# Managing Weather Risk for Cotton in Texas High Plains with Optimal Temporal Allocation of Irrigation Water

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## Abstract

Texas High Plains (THP) is a major cotton producing region in the US with low rainfall and decreasing irrigation water availability. Hence stochastic rainfall poses considerable production risk in the region and developing strategies to maximize the average profit and minimize the year to year variability in profits is an important concern. In this study, Cotton2K, which is a process based cotton growth simulation model, was used along with an economic optimization model to identify the optimal strategies for temporal allocation of irrigation water for center pivot irrigated cotton in THP. The study analyzed different strategies to allocate irrigation water during one growing season among three different growth stages of cotton (planting to first bloom, first bloom to first open boll, and first open ball to 60% open boll) at four different sub-optimal levels for irrigation water availability (6, 9, 12, and 15 acre-inches). The results showed that the profit and utility maximizing strategy was to apply all available irrigation water during stage II when six, nine, and twelve acre-inches of irrigation water were available. When fifteen inches of irrigation water was available, the optimal strategy was to use 90% of the available irrigation water in stage II and the rest in stage III. The sensitivity analysis indicated that these optimal decisions were not sensitive to variations in price of cotton lint and farmer's attitude towards risk.

Key words: Cotton, Irrigation, Economics, Risk, Cotton2K

JEL Classification: Q12, Q16

# Managing Weather Risk for Cotton in Texas High Plains with Optimal Temporal Allocation of Irrigation Water

The Texas High Plains (THP), even with its low average annual rainfall of 16 to 18 inches (Lascano, 2000) , is the largest cotton producing region in the US and is the principal contributor to the number one position of Texas in both cotton acreage and production in the USA (NAS, 2012). In semi-arid regions like THP, cotton production is primarily limited by water availability (Li et al, 2001). Hence, irrigation is an important aspect of crop production here. Since the region lacks any significant surface water source, the Ogallala aquifer is the primary source of irrigation water in THP. However, extensive pumping and slow recharge rates have contributed to rapid depletion of the aquifer (Lewis, 1990). The insignificant recharge makes the irrigation water in this region a fixed supply and hence excessive pumping reduces the economic life of the aquifer and leads to decreased returns from farming (Amosson et al. 2001). Many Texas farmers now are experiencing water shortages as some wells are becoming dry and, at some places, the water table is getting deeper, leading to higher cost of pumping. Moreover, policy restrictions are also in place to restrict the allowable annual water extraction in the area (HPUWCD, 2011). Hence, developing strategies that can increase the efficiency of the limited amount of irrigation water is of great importance in THP.

When the irrigation water availability is limited, producers are forced to adopt deficit irrigation to enhance the efficiency of the available irrigation water. Deficit irrigation is defined as a situation where irrigation water application is less than the full crop water requirement (Fereres and Soriano, 2007). Even though irrigation scheduling aims at achieving optimum supply of water for crop productivity (Jones, 2004), for deficit irrigation, optimal allocation among the growth stages of cotton is of prime importance because ensuring water supply at critical growth stages of the crop is vital under sub-optimal irrigation water availability. Deficit irrigation practices also have the potential to save considerable amount of irrigation water (Kirda, 2002)

The conventional irrigation strategies may not work well under deficit irrigation. The crop response to stress varies with the growth stages and hence temporal allocation of irrigation water is of extreme importance under deficit irrigation situations (Newman, 1966). Most of the modern irrigation scheduling technologies are either difficult to adopt under deficit irrigation or ignore the fact that the same level of water stress impacts cotton differently at different crop growth stages. For example, if the farmer chooses to replace the soil moisture lost from the profile at weekly intervals, that strategy may fail under limited availability of irrigation water since the required amount of water may not be available. If the farmer is adopting the deficit irrigation strategy to replace only a fraction of the crop water demand, he will be spreading the stress across the growing period of cotton and does not acknowledge the fact that the negative impact of the water stress on yield varies with crop stages.

Cotton growth can be divided into three growth stages, i.e. planting to appearance of first flower, flowering to appearance of first open boll, appearance of first open boll to maturity. Maintaining optimal soil moisture content over these growth stages is critical for maximizing cotton production and increasing the efficiency of irrigation water (Singh et al. 2010). Even though there are several studies on temporal allocation of irrigation water (Newman, 1966; Guinn et al., 1981; Jalota et al., 2006; Karam et al., 2006; Buttar et al., 2007), these field studies do not acknowledge the impact of year to year variability in the amount and distribution of rainfall on optimal irrigation water allocation. Developing easy-to-adopt strategies for efficient allocation of irrigation water across these crop growth stages to maximize profit and minimize the year to year variability, taking into consideration the stochastic weather will be of great help to the farmers. To perform a robust analysis, data on the lint yield of cotton is required at different water allocation treatments for a large number of years. This requirement eliminates the possible use of field experiments to generate data as it is cost and time prohibitive.

To address this problem, a crop growth simulation model, Cotton2K, (Marani, 2000), was used in this study to simulate the cotton yield under various irrigation scheduling and weather conditions. The simulated data was then used in an economic model to arrive at optimal strategies that maximize both profits and risk-adjusted profit. The volatility of cotton prices and the attitude of farmers towards risk are two important factors that may affect the irrigation choices made by the farmer. Hence a sensitivity analysis was also conducted to analyze the sensitivity of the optimal spatial allocation decisions to changes in lint price of cotton and to the differences in risk preferences of farmers.

## Methodology

As discussed earlier, optimal temporal allocation of irrigation water depends on the amount and distribution of the stochastic rainfall, particularly when the irrigation water availability is sub-optimal. Hence a large dataset with decades of data on crop response to different temporal allocation treatments is required to develop robust strategies. Since obtaining such a large dataset from field experiments is cost and time prohibitive, we simulated yield data with a crop growth simulation model (Cotton2K) and used this data to analyze profit and year to year variability in profit for a typical (126 acres) center pivot irrigated cotton field in THP.

### *Yield Simulation*

We used Cotton2K (Marani, 2000), which is a process based model that simulate plant and soil processes in detail to estimate the growth parameters and yield of cotton. Before the yield simulations for this study, Cotton2K was calibrated for the soil characteristics of the location and its performance was validated in an earlier study (Nair et al., 2013) to make sure that the model simulates cotton yield with considerable accuracy for the soil and weather conditions of THP.

After calibration and validation, Cotton2K was used to simulate the lint yield of cotton corresponding to 22 different treatments of temporal allocation of irrigation water at four levels of available irrigation water (6, 9, 12, and 15 acre-inches) for 110 crop seasons. The treatments were different strategies of allocating the available amount of irrigation water among the three growth stages of cotton. Stage I is the period from planting to first bloom, stage II is from first bloom to appearance of first open boll and stage III is from first open boll to 60% open boll. The percentages of irrigation water applied during each growth stage corresponding to the treatments are provided in Table 1. These treatments were selected for this study based on a previous study (Nair et al. 2011) showing that the treatments with higher percentage of irrigation water applied during the stage II performs well for center pivot irrigated cotton in THP. Hence treatments for this study are designed in such a way that the stage II receives at least 50% of the available irrigation water in all the treatments.

The lint yield of cotton was simulated for 110 cropping seasons from 1900 to 2009 keeping all soil conditions and agronomic practices constant for all treatments and all simulation years. The details of the initial soil conditions and agronomic practices are described in Nair et al. (2013). The daily precipitation and temperature data from the U.S. Historical Climatology Network (Easterling et al., 1999) for Plainview, TX, observation station were used for the simulations. The daily surface shortwave solar radiation and dew point temperatures during 1900 to 2009 were estimated via neural networks trained on a separate shorter term (2000–2004) data set of daily observations of surface shortwave radiation, precipitation, and temperature (Mauget et al., 2009).

### *Profit Maximization*

For profit maximization, the returns above total specified expenses were calculated for each treatment for each year keeping the price of cotton lint and cost of cultivation of cotton at constant levels using equation 1.

$$\pi_{ti} = [Y_{ti} \times (p + a)] - [C_s + (I \times C_i)] \tag{1}$$

were $\pi_{ti}$ are the net returns above total specified expenses realized for treatment $t$ in year $i$ in \$/acre, $Y_{ti}$ is the lint yield of cotton for treatment $t$ in year $i$ in lbs/acre, $p$ is the price of cotton lint in \$/lb, $a$ is a constant in \$/lbs obtained by subtracting the harvesting and ginning cost from the price of cotton seed, $C_s$ is the total specified cost of cultivation of cotton except the cost for harvesting, ginning, irrigation fuel, irrigation labor and repair and maintenance of center pivot in \$/acre, $I$ is the amount of irrigation water applied in acre-inches, $C_i$ is the sum of cost irrigation fuel, irrigation labor and repair and maintenance of center pivot per acre-inch of applied irrigation water in \$/acre-inch,

The prices received for cotton lint and cotton seed were held constant at $73.56/lbs and $0.09/lbs, respectively. They were the average monthly price from January 2006 to January 2011 (USDA, 2011). The specified costs and lint/ seed cotton ratios presented in the Texas A&M crop budget, 2011 for center pivot irrigated cotton in South Plains region (District 2) were used for profit calculations (Texas AgriLife Extension Services, 2011). The cost of ginning and the cost of harvesting were $0.08/lb and $0.03/lb respectively. It was assumed that 1.4 kg of cotton seed was produced for every 1 kg of cotton lint produced (Mitchell et al., 2007). The turnout percentage of lint from seed cotton was assumed to be 28% (Texas AgriLife Extension Services, 2011), resulting in a seed cotton yield that was 3.57 times the lint yield. Using these values, the constant a in equation 1 was calculated to be -0.06113 ($0.09 \times 1.4 - 0.08 - 0.03 \times 3.571$). The irrigation fuel cost ($ 10/acre-inch), irrigation labor cost ($0.64/acre-inch), and the repair and maintenance cost of the center pivot ($2/acre-inch) were added together to determine the value of $C_i$ to be $12.64 acre-inch. The total specified cost excluding the cost of ginning, harvesting and irrigation ($C_s$) was calculated as $374.12/acre. Using these values of $a$, $C_s$, and $C_i$, equation 1 was reduced to equation 2.

$$\pi_{ti} = [Y_{ti} \times (p - 0.06113)] - [374.12 + (I \times 12.64)] \tag{2}$$

The expected profit for each treatment was calculated as the average profit for the 110 years. After the calculation of the expected profit for each treatment, the profit maximizing treatment was selected using the grid search method.

*Utility Maximization*

For utility maximization, per acre returns were converted into total returns from the 126 acre center pivot irrigated cotton field. The effective value (asset value – liabilities) of a typical THP cotton farm was estimated to be $ 366.53/acre from the representative farm's economic outlook for December 2010 issued by Agriculture and Food Policy Center (AFPC 2010). The average farm size in Texas was 646.95 (USDA, 2009). Hence the initial wealth of a typical farmer was calculated to be $ 23, 7126.58. The terminal wealth of the farmer was calculated for each treatment as the sum of the initial wealth of the farmer and profits obtained from the 126 acre center pivot irrigated cotton field for each treatment.

The expected utility of the terminal wealth attained from the cotton field under a particular treatment can be estimated using equation 3.

$$E[U] = \int U(W)\, p(W)\, dW \tag{3}$$

where E is the expectation operator, $U(W)$ is the utility of terminal wealth, W, and $p(W)$ is the probability density function (pdf) of the distribution of W.

The utility function was assumed to be a Constant Relative Risk Aversion (CRRA) function (Coble, Zuniga, and Heifner, 2003; Mitchell and Knight, 2008) in the form $U(W) = -W^{(1-R)}$, where R is the coefficient of relative risk aversion. The value of R was held constant at 2, which represents moderate risk aversion and regarded as the typical degree of risk aversion for farmers (Coble, Zuniga, and Heifner, 2003; Mitchell and Knight, 2008).

The distribution obtained from the empirical data was used to arrive at utility maximizing temporal allocation treatments. This was done by dividing the empirical distribution into 20 equal sized bins. The mean terminal wealth of each bin and the probability of an observation being contained in that bin were calculated for each bin. From this data the expected utility of each field segmentation treatment was estimated as given below.

$$E[U] \approx \sum_{i=1}^{20} U(W)\, p(W) \tag{4}$$

where $U(W)$ is the mean of the utility of the terminal wealth corresponding to each bin and $p(W)$ is the probability that an observation falls in that bin. Once the expected utility of all the treatments are estimated, the treatment with maximum utility is picked using the grid search method.

*Sensitivity Analysis*

The expected utility of the different treatments were calculated at different price levels (55.41, 58.41, 66.62, 77.29, 126.55, 73.56, and 90.00 cents/lb) using R=2 as the constant value of the degree of risk aversion. Once the expected utility for all the treatments are calculated at these seven price levels, the price sensitivity is analyzed by assessing whether the choice of utility maximizing treatment vary with the change in price.

The sensitivity to risk preference was assesed by calculating the expected utility at seven different coefficients of risk aversion (1.25, 1.50, 1.75, 2.00, 2.50, 3.00, and 4.00) keeping the price of cotton lint constant at mean of monthly cotton lint price for the past five years (73.56 cents/lb). The sensitivity of the optimal choice to the degree of risk aversion is analyzed by assessing whether the utility maximizing choice vary with the change in price.

## Results and Discussion

The results are presented and discussed in three sections. The first section is on profit maximization, the second is on utility maximization, and the third is on the sensitivity analysis.

### *Profit Maximization*

The expected profits calculated for each treatment at each level of available irrigation water is presented in Table 2 in descending order.

The results show that applying all the available irrigation water in stage II is the profit maximizing strategy when the irrigation water availability is 12 acre inch or less. When the irrigation water availability is 15 acre inches, the profit maximizing strategy is to apply 90% of it during the second stage and the rest during the third stage. The results also indicate the general trend that the treatments with higher amount of irrigation water applied during stage II performed better than those with lower amounts of application in that stage. This shows that first bloom to first open boll is the most critical stage to ensure sufficient moisture availability for the crop. This result reiterates the argument that the highest water requirement of cotton is from first bloom to first open boll (Newman, 1966). Similar results were also obtained by Jalota *et al.* (2006) for cotton under deficit irrigation.

Allocating the available irrigation water in equal quantities throughout the growing season resulted in the lowest profit on an average at all these levels of irrigation water availability. Since the water requirement during the initial stage is very low, this strategy allows the crop to establish a good stand and very good vegetative growth during the initial stages of the crop, which would further increase the water demand during the reproductive. This inadequate water supply during the reproductive stage might have resulted in very low yield.

Another interesting result in Table 1 is the change in the schedule of the expected profit over different levels of irrigation water availability. At only six acre-inches of irrigation water availability, the treatment with 100% allocation in stage II is clearly superior to all other treatments. When the irrigation water availability increases to nine acre-inch, even though 100% allocation to stage II is still superior to all other treatments, treatments 3 and 4 each with 90% of water applied during stage II performs close to. At twelve acre-inches of irrigation water availability even treatments with 80% water allocated (treatment 7) is not far away from the best treatment. When the irrigation water availability is at fifteen acre inches, the treatments with 80% of water allocated to stage II (treatments 4 and 6) outperform treatment 2.

Since stage II is most responsive to irrigation water allocation, it is interesting to analyze the impact of irrigation water allocation on expected profits at the four different levels of irrigation water availability. The third degree polynomial fit for the response of expected profits to the percentage of irrigation water allocated during stage II at all four levels of irrigation water availability is presented in Figure 1 to facilitate comparison among the responses at different levels of irrigation water availability. It can be observed from Figure 1 that the profit increases at an increasing rate with percentage of the irrigation water applied at stage II, at lower amounts of irrigation water availability and the profit increases at a diminishing rate in response to the increase in percentage of irrigation water applied during stage II at higher levels of irrigation water availability. This indicates that the profit maximizing irrigation water application in stage II is 13.5 acre-inch (90% of 15 acre-inch) and irrigation application beyond this point will have detrimental effect on the expected profits. This shows that at lower levels of irrigation water availability, it is better to concentrate all the available irrigation water to stage II and as the irrigation water availability increases, application should be spread to stages I and III also to maximize the expected profit.

### *Utility Maximization*

The results of utility maximization showed that the profit maximizing strategies were same as the utility maximizing strategies at all levels of irrigation water availability. The results also indicate that the response of treatments to expected utility is more or less similar to that of expected profit with some slight changes. To demonstrate the differences in the preference of treatments between the objectives of profit maximization and utility maximization, the order of preference of each treatment for both profit maximization and utility maximization are provided in Figures 2 and 3 for six and nine acre-inches of irrigation water availability, respectively. The order of preference of the profit maximizing and utility maximizing strategies showed a similar pattern at 12 and 15 acre-inches of irrigation water availability. The order of preference is illustrated these Figures with the most preferred treatment having the highest value on the Y axis and the least preferred one the lowest.

Figures 2 and 3 show that the order of preference of treatments for the utility maximization is same as that of profit maximization for most of the highly preferred treatments. Only a few less preferred treatments show a different response to profit maximization and utility maximization. This may have happened because the treatments with higher expected profits also had lower variance, whereas the variance associated with treatments with lower expected profit showed considerable fluctuations. This reiterates the fact that even deficit irrigation has a risk reducing potential when it is properly allocated.

### *Sensitivity Analysis*

To analyze the sensitivity of the utility maximizing treatments to price, expected utility was calculated at different prices keeping the degree of risk aversion constant (R=2) for each treatment at each level of irrigation water availability. The results showed that the response of temporal allocation treatments to price changes was similar at all the four levels of available irrigation water considered in this study and hence only the response at twelve acre-inch is analyzed here in detail. The expected profit for the temporal allocation treatments at different cotton prices at twelve acre-acre inch of available irrigation water is presented in Figure 4. Figure 4 clearly illustrates that, not only the choice of the best treatment but also the ordering of all treatments with respect to their expected utility remains unchanged irrespective of the change in price of cotton lint for all price levels used in this study. This leads to the conclusion that the choice of the utility maximizing strategy of temporal allocation of irrigation water is insensitive to changes in price of cotton lint.

To analyze the sensitivity of the utility maximizing treatments to the degree of risk aversion of cotton producers, expected utility was calculated at different degrees of risk aversion keeping the price of cotton lint constant ($73.56/lb) for each treatment at each level of irrigation water availability. The response of temporal allocation treatments to producer’s degree of risk aversion was similar at all the four levels of available irrigation water considered in this study. Hence the response at twelve acre-inch is analyzed in detail.

Since the coefficient of relative risk aversion (R) is in the exponential position in the utility equation [$\mathrm{U(W)} = -\mathrm{W}^{(1-\mathrm{R})}$], the expected utility values varied a lot between different values of R making it impossible to represent it graphically for comparison. To tide over this problem, the expected utility value of all the treatments at each value of the coefficient of risk aversion was divided by the mean expected utility at that level of risk aversion to arrive at the relative expected utility of each field segmentation treatments. Since utility is an ordinal measure, this will not hinder the comparison.

Relative expected utility associated with the temporal allocation treatments at different levels of risk aversion for field receiving twelve acre-inch of irrigation water is presented in Figure 5. From Figure 5, it can be observed that the rank of all the treatments with respect to its associated expected utility was invariant to the different risk preference levels used in this study. Hence the choice of utility maximizing strategies of temporal allocation of irrigation water can be considered as insensitive to risk.

## Conclusions

Irrigation has the dual functions of increasing crop yield and reducing the production risk posed by the stochastic rainfall. Since Texas High Plains is a low rainfall region that solely depends on the very slowly rechargeable and depleting Ogallala aquifer for irrigation, efficient use of irrigation water to boost yield and reduce year to year variability in yield is an important concern for the cotton producers in THP.

The water requirement and response to moisture stress for cotton vary widely among its growth stages. The response of cotton to irrigation applications at different growth stages shows considerable variation even at the same total of amount irrigation water applied. Optimal allocation can increase yield and reduce production risk. Since the stochastic rainfall also plays a major in the response of cotton to temporal allocation of irrigation water, it is difficult to evolve an efficient strategy through field experiments.

In this study, cotton growth simulation model, Cotton2K was used to generate the yield response of cotton to different temporal allocation strategies and the simulated data was analyzed to evolve optimal strategies that will maximize the profit and utility from a typical center pivot irrigated cotton field in THP. The strategies analyzed were different ways to allocate the available irrigation water among three growth stages of cotton (planting to first bloom, first bloom to first open boll, and first open boll to 60% open boll). The temporal allocation strategies were optimized at four levels of available irrigation water (6, 9, 12, and 15 acre-inch).

The results showed that when the irrigation water availability is twelve acre-inch or lesser, both the profits and risk adjusted profits can be maximized by applying the entire amount of available irrigation water during stage II. However, at fifteen acre-inch irrigation water availability allocating 90% of the irrigation water to stage II and the rest to stage III was the optimal strategy. The sensitivity analysis revealed that the optimal decisions are insensitive to both the changes in price of cotton and the degree of risk aversion of the decision maker.

The important conclusion from this study is that the optimal temporal allocation of irrigation water increases the cotton yield and reduces the year to year variability in yield. Ensuring irrigation water availability during stage II is critical for center pivot irrigated cotton in THP. Stage II responds positively till 13.5 acre-inch of irrigation water application and profits can be maximized by allocating the entire amount of irrigation water to stage II when the water availability is below this limit. The initial moisture content in the soil profile and available rainfall seems to sustain cotton growth stage I. The optimal temporal allocation strategies also lead to reduction in year-to-year variability in profits.

## References

AFPC. 2010. “Representative Farms Economic Outlook for the December 2010 FAPRI/AFPC Baseline. Briefing Paper 10-4. Agrilife Research and Extension, Texas A&M System.

Amosson, S.H., L. New, L. Almas, F. Bretz, and T Marek. 2001. “Economics of Irrigation Systems”. Texas Agricultural Extension Bulletin B-6113, Texas Cooperative Extension, The Texas A&M University System.

Buttar, G.S., M.S. Aujla, H.S. Thind, C.J. Singh, K.S. Saini. 2007. “Effect of timing of first and last irrigation on the yield and water use efficiency of cotton”. Agricultural Water Management. 89: 236-242.

Coble, K. H., M. Zuniga, and R. Heifner. 2003. “Evaluation of the interaction of Risk Management Tools for Cotton and Soybeans.” Agricultural Systems. 75: 323-340.

Easterling, D.R., T.R. Karl, J.H. Lawrimore, and S.A. Del Greco. 1999. United States historical climatology network daily temperature, precipitation, and snow data for 1871–1997. ORNL/CDIAC-118, NDP-070. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN.

Fereres, E. and M. A. Soriano. 2007. “Deficit Irrigation for Reducing Agricultural Water Use”. Journal of Experimental Botany. 58(2): 147-159.

Guinn, G., J.R. Mauney, and K. E. Fry. 1981. “Irrigation scheduling and plant population effects on growth, bloom rates, boll abscission and yield of cotton”. Agronomy Journal. 73(3): 529-534.

High Plains Underground Water Conservation District No. 1. 2012. Summary of district rule revisions.www.hpwd.com/Downloads/FINAL%20District%20Rules%20As%20Amended%20July%2019,%202011/HPWD%20Rules%20Summary.pdf (accessed Mar.2012).

Jalota, S.K., A. Sood, G.B.S. Chahal, and B.U. Choudhary. 2006. "Crop water productivity of cotton (Gossypium hirsutum L.) – wheat (Triticum aestivum L.) system as influenced by deficit irrigation, soil texture and precipitation". Agricultural Water Management. 84: 137-146.

Jones, H.G. 2004. "Irrigation scheduling: advantages and pitfalls of plant-based methods". Journal of Experimental Botany. 55:2427-2436.

Karam, F., L. Rafic, M. Randa, A. Ducacache, O. Mounzer, and Y. Rouphael. 2006. "Water use and lint yield response of drip irrigated cotton to length of the season". Agricultural Water Management. 85(3): 287-295.

Lascano, R.J. 2000. A general system to measure and calculate daily crop water use. Agronomy Journal. 92:821–832.

Lewis, J.1990."The Ogallala Aquifer: An Underground Sea."EPA Journal. 16:42-45.

Li, H., R.J. Lascano, J. Booker, L. T. Wilson, and K. F. Bronson. 2001. "Cotton lint yield variability in a heterogeneous soil at a landscape scale". Soil and Tillage Research. 58: 245-258.

Marani, A. 2000. "Cotton2k Model Version 4.0." The Robert H. Smith Institute of Plant Sciences and Genetics in Agriculture, Hebrew University. http://departments.agri.huji.ac.il/fieldcrops/cotton (accessed Mar.2012).

Mauget, S., J. Zhang, and J. Ko. 2009. The value of ENSO forecast information to dual-purpose winter wheat production in the U.S. Southern High Plains. Journal of Applied Meteorology and Climatology. 48:2100–2117. doi:10.1175/2009JAMC2018.1

Mitchel, P. D., and T. O. Knight. 2008. “Economic Analysis of Supplemental Deductable Coverage as Recommended in the USDA’s 2007 Farm Bill Proposal.” Agricultural and Resource Economics Review. 37(1):117-131.

Mitchell, D.M., J. Johnson, and C. Wilde. 2007. Impacts of decreasing cottonseed to lint ratio on cottonseed markets. In: Proceedings of the Beltwide Cotton Conferences, New Orleans, LA. 9–12 Jan. 2007. Vol. 1. Natl. Cotton Counc. Am., Memphis, TN. p. 797–800.

Nair, S., S. Maas, C. Wang, and S. Mauget. 2013. Optimal Field Partitioning for Center-Pivot-Irrigated Cotton in the Texas High Plains. Agronomy Journal. 105:124-133.

Nair, S.S., C. Wang, S. Maas, and E. Segarra. 2011. “Optimal Spatial and Temporal Allocation of Irrigation Water for Cotton in Texas High Plains”. Paper presented in 2011 Beltwide Cotton Conference. Atlanta. Georgia.

National Agricultural Statistics Service. 2012. Statistics by state. NASS, Washington, DC. http://www.nass.usda.gov/Statistics_by_State/ (accessed Feb. 2012).

National Cotton Council. 2011. Monthly cotton prices received by farmers (upland). www.cotton.org/econ/prices/monthly.cfm (accessed Feb. 2011).

Newman, J.S. 1966. “Irrigation water management: Cotton and grain sorghum”. In: Report of progress 1965-66. South Plains Research and extension Center. Lubbock, TX. Pp. 63-72.

Singh, Y., S.S. Rao, P.L.Regar. 2010. “Deficit irrigation and nitrogen effects on seed cotton yield, water productivity and yield response factor in shallow soils of semi-arid environment”. Agricultural Water Management. 97:965-970.

Texas AgriLife Extension Service. 2011. Estimated costs and returns per acre: Cotton, pivot irrigated—herbicide-tolerant—insect-resistant. Texas A&M Univ., College Station. http://agecoext.tamu.edu/fileadmin/user_upload/Documents/Budgets/District/2/2011/cottonpihtir.pdf (accessed Nov. 2011).

USDA. 2009. “2007 Census of Agriculture”. Summary and State Data. Volume 1. Geographic Area Series. Part 51.

**Table 1. Description of temporal irrigation water allocation treatments**

| Treatment No. | Percentage of irrigation water applied | | |
|---|---|---|---|
| | Stage I | Stage II | Stage III |
| 1 (Control) | 33.33 | 33.33 | 33.33 |
| 2 | 0 | 100 | 0 |
| 3 | 10 | 90 | 0 |
| 4 | 0 | 90 | 10 |
| 5 | 20 | 80 | 0 |
| 6 | 0 | 80 | 20 |
| 7 | 10 | 80 | 10 |
| 8 | 30 | 70 | 0 |
| 9 | 0 | 70 | 30 |
| 10 | 20 | 70 | 10 |
| 11 | 10 | 70 | 20 |
| 12 | 40 | 60 | 0 |
| 13 | 0 | 60 | 40 |
| 14 | 30 | 60 | 10 |
| 15 | 10 | 60 | 30 |
| 16 | 20 | 60 | 20 |
| 17 | 50 | 50 | 0 |
| 18 | 0 | 50 | 50 |
| 19 | 40 | 50 | 10 |
| 20 | 10 | 50 | 40 |
| 21 | 30 | 50 | 20 |
| 22 | 20 | 50 | 30 |

**Table 2. The expected profits at different levels of available irrigation water**

| Available amount of irrigation water (acre-inches) | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6 | | 9 | | 12 | | 15 | |
| Water applied at 3 stages (%) | Expected profit | Water applied at 3 stages (%) | Expected profit | Water applied at 3 stages (%) | Expected profit | Water applied at 3 stages (%) | Expected profit |
| 0:100:0 | 19.86 | 0:100:0 | 176.80 | 0:100:0 | 295.40 | 0:90:10 | 300.24 |
| 10:90:0 | -1.48 | 10:90:0 | 136.04 | 0:90:10 | 262.37 | 0:80:20 | 297.95 |
| 0:90:10 | -13.19 | 0:90:10 | 134.68 | 0:80:20 | 241.99 | 0:100:0 | 267.54 |
| 10:80:10 | -20.30 | 20:80:0 | 73.43 | 10:90:0 | 239.90 | 0:70:30 | 256.56 |
| 50:50:0 | -24.60 | 0:80:20 | 71.56 | 10:80:10 | 219.47 | 10:80:10 | 249.19 |
| 20:80:0 | -30.11 | 10:80:10 | 58.87 | 20:80:0 | 203.03 | 10:90:0 | 242.77 |
| 0:80:20 | -33.56 | 0:70:30 | 33.01 | 0:70:30 | 178.08 | 0:60:40 | 221.93 |
| 0:50:50 | -33.85 | 30:70:0 | 23.35 | 10:70:20 | 162.32 | 10:70:20 | 219.41 |
| 40:50:10 | -45.72 | 10:70:20 | 19.54 | 20:70:10 | 147.58 | 20:80:0 | 191.56 |
| 10:70:20 | -50.80 | 20:70:10 | 18.43 | 30:70:0 | 133.58 | 20:70:10 | 189.66 |
| 40:60:0 | -52.59 | 0:60:40 | -0.71 | 0:60:40 | 98.40 | 30:70:0 | 182.47 |
| 20:50:30 | -55.31 | 40:60:0 | -3.04 | 20:60:20 | 71.62 | 10:60:30 | 179.29 |
| 30:70:0 | -56.56 | 30:60:10 | -18.82 | 30:60:10 | 71.21 | 20:60:20 | 163.29 |
| 0:70:30 | -56.99 | 10:60:30 | -20.12 | 10:60:30 | 62.46 | 40:60:0 | 146.81 |
| 20:70:10 | -57.38 | 50:50:0 | -23.70 | 40:60:0 | 54.05 | 30:60:10 | 144.51 |
| 10:50:40 | -58.16 | 20:60:20 | -23.76 | 0:50:50 | 47.13 | 0:50:50 | 112.69 |
| 20:60:20 | -58.31 | 0:50:50 | -43.28 | 10:50:40 | 13.17 | 10:50:40 | 105.98 |
| 30:50:20 | -62.17 | 20:50:30 | -45.74 | 30:50:20 | 12.78 | 20:50:30 | 101.94 |
| 0:60:40 | -65.53 | 30:50:20 | -48.60 | 40:50:10 | 9.31 | 30:50:20 | 81.03 |
| 10:60:30 | -75.61 | 10:50:40 | -53.20 | 20:50:30 | 2.22 | 50:50:0 | 66.44 |
| 30:60:10 | -77.42 | 40:50:10 | -53.67 | 50:50:0 | -2.26 | 40:50:10 | 64.44 |
| Control | -131.09 | Control | -56.82 | Control | -18.25 | Control | 4.26 |

**Figure 1. Impact of percentage of irrigation water applied during stage II on profit.**

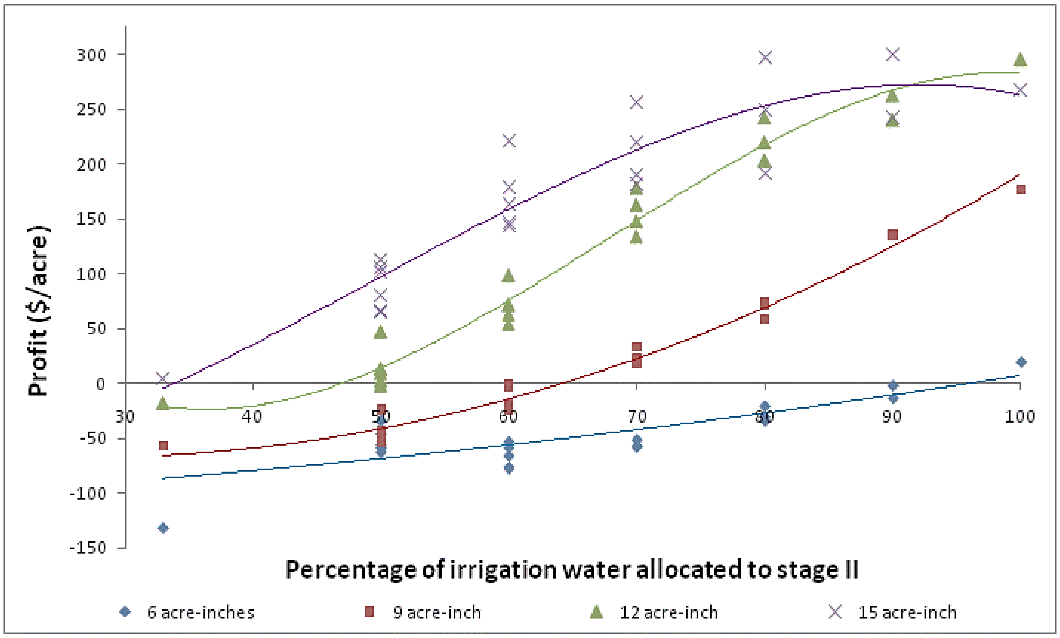

Figure 2. Comparison between order of preference of the treatments for profit maximization and utility maximization at 6 acre-inches of irrigation water availability.

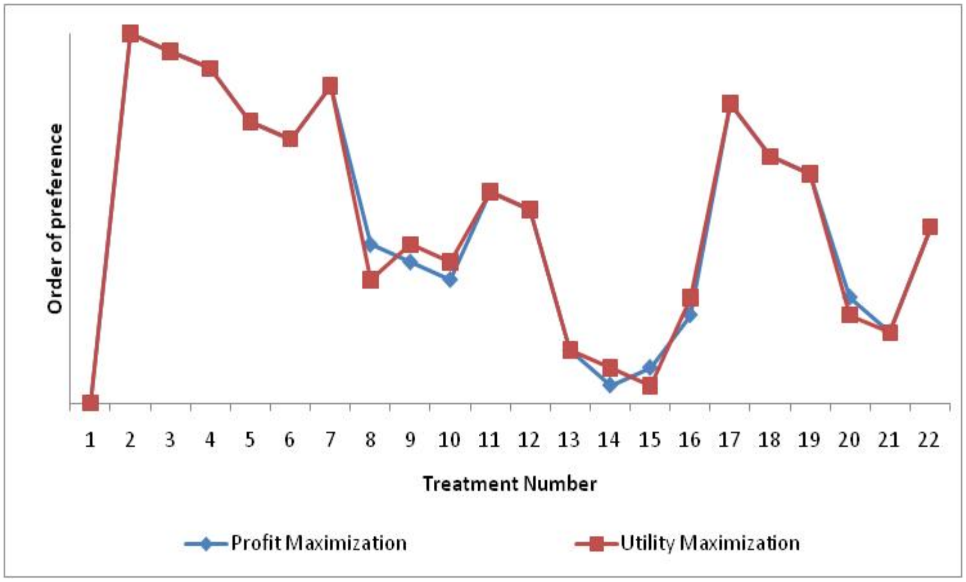

Figure 3. Comparison between order of preference of the treatments for profit maximization and utility maximization at 9 acre-inches of irrigation water availability.

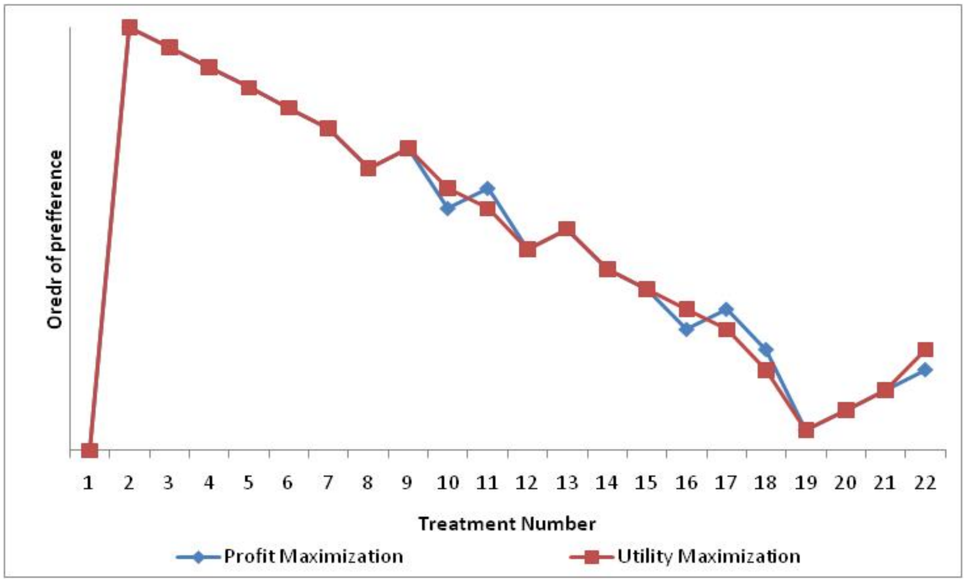

Figure 4. Expected utility of the temporal allocation treatments for different cotton prices at 12 acre-inches of irrigation water availability.

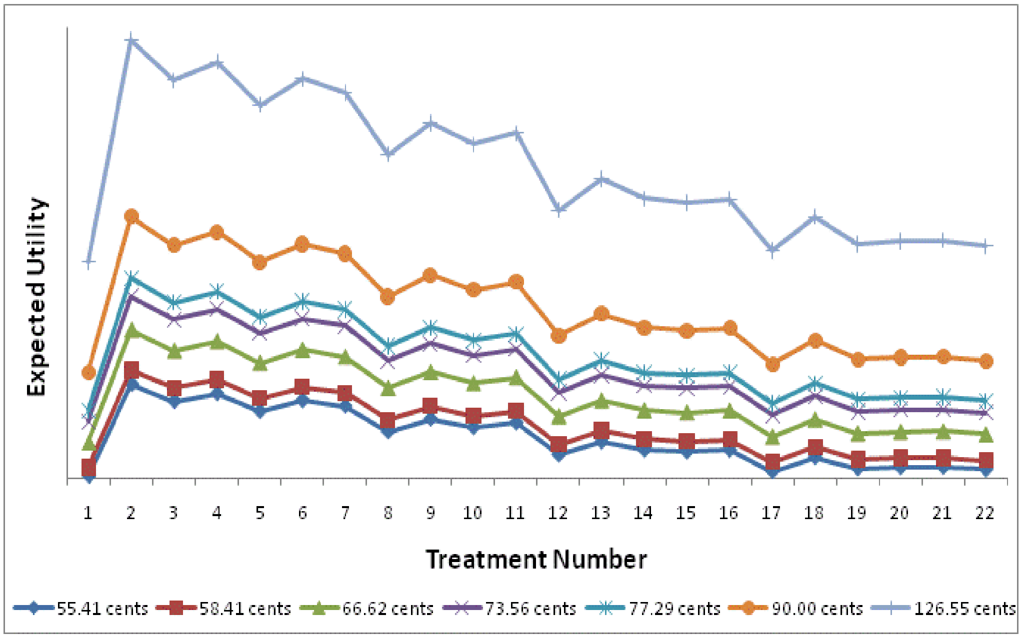

Figure 5. The relative expected utility of the temporal allocation treatments at different degrees of risk aversion at 12 acre-inches of irrigation water availability.