OPTIMAL SPATIAL AND TEMPORAL ALLOCATION OF IRRIGATION WATER FOR COTTON IN TEXAS HIGH PLAINS

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Abstract

Texas High Plains is the most important cotton producing area in the United States. The diminishing water level in the Ogallala aquifer, which is the principal source of irrigation in this region, coupled with the low average annual rainfall makes judicious use of irrigation water a very important concern in this area. When only a small amount of irrigation water is available, the efficiency of its allocation may be increased by irrigating only a fraction of the field (spatial allocation) and by optimally allocating water among three different growth stages of the crop (temporal allocation). Crop response to irrigation water also depends on the amount and distribution of rainfall. Hence to develop an efficient strategy for optimal spatial and temporal allocation of irrigation water, crop responses during multiple years are required, which are cost- and time-prohibitive. To tide over this problem, cotton growth simulation model, Cotton2K was used to simulate cotton yield for possible weather conditions simulated using a synthetic weather generator (WGEN) under different spatial and temporal allocation of irrigation water when only six inches of irrigation water is available. Then an economic model was used to identify the spatial and temporal irrigation water allocation strategies that maximizes the profit and minimizes the year-to-year yield variability for a center pivot irrigated cotton field in THP. The results indicated that irrigating 55% of the field and applying the entire amount of irrigation water during the second stage (from appearance of first flower to first open ball) is the profit maximizing strategy and irrigating 40% of the field and applying the entire amount of irrigation water during the second stage is the risk minimizing strategy.

Introduction

The Texas High Plains (THP) is the largest cotton producing area in the US and is the principal contributor to the number one position of Texas in cotton acreage and production in the USA. Even though the average annual precipitation is only 16 to 28 inches, the availability of irrigation water from the Ogallala aquifer is the principal reason for intensive irrigated cotton production in THP. The Ogallala aquifer is the largest underground fresh water body in North America underlying parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (McGuire, 2007). The Ogallala aquifer occupies 17,000 square miles of area and contains 3.3 billion acre feet of water, with approximately 170,000 wells pumping water from it. However, the aquifer experiences very slow recharge because of the low precipitation and it is estimated that 11% of the water in the Ogallala has been pumped since the 1930s and 25% of its water resource will be gone by 2020 (Lewis, 1990). Many Texas farmers now are experiencing water shortages as some wells are becoming dry and, at some places, the aquifer water is getting deeper, leading to a higher cost of pumping. Administrators in Texas are also looking for ways to control excess pumping by farmers along the lines of measures adopted in Kansas and New Mexico like water charges or restriction in pumping. Under these circumstances, the THP is experiencing and will continue to experience limited availability of irrigation water and higher cost of pumping. Hence, developing strategies to optimize the use of available irrigation water is of great importance in the THP.

The optimal irrigation scheduling in low rainfall areas like Texas High Plains (THP) poses the specific problem of finding an optimal strategy to allocate a finite quantity of irrigation water over an irrigation season on a particular area for a crop or combination of crops in the face of stochastically varying rainfall (Bontemps and Couture, 1999). Therefore, the decision variables are the timing of irrigation scheduling, the quantity of water to be applied each time, and the number of applications. Even though cotton requires much less water than crops like corn and alfalfa, better irrigation strategies can, with limited water availability, enhance profit and reduce weather-related risks and are therefore particularly important for cotton producers in the Texas Panhandle, who faces reduced availability of irrigation water (Almas, Colette, and Warminski, 2007). Apart from measures to improve irrigation efficiency improved irrigation application methods, the two fundamental decisions a farmer has to make in order to optimize the use of irrigation water are the quantity of water to be applied and how it is scheduled during the growing season.

When only a limited amount of irrigation water is available to the farmer to irrigate the field, the farmer can increase the amount of irrigation water only by partitioning the field into irrigate and dry land segments. This strategy forces the farmers to take informed spatial allocation decisions to irrigate the optimal fraction of the field so as to maximize the profit. Temporal allocation of irrigation water might seem straightforward as the farmer can follow a recommendation of the amount of irrigation water and the irrigation interval, but the variability in weather conditions from year to year can complicate the situation and add an element of risk in the decision making. Hence, the determination of average yield risk associated with different irrigation water allocation strategies can be of immense help to the farmer in decision making.

To find the spatially and temporally optimal irrigation water allocation strategy, data on yield response of cotton to different irrigation water allocation over multiple years is needed. Acquiring such a data set through field experimentation is cost- and time-prohibitive. We can overcome this problem by using crop growth simulation models to estimate the yield under various possible weather conditions. We used a synthetic weather generator, WGEN to simulate weather data for a large number of years for the THP and then used this weather data to simulate cotton yield using cotton growth simulation model, Cotton2K. An economic model was then used to arrive at an optimal management strategy that not only maximizes profit but minimizes weather-related risk as well. This technique helps us to arrive at spatial and temporal allocation strategies for center-pivot-irrigated cotton that can lead to maximum profit under deficit irrigation.

Even though numerous studies have examined the profitability and risk associated with different management strategies in agriculture like selection of crop, nutrient management and water management, the profitability and risk-reducing impact of the temporal and spatial allocation of irrigation water under deficit irrigation conditions are yet to be addressed. With the increasing popularity of deficit irrigation practices among THP producers, more research is needed to find the optimal way to partition the center-pivot-irrigated field and schedule irrigation by growth stage. Given the highly variable weather conditions in the THP, it is also useful to find the optimal management strategy that not only maximizes profit but minimizes weather-related risk as well. The present study aims at identifying the optimal strategy for spatial and temporal allocation of irrigation water that maximizes the profit and minimizes the risk for center pivot irrigated cotton in THP when only six inches of irrigation water is available.

Materials and Methods

In order to determine the spatial and temporal allocation strategy for irrigation water that maximizes the profit, it is required to have yield data for cotton under different spatial and temporal allocations of irrigation water. Moreover weather is the most important stochastic component that influences the yield of cotton, and to assess the yield variability induced by different weather conditions we require yield data for cotton under different weather conditions. Hence to develop optimal irrigation water allocation strategy, we must also take into account the year to year yield variability. These considerations imply that a very large number of yield data points corresponding to irrigation water allocation treatments for a large number of years are required. It is cost- and time-prohibitive to obtain such a data set by field experimentation and simulation is a widely accepted and useful tool in such a situation.

We used Cotton2K (Marani, 2000), which is a very descriptive mechanistic model that describes cotton growth, development and yield, to simulate cotton yield under a variety of spatial and temporal allocation of irrigation water for center pivot irrigated cotton in THP after calibration and validation of the model for THP. The cotton growth simulation model, cotton2K, requires a large amount of inputs including daily weather data, soil hydrology data, crop variety and location data, initial soil condition data and agronomic inputs data. The soil hydrology and initial soil conditions data of the Amarillo clay loam soil reported by Baumhardt, Lascano and Kreig (1994) was used to calibrate the model for the Texas high plains location. The model was then validated using the weather data and irrigation amounts to simulate the observed yields reported by Wanjura *et al.* (2000). This paper describes the yield response of cotton to different amounts of irrigation water application during different years from 1988 to 1999. We collected the weather data for these years and simulated the yield under the same amounts of irrigation water as in the paper. The results of the validation study showed that the yield of cotton predicted by the simulation model is in good agreement with observed yield of cotton and hence cotton2K can be used to simulate the yield of cotton in THP with considerable accuracy.

The possible weather data for the Texas High Plains area were generated using the weather simulation model WGEN (Richardson and Wright, 1984). WGEN is a weather simulation model that can be used to generate daily values of maximum and minimum temperatures, precipitation and solar radiation. The model can generate these values stochastically for time periods ranging from days to hundreds of years.

To design this study, a preliminary study was conducted with different temporal allocation treatments to select the treatments that perform well for multiple years. The different temporal allocation strategies are aimed at breaking down the total available irrigation water to different irrigation applications during different stages of crop growth. The given amount of available irrigation water is allocated over three crop growth stages: from planting to appearance of the first flower, from appearance of the first flower to first open boll, and from first open boll to maturity. Twenty two different treatments for allocating water among the three growth stages were used to simulate yield for 25 years. The details of the treatments are provided in Table 1.

Table 1. Description of the temporal water allocation treatments

Treatment No.	% water applied in three stages	Treatment No.	% water applied in three stages
1	Equally divided over season	12	40:20:40
2	100:0:0	13	40:0:60
3	0:100:0	14	20:80:0
4	0:0:100	15	20:60:20
5	80:20:0	16	20:40:40
6	80:0:20	17	20:20:60
7	60:40:0	18	20: 0:80
8	60:20:20	19	0:80:20
9	60:0:40	20	0:60:40
10	40:60:0	21	0:40:60
11	40:40:20	22	0:20:80

The average lint yields of cotton from these treatments are provided in Figure 1. Based on this yield data, nine best performing treatments were selected with treatment number 1 (allocating irrigation water equally throughout the growing season). The selected treatments and their description are provided in Table 2.

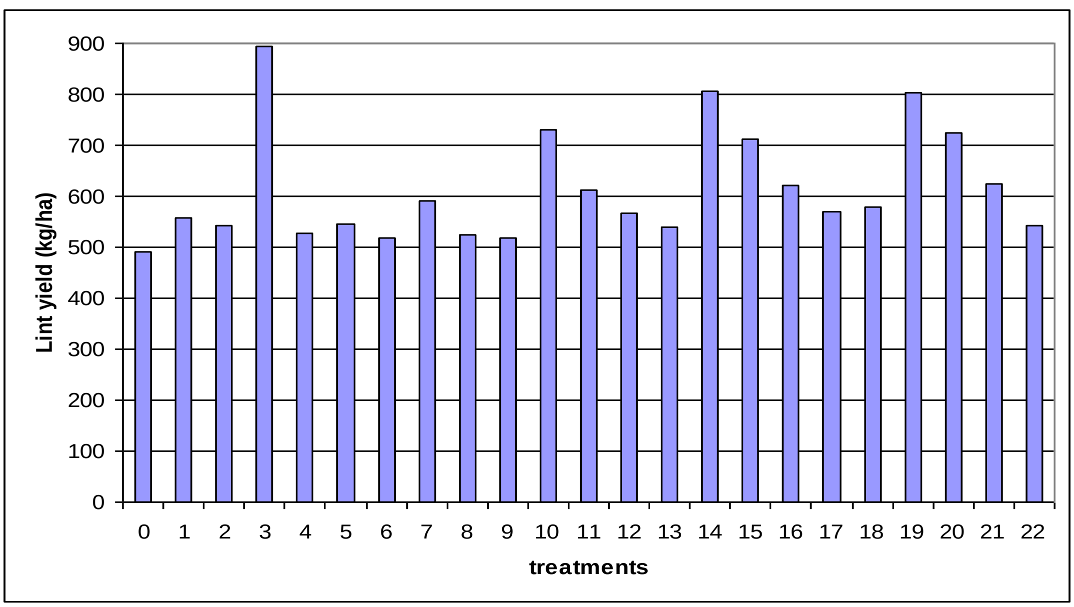

Figure 1. The average lint yield corresponding to different temporal allocations of irrigation water

Table 2. Description of the selected temporal water allocation treatments

Treatment No.	% water applied in three stages
1	Equally divided over season
2	0:100:0
3	40:60:0
4	40:40:20
5	20:80:0
6	20:60:20
7	20:40:40
8	0:80:20
9	0:60:40
10	0:40:60

The spatial allocation treatments are conceived as irrigating a hypothetical center-pivot-irrigated field to be partitioned into a segment of irrigated cotton and a segment of dryland cotton. It is assumed that only 6 inches of irrigation water are available for irrigation. When irrigation availability and weather conditions are given, different ways to partition the field lead to different yields. In this experiment, 8 different spatial allocation treatments were used for simulation with different fractions of the field irrigated. The spatial allocation treatments and their description are provided in Table 3.

Table 3. Description of the spatial allocation treatments

Treatment No.	Fraction of the field irrigated
1	0.125
2	0.250
3	0.375
4	0.500
5	0.625
6	0.750
7	0.875
8	1.000

Now these spatial allocation treatments were combined with selected temporal allocation treatments to provide 80 different water allocation treatment combinations. Then Cotton2K was used to simulate cotton yield for these treatments for 60 years using the possible weather data in THP simulated using the weather simulation model WGEN. Then linear interpolation was used to derive yield data corresponding to different fractions of field irrigated from 0.125 to 1 at an interval of 0.005 to have the data as a 10 X 71 X 60 array.

The economic optimization model is used to determine the irrigation schedule and field segmentation that can achieve an economic objective such as profit maximization. In particular, we will derive the optimal strategies (maximizing profit and minimizing risk) for a hypothetical situation, where only 6 inches of irrigation water are available. For the profit maximization part, the economic model will maximize the following profit function

$$\max_{\{d,j\}} Profit = \sum_{i=1}^{60} \{[(P d_k Y_{ijk}) + (1 - d_k)(P Y_{iR})] - [(C_{IRR} - C_{DRY}) d_k + C_{DRY}]\}$$

For the risk minimization part, the economic model will minimize the following variance function

$$\min_{\{d,j\}} Variance = \sum_{i=1}^{60} [\pi_{ijk} - \bar{\pi}_{jk}]^2$$

Here P is the price of cotton, which includes the price of lint and price of cotton seed (adjusted to the lint yield). d_k

is the fraction of field irrigated, Y_{ijk} is the lint yield of cotton in pounds per acre, C_{IRR} is the cost of cultivation of irrigated cotton, and C_{DRY} is the cost of cultivation of dryland cotton. The subscript i is for year (year 1 to year 60), the subscript j is for irrigation strategy for (strategy 1 to 10), and the subscript k is for fraction of the field irrigated. π_{ijk} is the profit for i^{th} year when j^{th} strategy, k^{th} field segmentation is used. $\bar{\pi}_{jk}$ is the mean profit over 60 years when j^{th} strategy, k^{th} field segmentation is used.

The optimization was done in MATLAB using the above described economic model. A sensitivity analysis was also performed by changing the price of cotton to analyze how the price change affects the optimum decisions.

Results and Discussion

The optimal strategies for the spatial and temporal allocation of irrigation water that maximizes the average profit over 60 years of simulated weather data for a hypothetical center-pivot irrigated cotton field in THP with only 6 inches of available irrigation water at different price levels are provided in Table 4. The results indicate that irrespective of the price level, the profit maximizing strategy for temporal allocation of irrigation water is to apply the entire available irrigation water during the second stage, i.e. from the appearance of first flower to the appearance of first open boll. It can also be observed that the spatial allocation strategy (percentage of the field irrigated) was influenced by the price of cotton. As the price of cotton increases, the optimal fraction of the field irrigated to maximize the profit also increases. When the price is low at 40 cents/lb, the average loss is minimum when only 50 % of the field is irrigated using all the available irrigation water. The optimal fraction of the field irrigated to maximize the average profit was 55 % when the price is 60 cents/lb and it became 72.5 % when the price increased to 80 cents/lb. Increase in price resulted in increase in average profit but there was no considerable difference in the variance, but low price resulted in a decrease in average profit and increase in variance.

Table 4. Profit maximizing strategies at different price levels

Price (cents/lb)	Fraction of field irrigated	Temporal Allocation	Average Profit ($)	Standard Deviation
40	50.00 %	0:100:0	-62.10	182
50	53.75 %	0:100:0	-18.53	98
60	55.00 %	0:100:0	33.81	109
70	55.00 %	0:100:0	68.74	116
80	72.5	0:100:0	112.63	136

The spatial and temporal irrigation water allocation strategy that minimizes the year to year variability in profit is provided in Table 5. It is interesting to note that irrigation water allocation strategy that minimized year to year variability in profit was not influenced by price of cotton. Irrigating only 40 % of the field and allocating the entire amount of irrigation water to the second growth stage minimizes the year to year variability in profit.

Table 5. Risk minimizing strategies at different price levels

Price (cents/lb)	Fraction of field irrigated	Temporal Allocation	Average Profit ($)	Standard Deviation
40	40.00 %	0:100:0	-67.61	89
50	40.00 %	0:100:0	-25.63	92
60	40.00 %	0:100:0	28.14	102
70	40.00 %	0:100:0	58.25	109
80	40.00 %	0:100:0	100.22	117

Summary

This Cotton yield in Texas high plains can be simulated with considerable accuracy using the cotton growth simulation model, cotton2K. The profitability and risk associated with different irrigation strategies and fraction of the center-pivot field irrigated were analyzed using the simulated yield data along with an economic optimization model. The results indicated that when only six inches of irrigation water is available, irrigating 55% of the field and applying all the water during the second stage (from appearance of first flower to the end of ball filling) is the best strategy to maximize profit at the prevailing price levels. The risk minimizing strategy was the combination of irrigation strategy 2 and irrigating 40% of the field.

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