Simulation of Soil Water-Crop Yield Systems: The Potential for Economic Analysis*

Harry P. Mapp, Jr. and Vernon R. Eidman

Economists have shown an increasing interest in systems theory and simulation. The recent reviews by Anderson [1] and LaDue and Vincent [10] indicate the literature is replete with models of business and farm firms developed by researchers from several disciplines. A smaller but no less sophisticated group of models is focused on simulated physical or biological processes. An even smaller segment of the literature deals with economic applications of models which simulate physical and biological phenomena.

Economists have become interested in models simulating physical and biological phenomena because of their experimental value. When a satisfactory approximation of reality can be created within the context of the model, experiments can then be conducted to determine the effects of changes in exogeneous factors on outcomes predicted by the model.

This approach is particularly valuable, and will be increasingly needed, in evaluating technology when we do not have the time (or money) to collect enough data to perform statistical analyses. For example, the statistical evaluation of a series of irrigation strategies for farm firm operators may require collection of field data over many years under different varietal and weather conditions for each of several irrigated crops. Construction of a model capable of simulating the soil water and crop growth process would greatly reduce the time and cost involved in evaluating irrigation strategies. Such a model is of interest for several reasons. Its use should reduce the cost of developing improved irrigation strategies, increase net returns of farmers, and reduce water use per year, thus prolonging the life of the system.

The purposes of this paper are: (1) to present a model capable of simulating soil water-crop yield relationships for several irrigated and dryland crops grown in the Oklahoma Panhandle, (2) to demonstrate the usefulness of the model by incorporating it into a farm firm simulator to evaluate alternative irrigation strategies, and (3) to discuss the potential value of creating more complete models of the soil water-crop yield system.

Model Development

The Production Subset

Building on earlier soil moisture-crop yield models [2, 3, 4, 5, 6, 7, 13, 14, 15] a multiple-crop simulation model was developed for the major dryland and irrigated crops in the Oklahoma Panhandle [11]. The model assumes that, under ideal soil water and atmospheric conditions, a specified maximum potential yield is achieved for each crop. If demands on the plant for moisture are greater than its ability to transpire moisture, plant stress occurs and final yield is reduced. The amount of yield reduction depends upon the length and severity of moisture and atmospheric stress in relation to the stage of plant development for each crop.

The crop yield reduction equation, which assumes the combined effects of soil water and atmospheric stress to be additive, may be stated in explicit form as

\[ YR_{ij}^k = 0_i \times SWD_{ij} + b_j^k \times (P_{ij} - P_n) \]

where \( YR_{ij}^k \) is yield reduction, day \( i \), stage \( j \), crop

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\( \theta_j \) is yield reduction, in units per day, resulting from adverse soil water conditions, stage \( j \), crop \( k \); \( \text{SWD}_i \) represents the proportion of soil water available for plant use, day \( i \), stage \( j \); \( b_j \) is yield reduction in units per day due to severe atmospheric demand upon the plant, stage \( j \), crop \( k \); \( P_{ij} \) is pan evaporation in inches, day \( i \), stage \( j \); and \( P_a \) is a critical pan evaporation level at or below which no yield reductions occur that are directly attributable to serve atmospheric conditions.

The model requires daily estimates of soil water and atmospheric stress. A soil water balance was constructed to provide daily soil water levels adjusted to reflect additions due to rainfall and irrigation applications and subtractions due to actual evapotranspiration. Daily rainfall events were generated from discrete empirical probability distributions for each of 14 two-week periods throughout the growing season. Daily pan evaporation values were generated from 14 lognormal distributions of pan evaporation. The soil water balance utilized rainfall and pan evaporation values and certain assumptions regarding the nature of the soil, characteristics of the soil profile and stage of plan development, to compute the level of soil water available for each crop each day throughout the growing season.

The coefficients \( \theta_j \) and \( b_j \) in equation (1) were estimated for three critical stages of plant development for grain sorghum, four critical stages for wheat, and five stages of development for corn. The stages of development and soil water and atmospheric stress coefficients for each crop are presented in Table 1.

**Table 1. SOIL WATER (\( \theta_j \)) AND ATMOSPHERIC STRESS (\( b_j \)) COEFFICIENTS FOR GRAIN SORGHUM, WHEAT AND CORN BY STAGES OF DEVELOPMENT**

<table>
<thead>
<tr>
<th></th>
<th>Preboot</th>
<th>Boot-Heading</th>
<th>Grain Filling</th>
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<tbody>
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<td></td>
<td>S.W.</td>
<td>S.W.</td>
<td>S.W.</td>
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<tr>
<td></td>
<td>Atm.</td>
<td>Atm.</td>
<td>Atm.</td>
</tr>
<tr>
<td>Grain Sorghum (^a/)</td>
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<td>2.04</td>
<td>1.27</td>
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<tr>
<td></td>
<td>1.30</td>
<td>1.65</td>
<td>1.50</td>
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<tr>
<td>Wheat</td>
<td>0.45</td>
<td>1.02</td>
<td>1.55</td>
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<tr>
<td>Vegetative 1</td>
<td>0.00</td>
<td>1.10</td>
<td>1.20</td>
</tr>
<tr>
<td>Silking</td>
<td>S.W.</td>
<td>1.55</td>
<td>S.W.</td>
</tr>
<tr>
<td>Milk</td>
<td>1.20</td>
<td>1.66</td>
<td>1.50</td>
</tr>
<tr>
<td>Corn</td>
<td>0.20</td>
<td>0.10</td>
<td>0.40</td>
</tr>
<tr>
<td>Vegetative 2</td>
<td>1.15</td>
<td>3.05</td>
<td>1.40</td>
</tr>
<tr>
<td>Silking</td>
<td>S.W.</td>
<td>1.60</td>
<td>1.57</td>
</tr>
<tr>
<td>Milk</td>
<td>0.60</td>
<td>1.14</td>
<td>0.10</td>
</tr>
<tr>
<td>Dough</td>
<td>S.W.</td>
<td>1.70</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
<td>Atm.</td>
<td>S.W.</td>
<td>Atm.</td>
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</tbody>
</table>

\(^a/\) The soil water stress coefficient of 0.30 for the preboot stage of grain sorghum development denotes that as soil water approaches wilting point, yield reduction approaches 0.30 bushels per acre per day. The atmospheric stress coefficient of 1.30 indicates that under the most severe atmospheric conditions, yield reduction approaches 1.30 bushels per day.

1. It is useful to distinguish between two concepts of evapotranspiration. Potential evapotranspiration refers to the quantity of water which would be evaporated and transpired under adequate soil water conditions for a particular crop and stage of plant development. In the literature, measures of potential evapotranspiration are frequently related to pan evaporation. Actual evapotranspiration indicates the amount of evapotranspiration which actually occurs. For a given plant and stage of development, the amount of actual evapotranspiration is a function of potential evapotranspiration and soil water conditions. The model computes potential and actual evapotranspiration daily for each crop.

2. Plottings of daily pan evaporation observations for each period of the growing season revealed all observations to be equal to or greater than zero and the distributions for each period to be positively skewed. The lognormal distribution was selected to represent pan evaporation on the basis of its characteristics (positively skewed probability density function having all values equal to or greater than zero), ease of estimation and ease of manipulation.

3. Coefficients were actually synthesized by combining, modifying and adjusting coefficients reported in research results by many authors, rather than being estimated using sophisticated mathematical procedures. While it may be argued that mathematical estimation is preferable, lack of adequate data for the study area effectively eliminated this alternative. The references used are cited elsewhere [11, 12].
The production subset of the model was completed by combining soil-water balance and crop-yield equations. A series of crop yields were generated, and these simulated yields were discussed at length with agronomists, agricultural engineers, irrigation specialists and extension agents in the field to verify the general validity of the production subset.  

**The Farm Firm Simulation Model**

To permit evaluation of irrigation strategies within the context of a whole farm decision model, the production subset was combined with a general agricultural firm simulation model developed by Hutton and Hinman [8], and modified to represent a typical Oklahoma Panhandle cash grain farm. The 640 acre representative farm was developed from surveys of 78 randomly sampled farm operators. It contained 595 acres of cropland, consisting of 170 acres of irrigated grain sorghum, 85 acres of irrigated wheat, 60 acres of irrigated corn, 30 acres of dryland grain sorghum and 85 acres of dryland wheat. The remaining acres of cropland were idle, diverted or lost to turnrows. The farm was assumed to have one irrigation well, and distribution system drawing water from an underground aquifer of sufficient saturated thickness to sustain a pumping capacity of 1,000 gallons per minute throughout the irrigation season over a 20-year simulated time period [11, pp. 91-101].

**SIMULATING IRRIGATION STRATEGIES**

To demonstrate the potential value of the crop yield-farm firm decision model, the impacts of two irrigation strategies on water use, net farm income and variability of net farm income were simulated over a 20-year period. For the analysis reported here, 15 replicates of 20 years each can be considered 300 simulated years of analysis. The 20-year period was used to trace the accumulative effect of following each rule elsewhere [11].

**Strategy Based on Current Practices**

The first irrigation strategy simulated is based on the presumption that an irrigation operator has an idea of which crops require water during different critical periods of the growing season. In addition, he knows which of the several crops requiring water during a specific period has the highest use value for the irrigation water available. He applies water during a specific period first to the crop which has the highest use value (marginal value product) for that unit of irrigation water. Once that crop has received an irrigation application, the crop having the highest marginal value product for the next unit of irrigation water receives the next irrigation application.

Following this line of reasoning, the crop year is divided into five irrigation periods, based on the critical stages of plant development for grain sorghum, wheat and corn. For each period, irrigation priorities are developed on the basis of potential yield reductions during critical stages of plant development. These periods and the irrigation priorities for each are presented in Table 2. Irrigations are initiated on the basis of soil water level in a crop's soil profile. If available soil water falls below a specified level during a critical stage of plant development, significant yield reductions can occur. Thus, farmers are assumed, based on the crops appearance and feel of the soil, to initiate an irrigation application when soil water falls below the specified critical soil water level for each stage of development for each crop. If a sufficient number of pumping days are available and actual evapotranspiration is not great, an entire crop can receive a 3.0 inch addition to its soil profile. However, if plants on that part of the field already irrigated begin to show signs of plant stress before the entire application can be completed, irrigators are assumed to reduce the application rate on remaining acres and return to the original portion of the crop to begin a new application. The assumptions appeared to describe the irrigation strategy followed by many of the "good managers" in the area.

Current irrigation strategy practices, based strictly on soil moisture or a fixed length irrigation schedule, induce irrigators to maximize output per acre for each crop rather than to maximize net returns to the fixed resources available on the farms. Thus, an irrigator may be able to increase net returns per acre by reducing water application to the point where marginal value produce of the last unit of water applied just equals the additional cost of applying that unit of water.

**Strategy Based on an Economic Decision Rule**

The second irrigation strategy simulated assumes that irrigators pump according to soil water...
Table 2. DELINEATION OF CRITICAL STAGES OF PLANT DEVELOPMENT AND IRRIGATION PRIORITIES

<table>
<thead>
<tr>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>15</td>
<td>23</td>
<td>31</td>
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<td></td>
<td>6</td>
<td>13</td>
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<td>18</td>
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<td>2</td>
<td>16</td>
<td>18</td>
<td>9</td>
<td>24</td>
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<td></td>
<td>1</td>
<td>15</td>
<td>22</td>
<td>30</td>
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</tbody>
</table>

Grain Sorghum

- Preplant
- a
- Preboot
- Boot-Heading
- Grain-Filling

Wheat

- Preboot
- Boot
- Flower
- Milk
- Preplant

Corn

- Preplant
- Vegetable 1
- Vegetable 2
- Silking
- Milk
- Dough

Critical Periods

<table>
<thead>
<tr>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
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</thead>
<tbody>
<tr>
<td>May 1 - May 15</td>
<td>May 16 - June 5</td>
<td>June 6 - August 4</td>
<td>August 5 - September 15</td>
<td>Sept. 16 - 30</td>
</tr>
</tbody>
</table>

Irrigation Priorities

- G, W, C
- W, C, G
- C, G
- G, C
- G, W

Pumping Days

|       | 14  | 20  | 56  | 39  | 14  |

- No stage name is given to grain sorghum between preplant irrigation applications and preboot stage. Moisture stress during this period has little effect if moisture is adequate during stages of development.

- Plant emergence occurs between May 1 and May 7.

- Irrigation priorities G, W and C represent grain sorghum, wheat and corn, respectively. All of the crop listed first in a critical period is irrigated before the second or third priority crops.

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5 Two critical stages of grain sorghum development overlap in the fourth irrigation period. From day 1 through day 25 of the period, grain sorghum is in the boot-heading stage and the potential yield reduction due to soil moisture stress alone is 2.04 bushels per day. For the remaining 14 days of the period, grain sorghum is in the grain-filling stage and the potential yield reduction is 1.27 bushels per day.

6 At the time of the study, gross revenue from nine and ten bushels of grain sorghum at $0.94 per bushel were $8.46 and $9.40, respectively. The cost of an additional irrigation, including variable pumping cost, additional labor cost and added harvesting and hauling costs, etc., totaled $8.49 and $8.60 for nine and ten bushel potential yield reduction, respectively. Added costs exceeded added revenues for a nine bushel potential yield reduction. However, added revenues exceeded added costs and an additional irrigation was justified if potential yield reduction was equal to or greater than ten bushels.
RESULTS

Each of the above irrigation strategies were simulated over a 20-year period and each simulation run was replicated 15 times. A portion of the results of these simulation runs is summarized in Table 3.

Under the irrigation strategy based on current practices, the mean of acre inches pumped ranged from 6,662 acre inches to 7,181 acre inches. Minimum pumping for any of the 300 years in the series was 3,007 acre inches, the maximum being 7,925 acre inches. Wide variations in the number of acre inches pumped reflected the operator's response to fluctuations in soil water and atmospheric stress conditions simulated by the model's production subset.

Variations in net farm income were even more dramatic. Mean net farm income, computed from the 15 replications of each year's simulation run, ranged from $10,598 to $19,293 and the standard deviation of net farm income ranged from $3,336 to $5,950. The maximum net farm income achieved during any simulation run was $31,737 and the minimum was $4,330. The coefficient of variation (standard deviation divided by the mean) for net farm income ranged from 0.17 to 0.44 over the 20-year simulated time period.

Under the irrigation strategy designed to re-

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7 Each simulation run (replicate) covered a 20-year simulated time period. During each year of the run, a set of daily rainfall and pan evaporation events were generated, crop yields were determined on the basis of soil water and atmospheric stress, crops were harvested and sold, decisions were made to replace fully depreciated machinery, taxes and family consumption expenditures were deducted, and the ending financial situation was calculated. Each replication traces the firm through an entirely different set of random weather events. In validating the model, many replications were utilized. Due to limited resources, only 15 replications were utilized in the analysis.
duce water use and apply an economic decision rule in deciding when to initiate certain irrigation applications, mean acre inches pumped ranged from 5,875 acres inches to 6,274. The maximum number of acre inches pumped during any simulated year was 6,795. The minimum was 2,722.

Under the second strategy, mean net farm income ranged from $11,125 to $19,845. The maximum achieved during any year was $31,541 while the minimum was $4,886. The coefficient of variation ranged from 0.19 to 0.44 over the simulation runs.

From the standpoint of water resource use, irrigation strategy containing an economic decision rule reduced the total quantity of irrigation water applied during every year simulated. Farm managers would be interested in the impact of reducing water use rates on the level and variability of net farm income. Figures presented in Table 3 indicate that adoption of the irrigation strategy containing an economic decision rule, while reducing water usage, would have little effect on net farm income. Mean net farm income was actually higher under the latter irrigation strategy in seven of the 20 years simulated. During years in which mean net farm income was higher under the “current practices” strategy, differences in income were not large. Had variable pumping costs been higher by about five cents per acre inch, average net farm income for the two strategies over period would have been approximately equal.

Variability of net farm income, as measured

<table>
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<th>Year</th>
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<td>Std. Deviation</td>
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<td>Minimum</td>
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<td>Maximum</td>
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Table 3. SIMULATED IRRIGATION PUMPING AND NET FARM INCOME UNDER ALTERNATIVE IRRIGATION STRATEGIES

by the standard deviation, was slightly larger under the strategy containing an economic decision rule. Relative variability of net farm income, as measured by the coefficient of variation, was also slightly under this latter strategy.

CONCLUDING REMARKS

Whether farm managers prefer an irrigation strategy based on current practices or one containing an economic decision rule depends upon a number of factors. These include the water resource situation from which they are pumping and the tradeoffs they are willing to make between level and variability of income. Many managers may be indifferent between the two strategies investigated in this study unless water supply is limited. However, they may be very interested (regardless of their water situation) in evaluating consequences of following alternative strategies on the net returns of their business.

Additional work is needed before a complete set of irrigation strategies can be evaluated and recommended to farmers in the area. The crop yield model must be expanded to include all major irrigated and dryland crops. Although the model makes reasonable predictions as judged by agronomists familiar with the area, additional
effort is needed to validate the portions of the model dealing with the effects of soil water and atmospheric stress at different stages of plant development for all crops under different soil and climatic conditions. Additional work is also needed to refine the parameters of the soil water balance. The analysis suggests that the type of crop yield-farm firm decision model developed in this study has substantial potential for analyzing a variety of farm firm decision problems. With slight modification, the model could be used to evaluate alternative dryland production strategies, grazing strategies, fertilization strategies and financial strategies. In each case, it can provide information on the underlying biological input-output process at a much lower cost and in less time than relying on the typical multi-period experimental procedure.

REFERENCES


