IRRIGATION DECISION RULES FOR COTTONGROWING IN THE BROOKSTEAD AREA OF THE DARLING DOWNS

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A decision problem faced by cottongrowers using irrigation is that of deciding the soil moisture level at which irrigation should occur. A simulation model was developed so that the effect on cotton yield of irrigation at different soil moisture levels could be explored. The output from the model was used to develop relationships enabling the determination of an optimal decision rule. The results indicate that under most situations heavy irrigation in the period "first open flowers to first open bolls" will be profitable.

1 INTRODUCTION

Most cottongrowers in the Brookstead area irrigate cotton using underground supplies of water. These producers must make many different decisions directly resulting from operating an irrigation system. Problems range from the proportion of the farm to irrigate to more specific questions such as the amount of water to apply to a particular crop. Linacre and Till[1] have discussed the technology of some of these problems while Flinn and Musgrave,[2] and Dudley[3] have discussed their economic structure. This paper is concerned with one of the problems, i.e., the problem of deciding the soil moisture level at which the cotton crop should be irrigated.

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[1] Linacre, E. T. and M. R. Till, "Irrigation and Amounts", *Journal of the Australian Institute of Agricultural Science*, Vol. 12, No. 3 (September, 1969), pp. 175–196.

[2] Flinn, J. C. and W. F. Musgrave, "Development and Analysis of Input-Output Relations for Irrigation Water", *Australian Journal of Agricultural Economics*, Vol. 11, No. 2 (June, 1967), pp. 1–19.

[3] Dudley, N. J., *A Simulation and Dynamic Programming Approach to Irrigation Decision Making in a Variable Environment*, (Agricultural Economics and Business Management Bulletin No. 9, University of New England, December, 1969).

Irrigation requires resources which can be used in other activities so that in making production plans the irrigation-timing question should form a submodel of an overall farm planning model. In this study, the need to do this directly has been overcome by using an opportunity cost approach, and by determining relationships enabling an optimal decision to be calculated for different water availability levels.

2 THE IRRIGATION TIMING PROBLEM

The irrigator using underground water is faced with two constraints when deciding how to use the available water. There is, firstly, an absolute limit to how much water can be used and secondly, a limit on the rate at which water can be used. These limits depend on the number of bores available and their capacities. Local irrigation authorities may also impose limits.[4] It may not be profitable, however, to use all the water available for cotton production. This will depend on the return obtainable from other uses of the water and the costs involved.

Given the availability constraint, the irrigator must decide on *when* to apply water, and *how* much water to apply at each irrigation. As the expected cotton yield is a function of water stress (as well as other factors), and as water stress is a function of soil moisture the variable "soil moisture level" is the logical variable on which to base the irrigation decision. As the response of the cotton crop to irrigation varies with the season, the soil moisture level at which irrigation should occur will probably vary throughout the season. Further, given the the stochastic environment in which the farmer operates, a decision rule telling the farmer the soil moisture level at which he should irrigate should depend on the conditions which exist at each particular point in time. Thus, for example, if the cotton bushes are smaller than expected at a particular point in time, the decision rule should indicate whether or not irrigation should occur at a higher (perhaps lower) soil moisture level than if the crop had reached the expected condition. Similarly, if price expectations change, the optimal irrigation policy may change.

Thus, the farmer requires a decision rule which indicates the soil moisture level at which irrigation should occur at various points throughout the life of the crop, and which depends on the current state of the cotton crop, the water availability situation, and the opportunity costs of the resources used in irrigating the cotton crop.

3 THE METHOD USED

The approach consisted of estimating the nature of the cotton-irrigation production function using simulation techniques and then using calculus to estimate the optimal soil moisture level at which to

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[4] On the Darling Downs, the Queensland Irrigation and Water Supply Commission permits farmers to pump for no more than 2,000 hours per annum at bore capacity *or* to use no more than 6 inches/acre/annum over the whole property, whichever is the lesser amount.

irrigate.[5] This is in contrast to the dynamic programming approach used by Flinn and Musgrave,[6] and Dudley[7] in solving this contrained maximization problem.

The first step consisted of estimating cotton yields using the simulation model. This was done for different values of:

(a) the total water available;
(b) the amount of water that could be applied per irrigation; and
(c) the soil moisture level at which irrigation occurred.

Secondly, using the yield estimates for several replications of the simulation runs, the relationships between the variables (a), (b), and (c) above and the following variables were estimated:

(i) the expected yield;
(ii) the expected water use; and
(iii) the expected number of irrigations (and thus labour use).

Given these estimates, and given information on the relevant prices and costs (opportunity costs), the optimal soil moisture level at which to irrigate at different periods of the season can be estimated.

When the decision maker has a quadratic utility function (i.e., the farmer is not indifferent to alternative risk levels), in order to make optimal decisions he must also have information on how irrigation at different soil moisture levels affects the per acre cotton return variance.[8] Thus, the output from the simulation model was used to determine the relationships between the variables (a), (b), and (c) above and:

(i) the standard deviation of yield;
(ii) the standard deviation of water use;
(iii) the standard deviation of the number of irrigations; and
(iv) the covariances between these variables.

Conceptually, an optimal decision rule could state that irrigation should occur once soil moisture reached a *different* level on *each different* day. To determine whether or not such a system would be optimal would require extensive simulation runs. There would be an extremely large number of possible combinations of the variable "soil moisture at which irrigation is set to occur" to be evaluated using the simulation

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[5] This approach to using the output of simulation models has been suggested by W. Candler and W. Cartwright, "Estimation of Performance Functions for Budgeting and Simulation Studies", *American Journal of Agricultural Economics*, Vol. 51, No. 1 (February, 1969), pp. 159–169.

[6] Flinn, J. C. and W. F. Musgrave, *op cit.*

[7] Dudley, N. J., *op cit.*

[8] See Dillon, J. L., "An Expository Review of Bernoullian Decision Theory in Agriculture: Is Utility Futility?", this *Review*, Vol. 39, No. 1 (March, 1971), pp. 3–80.

model. An approximation to this situation was assumed in this study. The growing season was divided into four periods for the purpose of evaluating different irrigation policy combinations. These periods were based on the phenological stages through which a cotton crop passes. The first stage is from planting to the appearance of the first flower buds; from this point to the first open flowers forms the second stage; while the third and fourth stages are from the first open flowers to the first open bolls and from this point to harvest, respectively.

4 THE MODEL

A soil water budget was used to estimate soil moisture levels. Calculated soil moisture levels were then used to estimate yield.

The water budget took the following form:

$$SM_i = SM_{i-1} + I_i + R_i - O_i - P_i - E_i$$

where

SM_i = soil moisture level at the end of week i

R_i = effective rainfall during week i (it was assumed rain occurred post irrigation)

I_i = irrigation during week i

O_i = runoff during week i

P_i = deep percolation during week i (water lost beyond the root zone)

E_i = actual crop evapotranspiration during week i (based on $SM_{i-1} + I_i + R_i - O_i - P_i$)

When SM_{i-1} reached a defined level, the crop was irrigated in week i. Run-off was determined by relating amount of rainfall and rate of rainfall to the soil moisture level and thus infiltration rate. Deep percolation was calculated by assuming that soil moisture could not exceed field capacity so that, after allowing for run-off, excess water was lost from the root zone.

Actual crop evapotranspiration was estimated by relating potential evapotranspiration to soil moisture level. Potential evapotranspiration was estimated by relating evaporation from a free water surface to stage of crop growth. Given potential evapotranspiration and actual evapotranspiration, the difference provides an estimate of crop moisture stress. Flinn and Musgrave[9] assumed that in periods where moisture stress occurred, no plant growth could occur. There is, however, considerable evidence to suggest that the important determinant of growth and yield is the degree of stress, particularly with cotton.[10] The degree of stress,

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[9] Flinn, J. C. and W. F. Musgrave, *op cit.*

[10] Nix, H. A. and E. A. Fitzpatrick, "An Index of Crop Water Stress Related to Wheat and Grain Sorghum Yields", *Agricultural Meteorology*, Vol. 6 (1968), pp. 321–337.

and timing of stress (as stress at different stages of crop growth affects yield differently) were used to estimate yield.

When the crop was irrigated it was assumed the soil was returned to field capacity provided water supplies made this possible. Thus, the assumed soil moisture level at which irrigation occurred used in each simulation series determined, in part, the quantity of water supplied as well as the timing of water application. The model used did not directly take into account the level of various non-water inputs other than nitrogen fertilizer. However, evidence suggests that optimal insecticide, weedicide, cultivation and fertilizer inputs are known.[11] The position largely arises from the fact that yields are extremely sensitive to critical levels of these inputs. The data used in estimating the yield-stress relationship was based on trials having these other inputs held at what is considered to be an "optimal" level. Similarly, it was assumed that a preplanting irrigation took place in order to bring the soil to near field capacity (necessary for crop establishment), that no irrigations were performed during the first 5 to 7 weeks of the crop (rooting structure reasons and infrequently required) and that irrigation activity ceased after approximately 20th February (quality reasons and yield only marginally affected).[12] Also, harvesting costs were not considered in the analysis as these vary only marginally with yield (unlike many crops).

The efficiency of water application was assumed constant at 75 per cent. This is a simplification of reality.

An irrigation decision rule should conceptually take into account any rainfall forecasts as water loss may occur if rain follows irrigation.[13] For this reason considerable time was spent in trying to relate daily meteorological forecasts to the subsequent level of rainfall, but it was found that the probability of forecast success was extremely low, though success in predicting simple "rain or no rain" outcomes was reasonable.[14] Part of this failure is due to extreme climatic variability on a daily basis from locality to locality and the fact that forecasts are only provided for quite extensive areas containing many localities. Due to these extremely low success probabilities it was obvious that the general forecasts should not be used when deciding whether to irrigate. However, a farmer should not irrigate if his general knowledge of local conditions indicates rain is imminent with a "reasonable" probability in his particular locality.

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[11] Evenson, J. P., (1970), *pers. comm.* (Cotton Agronomist, University of Queensland).

[12] For further discussion on these assumptions see Barlow, F. W. D., *et al.*, *Cotton in Queensland*, (Queensland Department of Primary Industries, Brisbane, 1968).

[13] See, for example, Byerlee, A. R., *A Decision Theoretic Approach to the Economic Analysis of Information*, (Farm Management Bulletin No. 3, University of New England, 1968).

[14] A problem in this analysis was in determining the meaning of the various terms used by the Meteorological Bureau.

The model clearly has a number of limitations. The more important of these are:

(i) no allowance was made for water movement from below the root zone to the root zone;

(ii) direct temperature effects on yield were not taken into account (other than through evaporation);

(iii) weekly soil water budget periods are an approximation of reality (daily periods would have provided greater accuracy);

(iv) no allowance was made for soil super-saturation (or soil moisture levels below wilting point, though this failed to be important as indicated by the weekly soil moisture level information provided by the simulation model);

(v) pre-season soil moisture level was assumed to be constant and post-season soil moisture level was considered to be unimportant;

(vi) the root zone was taken as being constant (not a significant error given a preplanting irrigation) and it was assumed that water was evenly distributed throughout the root zone);

(vii) it was assumed that the cotton crop could be irrigated once it reached a defined soil moisture level. If a large acreage requires irrigating at one point in time this may be impractical; and

(viii) it was assumed that it is possible to measure accurately soil moisture (which measurement technique to use is another information decision problem similar to the type discussed by Byerlee).

5 THE RELATIONSHIPS USED IN THE MODEL

The rainfall infiltration rate relationship used was determined from data presented by Swartz.[15] The relationship had the following form:

$$I = 3{\cdot}2688 - 0{\cdot}9792Q + 0{\cdot}0756Q^2$$

where

I = infiltration rate in inches per hour (1 inch = 25·64 mm)

Q = soil moisture level in inches of available water

The potential and actual evapotranspiration relationships were determined from information presented by Stern.[16] These had the following forms:

$$E_t = (0{\cdot}3872 + 0{\cdot}1031T - 0{\cdot}0052T^2)E$$

$$E_a = (0{\cdot}0528 + 0{\cdot}2952Q - 0{\cdot}0232Q^2)E_t$$

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[15] Swartz, G. L., "Water Entry Into a Black Earth Under Flooding", *Queensland Journal of Agriculture and Animal Sciences*, Vol. 23 (September, 1966), pp. 407–422.

[16] Stern, W. R., "Seasonal Evapotranspiration of Irrigated Cotton in a Low Latitude Environment", *Australian Journal of Agricultural Research*, Vol. 18 (1967), pp. 259–269 and Stern, W. R., "Soil Water Balance and Evapotranspiration of Irrigated Cotton", *Journal of Agricultural Science*, Vol. 69 (1967), pp. 95–101.

where

E_t = potential evapotranspiration (inches per period)
E = evaporation from a free water surface (inches per period)
T = age of crop (in weeks)
E_a = actual evapotranspiration (inches per period)

The stress-yield relationship was estimated from the results of many years of paddock cotton trials carried out at the Queensland Department of Primary Industries Biloela Research Station.[17] Daily soil moisture levels and thus stress levels were determined and functions relating the two estimated. The function selected for use in the model was:

$$\begin{aligned} Y = {} & 2{,}651{\cdot}54^{***} - 810{\cdot}10X_{11}^{***} + 778{\cdot}01X_{22}^{**} - 427{\cdot}70X_{31}^{***} \\ & - 1{,}799{\cdot}90X_{32}^{**} + 317{\cdot}96X_{11}X_{21}^{***} + 241{\cdot}13X_{11}X_{31}^{**} \\ & - 924{\cdot}30X_{11}X_{41}^{***} - 167{\cdot}94X_{21}X_{31}\dagger + 535{\cdot}78X_{21}X_{41}^{*} \\ & + 8{\cdot}77N^{***} \end{aligned}$$

$(R^2 = 0{\cdot}972)$

(Significance levels: ***—1%, **—5%, *—10%, †—30%)

where (all on a per acre basis—one acre = 0·4047 hectares)

Y = lb of seed cotton per acre
X_{11} = the sum of weekly stress in phenological stage 1 for all weeks with stress $>0{\cdot}15''$
X_{22} = the sum of weekly stress in phenological stage 2 for all weeks with stress $\leqslant 0{\cdot}25''$
X_{31} = the sum of weekly stress in phenological stage 3 for all weeks with stress $>0{\cdot}15''$
X_{32} = the sum of weekly stress in phenological stage 3 for all weeks with stress $\leqslant 0{\cdot}25''$
X_{41} = the sum of weekly stress in phenological stage 4 for all weeks with stress $>0{\cdot}15''$
N = lb of elemental nitrogen[18]

6 THE INPUT DATA

The soil moisture model required information on rainfall, rate of rainfall and evaporation from a free water surface. Weekly rainfall distributions were estimated from Meteorological Bureau records for stations in the area. These smoothed distributions were used to simulate sequences of rainfall data for use in the water budget. The rainfall data was tested for serial correlation but this was found to be absent.

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[17] The provision of this information by the Queensland Department of Primary Industries is gratefully acknowledged. In particular the assistance of P. Goyne and K. G. Trudgian is acknowledged.

[18] In the model, N was set at 92 lb which is the recommended level for the area.

Similarly, information on hourly rainfall was used to estimate rate-of-rainfall distributions (inches per hour). Serial correlation was also found to be absent in this data. However, as expected, rate of rainfall was partially correlated with level of rainfall so that the relationship between rainfall and rate of rainfall, together with a random part, was used to simulate the rate of rainfall sequences. The random part was based on the distribution of the error term obtained when estimating the relationship between rainfall and rate of rainfall.

No evaporation information was available for the Brookstead area other than estimates made by the Bureau of Meteorology based on other climatic information. Thus, distribution shapes were determined for a number of recording stations surrounding the Brookstead area. These distributions were found to be normal in all cases so it was assumed that evaporation in the area of interest followed a normal distribution. The normal distribution parameters for the area were based on those obtained from the nearest recording point after adjustments were made on the basis of the Bureau of Meteorology's estimates for the area of interest. Serial correlation was found in the evaporation information though it was independent of rainfall and rate of rainfall. Thus, sequences of evaporation information were simulated using the relationship between evaporation in subsequent periods, a trend value and a random part based on the distributions of the error terms obtained from the estimation of the relationship between subsequent period evaporation. For both evaporation and rate of rainfall estimation a weighting was given to the relationships and the random part according to the correlation coefficients.

7 THE RESULTS

Sixty growing seasons of climatic data were simulated. These were divided into four sets, each of fifteen growing seasons. Given this input data, the cotton yield simulation model was used to estimate the expected yield, expected water use and the expected number of irrigations for each set of fifteen growing seasons. Thus, there were four estimates of each of these variables. This procedure was repeated many times, each time for a different combination of:

(a) W_1 = total water available in phenological stage two (in inches)

(b) W_2 = total water available in phenological stage three (in inches)

(c) A_1 = maximum water that can be applied per week in phenological stage two (in inches)

(d) A_2 = maximum water that can be applied per week in phenological stage three (in inches)

(e) D_1 = available soil moisture level at which irrigation is set to occur in phenological stage two (in inches)

(f) D_2 = available soil moisture level at which irrigation is set to occur in phenological stage three (in inches)

Similarly, the simulation model output was used to estimate four separate estimates of the variances and covariances of the following variables:

(i) yield;

(ii) water use; and

(iii) number of irrigations;

for each combination of the variables (a)—(f) above.

The information on the expected values of these variables was used to estimate the following relationships:

(a) $$E(\text{Yield})\ (\text{lb}) = 1{,}497 + 97{\cdot}3W_2 + 115{\cdot}5D_2 - 7{\cdot}7W_2^2 + 6{\cdot}2W_1W_2 + 2{\cdot}3D_1A_1 + 2{\cdot}8D_1W_1 - 7{\cdot}5D_2W_1 + 8{\cdot}6D_2W_2 \qquad R^2 = 0{\cdot}88$$

(b) $$E(\text{Water Used})\ (\text{inches}) = 0{\cdot}653W_1 + 0{\cdot}275W_2 - 0{\cdot}037W_1W_2 + 0{\cdot}111D_1D_2 + 0{\cdot}097D_1W_1 - 0{\cdot}047D_1W_2 + 0{\cdot}016D_2A_2 - 0{\cdot}08D_2W_1 + 0{\cdot}095D_2W_2 \qquad R^2 = 0{\cdot}98$$

(c) $$E(\text{Number of Irrigations}) = 0{\cdot}47W_1 - 0{\cdot}114A_2 + 0{\cdot}366D_1 + 0{\cdot}318D_2 + 0{\cdot}004A_1^2 - 0{\cdot}02W_1 - 0{\cdot}043D_2W_1 + 0{\cdot}042D_2W_2 - 0{\cdot}002A_2W_1 \qquad R^2 = 0{\cdot}98$$

(In all cases the coefficients were significant at the 1% level.)

Given levels of A_1, A_2, W_1, and W_2, the relationships are linear except for the D_1D_2 interaction term in the water use relationship. This interaction term has occurred due to the effect of irrigation in the first period on the state of the crop and subsequent water use. If greater extremes of water use had been used the yield relationship would probably not have been linear.

Using these relationships, together with price and opportunity cost information, a producer can determine the profit maximising soil moisture levels at which to irrigate. This can be done for varying levels of A and W and a decision made regarding the acreage to plant. The form of the equation is such that, depending on A, W and the prices, it will be optimal to irrigate at high soil moisture levels *or* not at all where the opportunity cost functions are linear. (Where these later functions are not linear this will not be the case.) As an example assume the following parameter values:

$W_1 = 5''$, $W_2 = 15''$, $A_1 = 4''$, $A_2 = 4''$

Price of seed cotton/lb (P_c) = \$0.10

Cost of water/in (P_w) = \$2.00

Cost of labour, etc./irrigation (P_i) = \$1.50

Maximizing the profit equation subject to D_1 and D_2 being less than or equal to 7·0″ (this being the available water at field capacity) the solution is $D_1 = 0{\cdot}0''$ and $D_2 = 7{\cdot}0''$. That is, the crop should not be irrigated in the second phenological stage and continuously irrigated in the third phenological stage. At these levels E(yield) is 3,135 lb, and gross profit $279/acre. The solution indicates that the marginal cost of increasing D_1 above zero is $0.24 and the marginal return of increasing D_2 is $17.42. The latter figure indicates the high value of irrigating in this third phenological stage. The example assumes the opportunity costs are the same in both periods. If the cost of water in the second phenological stage was lower, it would pay to irrigate in this period. (If P_w falls to $1.50 in both periods, the optimal solution is $D_1 = 7{\cdot}0''$ and $D_2 = 7{\cdot}0''$.) Unless trickle irrigation is used it is, however, impractical to maintain soil moisture at field capacity. Thus, where D_1 and D_2 are limited to maximum values of 5·5″ (79 per cent of available water), the optimal solution is D_1 and $D_2 = 5{\cdot}5''$ and gross profit per acre is $258. In this case the marginal returns on D_1 and D_2 are $0.11 and $16.20 respectively. If D_2 is permitted to go as high as 5·995″ it no longer pays to irrigate in the second phenological stage. An examination of the yield/stress relationship indicates the reason for this result.

In order to estimate the variance of gross profit the following relationships were calculated (to obtain the variance of net return per acre, information on the costs excluded from this analysis would be needed):

$$\sigma_y = 374{\cdot}0$$

$$\begin{aligned}\sigma_w = {} & 0{\cdot}052A_2 + 0{\cdot}175W_1 + 0{\cdot}293W_2 - 0{\cdot}013W_2^2 - 0{\cdot}05D_2^2 \\ & + 0{\cdot}032D_1D_2 - 0{\cdot}008D_1A_2 + 0{\cdot}016D_2W_2 \qquad (R^2 = 0{\cdot}95)\end{aligned}$$

$$\begin{aligned}\sigma_i = {} & 0{\cdot}198W_1 + 0{\cdot}254D_1 - 0{\cdot}022W_1^2 + 0{\cdot}007W_2^2 - 0{\cdot}042D_1^2 \\ & + 0{\cdot}017D_1W_1 - 0{\cdot}01D_1W_2 - 0{\cdot}001A_1W_1 \qquad (R^2 = 0{\cdot}95)\end{aligned}$$

$$\sigma_{y,w} = 22{\cdot}1D_2^2 - 157.0D_2 - 3{\cdot}5D_2W_1 + 0{\cdot}5A_1W_2 \qquad (R^2 = 0{\cdot}58)$$

$$\sigma_{y,i} = 5{\cdot}2A_1 - 117{\cdot}4D_2 + 14{\cdot}8D_2^2 + 2{\cdot}4D_1D_2 \qquad (R^2 = 0{\cdot}66)$$

$$\begin{aligned}\sigma_{w,i} = {} & 0{\cdot}347W_1 + 0{\cdot}187W_2 - 0{\cdot}024D_2^2 - 0{\cdot}018W_1W_2 \\ & + 0{\cdot}021D_2W_2 - 0{\cdot}004A_1W_1 \qquad (R^2 = 0{\cdot}83)\end{aligned}$$

(all coefficients were significant at the 1% level)

where

σ_y = standard deviation of yield
σ_w = standard deviation of water use
σ_i = standard deviation for the number of irrigations
$\sigma_{y,w}$ = covariance between yield and water use
$\sigma_{y,i}$ = covariance between yield and the number of irrigations
$\sigma_{w,i}$ = covariance between water use and the number of irrigations

The standard deviation of yield was almost independent of the irrigation variables. When rainfall in the various periods was included as an independent variable a relationship was obtained which explained approximately 50 per cent of the variation. If evaporation and rate of rainfall information had also been included it is considered that an improved relationship would have been obtained.

The negative yield covariance terms are to be expected as, given a particular irrigation policy, a higher yield will be associated with a high rainfall season and thus a lower irrigation input will be necessary.

These relationships can be used to estimate the variance of gross profit per acre using the normal variance equations. As an example, given the case used before, where $W_1 = 5''$, $W_2 = 15''$, A_1 and $A_2 = 4''$, D_1 and $D_2 = 5{\cdot}5''$ and prices are assumed to be constant, the standard deviation of gross profit per acre is $40.20 (expected gross profit = $258). This figure is largely dependent on the yield variance. It can be seen from the standard deviation and covariance relationships that the variable values have little effect on the profit variance. The change in profit variance as D_1 and D_2 change are—$3.30 and $264.60 respectively, indicating the importance of the third phenological stage (the same applies for the expected yield). This positive effect of D_2 on the variance is largely due to the significant effect D_2 has on the negative yield covariance terms.[19]

8 CONCLUSION

The relationships determined enable a producer to select the soil moisture level at which irrigation should occur during phenological stages two and three (it is assumed that in the first stage a preplanting irrigation occurs and no irrigation occurs in the last stage prior to harvest). These relationships do not, however, allow the producer to update decisions as conditions change except for changes in prices, costs and water availability levels. To indicate the soil moisture level at which to irrigate, assuming expected soil moisture and crop conditions do not in fact occur, would require the estimation of further, similar, relationships. These would have to be estimated for each possible soil moisture level and crop state that could occur at each point in time.

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[19] In order to determine a policy which maximizes expected utility, this information would have to be used to estimate the whole farm profit variance. See Dillon, J. L., *op cit.*