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## Input use and capacity constraint under uncertainty: The case of irrigation

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Constraint under Uncertainty:  
The Case of Irrigation**

Philippe Bontems and Pascal Favard  
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# **Input Use and Capacity Constraint under Uncertainty: The Case of Irrigation**

## **Summary**

In this paper we consider a two periods model of cropping using irrigation. The farmer takes two kind of decisions, one related to the level of investment in irrigation capacity and the other one to the irrigation level in each period. In the first period, decisions are taken under uncertainty on the rainfall level which is resolved at the beginning of the second period. Assuming a CARA utility function, we show that taxing the investment may entail an increase in preventive irrigation although the investment decreases. Moreover, in the case of a logistic production function, the total water use is non monotonic with respect to the price of investment. Indeed, taxing capital may induce the farmer to increase the total level of irrigation although the irrigation capacity decreases. Surprisingly, the impact of an increase of water price is generally ambiguous even assuming risk neutrality.

**Keywords:** Irrigation, investment, uncertainty and risk aversion

**JEL:** D8, Q15

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# 1 Introduction

Uncertainty and risk play a huge role in agricultural production and especially on input choices. It is well-known, for example, that rainfall uncertainty induces the farmer to have a self-insurance behavior. Uncertainty leads him to invest in irrigation capital in order to prevent yield losses due to plant hydric stress. Many techniques are available to provide additional water to the plant such as flat irrigation or sprinkler irrigation. The cost of capital usually prevents the farmer to choose the stock of capital which renders him insensitive to the risk. This level of stock would be the one that provides the exact quantity of water to the plant at the right time such that the weather uncertainty has no impact on the farmer's objective. Of course, this corner solution is barely the optimum for the farmer due to the cost of this investment. This under-investment has a direct effect on the irrigation pattern. Because the level of capital is not sufficient to bring water at the right level or\and on all the cropping surface it could be optimal for the farmer to make preventive irrigation. Indeed soils have more or less the physical property to store water called field capacity. Ex-post this preventive supply may be too important and so the farmer has wasted water.

During the last years the number of water usage conflicts has considerably increased. This leads decision makers to limit water wastage. In order to restore the property rights on water usage the economist usually advocates for market. This kind of market already exist for water consumption by firms and households. These consumers require a given water quality and it is compulsory for them to buy water from a provider. There quantities are usually individually observable. As irrigation is less demanding in term of water quality, farmers usually have their own harnessing. This implies for the planner a tremendous cost of observability

of the consumption level. This cost of observability may induce large distortions in the optimal policy of water regulation. One solution for reducing regulation costs is to use indirect instruments: instead of water quantities the planner may choose to regulate irrigated surfaces or the level and/or the nature of the irrigation investment.<sup>1</sup> We call the decision to irrigate before knowing the rainfall level as *preventive irrigation*. Similarly let us call *curative irrigation* the level of water use after the revelation of information. If the level of preventive irrigation appears to be too high ex-post then farmers overuse water resources, as indicated above. The cost of capital leads farmers to under-invest that constraints the level of curative irrigation. To alleviate this constraint farmers may use preventive irrigation. Whatever their attitude towards risk this trade-off applies. When farmers are risk averse income effect obviously complicate this trade-off.

In order to highlight these points we consider a two periods model of cropping. The farmer has to take two kinds of decision, one related to the level of investment in irrigation capacity and the other to the level of irrigation. The uncertainty on the rainfall level is resolved at the beginning of period two. So when the farmer irrigates in period one he makes preventive irrigation and when he makes it in period two it is curative irrigation. Note that the farmer could irrigate one or two times an acre.

Assuming a CARA utility function, we show that taxing the investment may entail an increase in preventive irrigation although the investment decreases. Moreover, using a logistic production function, the total water use is non monotonic with respect to the price of investment. So taxing capital may induce the farmer to increase the total level of irrigation despite that the irrigation capacity de-

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<sup>1</sup>Another way to increase water use efficiency in agriculture is to promote adoption of new and more efficient irrigation technologies through water price reforms (see Green et al., Caswell and Zilberman). Note that here we are interested in analysing the level of investment in irrigation and not the particular technology adopted.

creases. One instrument for the decision maker in order to reduce the water consumption could be to tax the investment if the level of preventive irrigation is constrained or if there is no preventive irrigation at all. On the contrary when the level of preventive irrigation is positive and not constrained the decision maker should subsidy the irrigation investment. More surprising is the impact of an increase of water price which is generally ambiguous even assuming risk neutrality.

Our model is closely related to the literature on the impact of production risk on input decisions by a competitive firm (e.g. Feinerman et al., Ramaswami, Loehman and Nelson or more recently Roosen and Hennessy).<sup>2</sup> There, the main goal is to analyze the impact of uncertainty and risk aversion on inputs choices and especially to compare farmer's behaviors under risk neutrality and risk aversion. The different inputs can usually be freely adjusted from farmer's point of view. Here, we have basically two inputs, water use and irrigation capacity and the key feature of our model is that water use is constrained by the level of irrigation capacity in each period. This special relationship between inputs has not been analyzed in the literature up to our knowledge.

This paper proceeds as follows. Section two is devoted to the model and to the benchmark case of no uncertainty. The impact of the cost of capital is analyzed in section three while section four is devoted to the impact of water price. The last section concludes. All proofs are collected together in the appendix.

## 2 The model

Let us consider a homogeneous field of size unity. On this field the farmer crops a plant which needs a certain amount of water. If the level of rainfall is not sufficient

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<sup>2</sup>Not to mention the more general work of Chambers and Quiggin using the state-contingent approach.

the farmer can invest in capital in order to provide additional water to the plant by irrigation. Our model is a two-periods one where the farmer has to take three decisions. At the beginning of the first period the farmer chooses  $K$  the maximal level of water that he could bring in each period. The corresponding investment is  $\tau\Gamma(K)$ , where  $\tau$  is a positive parameter and  $\Gamma$  is an increasing and convex function. At the beginning the rain is not fallen and the farmer has to determine the preventive irrigation level  $x_1$ , which is constrained by the maximal capacity  $K$ . The rainfall level is known with certainty at the beginning of the second period. Thus the farmer chooses the curative irrigation level ( $x_2$ ), conditionally to the rainfall level  $\varepsilon$  which is random with the cumulative distribution function  $G$  and  $g$  the density over  $[0, \bar{\varepsilon}]$ .

Assume that  $f$  is the production function per acre. The unique input is water. The production function is assumed to be concave with respect to the pair  $(x_1, x_2)$ . Note that the production is a function of the total water available for the plant and not a sum of production function by period. Moreover we assume that the preventive and the curative irrigation are imperfect substitutes with the marginal productivity of curative irrigation is always greater than the preventive one. So whatever  $(x_1, x_2, \varepsilon)$  we have:

$$\frac{\partial^2 f(x_1, x_2, \varepsilon)}{\partial x_1 \partial x_2} < 0 \text{ and } \left| \frac{\partial f(x_1, x_2, \varepsilon)}{\partial x_2} \right| > \left| \frac{\partial f(x_1, x_2, \varepsilon)}{\partial x_1} \right|,$$

which implies the same inequality on marginal profitabilities.

Contrary to the most part of the literature we assume that the production level decreases when the total amount of water brought to the plant is too large, which is more realistic. In this case, the farmer faces two risks of losses in yield: one caused by over-irrigation and the other one by sub-irrigation.

The ex-post profit is:

$$\pi(x_1, x_2, K; \varepsilon, c, \tau) = pf(x_1, x_2, \varepsilon) - cx_1 - cx_2 - \tau\Gamma(K)$$

where  $p$  is the production price and  $c$  is the per acre irrigation price.

## 2.1 The ex post program

Farmer's risk preferences are represented by a VNM utility function  $u$ . The ex post program of the producer is:

$$\max_{\{x_2\}} u(\pi)$$

subject to the capital constraint in the second period:

$$K - x_2 \geq 0$$

with  $\pi \equiv \pi(x_1, x_2, K; \varepsilon, c, \tau)$ .

The Lagrangian of this program is:

$$L(x_2, \mu) = u(\pi) + \mu(K - x_2)$$

where  $\mu$  is the shadow cost of capital corresponding to the use of capital in the second period. The first-order condition, which is also sufficient<sup>3</sup>, is:

$$\frac{\partial L(x_2, \mu)}{\partial x_2} = u'(\pi) \frac{\partial \pi}{\partial x_2} - \mu = 0 \quad (1)$$

meaning that the farmer equalizes the marginal value of the curative irrigation level with the shadow cost  $\mu$  of capital. To determine the optimal value of curative irrigation use, three cases need to be considered.

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<sup>3</sup>The corresponding second-order condition is

$$\frac{\partial^2 L(x_2, \mu)}{\partial^2 x_2} = u''(\pi) \left( \frac{\partial \pi}{\partial x_2} \right)^2 + u'(\pi) \frac{\partial^2 \pi}{\partial x_2^2} \leq 0$$

which is true under our assumptions.



Case 1: No curative irrigation ( $x_2^* = 0$ )

Then  $\mu^* = 0$  and  $\pi \equiv \pi(x_1, 0, K; \varepsilon, c, \tau)$ , then (1) implies

$$\frac{\partial \pi}{\partial x_2} < 0.$$

Case 2: Unconstrained curative irrigation ( $x_2^* \in (0, K)$ )

Then  $\mu^* = 0$  and  $\pi \equiv \pi(x_1, x_2, K; \varepsilon, c, \tau)$ , then (1) implies  $x_2^*$  is solution of

$$\frac{\partial \pi}{\partial x_2} = 0$$

and so

$$\frac{dx_2^*}{dx_1} = -\frac{\frac{\partial^2 \pi}{\partial x_2 \partial x_1}}{\frac{\partial^2 \pi}{\partial x_2^2}} < 0.$$

Then, at the optimum, curative and preventive irrigation levels are imperfect substitutes.

Case 3: Constrained curative irrigation ( $x_2^* = K$ )

Then  $\mu^* > 0$  and  $\pi \equiv \pi(x_1, K, K; \varepsilon, c, \tau)$ , then (1) implies

$$\mu^*(x_1, K, \varepsilon) = u'(\pi) \frac{\partial \pi}{\partial x_2} > 0, \text{ so } \frac{\partial \pi}{\partial x_2} > 0.$$

## 2.2 The ex ante program

Having determined the optimal use of curative irrigation in the second period, we now solve the ex-ante program of the producer which is:

$$\max_{\{x_1, K\}} \mathbb{E} [u(\pi) + \mu^*(x_1, K, \varepsilon)(K - x_2^*)]$$

subject to the capital constraint in the first period:

$$K - x_1 \geq 0$$

with  $\pi \equiv \pi(x_1, x_2^*, K; \varepsilon, c, \tau)$ .

The Lagrangian of this program is:

$$L(x_1, K, \lambda) = \mathbb{E}[u(\pi)] + \lambda(K - x_1)$$

because  $\mu^*(x_1, K, \varepsilon)(K - x_2^*)$  is in any case equal to zero, so the first-order conditions, which are sufficient<sup>4</sup>, are as follows:

$$\frac{\partial L(x_1, K, \lambda)}{\partial x_1} = \mathbb{E}\left[u'(\pi) \frac{\partial \pi}{\partial x_1}\right] - \lambda = 0 \quad (2)$$

and<sup>5</sup>

$$\frac{\partial L(x_1, K, \lambda)}{\partial K} = \mathbb{E}\left[u'(\pi) \left(\frac{\partial \pi}{\partial K} + \frac{\partial \pi}{\partial x_2} \mathbf{l}_{x_2^*=K}\right)\right] + \lambda = 0 \quad (3)$$

Equation (2) indicates that the farmer equalizes the expected marginal value of preventive irrigation use to the shadow cost denoted by  $\lambda$ , corresponding to the first-period capital constraint. Equation (3) means that the optimal level of capital is determined by equalizing the expected marginal cost of capital with the shadow cost  $\lambda$ . Note that the expected marginal cost of capital is composed of two terms: increasing the capital level leads to an increase of the investment cost  $(\frac{\partial \pi}{\partial K})$  but in the same time alleviates the capital constraint in the second period, when it is binding  $(\frac{\partial \pi}{\partial x_2} \mathbf{l}_{x_2^*=K})$ .

### 2.3 Benchmark case: no uncertainty

To better understand the farmer's behavior under uncertainty, it is worth studying the benchmark case of perfect information. When the rainfall level  $\varepsilon$  is perfectly known, there is at least one capacity constraint binding. By assumption

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<sup>4</sup>The second-order conditions are

$$\begin{aligned} \frac{\partial^2 L(x_1, K, \lambda)}{\partial^2 x_1} &< 0 \\ \frac{\partial^2 L(x_1, K, \lambda)}{\partial x_1^2} \frac{\partial^2 L(x_1, K, \lambda)}{\partial K^2} - \left(\frac{\partial^2 L(x_1, K, \lambda)}{\partial x_1 \partial K}\right)^2 &> 0 \end{aligned}$$

which are true under our assumptions.

<sup>5</sup>We denote the indicator function  $\mathbf{l}_{x_2^*=K}$  which is equal to 1 when  $x_2^* = K$  and to 0 otherwise.

the marginal profitability of  $x_2$  is greater than the marginal profitability of  $x_1$ , thus  $x_2^* = K$ . There are three cases to consider.

Case 1: No preventive irrigation ( $x_1^* = 0$ )

Then  $\lambda^* = 0$  and so  $K$  is solution of  $\frac{\partial \pi(0, K, K; \varepsilon, c, \tau)}{\partial K} + \frac{\partial \pi(0, K, K; \varepsilon, c, \tau)}{\partial x_2} = 0$ . Differentiating the latter equation with respect to  $\tau$  we obtain  $\frac{dK}{d\tau} < 0$  and  $\frac{dK}{dc} < 0$ .

Case 2: Unconstrained preventive irrigation ( $x_1^* \in (0, K)$ )

Then  $\lambda^* = 0$  and so  $K$  is solution of  $\frac{\partial \pi(x_1, K, K; \varepsilon, c, \tau)}{\partial K} + \frac{\partial \pi(x_1, K, K; \varepsilon, c, \tau)}{\partial x_2} = 0$  and  $x_1$  is solution of  $\frac{\partial \pi(x_1, K, K; \varepsilon, c, \tau)}{\partial x_1} = 0$ . Straightforward computation implies  $\frac{dK}{d\tau} < 0$ ,  $\frac{dK}{dc} > 0$ ,  $\frac{dx_1}{dc} < 0$  and  $\frac{dx_1}{d\tau} > 0$ .

Case 3: Constrained preventive irrigation ( $x_1^* = K$ )

Then  $\lambda^* > 0$  and so  $K$  is solution of  $\frac{\partial \pi(K, K, K; \varepsilon, c, \tau)}{\partial K} + \frac{\partial \pi(K, K, K; \varepsilon, c, \tau)}{\partial x_1} + \frac{\partial \pi(K, K, K; \varepsilon, c, \tau)}{\partial x_2} = 0$ , so  $\frac{dK}{d\tau} < 0$  and  $\frac{dK}{dc} < 0$ .

As expected, increasing the cost of capital leads unambiguously to a decrease in the investment level. However, this does not lead necessarily to a decrease in the preventive water use. Indeed, when the preventive irrigation level is unconstrained, it is optimal for the farmer to increase this level in order to compensate the decrease in curative irrigation level.

Finally, an increase in the per acre irrigation price leads the farmer to increase his investment level when the optimal preventive irrigation level is interior. Indeed, when the per acre irrigation price increases, the farmer optimally reacts by substituting curative irrigation to preventive irrigation because the former is more productive than the latter. This leads the farmer to alleviate the second period capital constraint by investing in irrigation capacity. This is no longer true when the preventive irrigation level is not interior.

### 3 Comparative statics

Having characterized the optimal farmer's behavior, we turn now to some comparative statics with regards to the investment cost parameter  $\tau$  and to the per acre irrigation price  $c$ .

#### 3.1 The impact of capital taxation

One of the different ways to reduce water consumption in an imperfection information setting could be to reduce the farmer's incentives to invest in irrigation capacity. In order to do so, the regulator could modify through taxation the cost of capital. We capture the effect of capital taxation through the increase of parameter  $\tau$ .

As will be clear below, it is difficult to sign the variation of farmer's decisions with respect to the cost of capital for a general utility function  $u$ . Restricting our analysis to the CARA case allows us to obtain some interesting results.

**Proposition 1** *When the farmer's utility  $u$  is CARA (including risk neutrality) comparative statics with respect to the cost of capital ( $\tau$ ) reveals that:*

- (i) *the level of capital ( $K$ ) is monotonically decreasing and is nil for sufficiently high level of  $\tau$ ,*
- (ii) *the path of preventive irrigation ( $x_1$ ) is composed of four phases (see the figure 1). In the first phase the level of the preventative irrigation is nil and thus independent of  $\tau$ . In the second phase this level is increasing whereas it is decreasing during the third phase. After this phase there is no irrigation at all.*

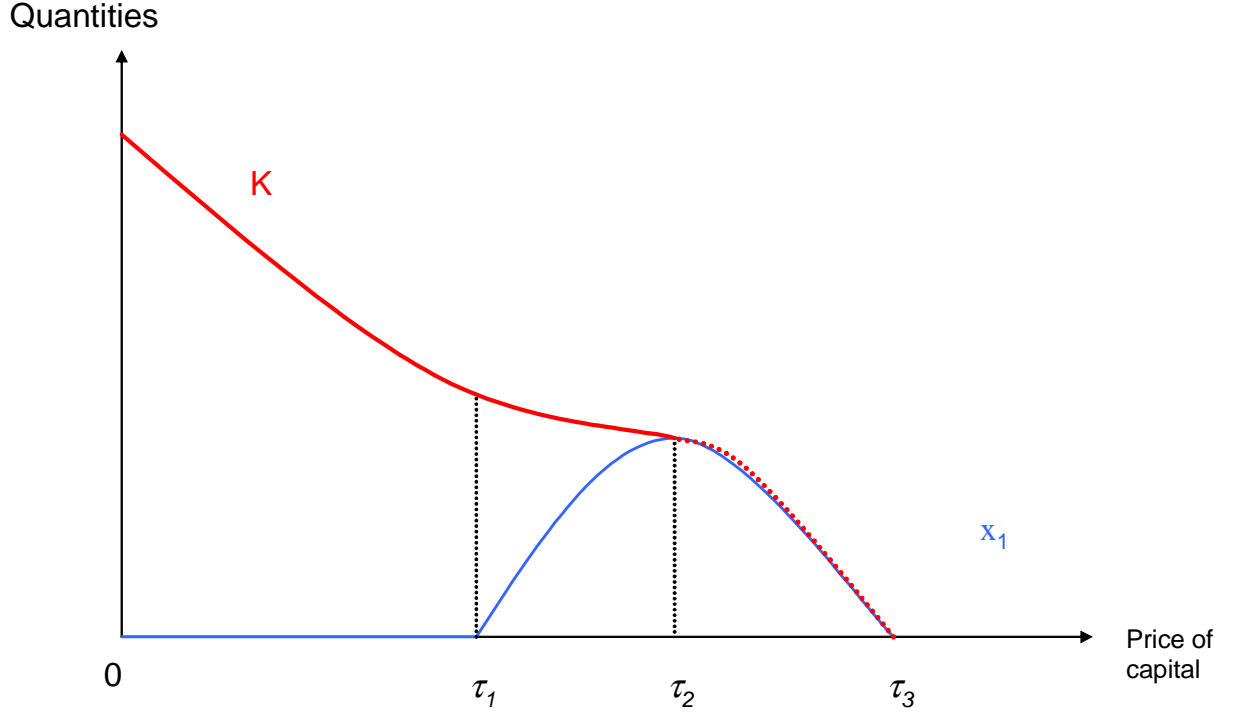


Figure 1: Optimal paths of ex ante variables

- (iii) *the relationship between  $\tau$  and the expected level of curative irrigation ( $E(x_2)$ ) is ambiguous, which implies that variation of the expected total amount of irrigation ( $x_1 + E(x_2)$ ) is also ambiguous.*

As expected, the level of investment in irrigation capacity decreases when the cost of capital increases. Concerning the level of preventive irrigation  $x_1$ , we analyze successively the different phases. There are several effects at work. First of all, when the cost of capital increases, the farmer has more and more incentives to use the irrigation capacity, so that the ratio  $x_1/K$  increases. This *capital effect* leads to have the highest preventive irrigation level. However, recall that the preventive irrigation level is only an imperfect substitute to the curative irrigation level. This *substitution effect* implies that the marginal productivity of  $x_1$  is lesser than the one of  $x_2$ , thus ceteris paribus, it is optimal for the

farmer to irrigate in period 2 given that the variable costs of irrigation levels are the same. Whatever the cost of capital  $\tau$ , the farmer has to trade-off between both effects. When the cost of capital is low, the substitution effect overcomes totally the capital effect. Thus, in the first phase, there is no preventive irrigation ( $x_1/K = 0$ ). For a sufficiently high level of cost, we get the opposite result that is to say, the capital effect overcomes totally the substitution effect ( $x_1/K = 1$  in the third phase). For intermediate values of  $\tau$ , an interior solution for  $x_1$  is obtained. As the ratio  $x_1/K$  monotonically increases with  $\tau$ , the preventive irrigation level  $x_1$  is increasing over the second phase.

In order to get further results, we solve our model in the particular case of a logistic production function  $f$ , with the following form:

$$f(x_1, x_2, \varepsilon) = r(\alpha x_1 + x_2 + \varepsilon) \left(1 - \frac{\alpha x_1 + x_2 + \varepsilon}{a}\right)$$

This specification satisfies our assumptions, in particular the level of production is decreasing if the amount of water supplied to the plant is too large.

**Proposition 2** *When the production function  $f$  is a logistic we have an additional result, whenever the preventive irrigation level  $x_1$  is interior ( $0 < x_1 < K$ ) the total expected water use ( $x_1 + E(x_2)$ ) increases with the cost  $\tau$  of capital. Otherwise this amount is decreasing.*

In the plausible case of a logistic production function, we get a counterintuitive result. Indeed, the total expected water use increases with the capital price for intermediate values of  $\tau$ . Consequently, as it may be difficult and costly for sure to ascertain if the preventive irrigation level is interior, raising the cost of capital in order to decrease the water use may have unexpected effects.

### 3.2 The impact of water price

In this section, we provide the comparative statics of the optimal farmer's behavior with respect to the per acre irrigation price  $c$ . In fact, raising the water price in order to reduce the water use in irrigation is certainly the policy that the economist would first advocate. Unfortunately, this instrument fails to reach this goal as shown in the following proposition.

**Proposition 3** *When the farmer is risk neutral (a fortiori when his utility is CARA) comparative statics with respect to the water price reveals that the impact of a price variation on the farmer's decisions is generally ambiguous.*

Contrary to the cost of capital, the water price affects the marginal profitabilities of preventive and curative irrigation levels which complicates the comparative statics. This effect is added to the ones discussed in the section above.

## 4 Conclusion

We have tried in this paper to analyze two ways of regulating water use in irrigated agricultural production. For that purpose we consider a two periods model of cropping under rainfall uncertainty. A natural way to decrease the total amount of water use by farmer is to increase the price of water. In our standard neoclassical model we have shown that the impact of an increase of water price is generally ambiguous due to the complex relationships between the decisions may before the uncertainty is resolved and decisions made after. As preventive irrigation is only an imperfect substitute of curative irrigation the farmer gives priority to the latter one. But as capital is costly the farmer try to write off this investment along the two periods, and so he is induced to bring preventive irrigation. Whatever the policy chosen by the planner these trade-offs remains true. However, when looking

at the capital taxation the marginal profitability of water use is independent of the cost of capital. In that case relationships are clearer than for a water price policy. Nevertheless, the relationship between the cost of capital and the total water use from an ex ante perspective can be non monotonic. Indeed it may happen that taxing capital leads to an increase of expected water use. Points highlighted in the paper entail that regulating water use could be problematic in practice if regulator wants to use price instrument. Quantity instruments such as quotas could provide a solution.



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# Appendix

## A Proof of proposition 1

We conduct this analysis by studying the impact on ex-ante decisions and then on the ex-post decision.

### A.1 Optimal preventive irrigation and capital investment

As above, we will consider successively the three cases of note.

Case 1: No preventive irrigation ( $x_1^* = 0$ )

Then  $\lambda = 0$  and  $\pi \equiv \pi(0, x_2^*, K; \varepsilon, c, \tau)$

Comparative static:  $K^*(\tau)$ . Totally differentiating equation (3), we obtain:

$$\frac{dK}{d\tau} = \frac{\frac{\partial \pi}{\partial \tau} \mathbb{E} \left[ \rho(\pi) u'(\pi) \left( \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] - \frac{\partial^2 \pi}{\partial K \partial \tau} \mathbb{E} [u'(\pi)]}{\mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_2^2} \mathbb{I}_{x_2^*=K} + \frac{\partial^2 \pi}{\partial K^2} \right) \right] - \mathbb{E} \left[ \rho(\pi) u'(\pi) \left( \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right)^2 \right]} \quad (4)$$

the denominator is always negative.

Then if  $\rho(\pi)$  is a constant, (4) becomes:

$$\frac{dK}{d\tau} = \frac{\rho \frac{\partial \pi}{\partial \tau} \mathbb{E} \left[ u'(\pi) \left( \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] - \frac{\partial^2 \pi}{\partial K \partial \tau} \mathbb{E} [u'(\pi)]}{\mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_2^2} \mathbb{I}_{x_2^*=K} + \frac{\partial^2 \pi}{\partial K^2} \right) \right] - \rho \mathbb{E} \left[ u'(\pi) \left( \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right)^2 \right]}$$

using (3) we get

$$\frac{dK}{d\tau} = \frac{-\frac{\partial^2 \pi}{\partial K \partial \tau} \mathbb{E} [u'(\pi)]}{\mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_2^2} \mathbb{I}_{x_2^*=K} + \frac{\partial^2 \pi}{\partial K^2} \right) \right] - \rho \mathbb{E} \left[ u'(\pi) \left( \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right)^2 \right]} < 0.$$

Case 2: Unconstrained preventive irrigation ( $x_1^* \in (0, K)$ )

Then  $\lambda = 0$  and  $\pi \equiv \pi(x_1, x_2^*, K; \varepsilon, c, \tau)$

Comparative static:  $x_1^*(\tau)$ ,  $K^*(\tau)$ . Totally differentiating the system (2) (3),

we obtain:

$$\begin{aligned} y_1 \frac{dx_1}{d\tau} + y_2 \frac{dK}{d\tau} &= y_3 \\ y_4 \frac{dx_1}{d\tau} + y_5 \frac{dK}{d\tau} &= y_6 \end{aligned}$$

where

$$\begin{aligned} y_1 &= \mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1^2} + \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \frac{dx_2^*}{dx_1} \right) \right] - \mathbb{E} \left[ \rho(\pi) u'(\pi) \left( \frac{\partial \pi}{\partial x_1} \right)^2 \right] \\ y_2 &= \mathbb{E} \left[ u'(\pi) \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \frac{dx_2^*}{dK} \right] - \mathbb{E} \left[ \rho(\pi) u'(\pi) \frac{\partial \pi}{\partial x_1} \left( \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] \\ y_3 &= \frac{\partial \pi}{\partial \tau} \mathbb{E} \left[ \rho(\pi) u'(\pi) \frac{\partial \pi}{\partial x_1} \right] \\ y_4 &= \mathbb{E} \left[ u'(\pi) \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \mathbb{I}_{x_2^*=K} \right] - \mathbb{E} \left[ \rho(\pi) u'(\pi) \frac{\partial \pi}{\partial x_1} \left( \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] \\ y_5 &= \mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_2^2} \mathbb{I}_{x_2^*=K} + \frac{\partial^2 \pi}{\partial K^2} \right) \right] - \mathbb{E} \left[ \rho(\pi) u'(\pi) \left( \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right)^2 \right] \\ y_6 &= \frac{\partial \pi}{\partial \tau} \mathbb{E} \left[ \rho(\pi) u'(\pi) \left( \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] - \frac{\partial^2 \pi}{\partial K \partial \tau} \mathbb{E} [u'(\pi)] \end{aligned}$$

This system of two equation has unique and real solution in  $\frac{dx_1}{d\tau}$  and  $\frac{dK}{d\tau}$  if and only if  $y_1 < 0$  and  $y_1 y_5 - y_2^2 > 0$ , which is true under our assumptions. Moreover  $y_4 = y_2$  because  $\frac{dx_2^*}{dK}$  is equal to zero when  $x_2^* < K$  and to one when  $x_2^* = K$ .

$$\frac{dx_1}{d\tau} = \frac{y_3 y_5 - y_6 y_2}{y_1 y_5 - y_2^2} \quad (5)$$

$$\frac{dK}{d\tau} = \frac{y_1 y_6 - y_2 y_3}{y_1 y_5 - y_2^2} \quad (6)$$

Then if  $\rho(\pi)$  is a constant, (5) and (6) become:

$$\begin{aligned} \frac{dx_1}{d\tau} &= -\frac{y_6 y_2}{y_1 y_5 - y_2^2} > 0 \\ \frac{dK}{d\tau} &= \frac{y_1 y_6}{y_1 y_5 - y_2^2} < 0 \end{aligned}$$

because  $y_2 < 0$ ,  $y_3 = 0$  and  $y_6 > 0$ .

Case 3: Constrained preventive irrigation ( $x_1^* = K$ )

Then  $\lambda > 0$  and  $\pi \equiv \pi(K, x_2^*, K; \varepsilon, c, \tau)$  so the system (2) (3) implies that  $K$  is solution of the following equation:

$$\mathbb{E} \left[ u'(\pi) \left( \frac{\partial \pi}{\partial x_1} + \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] = 0. \quad (7)$$

Comparative static:  $K^*(\tau)$ . Totally differentiating the above equation we obtain:

$$\frac{dK}{d\tau} = \frac{\frac{\partial \pi}{\partial \tau} \mathbb{E} \left[ \rho(\pi) u'(\pi) \left( \frac{\partial \pi}{\partial x_1} + \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] - \frac{\partial^2 \pi}{\partial K \partial \tau} \mathbb{E}[u'(\pi)]}{\mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1^2} + \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \frac{dx_2^*}{dK} + \frac{\partial^2 \pi}{\partial K^2} + \left( \frac{\partial^2 \pi}{\partial x_1 \partial x_2} + \frac{\partial^2 \pi}{\partial x_1^2} \right) \mathbb{I}_{x_2^*=K} \right) \right] - \mathbb{E} \left[ \rho(\pi) u'(\pi) \left( \frac{\partial \pi}{\partial x_1} + \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right)^2 \right]}$$

the denominator is always negative.

Then if  $\rho(\pi)$  is a constant, (4) becomes:

$$\frac{dK}{d\tau} = \frac{\rho \frac{\partial \pi}{\partial \tau} \mathbb{E} \left[ u'(\pi) \left( \frac{\partial \pi}{\partial x_1} + \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] - \frac{\partial^2 \pi}{\partial K \partial \tau} \mathbb{E}[u'(\pi)]}{\mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1^2} + \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \frac{dx_2^*}{dK} + \frac{\partial^2 \pi}{\partial K^2} + \left( \frac{\partial^2 \pi}{\partial x_1 \partial x_2} + \frac{\partial^2 \pi}{\partial x_1^2} \right) \mathbb{I}_{x_2^*=K} \right) \right] - \rho \mathbb{E} \left[ u'(\pi) \left( \frac{\partial \pi}{\partial x_1} + \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right)^2 \right]}$$

using (7) we get

$$\frac{dK}{d\tau} = \frac{-\frac{\partial^2 \pi}{\partial K \partial \tau} \mathbb{E}[u'(\pi)]}{\mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1^2} + \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \frac{dx_2^*}{dK} + \frac{\partial^2 \pi}{\partial K^2} + \left( \frac{\partial^2 \pi}{\partial x_1 \partial x_2} + \frac{\partial^2 \pi}{\partial x_1^2} \right) \mathbb{I}_{x_2^*=K} \right) \right] - \rho \mathbb{E} \left[ u'(\pi) \left( \frac{\partial \pi}{\partial x_1} + \frac{\partial \pi}{\partial x_2} \mathbb{I}_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right)^2 \right]} < 0.$$

## A.2 Optimal curative irrigation paths

Let us define  $\tau_1$  the level of  $\tau$  such as, with  $\pi \equiv \pi(0, x_2^*, K; \varepsilon, c, \tau_1)$ :

$$\mathbb{E} \left[ u'(\pi) \frac{\partial \pi}{\partial x_1} \right] = 0$$

$$\mathbb{E} \left[ u'(\pi) \left( \frac{\partial \pi}{\partial K} + \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} \right) \right] = 0$$

by assumption there is an unique pair  $(K_1, \tau_1)$  solution of this system. Over  $[0, \tau_1)$  there is no preventive irrigation.

Let us define  $\tau_2$  the level of  $\tau$  such as, with  $\pi \equiv \pi(K, x_2^*, K; \varepsilon, c, \tau_2)$ :

$$\begin{aligned} \mathbb{E} \left[ u'(\pi) \frac{\partial \pi}{\partial x_1} \right] &= 0 \\ \mathbb{E} \left[ u'(\pi) \left( \frac{\partial \pi}{\partial K} + \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} \right) \right] &= 0 \end{aligned}$$

by assumption there is an unique pair  $(K_2, \tau_2)$  solution of this system. Over  $[\tau_1, \tau_2]$  the preventive irrigation is not constrained.

Let us define  $\tau_3$  the level of  $\tau$  such as, with  $\pi \equiv \pi(0, 0, 0; \varepsilon, c, \tau_3)$ :

$$\mathbb{E} \left[ u'(\pi) \left( \frac{\partial \pi}{\partial x_1} + \frac{\partial \pi}{\partial K} + \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} \right) \right] = 0$$

by assumption there is an unique and finite  $\tau_3$  solution of this equation. Over  $(\tau_2, \tau_3]$  the preventive irrigation is constrained by the level of capital.

Let us analyze the relationship between the curative irrigation level and the cost of capital over these three intervals.

- $x_2^*$  over  $[0, \tau_1)$

First of all note that  $\frac{\partial \pi}{\partial x_2}$  is in our model independent of  $K$  and  $\tau$ . When  $x_2^* = 0$  then

$$\frac{\partial \pi(0, 0, K; \varepsilon, c, \tau)}{\partial x_2} < 0$$

which implies that

$$\frac{dx_2^*}{d\tau} = 0$$

because

$$\frac{d}{d\tau} \frac{\partial \pi(0, 0, K; \varepsilon, c, \tau)}{\partial x_2} = 0.$$

When  $x_2^* = [0, K)$  then  $x_2^*$  is given by:

$$\frac{\partial \pi(0, x_2^*, K; \varepsilon, c, \tau)}{\partial x_2} = 0$$

so

$$\frac{dx_2^*}{d\tau} = 0.$$

Finally when  $x_2^* = K$  then

$$\frac{\partial \pi(0, K, K; \varepsilon, c, \tau)}{\partial x_2} > 0$$

which implies that

$$\frac{dx_2^*}{d\tau} = \frac{dK}{d\tau}$$

because

$$\frac{d}{d\tau} \frac{\partial \pi(0, 0, K; \varepsilon, c, \tau)}{\partial x_2} > 0.$$

- $x_2^*$  over  $[\tau_1, \tau_2]$

First of all note that  $\frac{\partial \pi}{\partial x_2}$  is in our model independent of  $K$  and  $\tau$  and  $\frac{dx_1}{d\tau}$  is positive over  $[\tau_1, \tau_2]$ , when  $x_2^* = 0$  then

$$\frac{\partial \pi(x_1, 0, K; \varepsilon, c, \tau)}{\partial x_2} < 0$$

which implies that

$$\frac{dx_2^*}{d\tau} = 0$$

because

$$\frac{d}{d\tau} \frac{\partial \pi(x_1, 0, K; \varepsilon, c, \tau)}{\partial x_2} < 0.$$

When  $x_2^* = [0, K)$  then  $x_2^*$  is given by:

$$\frac{\partial \pi(x_1, x_2^*, K; \varepsilon, c, \tau)}{\partial x_2} = 0$$

so

$$\frac{dx_2^*}{d\tau} = -\frac{\frac{\partial^2 \pi}{\partial x_1 \partial x_2}}{\frac{\partial^2 \pi}{\partial x_2^2}} \frac{dx_1}{d\tau} < 0.$$

Finally when  $x_2^* = K$  then

$$\frac{\partial \pi(x_1, K, K; \varepsilon, c, \tau)}{\partial x_2} > 0$$

which implies that

$$\frac{dx_2^*}{d\tau} \leq \frac{dK}{d\tau}$$

because

$$\frac{d}{d\tau} \frac{\partial \pi(x_1, K, K; \varepsilon, c, \tau)}{\partial x_2} \leq 0.$$

- $x_2^*$  over  $(\tau_2, \tau_3]$

First of all note that  $\frac{\partial \pi}{\partial x_2}$  is in our model independent of  $K$  and  $\tau$  and  $\frac{dx_1}{d\tau}$  is equal to  $\frac{dK}{d\tau}$  over  $(\tau_1, \tau_2]$ , when  $x_2^* = 0$  then

$$\frac{\partial \pi(K, 0, K; \varepsilon, c, \tau)}{\partial x_2} < 0$$

which implies that

$$\frac{dx_2^*}{d\tau} = 0$$

because

$$\frac{d}{d\tau} \frac{\partial \pi(K, 0, K; \varepsilon, c, \tau)}{\partial x_2} < 0.$$

When  $x_2^* = [0, K)$  then  $x_2^*$  is given by:

$$\frac{\partial \pi(K, x_2^*, K; \varepsilon, c, \tau)}{\partial x_2} = 0$$

so

$$\frac{dx_2^*}{d\tau} = -\frac{\frac{\partial^2 \pi}{\partial x_1 \partial x_2}}{\frac{\partial^2 \pi}{\partial x_2^2}} \frac{dK}{d\tau} > 0.$$

Finally when  $x_2^* = K$  then

$$\frac{\partial \pi(K, K, K; \varepsilon, c, \tau)}{\partial x_2} > 0$$

which implies that

$$\frac{dx_2^*}{d\tau} = \frac{dK}{d\tau}$$

because

$$\frac{d}{d\tau} \frac{\partial \pi(K, K, K; \varepsilon, c, \tau)}{\partial x_2} > 0.$$

## B Proof of proposition 2

We show that:

Case 1: No preventive irrigation ( $x_1^* = 0$ ), we have so:

$$\frac{dE(x_2)}{d\tau} = \int_0^{\varepsilon_1} \frac{dK}{d\tau} dG(\varepsilon) < 0$$

Case 2: Unconstrained preventive irrigation ( $x_1^* \in (0, K)$ ), we have so:

$$\begin{aligned} \frac{d(x_1 + E(x_2))}{d\tau} &= \int_0^{\varepsilon_1} \frac{dK}{d\tau} dG(\varepsilon) - \alpha \int_{\varepsilon_1}^{\varepsilon_2} \frac{dx_1}{d\tau} dG(\varepsilon) + \int_0^{\bar{\varepsilon}} \frac{dx_1}{d\tau} dG(\varepsilon) \\ &= \int_0^{\varepsilon_1} \left( \frac{dK}{d\tau} + \frac{dx_1}{d\tau} \right) dG(\varepsilon) + (1 - \alpha) \int_{\varepsilon_1}^{\varepsilon_2} \frac{dx_1}{d\tau} dG(\varepsilon) + \int_{\varepsilon_2}^{\bar{\varepsilon}} \frac{dx_1}{d\tau} dG(\varepsilon) \end{aligned}$$

the last two terms are positive. It remains to show that the first one is also

positive. Indeed

$$\frac{dK}{d\tau} + \frac{dx_1}{d\tau} = \frac{y_6(y_1 - y_2)}{y_1 y_5 - y_2^2}$$

and  $y_1 - y_2$  is positive over  $[0, \varepsilon_1)$  because:

$$y_1 - y_2 = \int_0^{\bar{\varepsilon}} u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1^2} + \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \left( \frac{dx_2^*}{dx_1} - \frac{dx_2^*}{dK} \right) - \rho \frac{\alpha - 1}{\alpha} \left( \frac{\partial \pi}{\partial x_1} \right)^2 \right) dG(\varepsilon)$$



$$\begin{aligned}
& \int_0^{\varepsilon_1} (y_1 - y_2) dG(\varepsilon) \\
&= \int_0^{\bar{\varepsilon}} \int_0^{\varepsilon_1} u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1^2} + \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \left( \frac{dx_2^*}{dx_1} - \frac{dx_2^*}{dK} \right) - \rho \frac{\alpha - 1}{\alpha} \left( \frac{\partial \pi}{\partial x_1} \right)^2 \right) dG(\varepsilon) dG(\varepsilon) \\
&= \int_0^{\bar{\varepsilon}} \int_0^{\varepsilon_1} u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1^2} - \frac{\partial^2 \pi}{\partial x_1 \partial x_2} - \rho \frac{\alpha - 1}{\alpha} \left( \frac{\partial \pi}{\partial x_1} \right)^2 \right) dG(\varepsilon) dG(\varepsilon) \\
&= \int_0^{\bar{\varepsilon}} \int_0^{\varepsilon_1} u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1 \partial x_2} (\alpha - 1) - \rho \frac{\alpha - 1}{\alpha} \left( \frac{\partial \pi}{\partial x_1} \right)^2 \right) dG(\varepsilon) dG(\varepsilon) > 0
\end{aligned}$$

so

$$\frac{d(x_1 + E(x_2))}{d\tau} > 0$$

Case 3: Constrained preventive irrigation ( $x_1^* = K$ ), we have so:

$$\begin{aligned}
\frac{d(K + E(x_2))}{d\tau} &= \int_0^{\varepsilon_1} \frac{dK}{d\tau} dG(\varepsilon) - \alpha \int_{\varepsilon_1}^{\varepsilon_2} \frac{dK}{d\tau} dG(\varepsilon) + \int_0^{\bar{\varepsilon}} \frac{dK}{d\tau} dG(\varepsilon) \\
&= \frac{dK}{d\tau} ((1 + \alpha)G(\varepsilon_1) - \alpha G(\varepsilon_2) + 1) < 0.
\end{aligned}$$

## C Proof of proposition 3

Case 1: No preventive irrigation ( $x_1^* = 0$ )

Then  $\lambda = 0$  and  $\pi \equiv \pi(0, x_2^*, K; \varepsilon, c, \tau)$

Comparative static:  $K^*(c)$ . Totally differentiating equation (3), we obtain:

$$\frac{dK}{dc} = \frac{E \left[ \rho(\pi) u'(\pi) \frac{\partial \pi}{\partial c} \left( \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] - E \left[ u'(\pi) \frac{\partial^2 \pi}{\partial x_2 \partial c} \Big|_{x_2^*=K} \right]}{E \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_2^2} \Big|_{x_2^*=K} + \frac{\partial^2 \pi}{\partial K^2} \right) \right] - E \left[ \rho(\pi) u'(\pi) \left( \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right)^2 \right]} \quad (8)$$

the denominator is always negative.

When  $\rho(\pi)$  is a constant, so (8) becomes:

$$\frac{dK}{dc} = \frac{\rho E \left[ u'(\pi) \frac{\partial \pi}{\partial c} \left( \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] - E \left[ u'(\pi) \frac{\partial^2 \pi}{\partial x_2 \partial c} \Big|_{x_2^*=K} \right]}{E \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_2^2} \Big|_{x_2^*=K} + \frac{\partial^2 \pi}{\partial K^2} \right) \right] - \rho E \left[ u'(\pi) \left( \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right)^2 \right]} \leq 0$$

and so if the farmer is risk neutral ( $\rho = 0$ )  $\frac{dK}{dc} < 0$ .

Case 2: Unconstrained preventive irrigation ( $x_1^* \in (0, K)$ )

Then  $\lambda = 0$  and  $\pi \equiv \pi(x_1, x_2^*, K; \varepsilon, c, \tau)$

Comparative static:  $x_1^*(c)$ ,  $K^*(c)$ . Totally differentiating the system (2) (3), we obtain:

$$\begin{aligned} z_1 \frac{dx_1}{dc} + z_2 \frac{dK}{dc} &= z_3 \\ z_4 \frac{dx_1}{dc} + z_5 \frac{dK}{dc} &= z_6 \end{aligned}$$

where

$$\begin{aligned} z_1 &= \mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1^2} + \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \frac{dx_2^*}{dx_1} \right) \right] - \mathbb{E} \left[ \rho(\pi) u'(\pi) \left( \frac{\partial \pi}{\partial x_1} \right)^2 \right] \\ z_2 &= \mathbb{E} \left[ u'(\pi) \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \frac{dx_2^*}{dK} \right] - \mathbb{E} \left[ \rho(\pi) u'(\pi) \frac{\partial \pi}{\partial x_1} \left( \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] \\ z_3 &= \mathbb{E} \left[ \rho(\pi) u'(\pi) \frac{\partial \pi}{\partial c} \frac{\partial \pi}{\partial x_1} \right] - \mathbb{E} \left[ u'(\pi) \frac{\partial^2 \pi}{\partial x_1 \partial c} \right] \\ z_4 &= \mathbb{E} \left[ u'(\pi) \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \Big|_{x_2^*=K} \right] - \mathbb{E} \left[ \rho(\pi) u'(\pi) \frac{\partial \pi}{\partial x_1} \left( \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] \\ z_5 &= \mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_2^2} \Big|_{x_2^*=K} + \frac{\partial^2 \pi}{\partial K^2} \right) \right] - \mathbb{E} \left[ \rho(\pi) u'(\pi) \left( \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right)^2 \right] \\ z_6 &= \mathbb{E} \left[ \rho(\pi) u'(\pi) \frac{\partial \pi}{\partial c} \left( \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] - \mathbb{E} \left[ u'(\pi) \frac{\partial^2 \pi}{\partial x_2 \partial c} \Big|_{x_2^*=K} \right] \end{aligned}$$

This system of two equation has unique and real solution in  $\frac{dx_1}{dc}$  and  $\frac{dK}{dc}$  if and only if  $z_1 < 0$  and  $z_1 z_5 - z_2^2 > 0$ , which is true under our assumptions. Moreover  $z_5 < 0$  and  $z_4 = z_2$  because  $\frac{dx_2^*}{dK}$  is equal to zero when  $x_2^* < K$  and to one when  $x_2^* = K$ .

$$\frac{dx_1}{dc} = \frac{z_3 z_5 - z_6 z_2}{z_1 z_5 - z_2^2} \quad (9)$$

$$\frac{dK}{dc} = \frac{z_1 z_6 - z_2 z_3}{z_1 z_5 - z_2^2} \quad (10)$$

When  $\rho(\pi)$  is a constant, and so  $z_2 < 0$ . So (9) and (10) implies:

$$\frac{dx_1}{dc} \leq 0$$

$$\frac{dK}{dc} \leq 0.$$

Case 3: Constrained preventive irrigation ( $x_1^* = K$ )

Then  $\lambda > 0$  and  $\pi \equiv \pi(K, x_2^*, K; \varepsilon, c, \tau)$  so the system (2) (3) implies that  $K$  is solution of the following equation:

$$\mathbb{E} \left[ u'(\pi) \left( \frac{\partial \pi}{\partial x_1} + \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] = 0. \quad (11)$$

Comparative static:  $K^*(c)$ . Totally differentiating the above equation we obtain:

$$\frac{dK}{dc} = \frac{\mathbb{E} \left[ \rho(\pi) u'(\pi) \frac{\partial \pi}{\partial c} \left( \frac{\partial \pi}{\partial x_1} + \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] - \mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1 \partial c} + \frac{\partial^2 \pi}{\partial x_2 \partial c} \Big|_{x_2^*=K} \right) \right]}{\mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1^2} + \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \frac{dx_2^*}{dK} + \frac{\partial^2 \pi}{\partial K^2} + \left( \frac{\partial^2 \pi}{\partial x_1 \partial x_2} + \frac{\partial^2 \pi}{\partial x_1^2} \right) \Big|_{x_2^*=K} \right) \right] - \mathbb{E} \left[ \rho(\pi) u'(\pi) \left( \frac{\partial \pi}{\partial x_1} + \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right)^2 \right]}$$

the denominator is always negative.

When  $\rho(\pi)$  is a constant, so (8) becomes:

$$\frac{dK}{dc} = \frac{\rho \mathbb{E} \left[ u'(\pi) \frac{\partial \pi}{\partial c} \left( \frac{\partial \pi}{\partial x_1} + \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right) \right] - \mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1 \partial c} + \frac{\partial^2 \pi}{\partial x_2 \partial c} \Big|_{x_2^*=K} \right) \right]}{\mathbb{E} \left[ u'(\pi) \left( \frac{\partial^2 \pi}{\partial x_1^2} + \frac{\partial^2 \pi}{\partial x_1 \partial x_2} \frac{dx_2^*}{dK} + \frac{\partial^2 \pi}{\partial K^2} + \left( \frac{\partial^2 \pi}{\partial x_1 \partial x_2} + \frac{\partial^2 \pi}{\partial x_1^2} \right) \Big|_{x_2^*=K} \right) \right] - \rho \mathbb{E} \left[ u'(\pi) \left( \frac{\partial \pi}{\partial x_1} + \frac{\partial \pi}{\partial x_2} \Big|_{x_2^*=K} + \frac{\partial \pi}{\partial K} \right)^2 \right]}$$

so

$$\frac{dK}{dc} \leq 0.$$

and so if the farmer is risk neutral ( $\rho = 0$ )  $\frac{dK}{dc} < 0$ .

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