Adaptating irrigated agricultural systems to climate change: implications for water pricing

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Abstract:

We analyse the role of pricing systems in the adaptation to climate change. A stochastic agro-economic model is developed to reflect farmers' land allocation, water reservation and irrigation intensity decisions for different crops. The model is then used to assess how the representative farmer in south western France would adapt to given climate change scenarios. We show that a change in average rainfall or in rainfall variability would lead to different types of consequences and managerial implications. If average rainfall is the most affected variable, then the farmers will change their allocation of land to different crops and the manager's revenue will be reduced. But if rainfall variability is mostly affected, the farmer will only change the allocation of water between crops once the climatic event has been observed and the manager's revenue will be increased. Furthermore, with the different adaptation mechanisms and specific pricing systems, the impact of climate change on the farmers' profit would be significantly reduced. Finally, we formulate policy recommendations to facilitate adaptation to climate change and to reach water management objectives.

Keywords: climate change, irrigation water, agriculture, risk, drought, water pricing

INTRODUCTION

In southern European countries, agriculture is the major consumer of water, accounting for up to 80% of consumption in summer. For this reason, agriculture contributes significantly to inter-sectorial competition (Iglesias et al, 2007), making water management a serious challenge in Europe (Ceballos-Barbancho et al, 2008). Recognizing this challenge, European countries have adopted a rigorous legislative framework for water management (Mostert, 2003). In fact, the framework known as the European Water Framework Directive (WFD) came with new rules including economic-related regulations (Ghiotti, 2010). For example, water pricing and total cost recovery became mandatory for all water managers, including those for agricultural water (Carter and Howe, 2006; Petersen et al, 2009). This new regulatory context is a major challenge for farmers and agricultural water management companies in France because of the large fixed costs they have to recover. To cope with this situation more and more companies are implementing nonlinear pricing systems (Sidibé et al, 2012).

But an even more challenging problem is the prospect of climate change. Several studies highlight the fact that major changes in climate will occur in the coming years (Arnell, 1999; IPCC, 2006). Most of them suggest that climatic perturbations will tend to be amplified in the short and medium term. These changes are of major concern; they have led to various analyses of their potential impacts on water resources and on the economic activities that depend on these resources (Alcamo et al, 2007; Gosling, 2011; Falloon and Betts, 2011). These modifications will affect rainfall (specifically in Southern Europe; Milly et al, 2005) particularly by inducing greater variability (Giorgi, 2006; Lehner et al 2006). Giorgi and Lionello (2008) mention a sharp decrease in rainfall in the southern Mediterranean area. These various climatic changes are likely to have consequences for agriculture (Meza et al, 2008). For example, France has recorded at least three major drought episodes (2003, 2005 and 2011) in less than 10 years, with destructive impacts on agriculture. Velde et al (2010) estimate that the drought of 2003 led to a fall in productivity of over 1.5t/ha for maize in France.

Climate variability is one of the most significant factors influencing agricultural production in areas with high productivity (Kang et al, 2009). It may affect farmers in several ways: first, inter-annual variation in water availability, whether water is provided through rainfall or irrigation, induces a change in the level of production. Because of diminishing returns in agriculture (Tilman et al, 2002), for a fixed volume of water, the quantity produced with a variable resource is lower than that produced with the same amount of resource when it is regularly available. Second, in agriculture, various key decisions such as the choice of crops, the technical management plan or the provision of input, are taken without knowing the weather conditions which will prevail in the months or even the days ahead. Indeed, there is a time lapse between the most important decisions and the occurrence of most climatic events (e.g. rainfall). The farmer thus has to take decisions (e.g. land allocation) in the absence of certain information about weather which could have improved his/her choices. For example, a farmer who expects drought for several months in advance may decide to plant crops that require less water, even if they have a lower market value. After the occurrence of the climatic event, it is difficult to amend choices which have already been made. This irreversibility reduces the farmer's options.

Nevertheless, agriculture will have to adapt to the new climatic conditions. The objective of this paper is to show how a farmer would use various opportunities to adapt to different climate change scenarios and what would be the implications of these opportunities in terms of water management especially water pricing. The adaptation involves two main types of decision: long-run decisions (land allocation) and short-run decisions (adjustment of irrigation intensity for crops) (Amigues et al, 2006; Reynaud, 2009). We investigate the role of each of these. Moreover, we distinguish the effects related to a reduction in average rainfall and effects associated with greater variability in rainfall. We show that this distinction is very important as the two types of effect lead to different sets of policy recommendations.

The role of long and short-run adaptation strategies and the management response in order to mitigate the potential effects of climate change have not received adequate attention. Part of the literature has investigated farmers' responses to pricing systems in terms of land allocation and water use (Babcock et al, 1987; Moore et al, 1994; Perry and Narayanamurthy, 1998; Hassine and Thomas, 2001; Agbola and Evans, 2012, Arnberg and Hansen, 2012). For example, Babcock et al (1987) showed that considering input allocation and land allocation decisions separately leads to suboptimal decisions when farmers are risk averse. Agbola and Evans (2012) use a dynamic land allocation model with panel data and find differences in short-run and long-run land allocation behaviour of Danish farmers. But these papers take into account neither rainfall variability nor climate change. However, evidence across the world shows that changes in precipitation patterns will play a determining role in the response of farming systems to climate change (Abildtrup and Gylling, 2001; Salinger et al, 2005; Lobel and Burke, 2010). According to Lichtfouse (2011) the severity of drought will be one of the main reasons leading to a search for adaptation. We are aware that the problem we tackle here is similar to Kaiser et al (1995)'s article which associates an agronomic module with an economic model to assess the impact of gradual climate change on grain farming systems in southern Minnesota and more recently Reynaud (2009) who analyses farmer's responses to increased drought frequency using a mathematical programming model. But Kaiser et al (1995) do not deal with irrigated crops and Reynaud (2009) does not take water management objectives into account. However, in contrast with these studies, we consider the impact of water pricing, water use efficiency and cost recovery issues.

We use a plant growth model to estimate production functions. A stochastic microeconomic model is then associated with this to reflect the rational farmer's decisions in a risky climatic environment. This production function approach avoids the shortcomings of standard econometric approaches that are not well suited to explaining large changes in behaviour (Flichman and Jacquet, 2003) or standard Positive Mathematical Programming that poorly represents economic behaviour with respect to farm activities (Frahan et al, 2007). The model is applied to a representative farmer from Midi-Pyrénées which is one of the most important agricultural regions in France concerning irrigation. The study is particularly relevant in the present context because public authorities are asking for policy recommendations to cope with the impacts of climate change on agriculture.

The rest of the paper is organized as follows. In the next section, we present the theoretical model and the main underlying assumptions. We solve the farmer's problem and interpret the optimality conditions. We then present the irrigation district manager's problem. In section 3, we detail the empirical specifications for the empirical model. In section 4, we run simulations for different realistic climate change scenarios and we discuss our results. Section 5 concludes.

THE THEORETICAL MODEL

As noted by Reidsma et al (2010), in most agricultural production studies, farmers' responses to climate change are purely hypothetical and they do not account for optimal adaptation strategies or for management (Rosenzweig and Parry, 1994; Easterling et al. 2003; Reilly et al, 2003). For instance, Easterling et al (2003) associate a crop growth model with a climate model and compare maize yield under different behavioural rules for farmers. But they do not consider economic factors (e.g. relative prices) and the adaptation strategies are chosen exogenously. Meza and Silva (2009) made an attempt to model adaptation more realistically on maize and wheat yields in Chile by taking into account economic factors (prices and costs) and optimal choices. However, land use adjustments are not assessed. In contrast, our modelling approach captures the fundamental long-run and short-run adjustments available to the farmer. We detail these in the description of the farmer's problem. In this section we present the framework of the model. We describe and formalize the pricing system. We present the farmer's problem and then the manager's problem.

The water pricing model

The water pricing model considered in this paper is based on the system implemented by the *Compagnie d'Aménagement des Coteaux de Gascogne* (CACG) which is the largest water management company operating in south-western France. Faced with variable water demand, the company has developed an innovative system in order to better forecast that demand. In summary, the pricing system can be described in three chronological steps:

First, in spring, the water manager asks farmers to pay a subscription, at which point they have to state the quantity of water they wish to use in the coming irrigation season, i.e. summer. The amount of water they declare for this future consumption is called "reservation" or "water reserved." Secondly, during summer, water is actually used. This quantity is called "consumption." Each farmer uses the quantity of water he/she finds necessary. Note that the amount of water reserved is not necessarily the amount consumed. Finally, the manager bills the water according to the amount reserved and the amount effectively used. The pricing system can be formalized as follows:

$$F(S,C) = \begin{cases} pS & if\ C \leq S \\ pS + p'(C-S) & if\ C > S \end{cases} \qquad (1)$$

- *F(S,C)* is the water bill.
- *S* denotes the amount of water reserved by the farmer.
- *C* is the amount of water actually used during the farming season.
- *p* is the price of the quantity of water reserved.
- *p'* is the unit price of the consumption beyond the volume reserved, if consumption exceeds reservation.

When the volume consumed is less than the reservation, only the latter one is charged at price *p*. Beyond this value, the difference between actual consumption and the reservation is charged for at price *p'*, greater than *p*. The objective of the higher price is to discourage consumption in excess of the reserved amount.

The farmer's problem

We consider a representative farmer with a fixed area of agricultural land. We assume that the farming activities concern only crop growing (without livestock breeding). The farmer may allocate his/her land between several types of crops. But in practice, farmers generally make rotations with only 2 or 3 types of crop (Reynaud, 2009) because more crops would entail supplementary managerial costs. Therefore we consider here that the farmer will use only 2 types of crop although the results may be easily generalized. The farmer has access to irrigation water provided by the management company. Pricing is done in accordance with the system described in the previous section. Rainfall is the second source of water. This latter water source is variable and its variability is exogenous and cannot be controlled by the farmer. Nevertheless, the farmer knows the probability distribution of rainfall. Each possible rainfall amount corresponds to a state of nature and has a given probability that may be estimated with its frequency. For reasons of simplicity without losing generality, we suppose two states of nature: one with high rainfall, called "wet conditions" and another with low rainfall called "drought". In section 3, we discuss the concept of drought for additional clarity.

Two types of decision are made. Before knowing the state of nature that will occur, the farmer has to decide how to allocate his/her agricultural land between the crops. He/she also has to reserve water as requested by the water manager. These two decisions are the long-run decisions of our model. After the rainfall level has been observed, the farmer may choose the quantity of irrigation water to bring to each crop. This is the short-run decision. The problem of the rational farmer is to maximize the expected utility of his/her profit. The profit is the agricultural production value (production multiplied by price) minus other production costs and water costs. The problem can be formalized as follows:

$$\max_{S,A_1} E\left(\max_{C_{i,1},C_{i,2}} U\left(A_1.h_1\left(C_{i,1}+\pi_i\right)+(A-A_1).h_2\left(C_{i,2}+\pi_i\right) - F(S,C_i)\right)\right) \qquad (2)$$

- E() is the expected value function
- *U* is the farmer's utility function. It is assumed to be increasing, concave and differentiable.
- h_1 and h_2 are the production values associated with crop 1 and crop 2 respectively. They are assumed to be increasing, concave and differentiable. They represent the production functions multiplied by the prices minus the unit cost for other inputs.
- *A* is the total available agricultural land; A_1 represents the share of land allocated to crop 1 so that A-A_1 is the share for crop 2.
- π_1 is the amount of rainfall in the case of the wet conditions scenario and π_2 in the case of the drought scenario. Probability φ_1 and φ_2 are associated with wet conditions and drought (respectively). $\varphi_1+\varphi_2=1$ and $\pi_1 > \pi_2$.
- $C_{i,j}$ is the amount of water per unit area used for rainfall level π_i and crop j.
- $C_i = A_1 \times C_{i,1} + (A - A_1) \times C_{i,2}$

- S is the quantity of water reserved.
- p and p' are the parameters of the pricing system.

The farmer chooses the quantity of water to reserve and allocates land so as to maximize expected utility. Once the state of nature has been observed, he/she adjusts irrigation intensity so as to maximize utility for each given state of nature. The previous problem can be expanded as follows:

$$\max_{A_1,S}\begin{cases}\varphi_1 \max\limits_{C_{1,1}C_{1,2}} U\left(A_1 \times h_1(C_{1,1}+\pi_1)+(A-A_1)\times h_2(C_{1,2}+\pi_1)-F\left(S, C_{1,1}A_1+C_{1,2}(A-A_1)\right)\right)+ \\ \varphi_2 \max\limits_{C_{2,1}C_{2,2}} U\left(A_1 \times h_1(C_{2,1}+\pi_2)+(A-A_1)\times h_2(C_{2,2}+\pi_2)-F\left(S, C_{2,1}A_1+C_{2,2}(A-A_1)\right)\right)\end{cases} \quad (3)$$

The water pricing formula being:

$$F\left(S, C_{i,1}A_1+C_{i,2}(A-A_1)\right)=\begin{cases}pS & if\ C_i \le S \\ pS+p'\left(C_{i,1}A_1+C_{i,2}(A-A_1)-S\right) & if\ C_i > S\end{cases}$$

Note that this pricing formula is the same as the one presented in the previous subsection. We have just rewritten it to fit the multi-crop context. To solve problem (3), we have to consider, for each state of nature, the case where the farmer's actual consumption is lower than his/her water reservation and the case where the actual consumption is higher than the reservation. Therefore, we have four possible combinations:

1. consuming more than reservation in the case of drought and less or equal in the case of wet conditions $(C_{2,1}A_1+C_{2,2}(A-A_1)>S,\quad C_{1,1}A_1+C_{1,2}(A-A_1)\le S)$,
2. consuming equal or less than reservation in the case of drought as well as in the case of wet conditions $(C_{2,1}A_1+C_{2,2}(A-A_1)\le S,\quad C_{1,1}A_1+C_{1,2}(A-A_1)\le S)$,
3. consuming more than reservation in the case of drought as well as in the case of wet conditions $(C_{2,1}A_1+C_{2,2}(A-A_1)>S,\quad C_{1,1}A_1+C_{1,2}(A-A_1)>S)$,
4. consuming more than reservation in the case of wet conditions and less or equal in the case of drought $(C_{2,1}A_1+C_{2,2}(A-A_1)<S,\quad C_{1,1}A_1+C_{1,2}(A-A_1)\ge S)$.

We show in the Appendix that combinations 3 and 4 are not logically possible. In the rest of this subsection, we will be concerned only with combinations 1 and 2.

Combination 1

Let us consider combination 1. The problem (3) would be written as follows:

$$\max_{A_1,S}\begin{cases}\varphi_1 \max\limits_{C_{1,1}C_{1,2}} U\left(A_1.h_1(C_{1,1}+\pi_1)+(A-A_1).h_2(C_{1,2}+\pi_1)-pS\right)+ \\ \varphi_2 \max\limits_{C_{2,1}C_{2,2}} U\left(A_1.h_1(C_{2,1}+\pi_2)+(A-A_1).h_2(C_{2,2}+\pi_2)-pS-p'\left(C_{2,1}A_1+C_{2,2}(A-A_1)-S\right)\right)\end{cases} \quad (3')$$

The problem $(3')$ above can be considered as 3 problems each corresponding to the maximization of one parameter. Let us solve them one at a time.

- Derivative with respect to consumption

Consumption choice in the case of wet conditions ($C_{1,1}$ and $C_{1,2}$)

$\max_{C_{1,1}C_{1,2}} U\big(A_1.h_1(C_{1,1}+\pi_1)+(A-A_1).h_2(C_{1,2}+\pi_1)-pS\big)$ u.c. $C_{1,1}A_1+C_{1,2}(A-A_1)\leq S$

The solution gives rise to two first order condition equations:

$$h_1'(C_{1,1}+\pi_1)=h_2'(C_{1,2}+\pi_1) \quad (4)$$

$$C_{1,1}A_1+C_{1,2}(A-A_1)=S \quad (5)$$

Equation (5) indicates that the water reservation constraint should be met. Equation (4) indicates that the marginal production of both crops is the same for optimal water allocation.

Consumption choice in the case of drought ($C_{2,1}$ and $C_{2,2}$)

$$\max_{C_{2,1}C_{2,2}} U\Big(A_1.h_1(C_{2,1}+\pi_2)+(A-A_1).h_2(C_{2,2}+\pi_2)-pS - p'\big(C_{2,1}A_1+C_{2,2}(A-A_1)-S\big)\Big)$$

The first order conditions give the following equations:

$$C_{2,1}=h_1'^{-1}(p')-\pi_2 \ (6) \ \ and \ \ C_{2,2}=h_2'^{-1}(p')-\pi_2 \ (7)$$

Equations (6) and (7) show that the productivity of water should be equal to the price p'. Taking into account (6) and (7) and coming back to the choice of reservation and land, we obtain the following problem:

$$\max_{A_1,S}\begin{cases} \varphi_1 U\big(A_1.h_1(C_{1,1}+\pi_1)+(A-A_1).h_2(C_{1,2}+\pi_1)-pS\big)+ \\ \varphi_2 U\begin{pmatrix} A_1.h_1\big(h_1'^{-1}(p')\big)+(A-A_1).h_2\big(h_2'^{-1}(p')\big)-pS \\ -p'(A_1(h_1'^{-1}(p')-\pi_2)+(A-A_1)(h_2'^{-1}(p')-\pi_2)-S)\end{pmatrix}\end{cases}$$

- Derivative with respect to *S*

Let us denote

$$U_1=U\big(A_1.h_1(C_{1,1}+\pi_1)+(A-A_1).h_2(C_{1,2}+\pi_1)-pS\big)$$

$$U_2=U\begin{pmatrix} A_1.h_1\big(h_1'^{-1}(p')\big)+(A-A_1).h_2\big(h_2'^{-1}(p')\big)-pS \\ -p'(A_1.(h_1'^{-1}(p')-\pi_2)+(A-A_1)(h_2'^{-1}(p')-\pi_2)-S)\end{pmatrix}$$

Then: $$\varphi_1\big(h_1'(C_{1,1}+\pi_1)-p\big)U_1' + \varphi_2(p'-p)U_2'=0 \quad (8)$$

Equation (8) can be written as follows:

$$\frac{U_2'}{U_1'}=-\frac{\varphi_1\big(h_1'(C_{1,1}+\pi_1)-p\big)}{\varphi_2(p'-p)}$$

The ratio of marginal utilities (utility for drought over the utility for wet conditions) is equal to the ratio of the marginal productivity of water in the case of wet conditions to the additional price minus the basic price. These quantities are weighted by the probability of wet conditions and drought.

- Derivative with respect to A_1

$$\varphi_1\left(h_1'(C_{1,1}+\pi_1)(C_{1,2}-C_{1,1})+h_1(C_{1,1}+\pi_1)-h_2(C_{1,2}+\pi_1)\right)U_1' + \varphi_2\left(p'\left(h_2'^{-1}(p')-h_1'^{-1}(p')\right)+h_1\left(h_1'^{-1}(p')\right)-h_2\left(h_2'^{-1}(p')\right)\right)U_2' = 0 \qquad (9)$$

$$\frac{U_2'}{U_1'}=-\frac{\varphi_1\left(h_1'(C_{1,1}+\pi_1)(C_{1,2}-C_{1,1})+h_1(C_{1,1}+\pi_1)-h_2(C_{1,2}+\pi_1)\right)}{\varphi_2\left(p'\left(h_2'^{-1}(p')-h_1'^{-1}(p')\right)+h_1\left(h_1'^{-1}(p')\right)-h_2\left(h_2'^{-1}(p')\right)\right)}$$

Area A_1 is chosen such that the ratio of marginal utilities (utility for drought over the utility for wet conditions) is equal to the ratio of the marginal productivity of the area in the case of wet conditions and in the case of drought. The 6 variables of the problem are defined by the following six equations:

$$\begin{cases} h_1'(C_{1,1}+\pi_1)=h_2'(C_{1,2}+\pi_1) \qquad (4)\\ C_{1,1}A_1+C_{1,2}(A-A_1)=S \qquad (5)\\ C_{2,1}=h_1'^{-1}(p')-\pi_2 \quad (6)\\ C_{2,2}=h_2'^{-1}(p')-\pi_2 \quad (7)\\ \varphi_1\left(h_1'(C_{1,1}+\pi_1)-p\right)U_1'+\varphi_2\,(p'-p)U_2'=0 \qquad (8)\\ \varphi_1\left(h_1'(C_{1,1}+\pi_1)(C_{1,2}-C_{1,1})+h_1(C_{1,1}+\pi_1)-h_2(C_{1,2}+\pi_1)\right)U_1' + \\ \varphi_2\left(p'\left(h_2'^{-1}(p')-h_1'^{-1}(p')\right)+h_1\left(h_1'^{-1}(p')\right)-h_2\left(h_2'^{-1}(p')\right)\right)U_2'=0 \qquad (9) \end{cases}$$

Combination 2

Now, let us consider combination 2.

$$\max_{A_1,S}\begin{cases}\varphi_1\max\limits_{C_{1,1}C_{1,2}}U\left(A_1.h_1(C_{1,1}+\pi_1)+(A-A_1).h_2(C_{1,2}+\pi_1)-pS\right)+\\ \varphi_2\max\limits_{C_{2,1}C_{2,2}}U\left(A_1.h_1(C_{2,1}+\pi_2)+(A-A_1).h_2(C_{2,2}+\pi_2)-pS\right) \qquad (P2'')\end{cases}$$

This problem is similar to the resolution of combination 1. Let us solve each part of the problem.

- Derivative with respect to consumption

Consumption choice in the case of wet conditions ($C_{1,1}$ and $C_{1,2}$)

$\max_{C_{1,1}C_{1,2}} U\left(A_1.h_1(C_{1,1}+\pi_1)+(A-A_1).h_2(C_{1,2}+\pi_1)-pS\right)$ u.c. $\qquad C_{1,1}A_1+C_{1,2}(A-A_1)\leq S$

We obtain:

$$h_1'(C_{1,1}+\pi_1)=h_2'(C_{1,2}+\pi_1) \qquad (4')$$

$$C_{1,1}A_1+C_{1,2}(A-A_1)=S \qquad (5')$$

Consumption choice in the case of drought ($C_{2,1}$ and $C_{2,2}$)

$\max_{C_{2,1}C_{2,2}} U\big(A_1.h_1(C_{2,1}+\pi_2)+(A-A_1).h_2(C_{2,2}+\pi_2)-pS\big)$ u.c. $C_{2,1}A_1+C_{2,2}(A-A_1)\leq S$

We obtain:

$$h_1'(C_{2,1}+\pi_1)=h_2'(C_{2,2}+\pi_1) \quad (6')$$

$$C_{2,1}A_1+C_{2,2}(A-A_1)=S \quad (7')$$

Let us consider the problem of the choice of S and A_1.

- Derivative with respect to S

Let us denote

$$U_1=U\big(A_1.h_1(C_{1,1}+\pi_1)+(A-A_1).h_2(C_{1,2}+\pi_1)-pS\big)$$

$$\widetilde{U_2}=U\big(A_1.h_1(C_{2,1}+\pi_1)+(A-A_1).h_2(C_{2,2}+\pi_1)-pS\big)$$

$$\varphi_1\big(h_1'(C_{1,1}+\pi_1)-p\big)U_1'+\varphi_2\left(h_1'(C_{2,1}+\pi_1)-p\right)\widetilde{U_2'}=0 \quad (8')$$

Note that $\widetilde{U_2}$ is different from U_2 defined for the combination 1.

Equation (8') can be written as follow:

$$\frac{\widetilde{U_2'}}{U_1'}=-\frac{\varphi_1\big(h_1'(C_{1,1}+\pi_1)-p\big)}{\varphi_2\big(h_1'(C_{2,1}+\pi_1)-p\big)}$$

The ratio of marginal utilities (utility for drought over the utility for wet conditions) is equal to the ratio of the marginal productivity of water in the case of wet conditions to the additional price minus the basic price. These quantities are weighted by the probability of wet conditions and drought.

- Derivative with respect to A_1

$$\varphi_1\left(h_1'(C_{1,1}+\pi_1)(C_{1,2}-C_{1,1})+h_1(C_{1,1}+\pi_1)-h_2(C_{1,2}+\pi_1)\right)U_1'+\varphi_2\left(h_1'(C_{2,1}+\pi_1)(C_{2,2}-C_{2,1})+h_1(C_{2,1}+\pi_1)-h_2(C_{2,2}+\pi_1)\right)\widetilde{U_2'}=0$$

(9')

$$\frac{\widetilde{U_2'}}{U_1'}=-\frac{\varphi_1\left(h_1'(C_{1,1}+\pi_1)(C_{1,2}-C_{1,1})+h_1(C_{1,1}+\pi_1)-h_2(C_{1,2}+\pi_1)\right)}{\varphi_2\left(h_1'(C_{2,1}+\pi_1)(C_{2,2}-C_{2,1})+h_1(C_{2,1}+\pi_1)-h_2(C_{2,2}+\pi_1)\right)}$$

Area A_1 is chosen such that the ratio of marginal utilities (utility for drought over the utility for wet conditions) is equal to the ratio of the marginal productivity of the area in the case of wet conditions and in the case of drought. The six variables of the problem are defined by the following six equations:

$$\begin{cases} h_1'(C_{1,1}+\pi_1) = h_2'(C_{1,2}+\pi_1) \quad (4') \\ C_{1,1}A_1 + C_{1,2}(A-A_1) = S \qquad (5') \\ h_1'(C_{2,1}+\pi_2) = h_2'(C_{2,2}+\pi_2) \; (6') \\ C_{2,1}A_1 + C_{2,2}(A-A_1) = S \qquad (7') \\ \varphi_1\big(h_1'(C_{1,1}+\pi_1)-p\big)\,U_1' + \varphi_2\,\big(h_1'(C_{2,1}+\pi_2)-p\big)\widetilde{U_2'} = 0 \qquad (8') \\ \varphi_1\left(h_1'(C_{1,1}+\pi_1)(C_{1,2}-C_{1,1}) + h_1(C_{1,1}+\pi_1) - h_2(C_{1,2}+\pi_1)\right)U_1' + \\ \varphi_2\left(h_1'(C_{2,1}+\pi_2)(C_{2,2}-C_{2,1}) + h_1(C_{2,1}+\pi_2) - h_2(C_{2,2}+\pi_2)\right)\widetilde{U_2'} = 0 \;\; (9') \end{cases}$$

In the next subsection, we describe the manager's problem.

The manager's problem

In France water management companies have two types of objectives or constraints: natural, which is to allocate only the amount of water available for agriculture, and regulatory, which involves balancing their budget. More precisely, the management companies are subject to what is called a soft budget constraint, that is they do not have to balance their budget on a yearly basis but the average revenue on a few years should be equal to the average costs. They are not allowed to make a profit either. We consider here a water manager whose objective is to recover costs while meeting the water availability constraint.

We assume that the costs of water delivery are fixed. This assumption holds for the vast majority of water management situations where variable costs are quite negligible compared to the considerable fixed costs (Infrastructure, maintenance, labour costs…). Considering this fact the manager's budget objective can be written as follows:

$$\varphi_1 F\left(S, C_{1,1}A_1 + C_{1,2}(A-A_1)\right) + \varphi_2 F\left(S, C_{2,1}A_1 + C_{2,2}(A-A_1)\right) = B \qquad (10)$$

- B is the budget of the management company. It reflects its costs.

Let us now consider the water availability constraint. The management company has to allocate all available agricultural water to farmers. Water availability is not constant; it varies from year to year. However, water management companies have large reservoirs which enable them to store water in favourable years and release it in unfavourable years. This mechanism allows them to provide a regular amount of irrigation water year after year. The water availability constraint can therefore be written as an average. The following equation translates this fact:

$$\varphi_1\left(C_{1,1}A_1 + C_{1,2}(A-A_1)\right) + \varphi_2\left(C_{2,1}A_1 + C_{2,2}(A-A_1)\right) = Q \qquad (11)$$

- Q is the average amount of water the management company can provide on a yearly basis.

The manager's problem is to choose prices *p* and *p'* in order to satisfy equations (10) and (11). The two equation systems (3) to (9) and (3') to (9') with (10) and (11) define all variables including prices, land allocation, water reservation and irrigation intensity.

The question is how well our model reproduces the observed stylized facts, such as land allocation which is easy to observe, and what would happen in given relevant climate change scenarios. We will use a simulation analysis to answer these questions. For simulation purposes, we need to have an estimation of production functions, rainfall levels etc. In the next section, we detail how such estimations were undertaken.

THE EMPIRICAL SPECIFICATIONS

In this section, we present the Midi-Pyrénées area, the data, the methodology used to estimate production functions and the rainfall.

The study area

Our case study is concerned with the Midi-Pyrénées area in south western France. The Midi-Pyrénées region is interesting in many regards. It is the French agricultural region with the greatest number of farms (47,600) and the second biggest in terms of farmed area (2.29 million hectares) (Chambre Régionale d'Agriculture de Midi-Pyrénées). Cereal crops and oilseeds constitute the main types of agricultural production. The map shows how agriculture is distributed throughout Midi-Pyrénées, particularly cereals and oilseeds (Figure 1).

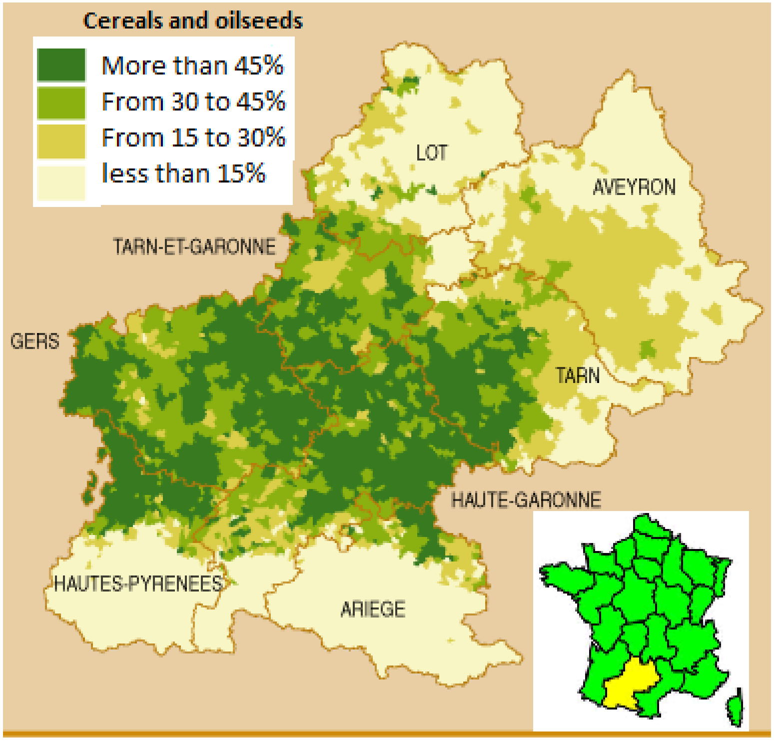

Figure 1: Agricultural map of Midi-Pyrénées region. Source: GeoFla IGN 2009 – INSEE 2009

Irrigated maize is a plant widely cultivated in the area. Given increasing demand and its resistance to water stress, more and more soybean is being cultivated. This trend is likely to continue because of the harsh weather conditions that are announced for Southern regions. In addition, the combination of maize and soybean has specific agronomic interest, for example, because of the ability of soybeans to fix nitrogen in the soil (Johnson et al, 2008). Therefore, this pairing of crops should be relevant for studying adaptation (Chavas and Holt, 1990); this is the reason why we have used it in our case study.

Production functions

The data we have used are agricultural and climatic parameters for a period of 10 years (1998 to 2007). We use a method similar to that developed in Reynaud (2009) and in Sidibé et al (2012). However, in contrast with Sidibé et al (2012), we consider all input costs, although the focus of the analysis will be on water only. We assume that the farmer allocates all other agricultural inputs optimally. Since there is little possibility of substitution between water and other agricultural inputs, water quantity should not be much affected by those costs (Schoengold et al, 2006). The estimation is based on the crop growth model STICS, a model used to estimate a production function with the vector of the quantity of water available at different dates (for details of STICS see Brisson et al, 2002). We complete this with a further step using a maximization program to find a production function with a simple variable which is the total amount of water supplied to the crops during the irrigation season. The graph in Figure 2 shows the production functions of maize and soybean.

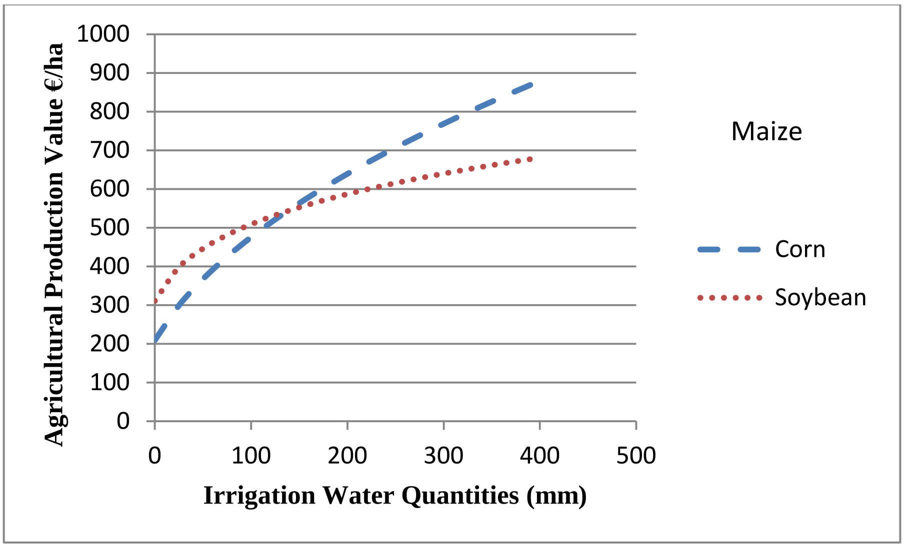

Figure 2: Production functions of maize and soybean

For small quantities of water soybean is more productive than maize but for high irrigation levels maize is more productive.

Rainfall levels

To determine the levels of rain in a dry summer or a wet summer, and their probability of occurrence (respectively φ and (1 − φ)), we use rainfall data from 1998 to 2007. However the concept of drought has several definitions including meteorological, agricultural and hydrological definitions (Amigues et al., 2006). Furthermore, various indices have been invented to describe drought (Palmer, Kincs, Blumenstock index . . . see Richard and Heim, 2002). Meteorological drought, defined as a significant negative deviation of rainfall from a certain average considered as “normal”, seems to be the most appropriate definition for our study. However, this definition remains subjective because it depends on what is meant by “normal” and by “significant” deviation from the “normal”. For these reasons we define drought by setting an arbitrary probability φ. A dry year is then defined as any year in which the rainfall is less than the rainfall that has a non-exceedance probability of φ. We then vary φ in order to check the stability of the results relative to the chosen value. The methodology and data are detailed in Appendix D (Tables D1, D2, and D3).

The utility function

To model the behavior of the farmer toward risk in relation to his/her profit, we need to define a utility function. Following Moschini and Hennessy (2001), we adopt a utility function with a relative risk aversion constant (CRRA), because of its simplicity and ease of interpretation. In addition, this functional form is the most commonly used in agricultural economics, which makes our results easily comparable with other studies in the literature. If we denote the farmer's profit as G, the utility function, of type CRRA, is written as follows:

$$U(G) = \frac{G^{1-\alpha}}{1-\alpha}$$

In this expression, α represents the degree of risk aversion of the farmer (Reynaud, 2009). A higher value of α means a more risk-averse farmer. The value is always between 0 and 1 for risk-averse behaviour. This coefficient is also called the Arrow-Pratt coefficient.

SIMULATION AND ANALYSIS OF THE RESULTS

The simulation analysis is based on the formulas established in the section "THE THEORETICAL MODEL". In the previous section, we described how we estimated the exogenous variables. Therefore, we now have all the ingredients to carry out the simulation analysis. The analysis will answer two fundamental questions. First: how good is the model? In other words how well does it represent reality? And second: what adaptation mechanisms would be used by both farmer and manager in given climate change scenarios? To answer the first question, we set a benchmark scenario corresponding to the climatic pattern observed over the past few years in the Midi-Pyrénées region. We then compare the results to the actual data. The second question is answered by a what-if analysis. We change rainfall average and variability, and observe the reactions of the farmers and of the water manager.

But before moving to the scenario analysis, it may be helpful to have some understanding of how a change in land allocation in favour of one crop or the other may impact on the demand for water. In the graph below, we show the water demand functions for different land allocations. A 1ha farm surface is considered. The price considered is price *p* in the formula.

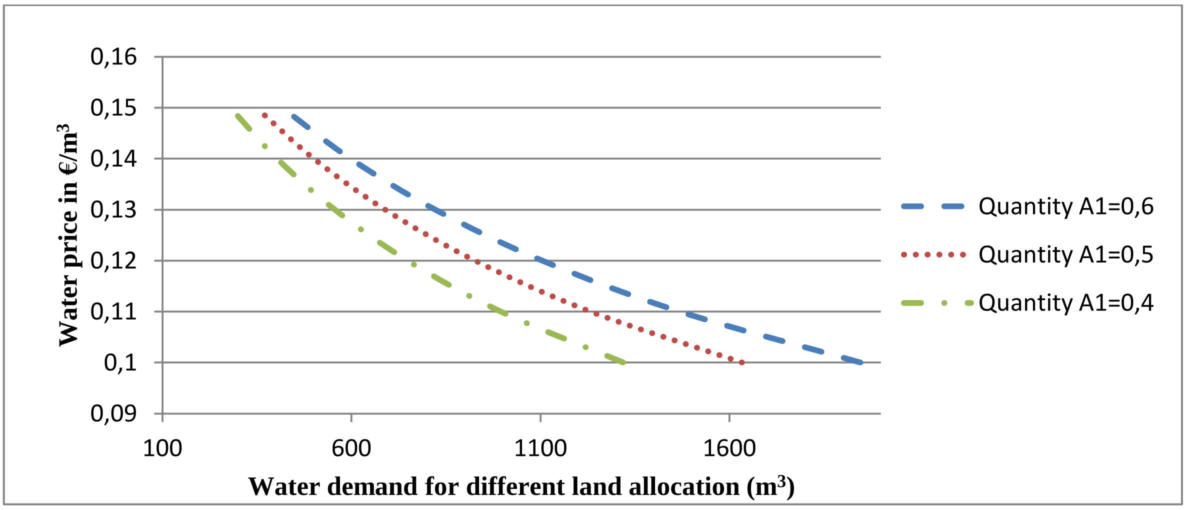

Figure 3: Water demand functions for different land allocation values between crops

First of all, the average water demand decreases as a greater proportion of land is allocated to soybean. This is easy to interpret because soybean is a less water-demanding crop than maize. Elasticity of demand is higher for higher prices and lower for lower prices for all land allocations. This is due to the fact that for high water levels the marginal production of water is low. Therefore a small increase in price would bring about a large decrease in demand. The elasticity of demand hardly changes from one land allocation to the other. When the maize acreage decreases from 60% to 50% water demand decreases by about 16%; when it decreases from 50% to 40% water demand decreases by 19%.

In the next subsection, we will see how the preceding observations are important in order to understand the farmer's adaptive behaviour in different scenarios and how it impacts on the manager's objectives. The following Tables (Table 1 and Table 2) present the results for all the scenarios.

Table 1: Allocation of water and irrigated land

	Maize irrigation intensity wet summer $C_{1,1}$ (mm)	Soybean irrigation intensity wet summer $C_{1,2}$ (mm)	Maize irrigation intensity dry summer $C_{2,1}$ (mm)	Soybean irrigation intensity dry summer $C_{2,2}$ (mm)	Water (m^3) reservation S	Area for maize production (%) A_1
Scenario 1 Benchmark	109	0	102	12	671	62
Scenario 2a average -10%	126	0	172	36	630	50
Scenario 2a' average -10%	104	0	93	18	646	62
Scenario 2b average -20%	142	0	226	56	603	42
Scenario 3a variance +50%	109	0	94	23	671	62
Scenario 3b variance +100%	108	0	88	33	671	62
Scenario 4 average -10% and variance +50%	125	0	169	49	624	50

Table 2: Water prices, farmer’s profit and manager’s revenue

	Price p (€/m^3)	Price p' (€/m^3)	Farmer's average profit (€/ha)	Manager's revenue (€/ha)
Scenario 1 Benchmark	0,137	0,247	519	92
Scenario 2a average -10%	0,133	0,144	508	90
Scenario 2a’ average -10%	0,142	0,143	501	92
Scenario 2b average -20%	0,131	0,132	508	88
Scenario 3a variance +50%	0,138	0,140	517	93
Scenario 3b variance +100%	0,140	0,151	507	94
Scenario 4 average -10% and variance +50%	0,134	0,151	507	91

Scenario 1: Benchmark

In this scenario, we match the model to the current climatic situation. The rainfall levels and variability considered are those observed over 10 years. We assume that the farmers are slightly risk-averse. In fact, Foudi and Erdlenbruch (2012) found that the risk preferences of irrigating farmers in France are close to risk neutrality with an Arrow-Pratt coefficient of 0.006. We use this value in our simulations but we still carry out some sensitivity analyses on this coefficient to show how more risk-averse farmers would react. Results for the benchmark, scenario 1, are in the first line of Table 1 and 2.

The simulation indicates that famers would allocate 62% of their land to maize production and 38% to soybean. This result fits well with the allocation of irrigated agricultural land in Midi-Pyrénées. In fact, a study by Agreste Midi-Pyrénées (2006) which is responsible for agricultural statistics, indicates that about 2/3 of irrigated land was allocated to maize production. The results also show that the farmers would have average irrigation intensity for maize of 109 mm. Agreste (Enquêtes pratiques culturales et terres labourables) indicates an average irrigation intensity of about 132 mm. Here again our results are in line with the Agreste statistics since the difference is lower than one dose (25 mm) (Teyssier, 2006).

Line 1 in Table 1 shows that in a wet summer, the farmer will irrigate maize but will not allocate any water to soybean. In fact, soybean is known to require little water, so it is not surprising that the farmer leaves it un-irrigated under favourable climatic conditions. But in the case of drought, the farmer supplies some water to soybean even though the quantity is low. This result is also to be expected. But a counter-intuitive result is that the farmer irrigates maize more in favourable years (wet conditions) than in drought years. This phenomenon may be explained by a substitution effect. In a wet summer maize is much more productive than soybean, therefore maize is irrigated and soybean is not. But in the case of drought, the marginal productivity of soybean becomes so high that it is profitable to transfer some water from maize to irrigate soybean. Note that the total quantity of irrigated water used in wet conditions is not higher than that used in drought. In the case of both drought and wet conditions the farmer uses the exact quantity of water he/she has previously reserved.

Line 1 in Table 2 shows that the water prices we find are within the range of those applied by agricultural water companies in France (Sidibé et al, 2012). Water cost represents about 15% of the farmer's profit. The water manager has his/her budget balanced (the budget objective is fixed at 92 €/ha). We find that the marginal effect of an increase in water availability (let us say 1m^3) leads to a marginal increase in agricultural production values of 0.137€. This value is the same as the water price meaning that the pricing system perfectly reflects water scarcity value.

Let us consider how a more risk-averse irrigating farmer would make his/her decision. When we fix the Arrow-Pratt coefficient at 0.3 we observe that the farmer changes the land allocation, cultivating more soybean: 39%. The intensity of irrigation does not change significantly. When we perform a stress test fixing the Arrow-Pratt coefficient at 0.95 (which corresponds to a very risk-averse farmer), the farmer allocates even more land to soybean: 42%. Although the production value per ha of maize is about 25% higher than that of soybean, in drought as well as in wet conditions, the result suggests that soybean cultivation has an insurance value for the farmer. In the next subsection, we analyse how a decrease in average rainfall would affect the representative farmer's decision and how the water manager would respond.

Scenario 2: Decreased average rainfall

In this scenario, we consider a decrease in average rainfall while keeping the variance constant. This will enable us to study the specific effects of a decreased average. According to the scenarios of the IPCC, the decrease in average rainfall will be between 5 and 20% in south western France by 2070. We consider a decrease in average rainfall of 10% in scenario 2a and of 20% in scenario 2b. Results of these scenarios are presented in Tables 1 and 2 in lines 2 and 4 respectively.

We compare the results of the benchmark and those of scenario 2a to show how adaptation to the new climatic conditions will take place. First of all, we notice that the farmer has increased the irrigation intensity for all crops and for all states of nature except for soybean in the case of wet conditions which remains the same i.e. without irrigation. The irrigation intensity for maize in wet conditions has increased by about 20% but up to 70% in drought. The soybean irrigation intensity has increased by 200%. This result can be explained by the fact that the decrease in average rainfall has decreased the rainfall in both dry and wet summers, variance being kept the same. The farmer tries to compensate for the decrease in rainfall by more intensive irrigation. The question is how the farmer can increase all the irrigation intensities so much while the total available irrigation water does not change. The answer lies in the crop land allocation. Note that the land allocation between the crops has changed. In fact, the proportion of land allocated to maize has decreased from 62% to 50%. Now the farmer's crop rotation allocates the same portion of land to each crop. More land has been allocated to soybean since it is more resistant to drought. In this way, more water becomes available for both crops per unit area; the farmer can then increase the irrigation intensity of each crop. The modification of land allocation may also explain why the reservation decreases between scenarios 1 and 2a. In a dry summer, the farmer uses more water than he/she has reserved.

Let us now analyse Table 2. When we observe the water price *p* and *p'*, at first sight the results may appear to be perplexing. Although climate change has decreased average rainfall, the manager has decreased the water price. In fact, we would intuitively expect greater water scarcity to mean a higher water price. But because a larger area is allocated to soybean (which is less water demanding), the demand function has gone down. If the manager was to maintain the same water price, the quantity of water demanded would be lower than the available quantity. To avoid that, he/she has to decrease the price slightly. But this leads to a decrease in the manager's revenue since the quantity of water sold is the same. That is why the manager's budget is no longer balanced as it was in the benchmark. It is about 2% lower. An interesting question may then be formulated: If the manager did not mind very much if the quantity of water sold was less than the quantity available, could he/she balance his/her budget by increasing the price? In fact, the answer is "no". This is because at the margin, the demand elasticity is high (-1.53). Therefore an increase in price leads to a much higher decrease in percentage demand, thus worsening the budgetary situation. One solution is to identify savings that can be made in the company's expenses.

In Table 2, we also see that the farmer's profit has decreased by about 2%. We might ask why a 10% decrease in rainfall brings about only a 2% decrease in the farmer's profit. There are three answers: the first is that the decrease of the water price directly benefits the farmer, the second is that the marginal increase in profit for the marginal water brought to crops is rather small. In other words, the last drops of water add little to the profit. Therefore, when they are removed, the profit is not much reduced. The third answer relates to the adaptation mechanisms used. The farmer can make two types of adjustment as a response to diminishing rainfall. He/she may change the irrigation intensity of each crop and for each state of nature, and also modify the land allocation. These mechanisms prove to be very powerful in the mitigation of climate change effects. We will now analyse the role that each mechanism plays.

What is the value of land reallocation? In other words, what would have happened if the farmer could not reallocate his/her farm land? To answer this question we "force" the model to keep the allocation constant, as for the benchmark, and we run a simulation: this is scenario 2a'. The results are presented in Tables 1 and 2, line 3.

All the farmer can do now is to adjust the intensive margin of water use. The farmer decreases the irrigation intensity of maize in both drought and wet conditions but increases the intensity for soybean in drought compared to the benchmark scenario. It is also interesting to see that the farmer's average profit has decreased compared to the scenario where land reallocation is possible. But the decrease is not very significant (about 1.5%). We also note that the water price has slightly increased whereas the manager chooses not to sell all the available water. The reason is as follows: if the price had to remain the same, the budget would not be balanced since the structure of water demand has changed (in fact if the price remains the same, the manager will make a profit). To balance the budget, the manager has, *a priori,* the possibility of decreasing or increasing the price. But since the demand is very elastic at the margin, decreasing the price would lead to an even higher demand, thus worsening the situation. The alternative is to increase the price. The change in demand is higher than the price increase and the problem of going over budget is solved. But another problem has been created which is that some water remains unsold. The manager is using the power of his/her monopoly to cover the budget. But this leads to some inefficiency since some water is left unused.

Let us analyse the extreme scenario of a decrease in rainfall of about 20%: scenario 2b (line 4 in Tables 1 and 2). The farmer further increases the irrigation intensity. But he/she still does not irrigate soybean in the case of wet conditions. The land allocated to soybean is further increased but by a smaller proportion (8% instead of 12 % previously). The water price decreases for the same reasons as those discussed previously. The manager will have a budget deficit unless he/she reduces his/her expenses. The farmer's profit decreases by 4% compared to the benchmark. Even in this extreme scenario, we see that, due to opportunities for adaptation, the effects of climate change are heavily mitigated. The reduction in agricultural production value is less than 5%.

Climate variability is thought to be one of the main threats to agricultural systems (Velde et al (2010)). In the next subsection, we analyse the implications of greater rainfall variability for farmers and water managers in south-western France.

Scenario 3: Increased rainfall variance

The IPCC does not give precise scenarios of rainfall variability in terms of change in variance. But variance can be used as a good estimator of rainfall variability. That is why we use it here. We will change the variance while keeping the average the same. Greater variability means very dry summers alternating with wetter summers. Let us suppose an increase in variance of 50%, scenario 3a. Results are presented in line 5 of Tables 1 and 2.

We find that the land allocation is the same as for the benchmark. Also the irrigation intensity is the same in the case of a wet summer. However in a dry summer, the irrigation intensity for maize has decreased while that of soybean has increased. The wet summer is even wetter because of the increased variance. Therefore, soybean does not need to be irrigated in order to obtain a good production level. All irrigation water is then allocated to maize. However, the dry summer is drier. The marginal productivity of soybean becomes higher compared to maize. Being aware of this, the farmer reduces the water allocated to maize and increases the irrigation intensity of soybean until the marginal productivities of both crops are the same.

The reason why land reallocation is negligible is as follows. While the choice of water allocation is made when the rainfall is observed, the choice of land allocation is made before rainfall is observed. Since the expected rainfall has not changed, the farmer does not significantly change his/her land allocation. Neither does he/she change water reservation.

Table 2 shows an increase in water price compared to the benchmark. This is due to an increased demand caused by an increase in rainfall variance. If the manager was to keep the same price as in the benchmark the quantity demanded would exceed the available quantity. So he/she has to increase the price. Because of this increased price, the manager's revenue is now slightly higher (1%). But the manager does not have the right to make profits. So he/she has to find other redistribution measures. The details of these measures are beyond the scope of this paper and can be found in the literature (Rogers et al, 2002). The farmer's profit decrease is very slight, less than 1%.

Let us suppose an increase in variance of 100% which may seem particularly high. Line 6 of Tables 1 and 2, presents the results of this scenario 3b. The farmer still does not change farm land allocation. In wet conditions, about the same amount of water is allocated to maize whereas soybean is still not irrigated. In fact, the water reservation does not change. Soybean does not need to be irrigated in wet conditions. Therefore, the farmer allocates all the reserved water to maize. In drought more water is allocated to soybean at the cost of less water for maize. This behaviour limits the decrease in profit since the productivity of soybean is high in the case of drought. The manager's revenue has increased by a further 1% for the same reasons as those discussed previously. The farmer's profit decreases by about only 2% compared to the benchmark.

The increase in rainfall variance has almost no effect on land allocation, farmer's average profit and manager's revenue. The farming system shows in this sense a very good resilience to increased variance. In the next section, we analyse the combined effect of a change in both average and variance.

Scenario 4: Decreased average and increased variance

According to the IPCC analyses, it is likely that climate change will bring about modification in both rainfall average and rainfall variance. We run simulations for a 10% decrease in average and a 50% increase in variance in scenario 4 (line 7 in the Tables). The preceding results suggest that the effects of rainfall scarcity outweigh those of rainfall variability. In fact, some results in line 7 look more like those in line 2 (scenario 2a) than those in line 5 (scenario 3a). The combined effect on the farmer's average profit is about the same as the addition of each effect taken separately. In the next section, we provide a summary of the results and we discuss the policy implications.

CONCLUSION

In this paper, we have studied a method of water pricing and developed an irrigation water management model taking into account the uncertainties related to rainfall. This paper demonstrates the crucial role of water pricing in coping with climate change. The model has been studied theoretically and used for simulations of different scenarios. It explains the stylized facts in the current situation fairly well. Without the simulation analysis, it would have been very difficult to predict the optimal adaptation strategy with exactitude. Here, we present the main findings.

Effective adaptation should be carried out not only among farmers, but also among water managers. Levers or coping mechanisms for farmers are mainly at two levels. In the long term, adaptation strategies involve improving the allocation of land between crops. In the short term, farmers will adjust the allocation of water between crops according to the observed climatic events and their severity. The manager must in turn adapt his/her management by changing the price of water only if the amount of available water decreases or if the budget target changes.

Crop diversification is not only related to risk aversion as that term is defined in the literature. In contrast with what seems to be commonly accepted (Chavas and Holt, 1990; Fafchamps, 1992; Di Falco and Perrings, 2005), even risk-neutral farmers have an interest in diversifying their crops and in balancing his/her water allocation to different crops. Indeed, diversification decreases the expected revenue risk by introducing a certain proportion of crops that have the ability to withstand drought and therefore provide a return even in the event of severe scarcity of rainfall.

With the water pricing method presented here, coping mechanisms are different depending on whether climate change affects the average or the variability of rainfall. If average rainfall is the most affected variable then the farmer will change the amount of land allocated to different crops. But if variability is mostly affected, the farmer will change only the allocation of water between crops once the climatic event is observed. The farmer will tend to better distribute water among crops. A reduction in average rainfall has a negative impact on the manager's budget while a greater variance has a positive impact.

With the different mechanisms discussed, the impact of the change on the farmers' profit can be significantly reduced. Although agronomic simulation models predict that lower rainfalls will reduce grain yields and affect agricultural production, they have not examined the possibility that farmers will adapt by making various types of production decisions that are in their own best interests (Darwin et al, 1995; Reilly, 1995). The results show that adaptation is significant, as suggested by other studies for developing countries (Mendelsohn and Dinar, 1999). Our study shows how some crops like soybean have great potential for mitigating the possible effects of the changes, in the context of the studied water pricing.

The role of decision-makers should be to facilitate adaptation. Under the effects of climate change, water management companies may collect less revenue than before. They might adapt to this new situation firstly by changing their water pricing, secondly, in some circumstances and especially in the case of decreasing rainfall average, by seeking to make savings to reduce their budget; but the necessary savings are not significant and should be easy to achieve. As we saw, agricultural systems in south western France using this kind of pricing are very resilient to possible climatic transformations. There are indeed significant opportunities for mitigation but there is a need to help farmers in that direction. For example, the public authorities should facilitate French farmers' access to the international soybean market and continue decoupling subsidies from crop types and acreage to allow more flexibility in farming decisions. The model may be applied to other agricultural areas and other crops. It may also be used to include the effects of changes in the quantity of water available to the manager both in average and in variability. Another insight would be to analyse the effects of other types of budget constraint different from the soft one studied here. This will be the object of another study.

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APPENDIX

Here, we show that, two combinations, number 3 and 4, are not possible:

Combination 3

It's not possible to have $C_{1,1}A_1 + C_{1,2}(A - A_1) > S$ and $C_{2,1}A_1 + C_{2,2}(A - A_1) > S$

reductio ad absurdum

$$\max_{A_1,S} \begin{cases} \varphi_1 \max\limits_{C_{1,1}C_{1,2}} U\left(A_1.h_1(C_{1,1} + \pi_1) + (A - A_1).h_2(C_{1,2} + \pi_1) - pS - p'(C_{1,1}A_1 + C_{1,2}(A - A_1) - S)\right) + \\ \varphi_2 \max\limits_{C_{2,1}C_{2,2}} U\left(A_1.h_1(C_{2,1} + \pi_2) + (A - A_1).h_2(C_{2,2} + \pi_2) - pS - p'(C_{2,1}A_1 + C_{2,2}(A - A_1) - S)\right) \end{cases}$$

Max/C

$$C_{1,1} = h_1'^{-1}(p') - \pi_1\,, \quad C_{1,2} = h_1'^{-1}(p') - \pi_1\,, \; C_{2,1} = h_1'^{-1}(p') - \pi_2\,, \quad C_{2,2} = h_2'^{-1}(p') - \pi_2$$

Max/S

$$\varphi_1\,(p - p')U'\left(A_1.h_1(C_{1,1} + \pi_1) + (A - A_1).h_2(C_{1,2} + \pi_1) - pS - p'(C_{1,1}A_1 + C_{1,2}(A - A_1) - S)\right) + \\ \varphi_2\,(p - p')U'\left(A_1.h_1(C_{2,1} + \pi_2) + (A - A_1).h_2(C_{2,2} + \pi_2) - pS - p'(C_{2,1}A_1 + C_{2,2}(A - A_1) - S)\right) = 0$$

$$\varphi_1\,U'\left(A_1.h_1(C_{1,1} + \pi_1) + (A - A_1).h_2(C_{1,2} + \pi_1) - pS - p'(C_{1,1}A_1 + C_{1,2}(A - A_1) - S)\right) + \\ \varphi_2\,U'\left(A_1.h_1(C_{2,1} + \pi_2) + (A - A_1).h_2(C_{2,2} + \pi_2) - pS - p'(C_{2,1}A_1 + C_{2,2}(A - A_1) - S)\right) = 0$$

Impossible because

$$U'\left(A_1.h_1(C_{1,1} + \pi_1) + (A - A_1).h_2(C_{1,2} + \pi_1) - pS - p'(C_{1,1}A_1 + C_{1,2}(A - A_1) - S)\right) > 0$$

and

$$U'\left(A_1.h_1(C_{1,1} + \pi_1) + (A - A_1).h_2(C_{1,2} + \pi_1) - pS - p'(C_{1,1}A_1 + C_{1,2}(A - A_1) - S)\right) > 0$$

Combination 4

Let us show that it's not possible to have $C_{1,1}A_1 + C_{1,2}(A - A_1) > S$ and $C_{2,1}A_1 + C_{2,2}(A - A_1) \leq S$

$$C_{2,1}A_1 + C_{2,2}(A - A_1) < C_{1,1}A_1 + C_{1,2}(A - A_1)$$

$$\max_{A_1,S}\begin{cases} \varphi_2 \max_{C_{2,1}C_{2,2}} U\big(A_1.h_1(C_{2,1}+\pi_2) + (A - A_1).h_2(C_{2,2}+\pi_2) - pS\big) + \\ \varphi_1 \max_{C_{1,1}C_{1,2}} U\Big(A_1.h_1(C_{1,1}+\pi_1) + (A - A_1).h_2(C_{1,2}+\pi_1) - pS - p'\big(C_{1,1}A_1 + C_{1,2}(A - A_1) - S\big)\Big) \end{cases}$$

First part of the equation

$$\max_{C_{2,1}C_{2,2}} \begin{matrix} U\big(A_1.h_1(C_{2,1}+\pi_2) + (A - A_1).h_2(C_{2,2}+\pi_2) - pS\big) \\ SC \;\; C_{2,1}A_1 + C_{2,2}(A - A_1) \leq S \end{matrix}$$

The first order conditions give:

$$h_1'(C_{2,1}+\pi_2) = h_2'(C_{2,2}+\pi_2)$$

$$C_{2,1}A_1 + C_{2,2}(A - A_1) = S$$

Second part of the equation

$$\max_{C_{1,1}C_{1,2}} U\Big(A_1.h_1(C_{1,1}+\pi_1) + (A - A_1).h_2(C_{1,2}+\pi_1) - pS \\ - p'\big(C_{1,1}A_1 + C_{1,2}(A - A_1) - S\big)\Big)$$

$$C_{1,1} = h_1'^{-1}(p') - \pi_1 \;\; (3)\,, \quad C_{1,2} = h_2'^{-1}(p') - \pi_1 \; (4)$$

So we obtain the following problem:

$$\max_{A_1,S}\begin{cases} \varphi_2\, U\big(A_1.h_1(C_{2,1}+\pi_2) + (A - A_1).h_2(C_{2,2}+\pi_2) - pS\big) + \\ \varphi_1 U\begin{pmatrix} A_1.h_1\big(h_1'^{-1}(p')\big) + (A - A_1).h_2\big(h_2'^{-1}(p')\big) - pS \\ -p'(A_1(h_1'^{-1}(p') - \pi_1) + (A - A_1)(h_2'^{-1}(p') - \pi_1) - S) \end{pmatrix} \end{cases}$$

Derivative with respect to S

Let's denote

$$U_2 = U\big(A_1.h_1(C_{2,1}+\pi_2) + (A - A_1).h_2(C_{2,2}+\pi_2) - pS\big)$$

$$U_1 = U\begin{pmatrix} A_1.h_1\big(h_1'^{-1}(p')\big) + (A - A_1).h_2\big(h_2'^{-1}(p')\big) - pS \\ -p'(A_1(h_1'^{-1}(p') - \pi_1) + (A - A_1)(h_2'^{-1}(p') - \pi_1) - S) \end{pmatrix}$$

$$\varphi_2\left(A_1.h_1'(C_{2,1}+\pi_2)\frac{\partial C_{2,1}}{\partial S} + (A - A_1).h_2'(C_{2,2}+\pi_2)\frac{\partial C_{2,2}}{\partial S} - p\right)U_2' + \varphi_1\,(p' - p)U_1' = 0$$

⇨

$$\varphi_2\big(h_1'(C_{2,1}+\pi_2) - p\big)\,U_2' + \varphi_1\,(p' - p)U_1' = 0$$

⇨

$$\frac{U_1'}{U_2'} = -\frac{\varphi_2\left(h_1'\left(C_{2,1}+\pi_2\right)-p\right)}{\varphi_1(p'-p)}$$

$h_1'\left(C_{2,1}+\pi_2\right)-p\ <0$ because $\frac{U_1'}{U_2'}>0$

$h_1'\left(C_{2,1}+\pi_2\right)<p$ but $p<p'$, so $h_1'\left(C_{2,1}+\pi_2\right)<p'$

$h_2'^{-1}\left(h_1'\left(C_{2,1}+\pi_2\right)\right)>h_2'^{-1}(p')$, because $h_2'^{-1}$ is a decreasing function

$h_2'^{-1}\left(h_1'\left(C_{2,1}+\pi_2\right)\right)-\pi_2>h_2'^{-1}(p')-\pi_1$, with $\pi_1\ >\pi_2$

Similarly,$h_1'^{-1}\left(h_2'\left(C_{2,2}+\pi_2\right)\right)-\pi_2>h_1'^{-1}(p')-\pi_1$, therefore we obtain

$C_{2,1}A_1+C_{2,2}(A-A_1)>C_{1,1}A_1+C_{1,2}(A-A_1)$ it is not compatible with the condition we set at the beginning of this demonstration.