Analysis of the adoption of irrigation technologies under uncertain water availability

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ANALYSIS OF THE ADOPTION OF IRRIGATION TECHNOLOGIES UNDER UNCERTAIN WATER AVAILABILITY

Abstract

This paper analyses the adoption process of water-conserving irrigation technologies by a risk averse farmer in a context of uncertain water availability. Firstly, it is analytically shown that the increase in water efficiency that the new technology allows results in a decrease in the cost of the effective irrigation water applied, as well as in an increase in both effective water applied and crop production. It is also concluded that the optimal amount of irrigation water applied depends on individual risk preferences of the producer, on the variance and asymmetry of the cost of water applied, and on the elasticity of the marginal productivity of the effective water applied. Lastly, it is theoretically shown that an increase in the level of uncertainty regarding water availability incentives the adoption of modern irrigation technologies only if this allows for a reduction in the amount of water applied.

Keywords: irrigation technology, adoption, risk, water availability
JEL Classification: Q25, Q12, D81

1. Introduction

The important role that more efficient irrigation technologies play in environmental resources conservation explains the increasing attention that the identification and analysis of the factors that determine their adoption have received in the field of Agricultural Economics. During the last two decades, numerous studies have tried to analyse which farmer, agro-climatic, institutional and socio-economic variables determine the adoption of these irrigation technologies.

Many authors argue that the diffusion and adoption process of new irrigation technologies will be relatively slow in absence of appropriate reforms in water policies. This argument is based on the general belief that farmers apply water in excess of crop requirements because they do not perceive restrictions in water supply. The reasons are the large water allotments allocated to farmers that use surface water and the excessive institutional protection over agricultural water use rights, both legally (through the preference given to agricultural uses over other uses except domestic ones) and economically (through subsidised water prices). Authors such as Caswell et al. (1990), Dinar y Letey (1991), Varela-Ortega et al. (1998) and Moreno and Sunding (2001) have theoretically studied different policy options as an instrument to encourage the adoption of water-conserving irrigation technologies.

However, the literature of irrigation technology adoption has paid little attention to the fact that the use in excess of irrigation water is not only explained by the fact that farmers do not perceive water scarcity, but also because water is a risk-reducing input (Boggess et al., 1993) and because farmers are usually risk-averse (Anderson et al., 1977). In general, a risk-averse producer will use a greater amount of a risk-reducing input than a risk-neutral or risk-loving producer. Therefore, risk-averse farmers can be expected to develop crop schedules and farm plans that involve water applications that exceed the net water requirements of crops, aiming to prevent plants from water stress and to reduce the variability of yields.

In the case of uncertainty in water availability, a risk-averse producer will allocate water less intensively, as analytically shown by Howitt and Taylor (1993). A farmers can rely on several strategies to cope with water supply uncertainty: using alternative supply sources such as groundwater (when available); increasing irrigation water efficiency through improvements in the management of the irrigation system or through the adoption of more efficient new irrigation technologies; changing to less water demanding crops; and reducing the irrigated area.

This paper adds to the existing literature on the adoption of irrigation technologies by theoretically analysing the decision process of the adoption of new irrigation technologies for a risk-averse farmer under uncertain water availability. The most direct precedent is the paper by Moreno and Sunding (2001) that analyse the impact of uncertainty in water price on the adoption of irrigation technologies.

First, a model of the decision process of a risk-averse producer regarding the adoption of water conserving irrigation technologies in a context of uncertain water availability has been formulated. Once the decision model is specified, it is used to analyse the influence of water supply uncertainty on the choice of irrigation technologies.

2. Methodology

Feder and Umali (1993), that revise the literature on the adoption of agricultural innovations, classify the existing models of farmer decision making under uncertainty in four categories:

- Models based on the expected utility theory;
- Safety-first algorithms;
- Bayesian models that allow to incorporate farmer’s experience and the process of learning to use the new technology;
- Farm programming models that incorporate constraints in the variability of some decision variables, such as land availability, land quality or financial credit.

However, these methods do not allow to incorporate the problem of investment under irreversibility and uncertainty. Purvis et al. (1995) are the first to incorporate it in the modelling of decisions regarding the adoption of agricultural technologies.

The above methods for decision analysis allow to evaluate the optimal decision for a rational decision-maker in a context of uncertainty. The most adequate method depends on the nature of uncertainty affecting the decision process, the number of options available for the decision-maker, and his preferences regarding risk (Hardaker et al., 1997). We have opted here to use the Expected Utility Theory (EUT) that is an adequate methodological framework for the intended theoretical analysis.

The individual decision process regarding the adoption of irrigation technological innovations is modelled using a microeconomic decision model similar to the one proposed by Caswell et al. (1990). Such model is a static one, in which the planning decisions regarding production activities are taken for the on-going agricultural season (that is, in the short run) and for a single annual crop.

We extend the deterministic model by Caswell et al. (1990) by incorporating uncertainty. The model proposed here maximises the expected utility of profit, expressed as a function of the three first moments of the probability distribution of profit as a Taylor series polynomial expansion. It is assumed that the producer maximises his expected utility in a two-step procedure. On a first stage, the farmer decides the optimal amount of water to be applied to the crop for each irrigation technology. Once the farmer has decided the optimal amount of water applied for each technology, the choice of the optimal irrigation technology will depend on the relative profitability of each technology. The producer will choose that technology that generates a greater level of the expected utility of profit.

Once the decision model has been specified, and the first-order conditions for expected utility maximisation have been obtained, a comparative static analysis over such conditions is used to study the influence of water supply uncertainty on the adoption of irrigation technologies.

3. Results

An utility function expressed as a function of the first three moments of the profit probability distribution can be approximated by a Taylor Series polynomial development as (Anderson et al., 1977):

$$U(\pi) = U[E(\pi)] + \frac{1}{2}U''[E(\pi)]\,V(\pi) + \frac{1}{6}U'''[E(\pi)]\,M_3(\pi) \tag{1}$$

where profit depends on the amount of irrigation water applied, $\pi = \pi(a)$. In our optimisation problem it is assumed that the farmer can only use the amount of irrigation water he is entitled to in his administrative concession. However, in most irrigation districts, the real water allotment available for the farmer, *D*, is below the volume of water allocated to him in his water concession, as irrigation districts have different levels of water supply reliability. That is, it is assumed that final water availability for the farmer, *D*, is a random variable.

Therefore, as the utility function of profit can be approximated as a function of the first three moments of the profit probability distribution, the objective function in our optimisation problem can be expressed as:

$$Max\; u[\pi(a)] = u[E[\pi(a)], V[\pi(a)], M_3[\pi(a)]] \tag{2}$$

Taking first derivatives with respect to the decision variable, *a*, we obtain the first order condition for expected utility maximisation as:

$$\frac{dU}{da} = \frac{\partial U}{\partial E(\pi)}\frac{dE(\pi)}{da} + \frac{\partial U}{\partial V(\pi)}\frac{dV(\pi)}{da} + \frac{\partial U}{\partial M_3(\pi)}\frac{dM_3(\pi)}{da} = 0 \tag{3}$$

Dividing equation (3) by $\frac{\partial U}{\partial E(\pi)}$, we obtain equation (4):

$$\frac{dE(\pi)}{da} + \frac{\partial U/\partial V(\pi)}{\partial U/\partial E(\pi)}\frac{dV(\pi)}{da} + \frac{\partial U/\partial M_3(\pi)}{\partial U/\partial E(\pi)}\frac{dM_3(\pi)}{da} = 0 \tag{4}$$

That can be written as:

$$\frac{dE(\pi)}{da} - REDQ\frac{dV(\pi)}{da} - MSQ\frac{dM_3(\pi)}{da} = 0 \tag{5}$$

where $REDQ = -\partial U/\partial V(\pi)/\partial U/\partial E(\pi)$ is called the "Risk Evaluation Differential Quotient", and measures the quotient among marginal utility of the variance of profit and marginal utility of mean profit. As marginal utility of profit is positive for a risk averse producer, while marginal utility of the variance of profit is negative, *REDQ* will be positive. $MSQ = -\partial U/\partial M_3(\pi)/\partial U/\partial E(\pi)$ is called the

"Marginal Skewness Quotient", and measures the quotient between marginal utility of the third-order moment of profit and marginal utility of expected profit. For a risk averse producer, the marginal utility of $M_3(\pi)$ will be positive. The more positive skewness of profit is, the probability of occurrence of lower levels of profit will get reduced, ceteris paribus. Therefore, if $\partial U/\partial M_3(\pi)>0$, then $MSQ<0$ for a risk averse producer.

Farm profit for a given technology, i, and a given land quality, α , can be expressed as:

$$\pi_{i,\alpha}(a) = P \cdot q\left(h_i(\alpha) \cdot a\right) - a \cdot C_i - CF_i \tag{6}$$

where P is output price; a is the amount of irrigation water applied per hectare; $h_i(\alpha)$ is irrigation efficiency; $q\left(h_i(\alpha) \cdot a\right)$ is the crop-water response function; C_i are variable costs associated with irrigation water applied; CF_i are fixed costs that do not depend on water application for a given technology i.

In order to simplify the analysis let us consider only two technologies: a traditional one for which the technological variable i equals 0, and a modern one for which i equals 1. Land quality, α , can take values between 0 and 1, both inclusive. Water application efficiency $h_i(\alpha)$ depends on both irrigation technology and land quality. It is also assumed that for land quality values less that one, $\alpha<1$, water application efficiency for the new technology is greater than for the traditional one. Irrigation effectiveness allows to differentiate between two different concepts, the amount of irrigation water applied and the effective irrigation water (the amount of irrigation water really taken up by the used by the crops' root system).

Let us also assume that a single crop is produced with a constant returns to scale technology, and that the production function depends only on effective irrigation water. In this case, the Hexem and Heady (1978) quadratic production function is used. It has all the properties of a Neo-Classical production function, that is, concavity and a zero intercept value ($f(0)=0, f'(.)>0,\ f''(.)<0$).

To further simplify, let us assume that both variable and fixed costs do not depend on land quality. Let us also assume that the variable cost of water coincides with its shadow price or opportunity cost. As we have previously assumed that water availability is a random variable, its shadow price will also be a random variable (Howitt and Taylor, 1993).

On the other hand, let us assume that fixed costs incorporate the annual cost of investment in irrigation technology i, as well as the costs of labour and other inputs that do not depend on the amount of water applied. It is therefore assumed that, for a given technology i, those inputs other than water are used in a fixed amount that is independent of applied irrigation water, and can be considered fixed. Fixed costs do not incorporate land rent. It is also assumed that the investment costs associated with the adoption of a modern and more efficient irrigation technology are higher than the investment costs of a more traditional irrigation technology ($CF_1 > CF_0$).

From the expression of farm profit (6), the mathematical expectation, the variance and the third-order moment of the probability distribution of profit are calculated. Differentiating them with respect to the decision variable, a, equations (7), (8) and (9) are respectively obtained.

$$\frac{dE\left[\pi_{i,\alpha}(a)\right]}{da} = P \cdot q'\left(h_i(\alpha) \cdot a\right) \cdot h_i(\alpha) - E(C_i) \tag{7}$$

$$\frac{dV\left[\pi_{i,\alpha}(a)\right]}{da} = 2\,a \cdot V(C_i) \qquad (8)$$

$$\frac{dM_3\left[\pi_{i,\alpha}(a)\right]}{da} = -3\,a^2 M_3(C_i) \qquad (9)$$

Substituting (7), (8) y (9) in equation (5) and rearranging we get the following equation (10), that results from the first order condition for expected utility maximisation.

$$P \cdot q'(h_i(\alpha) \cdot a) = \frac{E(C_i) + 2a\ \ REDQ \cdot V(C_i) - 3a^2 MSQ \cdot M_3(C_i)}{h_i(\alpha)} \qquad (10)$$

Note that equation (10) implies that, when water availability is uncertain, and for a given land quality and irrigation technology *i*, the optimal amount of irrigation water to be applied is that for which the marginal value product of the effective water equals the perceived marginal cost of applying it. This result coincides with the condition for the optimal resource allocation in neoclassical economic theory.

However, the stochastic nature of the resource availability implies that the optimal decision taken by a risk averse producer differ from those that would be taken in a certain environment. Such decisions depend on the individual risk preferences of the producer (characterised by *REDQ* y *MSQ*), as well as by the level of uncertainty he is exposed to (represented by the variance and third-order moment of the unitary cost of irrigation water). This result is similar to that of Calatrava (2002), that do not consider irrigation technology in his analysis, and therefore considers the marginal value product of applied irrigation water instead of the marginal value product of the effective irrigation water.

As $REDQ > 0$ and $MSQ < 0$ for a risk averse producer, the numerator in equation (10), that is, the marginal cost of applied water, will be greater or smaller than the expected shadow price of the resource $E(Ci)$ depending on the sign and value of the third-order moment of the probability distribution of the shadow price of the irrigation water applied, $M_3\,(C_i)$, that is, the asymmetry of the cost of water applications. If the marginal cost of applied water is greater than the expected shadow price of water the risk averse farmer will use less water than when availability is certain. On the contrary, if it is smaller, he will apply more irrigation water.

When the probability distribution of the marginal water cost is symmetric, that is, $M_3\,(C_i) = 0$, a risk averse producer will apply less water in the optimum than when availability is certain. The more variable is the cost, the less water will be used by the farmer. When the probability distribution of the cost of water is asymmetric, either positive ($M_3(C_i)>0$) or negative ($M_3(C_i)<0$), and the expression $2a\ REDQ\ V(C_i) > 3a^2\ MSQ\ M_3(C_i)$ holds, the farmer will also apply less water.

On the other hand, if the water cost is negatively asymmetrical ($M_3(C_i)<0$) and the expression $2a\ REDQ\ V(C_i) < 3a^2\ MSQ\ M_3(C_i)$ holds (either because *MSQ* is very negative due to a high level of risk aversion, or because the asymmetry is very negative[1]), then the producer will use more irrigation water than when its availability is certain.

From equation (10) it can also be concluded that the adoption of a more modern and efficient irrigation technology allows for a reduction in the cost of the effective irrigation water. In the

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[1] However, the empirical probability distributions of water availability are usually very negatively asymmetrical, what results in probability distributions of the shadow price of water that are very positively asymmetrical.

economic range of production where the allocation of water is efficient (phase II in the classical economic theory of production), marginal productivity of water is decreasing. With a decreasing marginal productivity of water, the decreasing cost of effective water (due to increased irrigation efficiency) results in an increase in both the output produced and the optimal amount of effective irrigation water. However, an increased in the effective water does not mean that irrigation water applied is increased. It may happen that irrigation water applied, and therefore demanded, be reduced or that it be increased.

Although the effects of an increase in irrigation efficiency over the amount of irrigation water applied are ambiguous, they depend on the specific characteristics of the production technology. Caswell and Zilberman (1986) show that the adoption of a more efficient irrigation technology results in water savings depending on the elasticity of the marginal productivity of the effective water (*EMP*), that can be expressed as:

$$EMP \equiv -f''(e) \cdot e / f'(e) \tag{11}$$

For a given technology and land quality, the own-price elasticity of the water demand function is the inverse of the *EMP* (Caswell et al., 1990). In the economic range of water allocation, *EMP* is positive and increasing with the amount of effective water. According to Caswell et al (1990), for the adoption of a more efficient irrigation technology to result in water savings, the following condition (12) must hold:

$$EMP^* = 1 - \left[\frac{u_0^a - u_1^a}{u_0^a}\right]\left[\frac{h_0}{h_1 - h_0}\right] < 1 \tag{12}$$

where u_i^a is the cost of water application with technology *i*.

For the adoption of a new technology to reduce water consumption, two conditions must hold. First, condition (12) must hold, what means that *EMP** should be less than one, that is inelastic, in order to allow for a reduction in water consumption. Condition (12) implies that water demand should be elastic. Second, the *EMP* should be greater than *EMP**, that is, the *EMP* of water should not be too low, that is the own-price elasticity of water should not be too high. These conditions hold under many circumstances, except when the marginal productivity of water increases with effective water.

As previously commented, once the farmers has calculated the optimal amount of water to be applied for each irrigation technology, then the choice of irrigation technology depends on the relative profitability of each technology. The producer will choose that technology that allows him to maximise his expected utility of profit. If a^* is the optimal amount of water to be applied, then the expected utility maximising profit for the *i* technology and a given land quality, α , will be given by the following equation:

$$\pi_{i,\alpha}(a^*) = P \cdot q\left(h_i(\alpha) \cdot a^*\right) - a^* \cdot C_i\left[E(C_i); V(C_i); M_3(C_i)\right] - CF_i \tag{13}$$

It is not possible to analytically establish a-priori whether a more efficient technology is also more profitable for a farmer. It may happen that the gains from an increase in irrigation efficiency and a reduced consumption of other non-water inputs be offset by the costs of the investment in the new technology. It is therefore necessary to empirically analyse each specific case and circumstances to compare the profitability of the alternative technological options.

Equation (13) represents the value of profit in the optimum. In that equilibrium point, the marginal value of applied water equals the marginal costs of applying water, $\overline{C_i}$, that is given by the following equation:

$$\overline{C}_i = E(C_i) + 2a^* \cdot REDQ \cdot V(C_i) - 3(a^*) \cdot MSQ \cdot M_3(C_i) \tag{14}$$

In the equilibrium, a change in the level of risk will result in changes in the expectation, variance and asymmetry of the cost of applied water, and a new equilibrium and a different level of profit will be reached. To analyse the effect of changes in the level of uncertainty regarding water availability on the choice of irrigation technology, a comparative statics analysis is performed with equation (13). Calculating the partial derivatives of the optimal profit for technology *i* (equation 13) with respect to the expectation, variance and asymmetry of the marginal cost of applied water in the optimum, $\overline{C_i}$, the following equations are obtained:

$$\left[\frac{\partial \pi_i^*}{\partial E(C_i)}\right]_{C_i=\overline{C}_i} = -a^* \tag{15}$$

$$\left[\frac{\partial \pi_i^*}{\partial V(C_i)}\right]_{C_i=\overline{C}_i} = -2(a^*)^2 \cdot REDQ \tag{16}$$

$$\left[\frac{\partial \pi_i^*}{\partial M_3(C_i)}\right]_{C_i=\overline{C}_i} = 3(a^*)^3 \cdot MSQ \tag{17}$$

As a^* is positive, and as *REDQ>0* and *MSQ*<0 for a risk averse producer, then the following conditions hold:

$$\left[\frac{\partial \pi_i^*}{\partial E(C_i)}\right]_{C_i=\overline{C}_i} < 0 \tag{18}$$

$$\left[\frac{\partial \pi_i^*}{\partial V(C_i)}\right]_{C_i=\overline{C}_i} < 0 \tag{19}$$

$$\left[\frac{\partial \pi_i^*}{\partial M_3(C_i)}\right]_{C_i=\overline{C}_i} < 0 \tag{20}$$

From equations (18), (19) and (20), it can be concluded that increases in the expectation, variance or asymmetry of the random cost of applied water will result on a reduction in the maximum profit achievable for a given technology *i*.

When the adoption of a more efficient irrigation technology results in a reduction of the amount of water applied, then $a^*_0 > a^*_1$. Then the reduction in the optimal profit as a result of increases in the level of uncertainty will be smaller with the more efficient technology. The adoption of efficient irrigation technologies reduces the adverse economic effects of increases in water supply risk. An increase in the uncertainty regarding water availability will therefore incentive the adoption or more efficient irrigation technologies if such adoption reduces water consumption. However, if the new technology does not result in water savings, the adoption will not be encouraged.

4. Conclusions

First, it has been theoretically shown that, for a given irrigation technology and a certain land quality, the optimal amount of irrigation water applied under uncertain water supply is that which equals the value of the marginal productivity of effective water and the perceived random cost of effective irrigation water. This result coincides with the condition for optimal resource allocation in neoclassical economic theory.

It has also been demonstrated that the increase in irrigation efficiency that the adoption of a new technology allows for results in a decrease in the cost of the effective irrigation water applied, what causes an increase in agricultural output and in the optimal amount of effective water applied.

However, it can not be asserted whether the technology adoption will result in an increase or a decrease in the amount of irrigation water applied, that is, in the amount of water demanded by the farmer. On one hand, the stochastic nature of water availability implies that the optimal allocation of irrigation water by a risk-averse farmer depends on his individual risk preferences, as shown by Calatrava (2002). Such preferences can be characterised by the Risk Evaluation Differential Quotient (REDQ) and the Marginal Skewness Quotient (MSQ). The optimal allocation of water also depends on the variance and asymmetry of the random cost of irrigation water. On the other hand, as shown by Caswell y Zilberman (1986), the irrigation technology adoption will reduce water use only if the elasticity of the marginal productivity of the effective water applied is less than one, that is, inelastic. This implies that water demand should be elastic in order to save irrigation water through the adoption of more efficient technologies.

It has also been shown that if a new irrigation technology results in a decrease in the amount of water applied, an increase in water supply uncertainty will incentive the adoption of such technology. On the contrary, if water applied increases with the new technology, an increase in uncertainty would discourage its adoption.

Lastly, it has to be pointed out that it is not possible to theoretically establish whether a modern and more efficient irrigation technology is more profitable for a farmer than a traditional one. It may happen that the investment costs in the new technology do not compensate gains due to increased irrigation efficiency and decreased variable costs. An empirical analysis should therefore be required to compare the profitability of irrigation technologies under each particular condition.

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