attributed to calibrations of the KSWB with historical data from conventional (tilled) management but the field study was managed with no-till techniques.

CYP users can designate potential irrigation schedules to optimize yields and net returns. These schedules can be tested for a range of annual precipitation to find yield and income risks from several input scenarios including wet, average, and dry years; different dates and amounts of irrigation events; inclusion or exclusion of pre-season irrigation (Stone et al., 1987); different soil types; different irrigation system application efficiencies; or different soil water contents before or during the growing season.

USER INPUTS

The CYP is structured with a series of tabs and sub-tabs that activate screens for input and output information (fig. 1). The first level of tabs is for “general input” and “results.” The general input tab activates a series of sub-tabs including “location and rainfall,” “soil information,” “irrigation efficiency,” “crop selection,” and “runoff & soil water.”

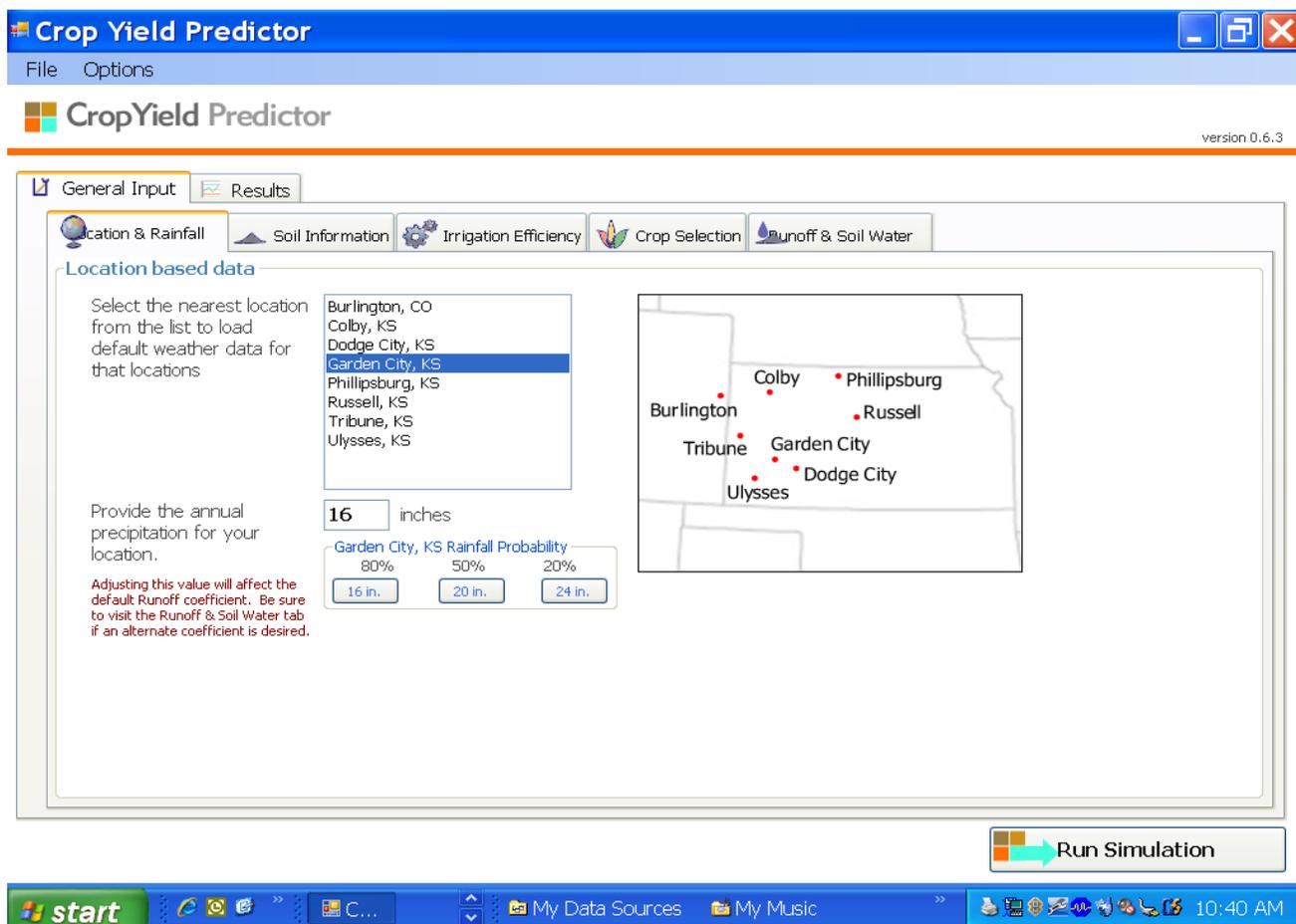


Figure 1. Example of input screen for the Crop Yield Predictor.

efficiency,” “crop selection and irrigation schedule,” and “runoff and soil water” that require the user to enter the information needed to execute the program. The results tab shifts the screen directly to the output screens of the last execution of the model.

Daily average weather data are stored in the CYP for each the designated geographic location and are recalled to populate the weather file for calculation of reference ET (ET_r). Daily average precipitation data for each location are used for the soil water balance. The user can choose an annual precipitation amount that is used to increase or decrease daily precipitation values with the ratio of the user’s annual precipitation and the average annual precipitation.

Soil characteristics for silt loam, loamy sand, and fine sand soils are stored in CYP files. Soil water characteristics, including volumetric soil water content at field capacity and wilting point, are needed for calculation of available soil water (ASW) capacity and drainage. ASW storage capacity is the amount of water in the top 1.8 m of soil profile (mm m⁻¹) between field capacity and permanent wilting. Soil texture influences the default runoff coefficient, which is the percentage of daily precipitation that does not infiltrate into the soil.

Irrigation application efficiency is defined as the percentage of water that infiltrates into the soil (net irrigation) from the water pumped or supplied to the field (gross irrigation). CYP asks users for gross irrigation and the calculated value for net irrigation is used in the daily water budget.

Single crop coefficient values (K_c) for corn, soybean, wheat, grain sorghum, sunflower, and alfalfa are stored in CYP. These values can be adjusted according to user modifications of growth stage events. For example, daily crop coefficients can be modified to accommodate differences in duration of the growing season. The user also designates the “maximum grain yield” which reflects the capability of the field to produce grain with no water stress. The ratio of the maximum yield value and the non-stressed yield calculated by CYP scales the predicted yields.

The CYP user pre-determines an irrigation schedule by manually entering irrigation amounts on the date of each irrigation event or by importing trial irrigation schedules developed in Excel (Microsoft Corp., Redmond, Wash.). CYP can also develop irrigation schedules with uniform frequency of irrigation events between two dates during the growing season. When pumping capacity is the limiting factor, CYP calculates the number of the irrigation events that are possible between the starting date and ending dates. When the total irrigation amount controls the schedule, all of the water is applied between the two designated dates with a uniform frequency without regard to the pumping capacity. The uniform frequency schedules can be modified after they are entered into the scheduling table.

The runoff coefficient is the percentage of daily precipitation that does not infiltrate. The user enters the runoff percentage or CYP calculates a default runoff coefficient using crop type, total annual precipitation, soil texture, and percent surface coverage by crop residue.

The CYP user can enter a value for ASW on any date during the growing season and the daily soil water balance is adjusted from that date forward. If an ASW value is not defined by the user on the starting date of the growing season, a default value is generated internally by CYP.

Variable costs are needed to estimate the net economic return of each scenario. The CYP user can fill out tables for input costs, operation costs, and irrigation costs or use CYP default costs.

CYP OUTPUTS

Results of a simulation are tabulated and presented in graphs of daily available soil water, crop ET, and drainage. Results from additional scenarios can be retained for comparison from one execution of CYP to the next.

Evaporation during the non-growing season is calculated for water loss from bare soil. A daily evaporation coefficient (Doorenbos and Pruitt, 1977) is multiplied by ET_r to calculate evaporation.

Effective crop evapotranspiration (ET_e) is the evapotranspiration that contributes to crop yield. ET_e is calculated in four steps. First, long-term average daily weather data, including maximum temperature, minimum temperature, and solar radiation, have been derived from at least 30 years of records at each geographic location. These average daily weather data combine for a calculation of reference ET (ET_r) with the method described by Jensen and Haise (1963) for a well-watered crop in semi-arid regions. When the maximum air temperature is more than 33°C, ET_r is adjusted to account for additional advective energy. Second, daily ET_r is multiplied by a crop coefficient (K_c) to produce a value for maximum ET (ET_m) that accounts for increasing ET_m during vegetative growth, nearly constant ET_m during reproduction and early grain fill, and declining ET_m as the crop matures. Adjusting growth stage dates allows CYP to recalculate daily crop coefficients (K_c) for the duration of the growing season (fig. 2). Calculation of ET_m assumes that the crop is not experiencing water stress and there are no “spikes” in soil water evaporation immediately after surface wetting because small precipitation events occur daily and all precipitation is assumed to infiltrate except runoff. Third, ET_m is multiplied by a soil water stress coefficient (K_s) (Jensen et al., 1971) producing an actual crop ET (ET_a), which is the water extracted from the soil and accounts for the effect of soil water depletion on the ET_m. Finally, ET_a is reduced to account for the crop’s susceptibility to water stress during four growth periods (vegetative, flowering, seed formation, and ripening) to produce ET_e. The ratio of ET_a to ET_m and water stress factors by crop and growth periods convert ET_a to ET_e. These four steps combine the effects of weather parameters, crop development during the growing season, water stress from soil water availability, and the crop’s susceptibility to stress during four growth periods. Klocke et al. (2010) described the derivation of ET_r, ET_m, ET_a, and ET_e in more detail.

Estimated crop yield (Y_e) is calculated from linear relationships of yield as a function of effective ET (ET_e), developed from long-term field studies in west-central Kansas:

$$\text{Yield [Mg ha}^{-1}\text{]} = 0.042 [\text{Mg ha}^{-1} \text{ mm}^{-1}] * \text{ET}_e [\text{mm}] - 12.33 [\text{Mg ha}^{-1}] \text{ for corn,}$$

$$\text{Yield [Mg ha}^{-1}\text{]} = 0.030 [\text{Mg ha}^{-1} \text{ mm}^{-1}] * \text{ET}_e [\text{mm}] - 5.67 [\text{Mg ha}^{-1}] \text{ for grain sorghum,}$$

$$\text{Yield [Mg ha}^{-1}\text{]} = 0.015 [\text{Mg ha}^{-1} \text{ mm}^{-1}] * \text{ET}_e [\text{mm}] - 4.04 [\text{Mg ha}^{-1}] \text{ for winter wheat,}$$

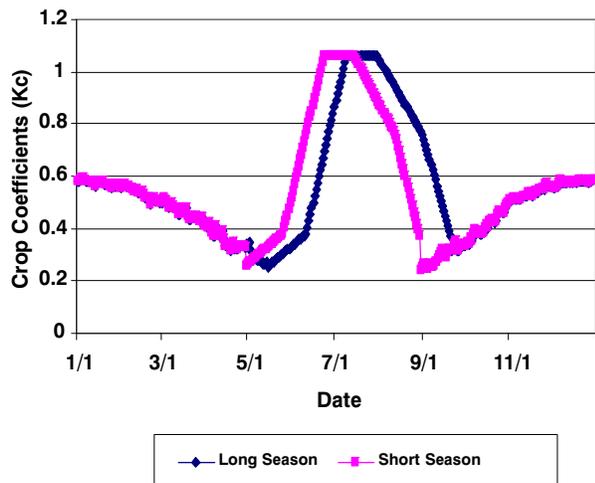


Figure 2. Example of Kc for short season corn.

$$\text{Yield [Mg ha}^{-1}] = 0.10 [\text{Mg ha}^{-1} \text{ mm}^{-1}] * \text{ETe [mm]} - 1.3 [\text{Mg ha}^{-1}] \text{ for sunflower,}$$

$$\text{Yield [Mg ha}^{-1}] = 0.011 [\text{Mg ha}^{-1} \text{ mm}^{-1}] * \text{ETe [mm]} - 2.39 [\text{Mg ha}^{-1}] \text{ for soybean.}$$

where ETe is the water that actually contributes to crop yield.

Net Return is calculated from the gross income minus variable costs. For deficit irrigation, net return is a better indicator of the optimum irrigation scheduling scenario than considering only crop yield results

Drainage during the growing and non-growing seasons is calculated using a Wilcox-type drainage equation (Miller and Aarstad, 1972) that was field calibrated for each soil type. Drainage depends on total soil water described by an exponential function relating drainage to total soil water.

Three graphs of daily values for the each simulation are generated: (1) daily available soil water; (2) ETr, ETm, and ETa (fig. 3); and (3) drainage. Daily ASW is:

$$\text{ASW}_t = \text{ASW}_y + P_y + I_y - D_y - \text{ETa}_y$$

where ASW_t is the available soil water at the beginning of today; ASW_y is the available soil water at the beginning of yesterday; P_y is the precipitation that infiltrated into the soil yesterday; I_y is the irrigation that infiltrated into the soil yesterday; D_y is the water that drained from the 1.8 m depth in the soil yesterday; and ETa_y is the water that the crop consumed yesterday.

EXAMPLES OF CYP SIMULATIONS

CYP was executed with the input values in table 1. The simulations were designed to show the effects of annual precipitation probabilities (table 2), growing season irrigation amounts (table 3), and pre-season irrigation on ETe (table 4), on crop yield, income, net return, and daily ASW (figs. 4, 5, 6).

Differences in ETe, yield expectations, net economic returns, and ASW from year to year due to variability in annual precipitation were evaluated by choosing precipitation probabilities of 20% (wet year), 50% (average year), and 80% (dry year) (table 2). Operational and

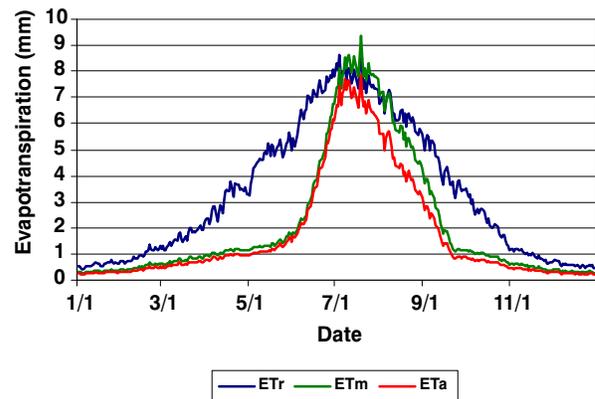


Figure 3. Example of ETr, ETm, and ETa. planted early and long season corn planted later.

irrigation costs were calculated for the average year and applied to all precipitation probabilities because input costs would be spent in spite of possible precipitation outcomes. When the outcomes from the average year were used as a baseline, ETe was +4% for the wet year and -5% for the dry year. Likewise, yield expectations were +9% for the wet year and -13% for the dry year. Net returns were +25% for the wet year and -40% for the dry year. ASW increased during the wet

Table 1. Input values for scenarios in tables 3, 4, and 5.

Location	Garden City
Crop	Corn
Soil type	Ulysses Silt Loam
Runoff	5%
Application efficiency	90%
Gross irrigation	25 mm per event
Crop price	\$165 Mg ⁻¹
Irrigation costs	\$0.14 ha ² mm ⁻¹
ASW on January 1	45%

Table 2. Effects of the amount of annual precipitation with probabilities of 80% (380 mm), 50% (483 mm), and 20% (584 mm) forgrowing season irrigation equal to 254 mm.

	Annual Precipitation (mm)		
	380	483	584
Effective ET (mm)	533	559	584
Yield (Mg ha ⁻¹)	10.0	11.5	12.5
Gross income (\$ ha ⁻¹)	1647	1901	2056
Operational costs (\$ ha ⁻¹)	1040	1040	1040
Irrigationcost (\$ ha ⁻¹)	233	233	233
Net return (\$ ha ⁻¹)	374	628	783

Table 3. Effects of growing season irrigation with annual precipitation equal to 483 mm.

	Gross Irrigation (mm)		
	203	254	305
Effective ET (mm)	533	546	559
Yield (Mg ha ⁻¹)	10.9	11.9	12.9
Gross income (\$ ha ⁻¹)	1791	1957	2123
Operational costs (\$ ha ⁻¹)	859	1074	1233
Irrigation cost (\$ ha ⁻¹)	188	233	275
Net return (\$ ha ⁻¹)	744	650	615

Table 4. Effects of pre-season irrigation for growing season irrigation equal to 203, annual precipitation equal to 483 mm.

	Pre-season Irrigation (mm)		
	0	53	102
Effective ET (mm)	508	521	533
Yield (Mg ha ⁻¹)	9.8	10.9	11.7
Gross income (\$ ha ⁻¹)	1625	1791	1924
Operational costs (\$ ha ⁻¹)	859	1074	1233
Irrigationcost (\$ ha ⁻¹)	188	233	275
Net return (\$ ha ⁻¹)	578	484	416

year which increased water availability during the crop's peak needs for water and caused the year-ending ASW to increase. The opposite trend occurred during the dry year (fig. 4). Precipitation probabilities have a large effect on profitability.

CYP users can compare a range of irrigation amounts to find the resulting ETe, crop yields and net returns (table 3). Growing season irrigation amounts equal to 203 mm (low), 254 mm (median), or 305 mm (high), which were $\pm 20\%$ of 254 mm, were evaluated. Fertilizer, seed, and harvesting costs were calculated considering the yield expectations from each amount of irrigation. Using the median amount of irrigation as a baseline, ETe was $\pm 2\%$ of the median irrigation

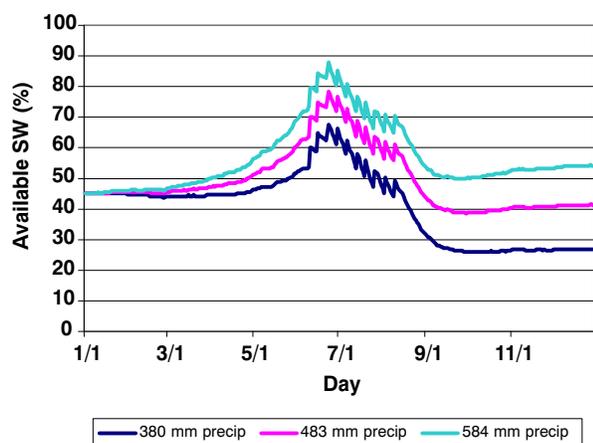


Figure 4. ASW for 80% (380 mm), 50% (483 mm), and 20% (584 mm) annual precipitation probabilities and growing season irrigation season irrigation equal to 254 mm.

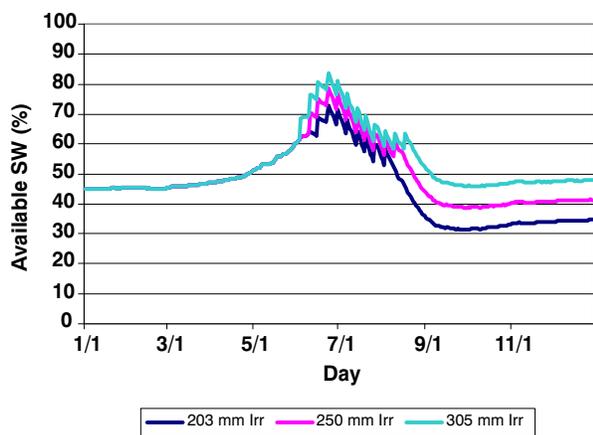


Figure 5. ASW for 203, 254, and 305 mm of irrigation and annual precipitation equal to 483 mm.

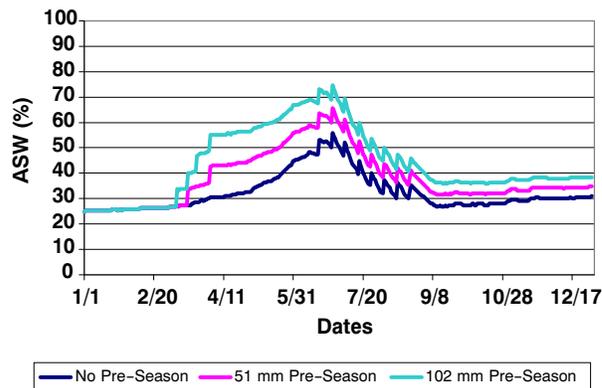


Figure 6. Effects of pre-season irrigation for growing season irrigation equal to 203 mm and annual precipitation equal to 483 mm.

for the low to high irrigation. Likewise, yield was $\pm 8\%$ of the median irrigation and net return that was $+14\%$ more for the low irrigation and -5% for the high irrigation. Gross income increased with more irrigation, but operating and pumping costs also increased resulting in decreased net return as irrigation increased. Even though more net return resulted from the least irrigation, income variability would increase from year to year with less irrigation (Klocke and Currie, 2009). An irrigator would need to evaluate the tradeoffs of income risks, which are beyond the capabilities of CYP. The CYP considered average results over years rather than possible results for individual years.

One approach to apply more water with an irrigation system that has limited capacity to deliver water is to start the irrigation season earlier and irrigate later (fig. 5). An irrigation system with limited capacity can only apply water at frequency dictated by the system. In this example, peak ASW was 82%, 78%, and 72% for the most to the least amount of irrigation. ASW at the end of the irrigation season was slightly more than the ASW on 1 January for the highest irrigation amount, but the ASW decreased from 45% on 1 January to 32% at the end of the irrigation for the least irrigation.

The value of pre-season irrigation is an issue when non-growing season precipitation is less than average and irrigators perceive that they will not be able to keep up with ET requirements later in the growing season (Stone et al., 2008). Often precipitation during April, May, and early June occurs in the Great Plains region that is difficult to predict during March when irrigators usually make pre-season irrigation decisions. The CYP can be used to forecast the advantage of pre-season irrigation to impact potential crop yields and net returns (table 5). In this example, either 53 or 102 mm of pre-season irrigation was applied in late March and early April on corn in two or four irrigation events. ETe was 3% and 5% more for 53 and 102 mm of pre-season irrigation compared with no pre-season irrigation. Likewise, yields 10% and 20% more for 53 and 102 mm of pre-season irrigation compared with no pre-season irrigation. However, net returns were 17% and 28% less for 53 and 102 mm of pre-season irrigation compared with no pre-season irrigation. Increased crop yield and gross income did not compensate for the additional operational costs and pumping costs. ASW during April was 30%, 42%, and 57% after 0, 53, and 102 mm of pre-season irrigation were applied (fig. 6), but the differences in ASW decreased by the time of the crop's peak

water needs and the ASW at the end of the year ranged from 30% to 40%. Drainage increased (data not shown) during April through early July as pre-irrigation increased ASW, which illustrates that pre-season irrigation has less impact on crop yield than irrigation applied at the time of the crop's water needs.

CONCLUSIONS

The Crop Yield Predictor (CYP) is an example of taking a crop simulation model and translating it into a decision tool for those who make irrigation scheduling decisions for deficit irrigation management. CYP, which is a vehicle for technology transfer, uses a simulation model that normally is not accessible by the decision makers in the field. CYP has been developed for a specific region, western Kansas, but it demonstrates the type of information needed to execute many crop simulation models. CYP users can ask "what if" questions to find the effects of input variables on outcomes rather than finding optimum solutions without the knowledge of effects of those input variables.

The CYP makes yield predictions with a crop simulation model adapted from the Kansas Water Budget (KSWB) to become an interactive model where the user can enter a western Kansas location, annual precipitation, soil type, crop type, a potential irrigation schedule, runoff, initial available soil water (ASW) content, crop production costs, and commodity prices to predict effective ET, grain yield, relative grain yield, daily ASW, daily drainage, daily crop ET, and net economic returns. Alternative irrigation schedules and annual precipitation can be entered into CYP to predict changes in results. CYP users can test the effects of input variables on the program outputs. The alternative schedules can guide CYP users in choosing irrigation starting dates, ending dates, and irrigation frequencies.

Multiple executions of the CYP illustrated that: (1) increases in annual precipitation, from 380 to 584 mm, had a positive impact on crop yields and a positive impact on net economic returns; (2) increases in growing season irrigation, from 203 to 305 mm, had positive impacts on crop yields but a negative impact on net returns; (3) pre-season irrigation, from 0 to 103 mm, had positive impacts on crop yields but negative impacts on net returns.

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