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SIMULATION OF SOIL WATER-CROP YIELD SYSTEMS: THE POTENTIAL FOR ECONOMIC ANALYSIS*

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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 repleat 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

$$(1)\quad YR_{ij}^{k} = 0_{j}^{k}\ SWD_{ij} + b_{j}^{k}\ (P_{ij} - P_{a})$$

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

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k; θ_j^k is yield reduction, in units per day, resulting from adverse soil water conditions, stage j, crop k; SWD_{ij} represents the proportion of soil water available for plant use, day i, stage j; b_j^k 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 substractions due to actual evapotranspiration.[1] 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.[2] 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 θ_j and b_j in equation (1) were estimated[3] 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 (θ_j) AND ATMOSPHERIC STRESS (b_j) COEFFICIENTS FOR GRAIN SORGHUM, WHEAT AND CORN BY STAGES OF DEVELOPMENT

	Preboot		Boot-Heading		Grain Filling	
	S.W.	Atm.	S.W.	Atm.	S.W.	Atm.
Grain Sorghum[a/]	0.30	1.30	2.04	1.65	1.27	1.50

	Preboot		Boot		Flower		Milk	
	S.W.	Atm.	S.W.	Atm.	S.W.	Atm.	S.W.	Atm.
Wheat	0.45	0.00	1.02	1.10	1.55	1.20	1.66	1.50

	Vegetative 1		Vegetative 2		Silking		Milk		Dough	
	S.W.	Atm.	S.W.	Atm.	S.W.	Atm.	S.W.	Atm.	S.W.	Atm.
Corn	0.20	0.10	1.15	0.60	3.05	1.60	1.14	0.40	1.57	0.10

[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.

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[1] It is useful to disinguish 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 combing, 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.[4]

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 illigation 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

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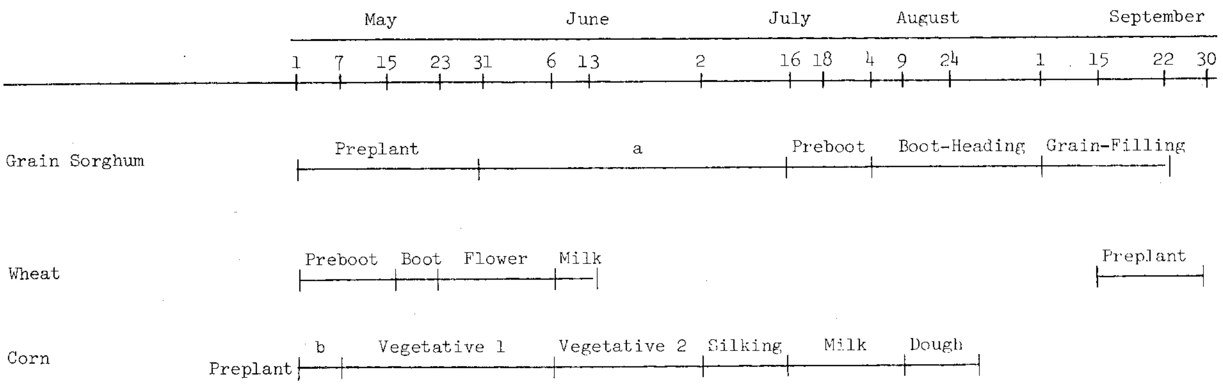
[4] For a complete discussion of the development of the Production Subset, see Mapp [11, pp. 52-64]. Model verification is discussed in detail in [12].

Table 2. DELINEATION OF CRITICAL STAGES OF PLANT DEVELOPMENT AND IRRIGATION PRIORITIES



	(1)	(2)	(3)	(4)	(5)
Critical Periods	May 1- May 15	May 16- June 5	June 6 - August 4	August 5 - September 15	Sept. 16-30
Irrigation Priorities[c]	G,W,C	W,C,G	C,G	G,C	G,W
Pumping Days	14	20	56	39	14

[a] 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.

[b] Plant emergence occurs bewteen May 1 and May 7.

[c] 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.

depletion levels and crop priorities established earlier. However, they reduce the total amount of irrigation water pumped by establishing maximum amounts of water to be added to each crop during each stage of plant development. It also incorporates an economic decision rule for irrigating grain sorghum during the fourth irrigation period. The decision to irrigate is a function of soil moisture and potential yield reduction based on the number of days remaining in the period, as depicted in Figure 1. In deciding whether or not to irrigate, the operator projects current moisture conditions to the end of the period and evaluates whether soil water is sufficiently low, that yield reduction (assuming no further rainfall) will equal or exceed ten bushels per acre. As long as at least eight days remain in the period, a reduction of ten bushels per acre is possible.[5] Whenever the potential yield reduction equals or exceeds ten bushels, an additional irrigation is scheduled.[6]

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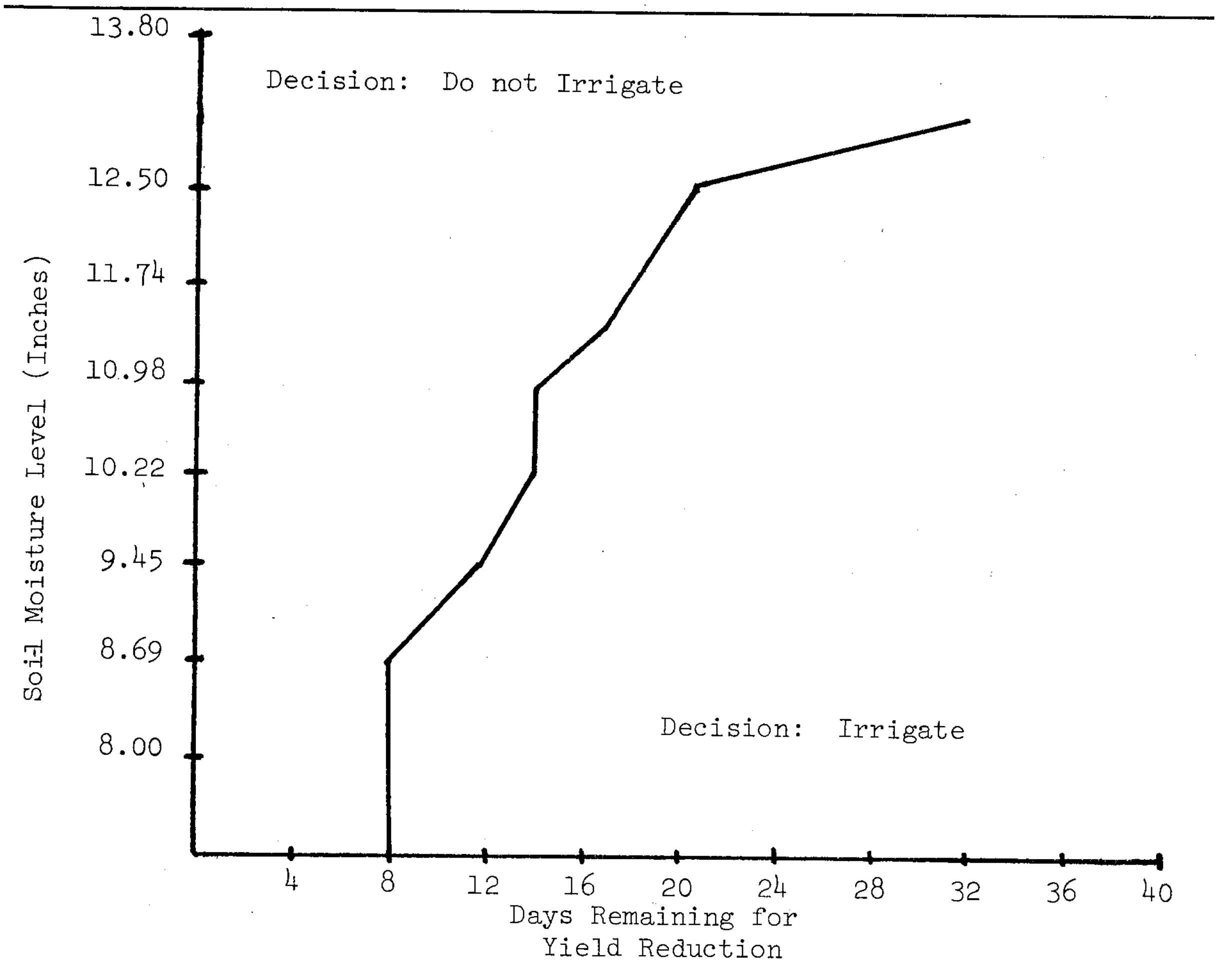
[5] Two critical stages of grain sorghum development overlap in the fourth irrigation period. From day 1 through day 25 of the period, grain sorghum is in the boot-heading stage and the potential yield reduction due to soil moisture stress alone is 2.04 bushels per day. For the remaining 14 days of the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

Figure 1. ECONOMIC DECISION RULE FOR IRRIGATING GRAIN SORGHUM DURING IRRIGATION PERIOD 4



RESULTS

Each of the above irrigation strategies were simulated over a 20-year period and each simulation run was replicated 15 times.[7] 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 acre 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.

Table 3. SIMULATED IRRIGATION PUMPING AND NET FARM INCOME UNDER ALTERNATIVE IRRIGATION STRATEGIES

	Year																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Irrigation Strategy Based on Current Practices Acre Inches Pumped																				
Mean	6692	6711	6835	6777	6861	6743	7065	7043	6900	6662	6948	7181	6963	7233	6871	7061	6974	6843	6972	6823
Std. Deviation	1249	971	622	910	1134	806	429	739	833	795	866	635	1095	596	916	741	710	1127	846	705
Maximum	7813	7745	7474	7862	7921	7921	7670	7865	7742	7865	7925	7835	7802	7895	7685	7835	7865	7925	7791	7862
Minimum	3007	4297	5602	4770	3911	5325	6142	5878	5051	4740	4950	5681	4005	5947	4567	4791	4860	3352	5130	5227
Range	4806	3448	1872	3092	4010	2596	1528	1987	2691	3125	2975	2154	3797	1948	3118	3044	3005	4573	2661	2635
Net Farm Income																				
Mean	10598	12434	14413	14767	16754	17192	16421	15353	16601	18563	17420	16172	17506	16974	18548	17794	19644	18908	17364	19293
Std. Deviation	3872	5526	3340	4307	4152	5243	4112	4191	4764	4613	4545	3490	5950	4022	3774	3374	3744	4423	5045	3336
maximum	16403	24868	21941	22167	26548	26226	24518	23334	25546	26076	26156	22400	31737	23400	27602	22434	27433	26993	24284	25059
Minimum	4330	4443	9930	7454	11030	8516	7454	9988	8612	10998	10232	12213	8665	10124	13451	12118	13455	9660	9324	13491
Range	12073	20425	12011	14713	15518	17710	17064	13346	16934	15078	15924	10187	23072	13276	14151	10316	13948	17333	14960	11568
Irrigation Strategy Including Economic Decision Rule Acre Inches Pumped																				
Mean	5875	6010	6035	6070	5931	6000	6249	6157	6107	5960	6131	6274	6173	6209	6073	6209	6161	6032	6099	6130
Std. Deviation	1046	668	391	651	696	488	225	458	576	645	451	343	765	460	559	436	410	806	511	416
Maximum	6795	6750	6495	6780	6735	6735	6660	6735	6735	6570	6735	6795	6735	6735	6645	6645	6645	6645	6795	6645
Minimum	2722	4297	5265	4695	3911	5130	5850	5402	4699	4320	4950	5535	3915	5310	4477	4791	4860	3352	4950	5160
Range	4073	2453	1230	2085	2824	1605	810	1333	2036	2250	1785	1260	2820	1425	2168	1854	1785	3293	1845	1485
Net Farm Income																				
Mean	11125	12634	14527	14874	16595	17001	16442	15260	16570	18682	17130	16045	17134	16821	18293	17515	19845	18901	17177	19275
Std. Deviation	4138	5573	3800	4766	4415	5828	4486	4578	5089	4859	5089	3864	6111	4563	4157	3777	3829	4815	5696	3607
Maximum	17467	24866	22849	23613	26549	26348	24757	23944	26176	26617	25974	23029	31541	23656	27520	22035	26908	26596	24582	24621
Minimum	5192	4886	8380	7876	10660	7238	5724	9026	8694	11494	9576	11520	8124	8106	12036	10614	13268	8054	8356	12816
Range	12275	19980	14469	15737	15889	19110	19033	14918	17482	15123	16398	11509	23417	15550	15484	11421	13640	18542	16226	11895

Variability of net farm income, as measured 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

[1] Anderson, Jock R. "Simulation: Methodology and Application in Agricultural Economics," *Review of Marketing and Agricultural Economics,* March 1974, pp. 3-55.

[2] Anderson, Raymond L. "A Simulation Program to Establish Optimum Crop Patterns on Irrigated Farms Based on Pre-season Estimates of Water Supply," *American Journal of Agricultural Economics,* Vol. 50, No. 5, December 1968, pp. 1586-1590.

[3] Anderson, Raymond L. and Arthur Maass. *A Simulation of Irrigation Systems—The Effect of Water Supply and Operating Rules on Production and Income on Irrigated Farms,* USDA Technical Bulletin No. 1431, Washington, January 1971.

[4] Fleming, P. M. "A Water Budget Method to Predict Plant Response and Irrigation Requirements for Widely Varying Evaporative Conditions," *Proceedings 6th International Congress Agricultural Engineering,* Geneva, 1964, pp. 108-120.

[5] Flinn, J. C. "The Demand for Irrigation Water in an Intensive Irrigation Area," *Australian Journal of Agricultural Economics,* Vol. 13, 1969, pp. 128-143.

[6] Flinn, J. C. "The Simulation of Crop-Irrigation System," *Systems Analysis in Agricultural Management,* edited by J. B. Dent, J. R. Anderson, John Wiley & Sons, Sidney, 1971.

[7] Flinn, J. C., and W. F. Musgrave. "Development and Analysis of Input-Output Relations for Irrigation Water," *Australian Journal of Agricultural Economics,* Vol. 11, 1967, pp. 1-19.

[8] Hutton, R. F. and H. R. Hinman. *A General Agricultural Firm Simulator,* Agricultural Economics and Rural Sociology Report No. 72, Pennsylvania State University, State College, 1968.

[9] Jose, H. Douglas. "Decision Strategies for the Multiple Use of Winter Wheat in Oklahoma," unpublished Ph.D. dissertation, Oklahoma State University, Stillwater, July 1974.

[10] LaDue, Eddy L. and Warren H. Vincent. "Systems Theory and Simulation: A Critique of Literature," Agricultural Economics Report No. 261, Michigan State University, East Lansing, March 1974.

[11] Mapp, Harry P., Jr. "An Economic Analysis of Water-Use Regulation in the Central Ogallala Formation," unpublished Ph.D. dissertation, Oklahoma State University, Stillwater, May 1972.

[12] Mapp, Harry P., Jr., Vernon R. Eidman, John F. Stone and James M. Davidson. *Simulating Soil Water and Atmospheric Stress—Crop Yield Relationships in Economic Analysis,* Oklahoma Agricultural Experiment Station Technical Bulletin T-140, Stillwater, February 1975.

[13] Moore, Charles V. "A General Analytical Framework for Estimating the Production Function for Crops Using Irrigation Water," *Journal of Farm Economics,* Vol. 43, No. 4, November 1961, pp. 876-888.

[14] Shaw, R. H. *Estimation of Soil Moisture Under Corn,* Iowa Agricultural Experiment Station Research Bulletin 520, Ames, 1963.

[15] Taylor, S. A. "A Use of Mean Soil Moisture Tension to Evaluate the Effect of Soil Moisture on Crop Yields," *Soil Science,* Vol. 74, 1952, pp. 217-226.