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Evaluation of Irrigation Strategies with the DSSAT Cropping System Model

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Abstract. *Water is becoming an increasingly valuable commodity with shortages and water rationing more commonplace. Since irrigation is the largest consumptive use of water in South Dakota, accounting for over 70% of the water withdrawals, irrigation water management is critical to make the best use of the water available. This project uses the CERES-Maize cropping system model (available in DSSAT v4) to study the impact of various irrigation management strategies on corn production. SDSU management software developed by Oswald (2006) is used to simulate a center pivot for specific locations and years. Weather data from several sites in the Great Plains together with soil, crop, and irrigation inputs are used in the modeling. The objective of this paper is to demonstrate a low-cost and low-time method (compared to field testing) for evaluating irrigation strategies for limited water scenarios. When the pivot simulator and crop model were integrated, differences in ET calculations resulted in different soil water balances. When the method is modified such that water balances in the SDSU management software and DSSAT are similar, this may be a valuable tool for irrigation management research.*

Keywords. Irrigation Management, Scientific Irrigation Scheduling, Center Pivot Irrigation, Deficit Irrigation, Irrigation Simulation, DSSAT, Water Conservation, Irrigation Water, Crop Models, Evapotranspiration.

Introduction

Water is becoming an increasingly valuable commodity with shortages and water rationing more commonplace. One study predicts that in the year 2050, there will be an annual water shortage of 640 billion cubic meters (Spears, 2003). Irrigation is the largest consumptive use of water in many places, accounting for 65% of the fresh water use in the Western 22 states. Drought in western South Dakota has reduced water supplies for several irrigation projects, and low water flows in the Missouri River have restricted irrigation from the reservoirs. Since irrigation is the largest consumptive use of water in South Dakota, accounting for over 70% of the water withdrawals, irrigation water management is critical to make the best use of the water available.

As competition for irrigation water supplies becomes greater, it will be necessary for irrigation farmers to optimize their use of the water available to them. A variety of options are available to irrigation farmers to conserve water, including converting from low efficiency surface irrigation to sprinklers or drip irrigation. Using science-based knowledge and irrigation scheduling has been shown to conserve water for all types of irrigation methods.

Research has demonstrated efficient irrigation water management and simple deficit irrigation strategies. However, specific deficit strategies have not been developed for use with center pivot management. In this project, SDSU management software developed by Oswald (2006) was used to simulate a center pivot for specific locations and years. The CERES-Maize crop model (Jones and Kiniry, 1986, available in DSSAT, 2005) was used to study the impact of various irrigation management strategies on corn production, determining the best management practices when water is limited. The process of selecting the best irrigation strategy ensures that production is optimized while conserving the available water.

When other factors are held constant, yield (Y) can be described as a function of available irrigation water (w) and the strategy used to apply that water (s).

$$Y = f(w,s) \tag{1}$$

The yields for multiple years could be averaged to determine Y_{avg}. For a given amount of water available, which strategy will result in the maximum yield (Y_{avg})? The objective of this paper is to demonstrate a method for answering that question. If using a modeling approach is effective, much time and money could be saved compared to answering this question with only field research.

Past Research

English, et al. (2002), in an article entitled “A Paradigm Shift in Irrigation Management,” discusses the changing context in which irrigation takes place. Due to “accelerating competition for water and rising concern about the environmental effects of irrigation”, among other things, irrigating for maximum yield may not always be the best option. A new paradigm is promoted: the maximization of net benefits. This more complex goal requires more information, including “more detailed models of the relationships between applied water, crop production, and irrigation efficiency.”

Varlev, et al. (1995) used a mathematical function for yield to develop practical rules for deficit irrigation. The function calculated a relative yield based on daily water deficits, taking into account how crop response to water stress varies according to its stage of development. The function was optimized to determine the best distribution of available irrigation water. Among other guidelines, the paper concluded, “the farmer should satisfy 75-80% of the required irrigation depth starting from the most sensible to the least sensible phases of development.”

Klocke, et al. (2004) performed field testing of corn in Nebraska to compare irrigation strategies, including farm-based irrigation management, best management practices (BMPs), and two limited irrigation strategies. The BMP included maintaining the soil water balance between field capacity and 50% depletion for most of the season. The "late initiation" strategy, which allowed 70 % depletion until two weeks before tassel emergence, produced an average yield of 93% of the BMP yield with irrigation water only 76% of BMP irrigation water use. The "limited allocation" strategy had a goal of only 250 mm (10 in.) or 150 mm (6 in.) (depending on location) of irrigation water use, and produced an average yield of 84% of the BMP yield with irrigation water only 57% of the BMP irrigation water use.

Dogan, et al. (2006), compared DSSAT simulation results with field data for corn in Kansas. Recognizing the potential benefit of using crop models to evaluate irrigation decisions in limited water situations, field sites with various irrigation scenarios were used. It was noted that "the CERES-Maize model may be adequate for large spatial and temporal simulations, but may not be adequate to simulate individual sites and deficit yield conditions."

Methods and Materials

SDSU Management Software Setup and Modifications

SDSU management software, developed by Oswald (2006) in LabVIEW® Version 7.1, was used to simulate a center pivot irrigator and its movement throughout a field. Location, crop type, soil water holding capacity, pumping rate, and historical weather data (16 to 24 years, depending on location) were inputs. The program calculates a daily soil balance for each portion of the field, using rainfall, irrigation, ET, and drainage/runoff. The software schedules irrigation events in order to minimize water stress with a goal of maximum yield. The program incorporates an estimate of future ET in the decision making routine because it may take several days for the irrigator to travel around the field. Except when pumping rate isn't high enough to keep up with ET demands, the scheduling logic is generally able to maintain soil moisture at the desired levels throughout the field.

For irrigation scheduling purposes, it is helpful to define soil water content as a percentage, with zero being the soil moisture at the wilting point and 100% being the soil moisture at field capacity. This is the amount of water that is available to the crop. Equation 2 shows how plant available water is calculated.

$$PAW = (\theta - \theta_{WP}) / (\theta_{FC} - \theta_{WP}) * 100 \quad (2)$$

where

PAW = plant available water (%)

θ = soil volumetric water content

θ_{WP} = water content at the wilting point

θ_{FC} = water content at field capacity

An irrigation strategy offers a guideline for making irrigation decisions. A historically common strategy was to maintain the plant available water at 50% or higher throughout the growing season. If a producer knows the soil water content in his field, he can estimate current ET and decide when, and how much, to irrigate in order to avoid letting the soil drop below 50% plant available water. Knowing that some crops are less sensitive to water stress early in the season, another option may be to withhold irrigation for a specified time, and then to irrigate to achieve 50% plant available water for the remainder of the season. A more involved strategy, for corn as an example, might require a higher plant available water level during tasseling, when corn is most sensitive, and lower, but specified levels, for early and late season.

A method was needed to numerically describe an irrigation strategy so that strategies could be changed and tested easily. An irrigation strategy was defined by the minimum plant available water as it varies through the season. Irrigation events are scheduled to avoid letting the soil dry below this point. Figure 1 illustrates the general shape of the minimum plant available water function, and the parameters which characterize it.

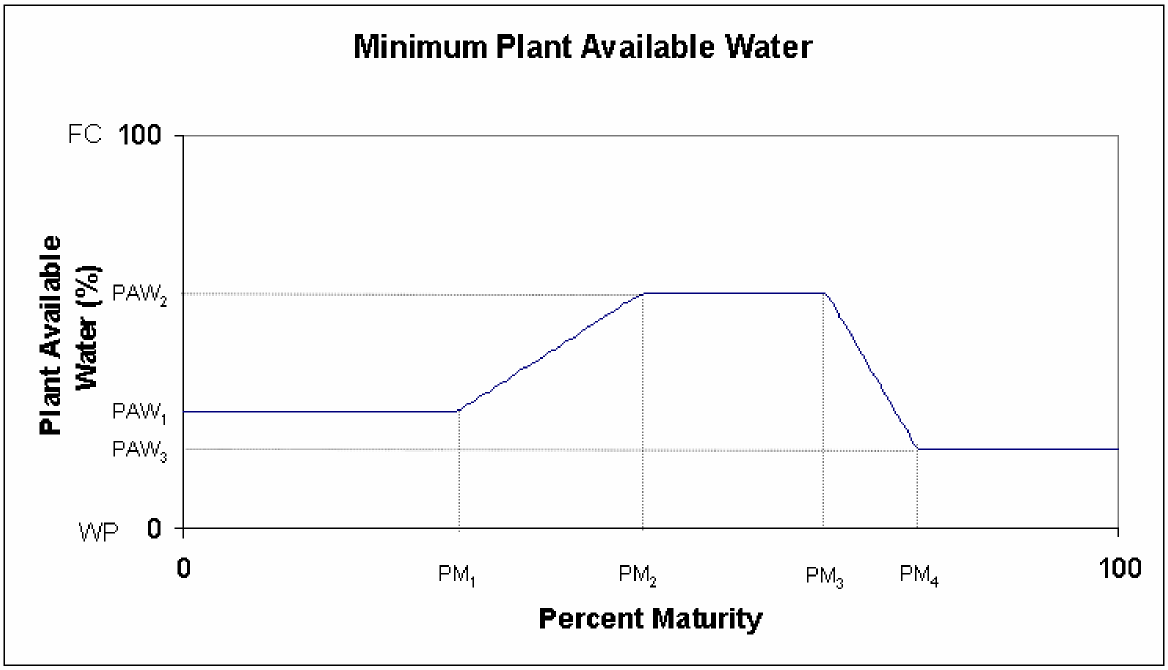

Figure 1. Minimum plant available water changes throughout the season.

After parameters for a strategy are selected, the minimum plant available water can be calculated for any time in the growing season with a linear equation. For example, the strategy for the second phase of the season is defined by the following function:

$$MPAW(PM) = ((PAW_2 - PAW_1) / (PM_2 - PM_1)) * PM + PAW_1 \qquad (3)$$

where

MPAW = Minimum Plant Available Water

PM = Percent Maturity

PAW_1 = soil water parameter

PAW_2 = soil water parameter

PM_1 = time parameter

PM_2 = time parameter

Multiple strategies are defined in an Excel document, with each row being one strategy and each column being a parameter. This document is an input into the SDSU management software, which runs one center pivot simulation for each strategy.

The center pivot SDSU management software divides the field into 60 sections, each a 6˚ pie shape with its own water balance. Output data were taken from the location at 180˚. In order to determine whether this was representative of the whole field, data were also collected from two other positions in the field. Water balances varied for each position, indicating that a more thorough analysis would be required. The software was modified to graph the mean, mean +/- one standard deviation, maximum, and minimum moisture for the 60 pie pieces. Figure 2 illustrates the variability in soil moisture contents throughout the corn field for a particular season in Brookings, SD for one year. Further statistical analysis of the variance in yield due to location in field will be performed in order to determine the minimum number of locations required to get a representative mean yield (e.g. a solution might be to run DSSAT for three locations within the field and average the yields).

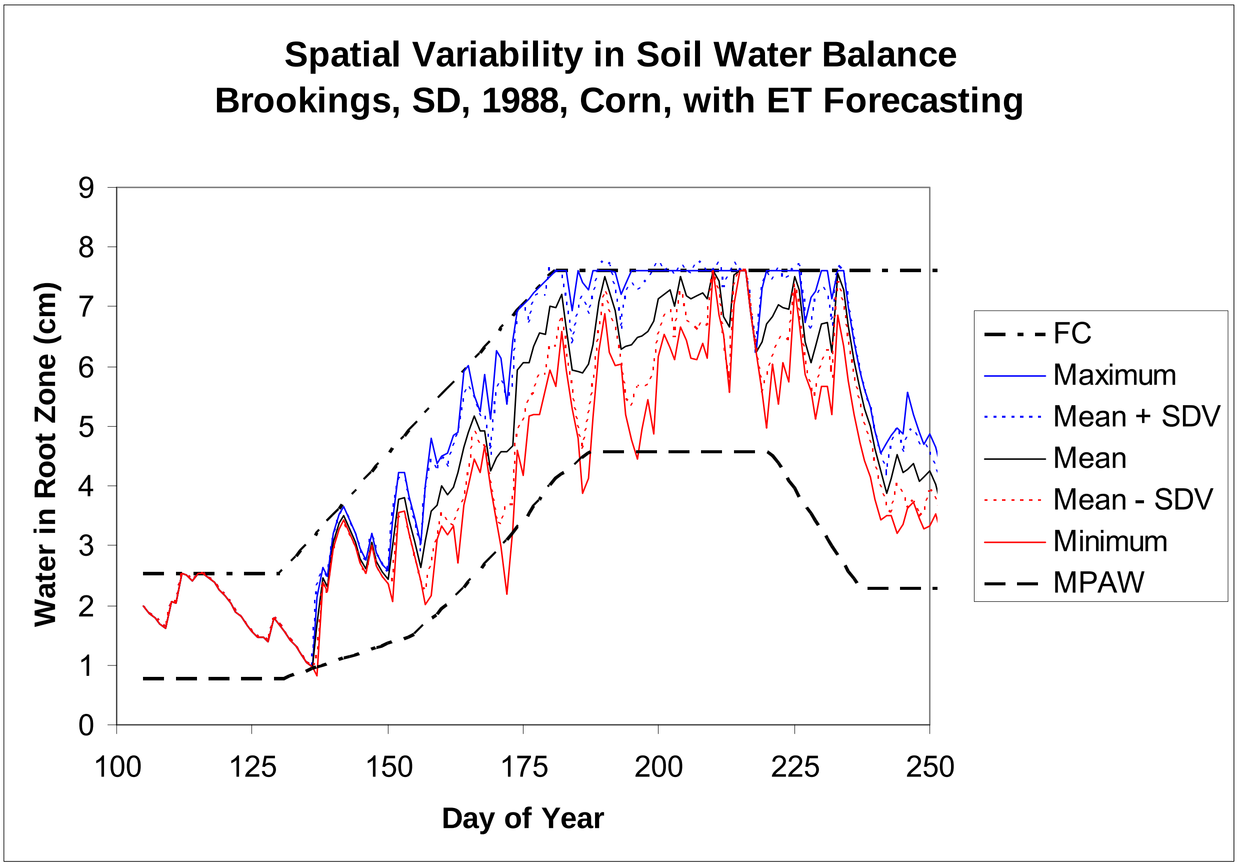

Figure 2. Spatial variability in soil water balance. The lower line correlates to the minimum plant available water (multiplied by root depth), and the upper line correlates to field capacity. The remaining five lines are statistical results from all water balances in the field at a given time.

The SDSU management software was designed for a common scenario where ample water is available and the goal is to produce the physiological optimum yield. As such, the software uses ET forecasting to irrigate so that no part of the field has a soil water balance below the minimum plant available water, if possible. In figure 2, for example, only rarely did any portion of the field dry to a point below the minimum plant available water line. This works well if the goal is to prevent any water stress that would result in yield reduction. Under water limited scenarios, however, a more conservative approach may be desirable. The SDSU management software was updated to make the ET forecasting optional. If ET forecasting is turned off, portions of the field may be too dry, but the average part of the field is maintained above the minimum plant available water line. Figure 3 illustrates how this approach makes the minimum plant available water a target for the mean of the soil water balances in the field.

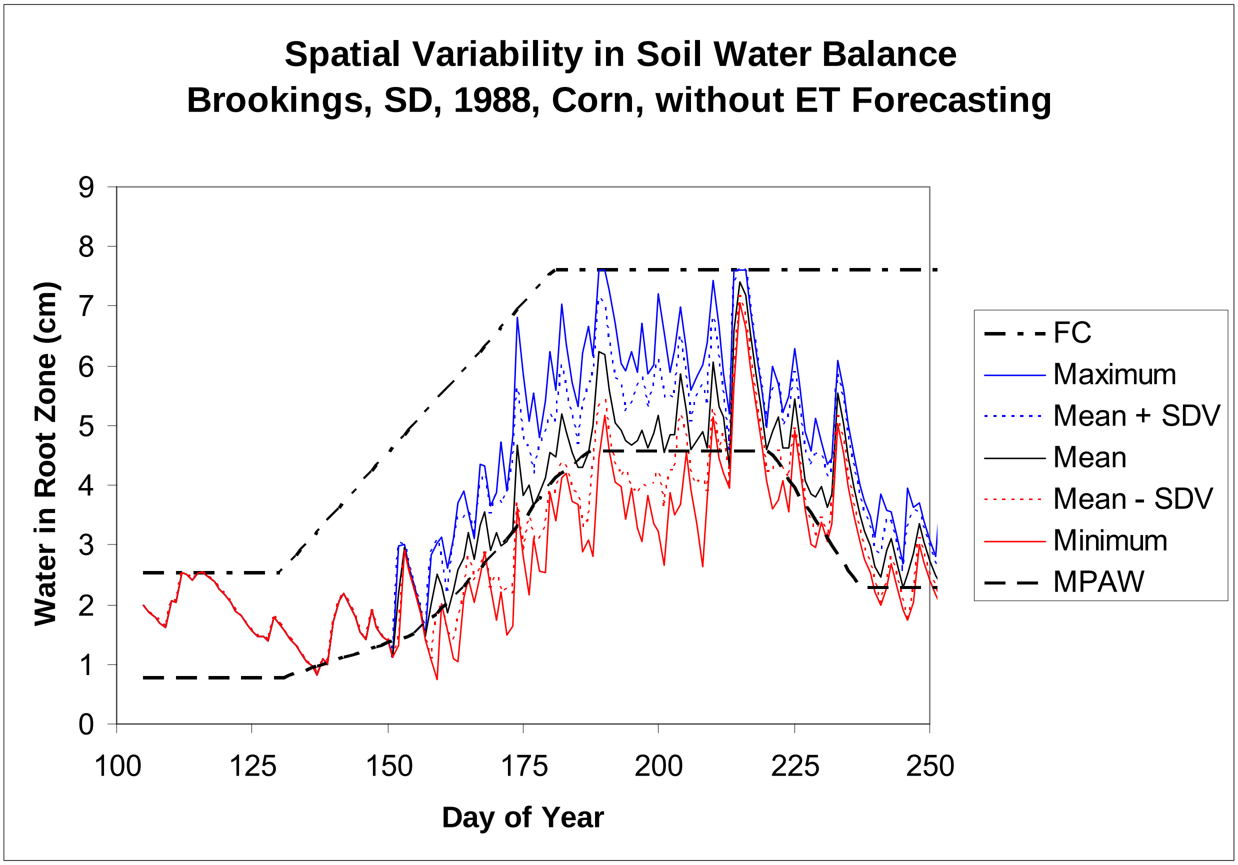

Figure 3. Spatial variability in soil water balance. The SDSU management software was run without the ET forecasting option, resulting in lower soil water levels.

The SDSU management software was designed with a tall crop reference ET calculation, according to ASCE Standardized ET (2005). Since DSSAT uses the short crop reference ET equation (FAO-56), the SDSU management software was adapted to include both tall crop and short crop reference ET options. The crop coefficients were also adjusted accordingly.

In order to streamline the modeling process, the simulation software output format was modified to a format that matches the DSSAT input file. Specifically, two new output files were created. The first one identifies the treatments (i.e. one for each strategy, one with no irrigation, and one with no water stress) and corresponding treatment names. The second file specifies the dates and amounts of irrigation for each treatment. These two files can simply be “cut and pasted” into their appropriate places the .mzx input file for DSSAT.

DSSAT Setup

The DSSAT Cropping System Model (DSSAT, 2005) can simulate growth and yield for a variety of crops; CERES-Maize (Jones and Kiniry, 1986) is the subroutine which is used to model corn. Inputs include location, weather data, cultivar, soils data, and management decisions (including irrigation). The soil profile is divided into multiple layers, and the water content in each layer is computed by a water balance. DSSAT runs on a daily time step and simulates growth and development throughout a growing season.

Weather data were downloaded from the High Plains Regional Climate Center. Precipitation, solar radiation, average wind, dew point temperature (converted from average RH), and maximum and minimum temperature were uploaded into DSSAT. Locations across the Great Plains were selected: Akron, CO; Oakes, ND; Brookings, SD; Ord, NE; St. John, KS; and Rockport, MO.

The soil characteristic which is most relevant in this study is water holding capacity. A soil with a larger water holding capacity is able to store more water in the root zone, retaining water from large rainfalls which might otherwise be lost to deep percolation or runoff. Having an effect on the water balance, soil water holding capacity can impact irrigation decisions. Water holding capacity is the difference between the field capacity and the wilting point, as defined in equation 4.

$$WHC = (\theta_{FC} - \theta_{WP}) * 100 \qquad (4)$$

where

WHC = water holding capacity (cm/m)

θ_{WP} = water content at the wilting point

θ_{FC} = water content at field capacity

The Deep Silty Loam (a general soil without difficult anomalies, e.g. hard pan, low hydraulic conductivity) in DSSAT was selected and used as an initial soil profile. The wilting point and the field capacity were modified to create soil profiles with water holding capacities of 8.3, 12.5, and 16.7 cm/m (1.0, 1.5, and 2.0 in/ft, respectively). Figure 4 demonstrates the effect that soil water holding capacity may have on yield.

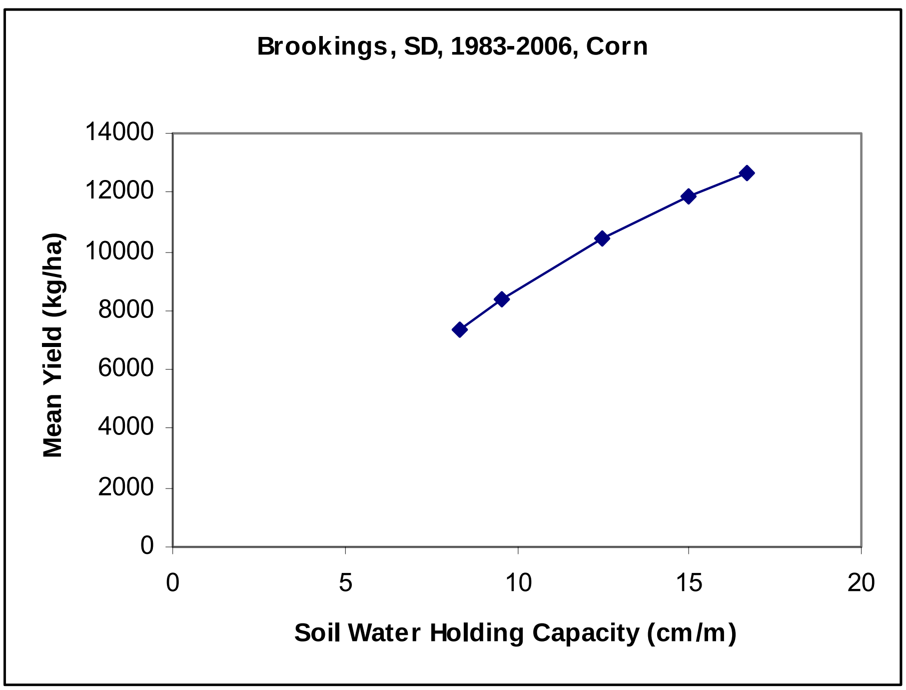

Figure 4. Mean corn yield (dry weight basis) determined from CERES-Maize for soil profiles with various water holding capacities.

Cultivars needed to be selected that would match the growing season for each location. Other than this requirement, cultivars should be nearly identical in order to minimize variability due to cultivars. DSSAT has a series of maize varieties that are very similar except for the season length, ranging from 2500 – 2600 GDD (Growing Degree Days) to 2750 – 2800 GDD. Each of these cultivars was tested in each location. The cultivar that had the highest mean yield (across several years of weather data) was chosen. Table 1 shows the planting dates that were used and the hybrids that were selected for each location.

Table 1. Planting dates and cultivars chosen for each location.

Location	Planting Date	Hybrid
Oakes, ND	May 1	2600 – 2650 GDD
Brookings, SD	April 15	2600 – 2650 GDD
Akron, CO	April 1	2650 – 2700 GDD
Ord, NE	April 1	2700 – 2750 GDD
Rockport, MO	April 1	2700 – 2750 GDD
St. John, KS	April 1	2750 – 2800 GDD

The mean yield from the best variety was then compared to the mean county average (USDA NASS) for each location. Figures 5 and 6 show this comparison for non-irrigated yields and irrigated yields, respectively. DSSAT yields are expected to be higher because it does not account for (in this project) nutrient deficiencies, weeds, pests, disease, etc.

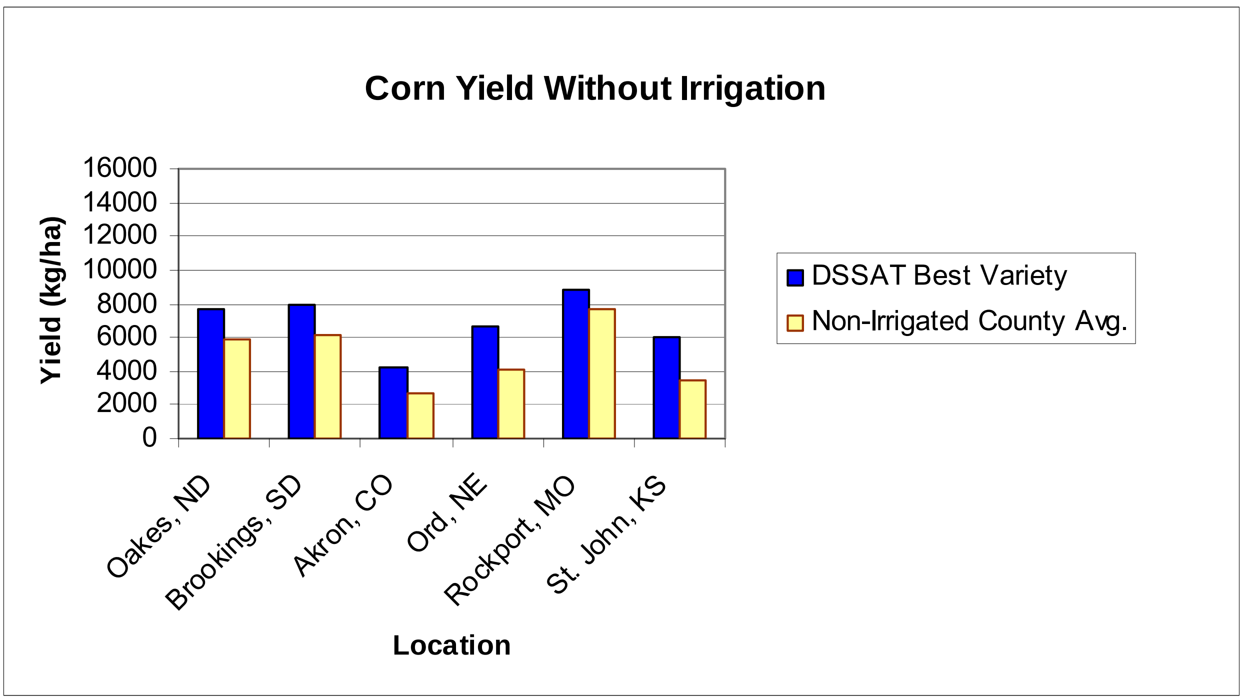

Figure 5. Mean corn yield for 16 to 24 years (depending on weather data availability for each site). DSSAT data reflects the cultivar which produced the highest yield for each site. NOTE: Rockport, MO, county average data did not differentiate between irrigated and non-irrigated yields.

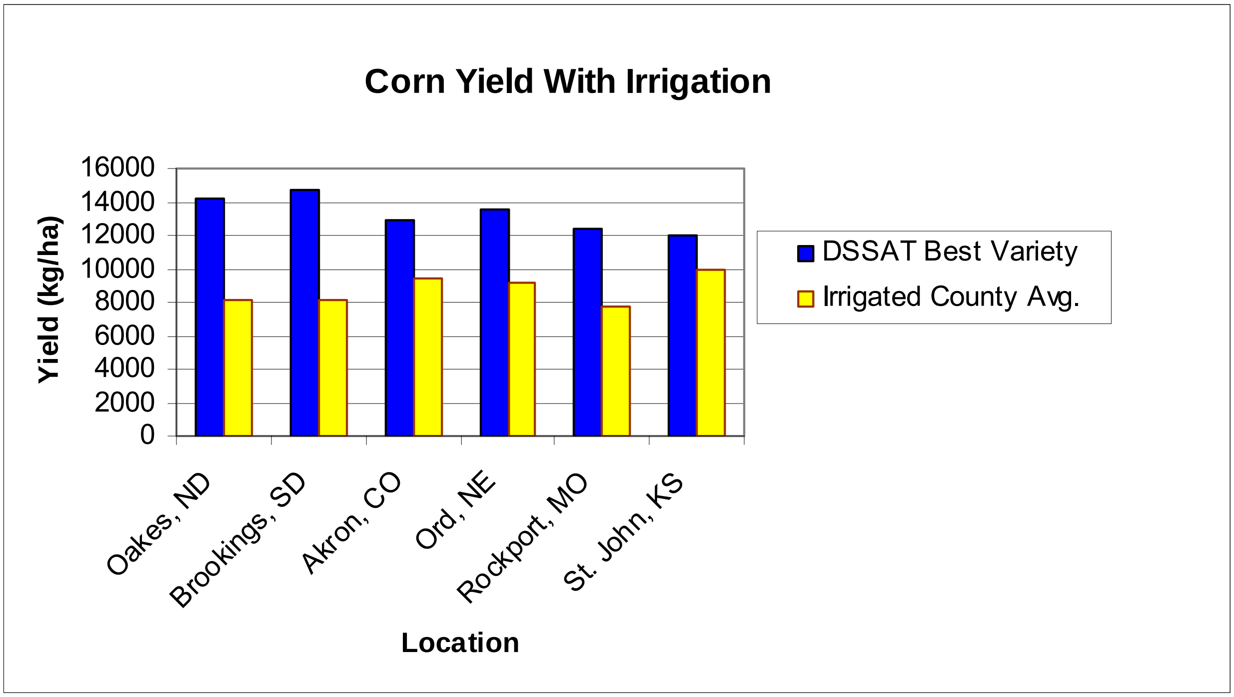

Figure 6. Mean corn. DSSAT simulations were run with no water stress in order to imitate full irrigation. NOTE: Rockport, MO, county average data did not differentiate between irrigated and non-irrigated yields.

DSSAT and county average yields were also compared on a yearly basis, as shown in Figure 7.

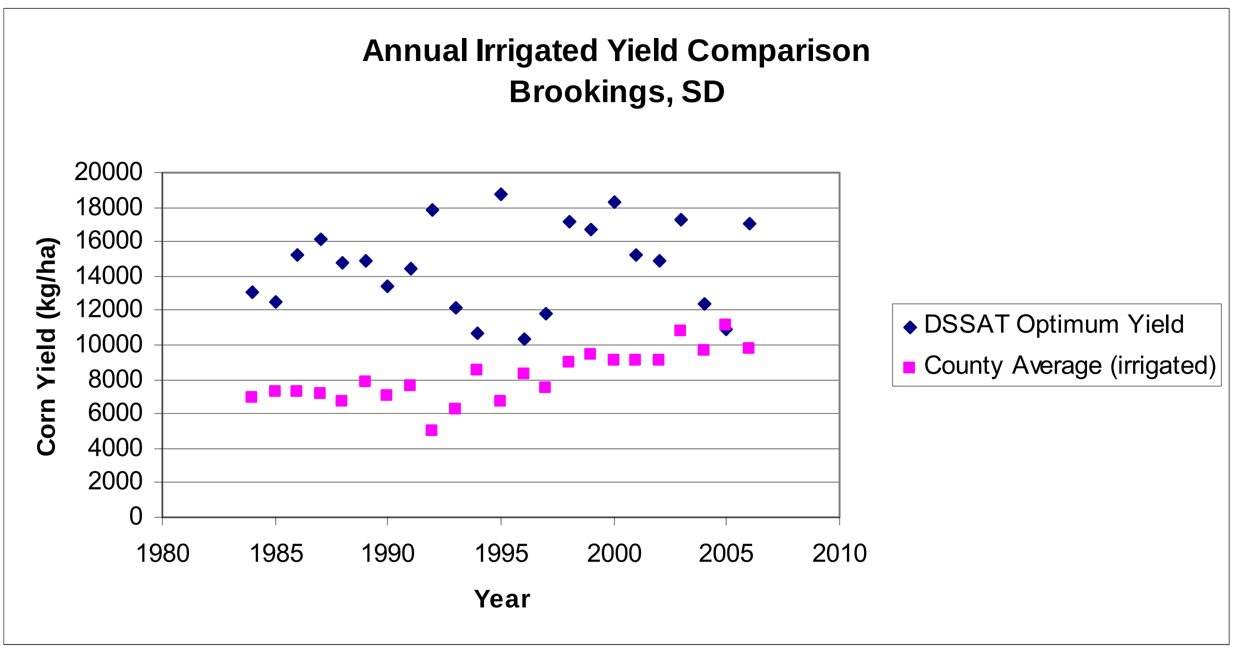

Figure 7. Yearly corn yields for Brookings, SD. DSSAT simulations were run with no water stress in order to imitate full irrigation.

While county average data shows relatively consistent yields from year to year, DSSAT data shows much more scatter. For evaluating a specific irrigation strategy, yields from all years are averaged in order to reduce this variation.

FAO 56 was selected for the ET method in DSSAT. During a sensitivity analysis, it was observed that ET did not respond to changes in RH. T_{dew} showed an improved response, so all RH data was converted to dew point temperature before uploading it into DSSAT.

Results

DSSAT's sensitivity to irrigation for a specific site and year was evaluated. The driest year (within the weather data) for Brookings was selected. Simulations were run with three different strategies and four pumping rates (affecting the center pivot's ability to keep up with high ET demands). A simulation without any irrigation was also performed. A graph of yield v. seasonal irrigation is show in Figure 8. Potential yield is reached with 35cm of irrigation water.

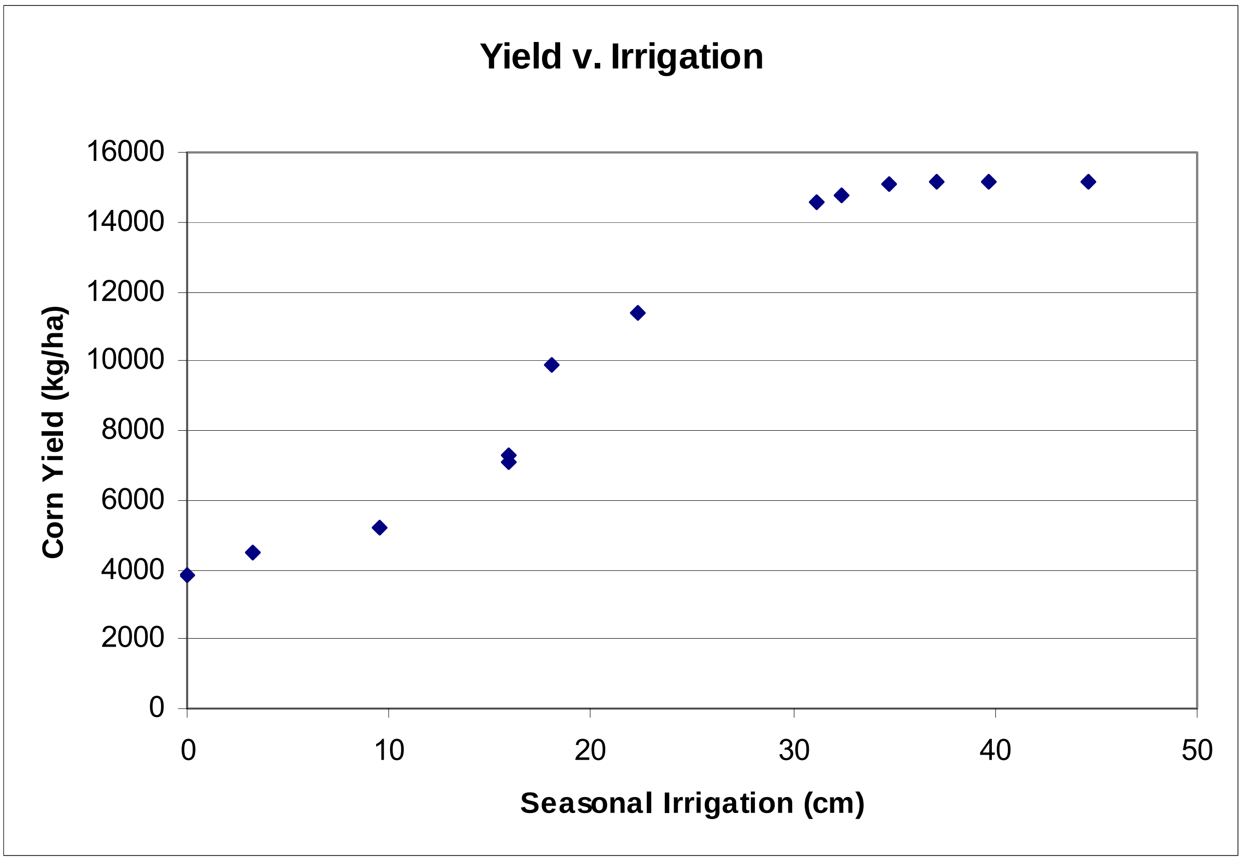

Figure 8. Yield response to irrigation for Brookings, SD, 1988, with various irrigation strategies and pumping rates.

DSSAT was not showing as much water stress as the SDSU management software indicated, so ET results were compared. First, reference ET from the SDSU management software was compared with reference ET from DSSAT. Three locations were selected, and three seasons (dry, normal, wet) for each were simulated. Percent error in seasonal reference ET ranged from 5.0% to 13.1%, with the SDSU management software always calculating a higher seasonal ET. The SDSU management software code was verified, and some of the DSSAT code was studied, yet the reason for this difference remains unknown. Crop ETs were compared next. The same locations and seasons were used, with the results shown in table 2.

Table 2. Seasonal crop ET comparison.

	LabVIEW v. DSSAT % Error		
	Dry Year	Normal Year	Wet Year
Akron, CO	13.8*	3.4*	10.3
Brookings, SD	8.0	3.6	-0.1
Rockport, MO	5.2	-2.8	5.2
*short season due to early crop failure in DSSAT			

In the SDSU management software, crop ET is obtained by multiplying the reference ET by a crop coefficient and a water stress coefficient. DSSAT treats the reference ET as a maximum and uses a partitioning method to determine transpiration and evaporation. These two components were summed to get crop ET from DSSAT.

The differences in ET calculations result in different soil water balances. Figure 9 compares the soil water balance in the SDSU management software to the soil water balance in DSSAT. The DSSAT plant available water is based on a weighted average of the layers in the top three feet.

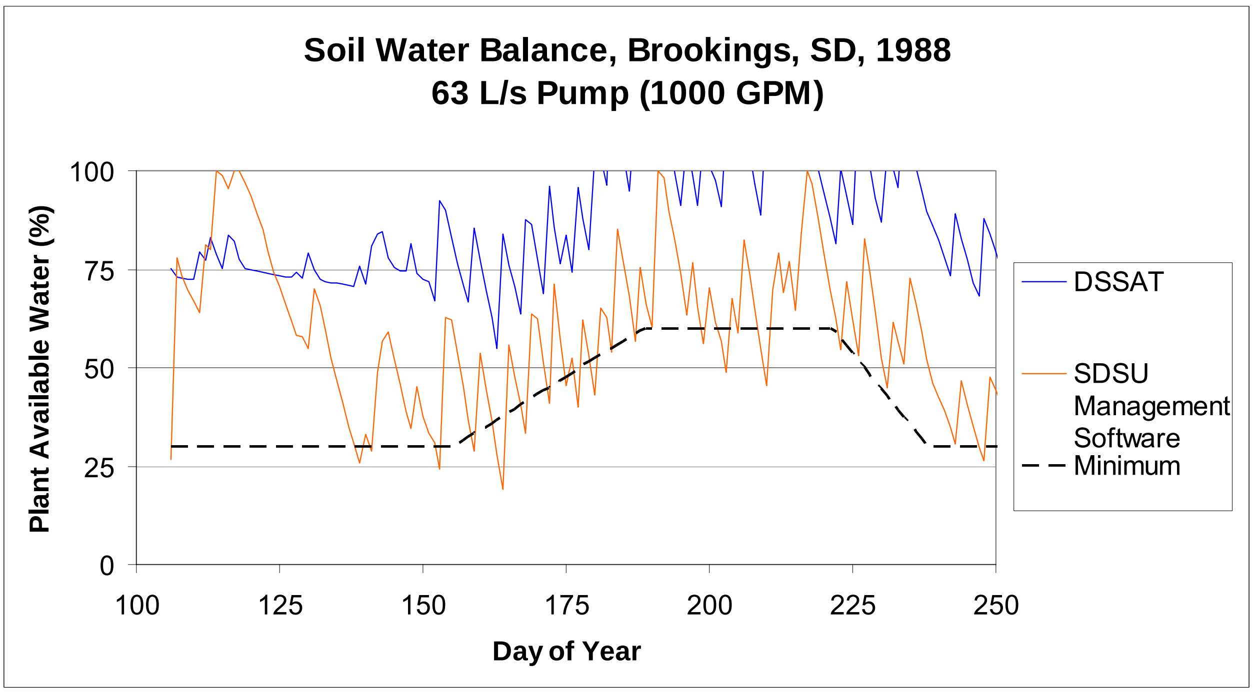

Figure 9. Soil water balance comparison with a high pumping rate (i.e. irrigation can keep up with ET demand).

In this case, the soil water balance in DSSAT is consistently higher than the SDSU management software soil balance. The simulation was run again, only with a pumping rate of 13 liters per second. This forced a situation with severe water stress, as shown in figure 10. In the situation with the low pumping rate, the DSSAT water balance is again high in the first portion of the season. However, after the drought forced both balances to near-zero, they remained similar for the rest of the season.

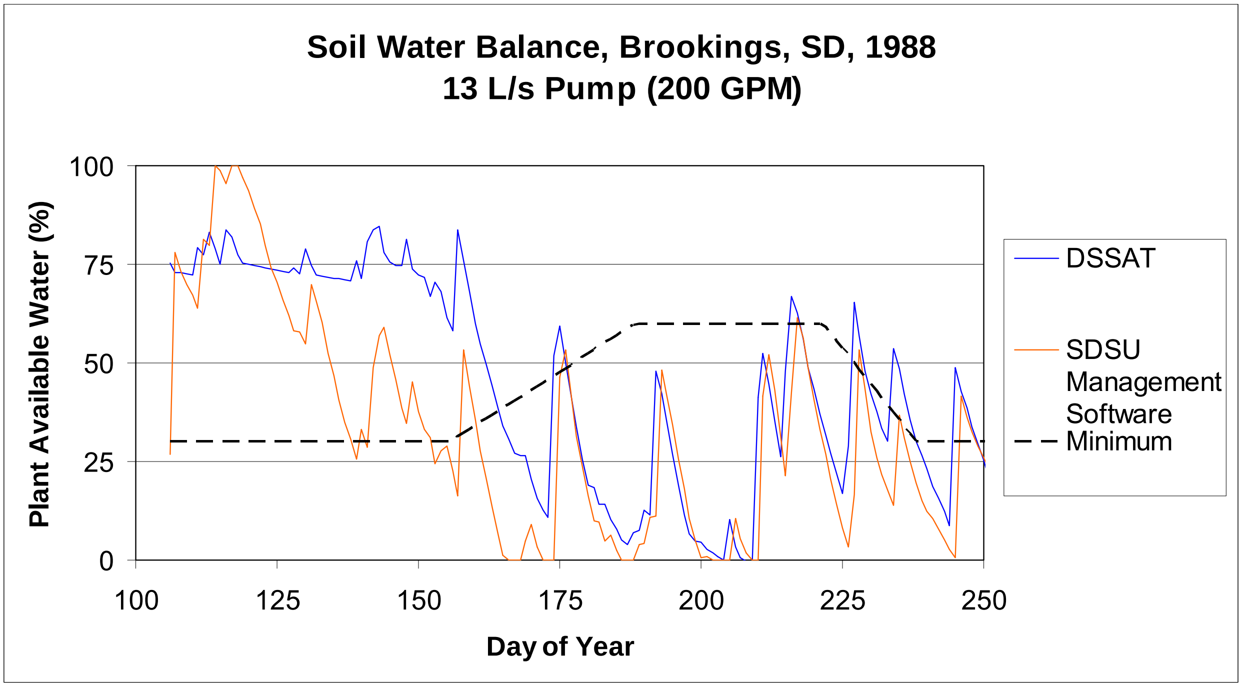

Figure 10. Soil water balance comparison with a low pumping rate.

Discussion

Differences in calculated ET for the two models are having a detrimental effect on the value of yield data. The SDSU management software calculates a higher seasonal crop ET than DSSAT does. With a lower ET, DSSAT calculates a higher soil water balance, resulting in less water stress on crop growth. Figures 9 and 10 indicate that differences in ET may be primarily early in the season. The differences may be due in large part to the methods of calculating crop ET (crop coefficient v. partitioning). One option to reconcile this may be to update the SDSU management software to include ET partitioning as an option. Differences in ET must be minimized so that variation in yield adequately reflects changes in irrigation strategy.

Conclusion

As competition for irrigation water supplies becomes greater, it will be necessary for irrigation farmers to optimize their use of the water available to them. Using DSSAT is one potential method for evaluating deficit irrigation strategies. When the method is modified such that water balances in the SDSU management software and DSSAT are similar, this may be a cost effective way to develop irrigation strategies for limited water scenarios. Further research is needed to finish integrating the SDSU management software and DSSAT. Once optimum strategies are developed, field testing should be performed to verify them.

Acknowledgement

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