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THE VALUE OF SOIL WATER AND WEATHER INFORMATION IN INCREASING IRRIGATION EFFICIENCY*

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Abstract

Different levels of soil water and weather information are compared to a situation of very limited information. Generalized stochastic dominance is used to generate a value for each level of information for decisionmakers whose coefficients of absolute risk aversion fall within predetermined bounds. Information is found to have a positive value which is subject to diminishing returns and which varies by level of risk aversion.

The economics profession has become increasingly interested in analyzing and evaluating information in recent years. Although various definitions of information might be given, it can be thought of as data in a form that is of real or perceived value for making current or prospective decisions (Davis, p. 42). The production of information is a process involving inquiry, communication, and decision activities (Marschak). A means of inquiry is developed to selectively collect data from the environment. These data are transmitted as signals to the decisionmaker via a communication channel. The process is completed when decisions on actions to be taken are made based on the signals received.

Information can be viewed as the basis for the existence of firms (Alchian and Demsetz). Entrepreneurs can more efficiently monitor the marginal productivity of inputs and distribute rewards accordingly than the input owners themselves. Those firms which can more accurately gauge input marginal productivities earn higher profits. Observed "inefficiency" in input use may be due to the fact that information gathering is a costly activity (Pasour and Bullock). Managers may feel that the cost of acquiring the information needed to increase efficiency exceeds the benefits.

Eisgruber notes that procedures for estimating information costs and returns have not been developed for ready empirical application. He states several reasons for this including that information systems generally do not have a market price; that information is not a physical good; that the impact of information is not readily measurable; and that public and private values of information often diverge considerably.

Recent technological developments have greatly increased the potential productivity of information. This increased productivity has raised questions as to how much should be invested in producing information and how information can best be used. Economists can help answer these questions by developing ways to quantify the costs and returns from information production.

Methods to estimate the returns from information should allow for the possibility of nonlinear decisionmaker utility functions and should consider the effect that information has on the distribution of outcomes rather than just the effect on expected returns. Lavalle proved that the maximum an expected utility maximizing agent could afford to pay for the information is the difference between the minimum he/she would accept to give up the opportunity to make the decision without information and the maximum the individual would pay to buy back the right to make the decision when the information is revealed.

Byerlee and Anderson define the value of a predictor which is subject to error as an amount V_z which satisfies the following equality:[1]

$$\int\int U(\pi(\theta,X^*(k)) - V_z)g(\theta|k)f(k)d\theta dk - \int\int U(\pi(\theta,X_0^*))g(\theta|k)f(k)d\theta dk = 0 \tag{1}$$

where U is a von Neumann Morgenstern utility function; π, profit; θ, a random disturbance; X, a choice variable of production; $g(\theta|k)$, the probability of observing the random variable θ given the prediction k; f(k), the probability of generating the prediction k; $X^*(k)$, the optimal level of X given the prediction k, and X_0^*, the level of the choice variable which maximizes expected utility under the prior distribution. This is subject to the constraint that $X^*(k)$ be chosen to maximize expected utility for every k for which $f(k) > 0$ as shown in (2):

$$\partial(\int U(\pi(\theta,X) - V_z)g(\theta|k)d\theta)/\partial X = 0 \tag{2}$$

V_z is an ex ante measure of the value of information which incorporates uncertainty about the actual prediction to be generated by the predictor as well as uncertainty about the true value of the random variable given the prediction. However, V_z would be difficult to solve for analytically for most functional forms of utility. In this study a methodology employing simulation and generalized stochastic dominance (Meyer) is developed to generate estimates of the value of information to irrigators under uncertainty.

Problem Statement

As a result of dwindling water supplies and increasing pumping costs, irrigators and consumers in many areas are interested in increasing the efficiency of irrigation water use. Increased efficiency could free additional water for other uses, enable greater production from irrigated agriculture, and increase net returns from irrigation thus providing benefits for consumers and irrigators.

Irrigators' objectives with respect to irrigated enterprises may include increasing expected returns and reducing the variability of returns. Uncertainty exists about the optimal timing and amount of irrigation applications to attain these objectives. Better information about soil water levels and future weather events could potentially reduce this uncertainty and improve the distribution of net returns from irrigated enterprises. The question asked in this study is, "How much could irrigators with possibly nonneutral risk preferences afford to pay for these kinds of information?"

Review of Previous Irrigation Scheduling Work

Much previous research has dealt with the question of the optimal allocation of water to irrigated enterprises. Generally researchers have recognized that the timing of water applications may be as important as how much water is applied. Thus, attention is usually devoted to estimating an economically optimal rule for scheduling irrigation (Dudek *et al*.; Swaney *et al*., 1983a). Stochastic dynamic programming (Bras and Cordova; Burt and Stauber; Zavaleta *et al*.) has been used to find an optimal decision rule for water application. Advantages of this method are: 1) it is a formal optimization method; 2) it recognizes the role of time in production; and, 3) it uses information revealed as the season progresses. A disadvantage is that the procedure is computationally cumbersome, requiring that the number of state and control variables be kept small. Also, the approach requires that a utility function be specified. A linear utility function is usually assumed.

Diverse methods are used to incorporate risk into the analysis of irrigation scheduling. Palmer et al. compared several irrigation application schedules in terms of the level of net cash returns which could be reached with a given probability. Harris et al. used first and second degree stochastic dominance while Nielson used generalized stochastic dominance (GSD) to compare several possible irrigation strategies with a conventional strategy. Boggess derived a set of efficient irrigation strategies in E-V space.

Several studies have analyzed the effect of better soil water and/or weather information on the distribution of net returns from irrigated agriculture (Dudek et al.; Nielson; Swaney et al., 1983b; Zavaleta et al.). However, none of these studies have estimated the value of soil water and weather information to the operator of a representative farm when the operator has nonneutral risk preferences.

A Conceptual Model for Estimating the Value of Information

The focus of the study is a representative crop farmer whose goal is maximization of expected utility. Utility is a function of the random variable, before-tax net income (BTNI), calculated as follows:

(3) $BTNI = (DY + IY)P + OFI - OC - PC - IC - YC$

where the variables represent dryland yields (DY), irrigated yields (IY), output prices (P), off-farm income (OFI), overhead costs (OC), production costs (PC), irrigation variable costs (IC), and yield-related costs (YC).[2] OFI, OC, and PC are assumed to be fixed regardless of weather or irrigation decisions; the remaining variables are random.

In this setting information about soil water or future weather allows the manager to improve the timing and/or amount of water applied, thus lowering IC and/or raising IY and generating a more desirable distribution of BTNI given his risk preferences. For a given level of information, a series of irrigation strategies (choices about the timing and amount of water to apply) could be followed. A search is made of several possible strategies and the strategy chosen which maximizes the value of that level of information for a given set of risk preferences. The value of information is the amount which can be deducted from each element of a BTNI distribution corresponding to information before its expected utility no longer exceeds the expected utility from a BTNI distribution generated without information. This measure of information value corresponds to V_z in equation (1).

The value of information is quantified using GSD. This approach permits comparison of BTNI distributions for a group of agents whose coefficients of absolute risk aversion lie within specified bounds over the range of outcomes evaluated. The advantage of the approach is that a specific utility function need not be assumed; rather, the analysis can be applied to as large (small) a group as desired by expanding (reducing) the absolute risk aversion interval.

The GSD methodology is extended to provide a lower bound on the estimate of the value of information; information may be worth more than this to some but not all decisionmakers characterized by absolute risk aversion coefficients in the specified interval. The lower bound on the value of information is that amount by which each element of a BTNI distribution generated with information can be lowered before it no longer dominates a BTNI distribution generated without information. The first step in calculating the value is to select a decision rule i for scheduling irrigation and to calculate the value of information V_i using this rule.

This is done by finding an amount V_i such that inequalities (4) and (5) are simultaneously satisfied.

(4) $$\int_0^1 (G(X) - F_i(X - V_i))U'(X)dX > 0$$

(5) $$\int_0^1 (G(X) - F_i(X - V_i - Y))U'(X)dX \leq 0$$

X represents BTNI; F_i and G are cumulative BTNI distributions generated with and without information, respectively; U is a von Neumann Morgenstern utility function; V_i is the value of information which generates F_i using decision rule i; and Y is a small positive amount. The restriction is imposed that agent's absolute risk aversion coefficients lie between specified upper and lower boundaries as shown in (6):

(6) $$r_2(X) \geq - U''(X)/U'(X) \geq r_1(X)$$

Initially V_i is set equal to zero to determine if $F_i(X)$ dominates G(X). If so, V_i is augmented by Y until inequalities 4 and 5 are satisfied. Finally, a search is made of a series of possible irrigation strategies and that strategy selected which maximizes the value of information as shown in (7):

(7) $$V_i^* = \max (V_i: i = 1, \ldots . n)$$

where n is the number of strategies evaluated for a given level of information. V_i^* is a lower bound on the value of information for agents whose absolute risk aversion functions over the range of income considered lie within the specified interval. The value may be higher than this for some but not all agents in that interval.

Empirical Methodology

A model of a 640-acre crop farm producing 260 acres of irrigated corn and soybeans under southwest Minnesota conditions is the setting for evaluating information. Farm costs are divided into variable costs which are presumed to be affected by weather or irrigation decisions (IC and YC) and fixed costs (OC and PC). Variable costs include electricity, lubrication, and repair charges connected with irrigation as well as crop hauling, drying, and storage costs. All other costs are presumed fixed, i.e., unaffected by the level of irrigation water applied or final yield.

Distributions of output prices are generated based on five-year price projections made by the Minnesota Agricultural Extension Service in 1983 as well as historical real price variability observed from 1958 through 1982. The distributions are used to generate 11 random prices for each crop following a procedure developed by King which takes into consideration correlations among prices for different crops in the same year.

A crop growth and yield model developed by Hill and Hanks is used to estimate yields as a function of random weather, irrigation applications, crop variety, and soil characteristics. Variations of the yield prediction equations developed by Hill and Hanks for corn and soybeans were statistically estimated using weather, irrigation, and yield data from several Minnesota sites.[3] The estimated equation for corn is (t statistics are in parentheses):

$$(8) \qquad Y_c = \underset{(78.6)}{155.6} * (T/T_p)^{\underset{(10.6)}{2.61}}$$

Y_c refers to estimated corn yield in bushels per acre, T is cumulative daily actual plant transpiration estimated by the Hill model for the tassel, silk, dough, and early dent stages, and T_p is cumulative daily potential transpiration for these stages.[4] The R-squared value for the equation is .81.

The estimated equation for soybeans is:

$$(9) \qquad Y_s = \underset{(50.6)}{49.6} * (T/T_p)^{\underset{(4.34)}{1.067}} * SYF$$

Y_s is estimated soybean yield, T and T_p are cumulative actual and potential plant transpiration for the beginning pod fill, end flowering, and physiological maturity stages, and SYF refers to soybean yield factor.[5] The R-squared value for the estimated equation is .79.

Random weather variability for analyzing the irrigation strategies is provided by 12 years of weather data from the Lamberton Experiment Station in southwest Minnesota. Each year is assumed to be an independent, equally likely outcome. Estimates of dryland crop yields for each year of weather are taken from the Lamberton Experiment Station and southwest Minnesota farm data. Each year of weather data is combined with each of the 11 output prices to make a total of 132 incomes per net income distribution.

Three levels of soil water information are analyzed. They are: 1. soil water information provided by the Checkbook method (Werner); 2. intermediate soil water information (knowledge of actual soil water levels plus or minus a uniformly distributed error not to exceed 10% of plant available soil water holding capacity); and, 3. perfect soil water information. The three levels of weather information compared are: 1. no information on either potential crop transpiration demand (Tp) or rainfall for the future; 2. knowledge of Tp for the next three days; and, 3. perfect weather information, i.e., knowledge of Tp and rainfall for the next three days. Six combinations of soil water and weather information are evaluated. They are:

1. Checkbook soil water information, no weather information
2. Intermediate soil water, no weather information
3. Perfect soil water, no weather information
4. Intermediate soil water, future Tp information
5. Perfect soil water, future Tp information
6. Perfect soil water, perfect weather information

These information levels are compared with a benchmark strategy based on very little soil water or weather information.[6]

Several irrigation decision rules are evaluated for each information level. Decision rules vary according to the actual or anticipated soil water depletion level at which irrigation is triggered.[7] The trigger level which maximizes the value of a level of information for a given set of risk preferences is selected. This search procedure is a way of approximating the necessary first order conditions for maximizing the value of information as shown in equation (2).

The value of information is analyzed for six absolute risk aversion intervals. The placement of the intervals is based on a study by Wilson of Minnesota swine producers' risk attitudes. He found that 69% of the producers with identifiable risk attitudes fell within an interval from -.0002 to +.0003. This interval is divided into three subintervals: -.0002 to -.00005, -.00005 to .0001, and .0001 to .0003. Additionally, a very risk averse interval, .0003 to .0015, a very risk seeking interval, -.001 to -.0002, and risk neutrality are included.

Results

Before-tax information values are generated on a whole farm basis. They are presented in Table 1 as per irrigated acre amounts to make them easier to interpret. The optimal irrigation strategies for each combination of risk aversion interval and level of information are presented in parentheses. For example, the expected profit maximizing strategy for the risk neutral irrigator given Checkbook information is to apply .75 of an inch of water to corn when the Checkbook shows 25% depletion of plant available soil water and .75 of an inch to soybeans when 40% depletion is indicated. Where some weather information is also available the depletion refers to anticipated depletion after three days based on the given information and assuming no irrigation.

Generally, the results show that more information has greater value.

Table 1. Before-Tax Values[a] of Selected Information Scenarios and Optimal Irrigation Strategies[b] Derived on a Whole-farm Basis

Infor-mation Level	Coefficient of Absolute Risk Aversion Interval Risk Seeking -.001 to -.0002	-.0002 to -.00005	-.00005 to .0001	Risk Neutral 0.0 to 0.0	.0001 to .0003	Risk Averse .0003 to .0015
Checkbook	0.00 --	1.00 (25/40)	2.40 (25/40)	3.68 (25/40)	14.40 (15/30)	14.40 (15/30)
Int. Soil no Weath.	0.50 (35/40)	1.40 (35/40)	3.00 (30/35)	5.04 (30/35)	15.00 (20/25)	15.00 (20/25)
Perf. Soil no Weath.	0.00 --	2.40 (30/45)	4.20 (30/45)	5.78 (30/45)	16.00 (25/40)	15.90 (25/40)
Int. Soil Fut. Tp	0.10 (40/~~5~~5) 4	2.40 (45/50)	4.40 (50/55)	6.12 (50/55)	15.70 (35/40)	15.70 (35/40)
Perf. Soil Fut. Tp	0.40 (40/55)	3.00 (45/60)	4.90 (45/60)	6.66 (45/60)	16.50 (45/60)	16.50 (45/60)
Perf. Soil and Weath.	1.00 (40/55)	4.20 (45/60)	5.60 (45/60)	6.98 (45/60)	16.30 (45/60)	16.20 (45/60)

[a] Table entries on upper line refer to values of information (1983 dollars) per irrigated acre for the absolute risk aversion coefficient interval specified above the column. The value of an information level is the amount by which each element of its before-tax net income distribution can be lowered before it no longer dominates the distribution derived with the benchmark strategy.

[b] Figures in parentheses denote the percentage depletion level at which irrigation is initiated for corn/soybeans. Where no weather information is available, the trigger level refers to soil water depletion. Where some future weather information is assumed, the trigger level refers to the depletion level to which soil water levels would fall over the next three days given the available weather information and given that no irrigation occurs.

However, perfect information does not seem to offer a high potential payoff relative to what can be gained with existing information systems. The results for the risk neutral case are discussed first.

Risk Neutrality and the Value of Information

The expected return to perfect soil water and weather information is $6.98 per acre. The Checkbook information system yields an expected return of $3.68 per acre or about 53% of the return to perfect information. Perfect soil water information alone generates an expected return of $5.78 or 83% of the expected return to perfect information. According to these results, a large share of the return to perfect information can be gained by soil water information alone. Soil water information is site specific and, therefore, has the characteristics of a private good. Its economic return is maximized at the point where its expected marginal return to the producer equals its marginal cost. Weather information, by contrast, displays characteristics of a public good (Henderson and Quandt, pp. 298-302) meaning that its use by one producer does not preclude its use by others. Therefore, its marginal social return exceeds its marginal private return and, if left to individual producers, too little of such information would be produced. The finding that soil water information gives a large fraction of the total gain from information implies that, given better information-producing technology, profit maximizing irrigators will have the incentive to exploit the optimal amount of a large part of such information.

The finding that weather information generates a small fraction of potential returns to perfect information need not imply that research on ways to produce better weather information would have a low rate of return. The return might be high if the per acre cost of producing better weather information were low and it could be applied to many acres.

The analysis shows that it does not pay to sacrifice yields to conserve water and lower pumping costs.[8] Rather, at all levels of information, strategies which keep yields near a maximum are preferred. Thus, better information yields a return because it enables the irrigator to maintain near maximum yields with less water and lower pumping costs.

Risk Preferences and the Value of Information

The results in Table 1 show the value of information to be sensitive to risk preferences. For example, individuals in the most risk seeking interval would not pay anything for Checkbook information, while the risk neutral producer could afford to pay $3.68, and individuals in the most risk averse interval could pay $14.40 per acre. The other information levels show similarly large increases in value with risk aversion. This trend appears to be largely due to the value of information in 1976, a drought year in Minnesota. Irrigating with the benchmark, no information strategy leads to reduced yields in 1976. These yield reductions are partially prevented by irrigating with information and following the decision rule which makes the best use of that information. So because information does the best job of increasing income in the very dry year, 1976, and because income is already very low then due to low yields from unirrigated crops, information value increases with risk aversion. When 1976 is left out, the tendency for information value to increase with risk aversion disappears.

The relationship of information value to risk attitudes is also sensitive to the scale of analysis. The results in Table 1 are derived on a whole farm basis, in recognition of the fact that better information for irrigation will alter the distribution of net income from the whole farm. The analysis could be completed at the enterprise level if returns from the irrigated enterprise are independent of returns from other parts of the farm business.[9] Contrasting the results at the enterprise level with those at the whole farm level illustrates the importance of evaluating results at the whole farm level when independence does not exist.

The results derived at the enterprise level are shown in Table 2. They are similar to the results derived on a whole farm basis in that information value increases with risk aversion. However, information value varies less by risk aversion on an enterprise basis. For example, on a whole farm basis the value of Checkbook information varies from 0 to $14.40 per acre as risk aversion increases. This compares with a variation from $2.60 to $5.60 when the analysis is done for the 260-acre irrigated enterprise alone. The reduced range of information value follows because income varies less at the enterprise level than at the whole farm level where uncertainty about unirrigated crop yields adds to income variability. The reduced income variability means that improvements in the lowest incomes due to information have less value to the risk averse irrigator at the enterprise level than they would have at the whole farm level.

More years of weather data[10] might help to stabilize the estimated payoff from information in the highest (lowest) income years. This in turn would stabilize the estimated value of information by degree of risk aversion. However, even if a very stable relationship could be estimated, it seems likely that the value estimated at the enterprise level would understate the value at the whole farm level. This would be true if, as was found in this study, information reduces income variability and increases the lowest income. Then, the greater variability of income at the whole farm level caused by the uncertainty of unirrigated crop yields would mean information value would be higher when derived at the whole farm level.

Irrigation water is traditionally thought of as a risk reducing input meaning that greater risk aversion should cause one to use more water. Table 1 provides some support for that view as for four of the six information levels irrigation is

Table 2. Values of Selected Information Scenarios[a] and Optimal Irrigation Strategies[b] Derived on an Irrigated Enterprise Basis

	Coefficient of Absolute Risk Aversion Interval					
	Risk Seeking			Risk Neutral		Risk Averse
Information Level	-.001 to -.0002	-.0002 to -.00005	-.00005 to .0001	0.0 to 0.0	.0001 to .0003	.0003 to .0015
Checkbook	2.60 (25/40)	2.90 (25/40)	3.30 (25/40)	3.68 (25/40)	3.90 (25/40)	5.60 (15/30)
Int. Soil no Weath.	3.30 (30/35)	4.10 (30/35)	4.70 (30/35)	5.04 (30/35)	5.30 (30/35)	7.00 (30/35)
Perf. Soil no Weath.	4.30 (30/45)	4.90 (30/45)	5.40 (30/45)	5.78 (30/45)	6.00 (30/45)	7.70 (30/45)
Int. Soil Fut. Tp	4.70 (50/55)	5.20 (50/55)	5.80 (50/55)	6.12 (50/55)	6.30 (50/55)	8.00 (50/55)
Perf. Soil Fut. Tp	5.10 (45/60)	5.80 (45/60)	6.30 (45/60)	6.66 (45/60)	6.80 (45/60)	8.50 (45/60)
Perf. Soil and Weath.	5.90 (45/60)	6.20 (45/60)	6.60 (45/60)	6.98 (45/60)	7.00 (45/60)	8.50 (45/60)

[a] Table entries on upper line refer to values of information (1983 dollars) per irrigated acre for the absolute risk aversion coefficient interval specified above the column. The value of an information level is the amount by which each element of its before-tax net income distribution can be lowered before it no longer dominates the distribution derived with the benchmark strategy.

[b] Figures in parentheses denote the percentage depletion level at which irrigation is initiated for corn/soybeans. Where no weather information is available, the trigger level refers to soil water depletion. Where some future weather information is assumed, the trigger level refers to the depletion level to which soil water levels would fall over the next three days given the available weather information and given that no irrigation occurs.

started sooner (lower depletion) for the risk averse irrigator than for the risk neutral irrigator. This translates into a somewhat higher expected seasonal irrigation application. However, the largest expected increase from risk neutrality to risk aversion is only 12% for the intermediate soil, future Tp information scenario. When the analysis is done on an enterprise basis, the preferred irrigation strategy generally does not vary by risk aversion. This reflects the reduced income variability on an enterprise basis and, hence, the lesser importance to the risk averter of a strategy which maximizes the lowest income as opposed to a strategy which maximizes expected income.

Summary and Conclusions

Increasing irrigation efficiency could benefit producers and consumers by saving water for other uses and/or leading to more output from irrigation water. Irrigation efficiency can be increased by providing the irrigator with better soil water and weather information. In this study results from irrigating with six combinations of soil water and weather information are compared with results from using a benchmark strategy, which is based on little information.

The analysis shows that, while better information has a higher value, it is subject to diminishing returns. Further, the benefits of better information relative to that which is already available to irrigators do not appear to be large. In the risk neutral case over 50% of the returns from perfect information is provided by the Checkbook method, which is currently recommended by the Minnesota Agricultural Extension Service. Perfect soil water information alone provides about 83% of the increased return from soil water and weather information.

Another finding is that it does not pay to sacrifice yield in order to save water and lower pumping costs. For all levels of risk aversion the preferred strategies are those which keep expected yields near a maximum. The value of information stems from its ability to maintain these yields with less water and pumping costs.

The value of information increases significantly with risk aversion. However, this finding is sensitive to inclusion of 1976, a drought year. Also the amount of variation in value by degree of risk aversion depends on the scale of analysis. Restricting the analysis to the irrigated enterprise alone reduces overall income variability and, thus, diminishes somewhat the increased value of information for risk averters.

More research could help substantiate the relationship between risk aversion and value of information. If more years of weather data were available, the value of information to the risk averter (seeker) might be less sensitive to deletion of the weather year producing the worst (best) income. Also more investigation of actual irrigation practices along with elicitation of irrigator risk preferences might reveal variations in strategies followed by irrigators who schedule with relatively little soil water or weather information. This might facilitate a more accurate estimate of information value, especially for risk averse agents.

The results reported here are dependent on the climatic patterns, crops, irrigation technology, and costs assumed. Thus they cannot be extended to other areas of the country where conditions are different without further research. However, the results for the risk neutral irrigator appear similar to those reported by Zavaleta _et_ _al_. and Dudek _et_ _al_. Zavaleta found that perfect weather information could increase expected returns to sorghum irrigators in the Texas High Plains by slightly over $10 per acre compared with $6.98 found in this study. Dudek found that for surface irrigators in Idaho elasticity of demand for an irrigation scheduling service based on perfect soil water information exceeded one when the price rose to $5.00 per acre. In this study scheduling with perfect soil water information increases expected returns by $5.78 per acre.

Research on the costs of providing the kinds of information evaluated in this study would be useful. The findings from such research would help irrigators and those advising them to determine the optimal amount of information to utilize in their operations.

The focus of this study is on the distribution of net returns for one year meaning the possibility of learning from one year to the next is ignored. A useful extension would be to evaluate information in a multiyear setting where learning is possible (Chavas and Pope; Grossman et al.). In that case information might facilitate learning and improve the ability to manage the system in later years as well as leading to a more desirable distribution of immediate outcomes. When future earnings are discounted, the number of years required after acquiring the irrigation system to achieve maximum scheduling efficiency is important because earnings from the early years of system operation are discounted the least. Information could produce substantial benefits by shortening this learning period.

Footnotes

[1] The notation of Byerlee and Anderson has been altered.

[2] The analysis reported here evaluates information on a before-tax basis, implicitly assuming that expenditures for information are tax deductible. The effects of taxes on the value of information have been reported elsewhere (Bosch).

[3] More details concerning the estimation procedure can be found in Bosch.

[4] Potential crop transpiration is the daily amount of water the plant can give off to the atmosphere if soil water is not limiting.

[5] SYF penalizes yield in years when seasonal transpiration is below a minimum required for dry matter accumulation. SYF is calculated as follows: SYF = $(T/10.0)^{1.6}$ where T is actual transpiration for the entire season. SYF is constrained to be less than or equal to 1.0. The parameters used for SYF are taken from Hill and Hanks.

[6] The benchmark strategy was devised in consultation with extension irrigation engineers and researchers familiar with irrigation practices in Minnesota.

[7] Irrigation applications consisted of .75 of an inch effective water.

[8] Pumping costs are calculated to be $1.94 per effective acre inch of water where the system is assumed to operate at 85% efficiency. In addition an electricity "demand" charge of approximately $295 is imposed for each calendar month in which the system operates.

[9] Nonirrigated enterprises are important to irrigation as indicated by 1982 Census of Agriculture statistics showing that, for all Minnesota farms with irrigated enterprises, the average farm size was 501 acres and the average amount of irrigated land, 145 acres.

[10] Twelve years of the required daily weather data needed for the crop simulation model are available for the study area.

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