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Regulating intra-annual agricultural water use under climate and price uncertainty

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Abstract. We propose a framework allowing to optimize land allocation across crops and intra-annual water use for a farmer facing both climate and price uncertainty. Agricultural production technologies are represented through climate-contingent crop yield functions estimated using data generated by a biophysical crop growth model. These crop yield functions are then integrated into a decision model under uncertainty. An empirical application is developed for a region located in Southwest of France. We analyze in particular how the timing of climatic uncertainty modifies farmer's optimal decisions.

Keywords. Water management – Agriculture – Risk – Water pricing.

Réguler la demande en eau intra-annuelle pour l'agriculture dans un contexte d'incertitude climatique et des prix

Résumé. Nous proposons un modèle permettant d'optimiser les choix d'assolement et d'irrigation intra-annuelle d'un agriculteur dans un contexte d'incertitude climatique et d'incertitude sur les prix agricoles. Les technologies de production sont représentées par des fonctions de production qui dépendent des aléas climatiques. Ces fonctions sont estimées à partir de sorties d'un modèle de croissance de plante et sont ensuite intégrées dans un modèle microéconomique de décision en univers incertain. Une application empirique est développée pour une région située dans le sud-ouest de la France. Nous analysons en particulier comment le timing de la résolution de l'incertitude climatique affecte les décisions optimales de l'agriculteur.

Mots-clés. Gestion de l'eau – Agriculture – Risque – Tarification de l'eau.

I – Introduction

In this article, we propose a framework allowing to optimize land allocation across crops and intra-annual water use for a farmer facing both climate and price uncertainty. Focusing on intra-annual agricultural water consumption is relevant from a policy point of view for several reasons. First, the social value of water is higher in summer when high competition across water users results in scarcity rents. As a result, it makes economic sense to charge more water in summer since the opportunity cost of water consumption is higher. Another motivation for focusing on intra-annual water use is that many countries which are not considered as being explicitly water-stressed experience however some scarcity problems at some specific period of the year. Hence, the number of French administrative districts ("départements") having implemented summer water restrictions has increased from 25 on average over the period 1998-2002 to 51 between 2003 and 2004. From a public policy point of view, this means that intra-annual water consumption matters and that reallocation of water consumption from a peak toward an off-peak period should be promoted. This is especially relevant in a context of climate change since, it is expected "more frequent summer droughts" in Europe (European Environment Agency, 2009).

If the agronomical literature on intra-annual water use is abundant, the economic literature is more limited. McGuckin *et al.* (1987) have developed a dynamic programming model of

irrigation scheduling which account for stochastic weather conditions. The decision to irrigate or not to irrigate is based on two state variables, namely soil moisture and potential evapotranspiration. The general recursive equation is solved numerically. The dynamic programming decision rules significantly outperform nonstress irrigation strategies. Bontemps and Couture (2000) have developed an optimal control approach in order to explain the optimal irrigation management plan of a risk neutral farmer. The discrete irrigation decision is based on three state variables: the water soil content, the crop biomass and the remaining water quota. Shani *et al.* (2004) have used an analytical optimal control approach to derive the optimal irrigation scheme based on the dynamic response of the biomass yield to soil moisture. The optimal policy consists in driving the water content towards the turnpike as quickly as possible, and then to irrigate at the rate required to maintain the soil water content at that level. Shani *et al.* (2004) demonstrate that this type of policy is robust to various situations. Peterson and Ding (2005) have specified an irrigated corn production function in western Kansas by including four water inputs corresponding to water applied at different stages of growth (preplant, vegetative, flowering, ripening). They estimate a Just-Pope production function using data generated from a daily-loop plant growth simulator designed for western Kansas conditions. Interestingly, they show that water is a risk decreasing input in some growth stages (flowering, ripening) and a risk increasing input in others (preplant, vegetative). Although this framework constitutes a step towards a more realistic representation of crop yield function, it does not take explicitly into account the sequentiality of the irrigation scheduling problem. It neither integrates the timing of climate uncertainty resolution.

Compared to the existing literature, we propose to include explicitly uncertainty on climate and on crop prices into the decision problem of a farmer. Second we develop a framework allowing to assess the value of water at any point of time within the irrigation campaign. This is for instance especially important for a water agency wishing to implement peak-load pricing. Third, we introduce the choice of sowing date as a decision of the farmer. Sowing is a particularly important technical operation since it determines the timing of crop cycles (Maton *et al.*, 2007). Last, we simultaneously consider the optimization of land shares and water use.

The paper is organized as follows. In Section II we present the theoretical model of agricultural land and water use under climate and price uncertainty. Section III provides an empirical application of this model in Southwest France. In Section IV we consider the regulation of intra annual water consumption by various economic tools.

II – A model of land and intra-year water use under uncertainty

1. Characterization of the representative farmer

We consider a representative farmer that may potentially produce different crops indexed by $k \in \{1, \dots, K\}$ on a total land area L (in ha). The farmer faces both a climate risk and an output price risk. The farmer's utility function is denoted by $U(\cdot)$ with $U' > 0$ and $U'' < 0$. The farmer must take three types of decisions: allocation of land across all possible crops (*land use choices*), choice of a sowing date for each crop (*sowing date choices*) and irrigation level for each crop at each date of the growing season (*water use choices*).

A. Output price and climate uncertainty

Climate is viewed as a stochastic event $\tilde{\epsilon}$ characterized by a discrete probability distribution function known by the farmer. The possible climate realizations are indexed by $c = 1, \dots, C$. We denote by $\lambda_c \in [0, 1]$ with $\sum_c \lambda_c = 1$ the probability associated to the realization of climate state

of the nature c . Crop prices at the harvesting date are also assumed to be stochastic. We denote by $\tilde{p} \in \square^K$ the stochastic vector of crop prices. We denote by $\eta_n \in [0,1]$ with $\sum_n \eta_n = 1$ the associated probability distribution, which is assumed to be independent from the climate risk.

B. Timing of farmer's decisions

At the beginning of the year, the farmer chooses the share of land to be allocated to each crop and decides which amount of this share may be eventually irrigated. The land use choice is taken before observing the realization of climate and price risks. The farmer knows however the probability associated to each possible climate and price realization.

Having made the land use choice, the farmer can choose for each crop (either irrigated or non-irrigated) a sowing date among a set of possible dates. This choice is made *ex-ante* that is given the probability distribution associated to climate and price risks.

Then the farmer may starts to irrigate. Some irrigation decisions are taken before observing the climate risk realization and are based on the probability distribution of this risk. However, from a given date, the climate realization is observed by the farmer and then all the remaining irrigation decisions are taken conditionally to this realization. This reflects the view that, at the beginning of the irrigation campaign, the farmer has an imperfect knowledge of the type of climate that will be realized. However, this knowledge increases with time and becomes perfect from a given date. Both the climate risk realization and the irrigation decisions determine crop yields. Finally, the crop price risk is realized, which determines the final farmer profit.

C. A climatic-contingent agricultural production technology

We denote by $t = 1, \dots, T$ the time index for the intra-annual irrigation dates (typically t may index days or weeks). As a result, the climatic-contingent yield function for crop k with a sowing date s writes $Y_{ks}^{\tilde{\varepsilon}} = f_{ks}^{\tilde{\varepsilon}}(w(1), \dots, w(t), \dots, w(T))$, where $w(t)$ is the quantity of irrigation at time t . This function is contingent to the realization of the climate risk $\tilde{\varepsilon}$. It gives for any crop and any sowing date given a climate realization, the agricultural product that may be obtained from this crop by unit of area if the vector of irrigation $w = w(1), \dots, w(t), \dots, w(T)$ is implemented.

D. Farmer's decision variables

Ex-ante, that is before observing the realization of the climatic and the price risks, the farmer allocates his agricultural land among the K possible crops (irrigated or not) and choose a sowing date for each crop. We denote by δ_{kis} the share of land allocated by the farmer to crop k , if the sowing date s is chosen with $s \in \{1, \dots, S\}$. Index i corresponds to the decision to irrigate ($i = 1$) or not to irrigate ($i = 0$) the crop considered.

We denote by \bar{t} with $\bar{t} \in \{1, \dots, T\}$ the date from which the climate risk realization is observed by the farmer. From date 1 to \bar{t} , irrigation decisions are taken using the probability distribution of price and climate risks. From, $\bar{t} + 1$ the irrigation decisions are conditional to the climate risk realization. We denote by $\omega_{ks}(t, \tilde{\varepsilon})$ the quantity of water applied at date t to an irrigated crop k with a sowing date s if climate risk $\tilde{\varepsilon}$ is realized. Since the climate realization is only observed by the farmer after date \bar{t} , we must impose the constraint $\omega_{ks}(t, \tilde{\varepsilon}) = \omega_{ks}(t) \quad \forall t \in \{1, \dots, \bar{t}\}$ in the farmer optimization program, which simply states that the quantity of water applied at date t to crop k with a sowing date s cannot depend upon $\tilde{\varepsilon}$ for $\bar{t} \in \{1, \dots, T\}$.

2. The farmer optimization program under climate and price uncertainty

For a given crop k and a land irrigation choice $i \in \{0,1\}$, we denote by Ψ_{ki} the unit cost of production per unit of area and by Δ_{ki} the coupled payment received by the farmer. We denote by μ the unit water price. We can then write the unit profit from a crop k with a sowing date s if climate risk $\tilde{\varepsilon}$ and price risk \tilde{p} are realized as:

$$\pi_{kis}(\cdot) = \begin{cases} \tilde{p} \cdot \bar{f}_{ks}(\omega_{ks}(1, \tilde{\varepsilon}), \dots, \omega_{ks}(t, \tilde{\varepsilon}), \dots, \omega_{ks}(T, \tilde{\varepsilon})) - \Psi_{k1} + \Delta_{k1} - \mu \cdot \sum_t \omega_{ks}(t, \tilde{\varepsilon}) & \text{if } i = 1 \\ \tilde{p} \cdot \bar{f}_{ks}(0, \dots, 0, \dots, 0) - \Psi_{k0} + \Delta_{k0} & \text{if } i = 0 \end{cases} \quad (1)$$

With irrigation ($i = 1$), the farmer uses an irrigation vector $(\omega_{ks}(1, \tilde{\varepsilon}), \dots, \omega_{ks}(t, \tilde{\varepsilon}), \dots, \omega_{ks}(T, \tilde{\varepsilon}))$ which involves a water cost. Without irrigation ($i = 0$), the only cost paid by the farmer is the unit production cost Ψ_{k0} . We denote the total profit by $\Pi(\cdot)$ which is defined as follows:

$$\Pi(\cdot) = \sum_{k,i,s} L \cdot \delta_{kis} \cdot \pi_{kis}(\cdot) \quad (2)$$

where L is the total agricultural land of the farmer. The total profit conditional to the climate risk $\tilde{\varepsilon}$ and the price risk \tilde{p} is simply the sum of the conditional unit profit weighted by the land area.

We can now derive the optimization program of the farmer under price and climate uncertainty. Denoting by D the decoupled payment received by the farmer, the optimization problem P writes:

$$\text{Max } EU = \sum_{c,n} \lambda_c \cdot \eta_n \cdot U[D + \Pi(\cdot)] \quad (\text{P.1})$$

with respect to:

$$\delta_{kis} \quad \forall k, i, s \quad (\text{P.2})$$

$$\omega_{ks}(t, \varepsilon_c) \quad \forall k, s, t, c \quad (\text{P.3})$$

subject to:

$$\delta_{kis} \geq 0 \quad \forall k, i, s \quad (\text{P.4})$$

$$\sum_{k,i,s} \delta_{kis} \leq 1 \quad (\text{P.5})$$

$$\omega_{ks}(t, \varepsilon_c) \geq 0 \quad \forall k, s, t, c \quad (\text{P.6})$$

$$\omega_{ks}(t, \varepsilon_c) \leq \bar{\omega} \quad \forall k, s, t, c \quad (\text{P.7})$$

$$\omega_{ks}(t, \tilde{\varepsilon}_c) = \omega_{ks}(t) \quad \forall t \in \{1, \dots, \bar{t}\} \quad \forall k, s, c \quad (\text{P.8})$$

The criterion (P.1) of this program simply corresponds to the expected utility of the total profit of the farmer. The expectation is taken with respect to the climate risk and to the price risk. This criterion is optimized with respect to δ_{kis} that is the share of agricultural that must be allocated to any irrigated or non-irrigated crop with any sowing date. Constraints (P.4) guaranty that land shares are non negative. The next set of constraints (P.5) corresponds to a land availability constraint.

For irrigated crops, the farmer also optimizes the water applied at any date of the irrigation campaign (P.3). The water applied at each date must be non negative (P.6) and is bounded by $\bar{\omega}$, equations (P.7). This upper limit may be viewed as a technical constraint resulting from irrigation equipments or infrastructures. Constraints (P.8) capture the fact that the climate

realization is only observed by the farmer after date \bar{t} . Hence, the quantity of water applied at date t to crop k with sowing date s cannot depend upon the climate state of the nature for period 1 to \bar{t} .

III – An empirical application to Southwest of France

1. Specification and calibration of the model

A. Characteristics of the farmer

The model has been calibrated for representing a typical farmer located in Southwest of France in the Neste system. The total agricultural land to be allocated across crops is 40 ha which corresponds to the average farm size in that area. We have considered the three main crops produced in that area, $k = \text{corn, sunflower, soy}$. The irrigation season is divided into 9 slots of 10 days (from 1st June to 31st August).

Farmer's preferences are represented by a constant absolute risk aversion (CARA) utility function. As mentioned in (Hardaker and Lien, 2007), a CARA utility function is relevant in the case of moderated risks, such as risks affecting only one year farmer's income. Following the empirical agricultural economics literature, we have chosen to consider a moderately risk-averse farmer. The CARA parameter has been fixed to 0.2.

B. Climate and price risks

The farmer faces an uncertainty with respect to the type of climate year that could be realized. We observe 20 years of daily weather records from 1986 to 2005. Each year will then be viewed as a possible realization of the climate risk. Output prices are also stochastic. For each crop, we have fitted a normal distribution based on 10 years of price observations. We then discretize the distribution considering three possible values for each crop, $n = 1, 2, 3$. The probabilities associated to these values are respectively 0.25 for the extremes and 0.5 for the median (average crop price).

C. Irrigation vectors

Corn and soy are typically intensively irrigated during the summer in Southwest of France. At each date $t = 1, \dots, 9$, we assume that the farmer may choose one of the three following water doses $\{0, 20, 40\}$ where a water dose is measured in mm per ha. As a result, there are 19,683 possible irrigation vectors for corn and soy. Sunflower irrigation is typically more limited in practice. We restrict the total irrigation to 160 mm/ha or less resulting in 14,318 possible irrigation vectors for sunflower.

D. Economic calibration of the model

The optimization problem of the farmer requires to specify a number of economic parameters (crop prices, unit production costs and decoupled payment per crop, etc.). Values for those parameters come from various statistical publications. They reflect the 2005 economic conditions, see Table 1.

E. Crop yield functions

For a given climate realization, for a given crop, we wish to estimate a crop yield function corresponding to the relationship between an irrigation vector (quantity of water applied by the farmer at various dates of the growing season) and the crop yield.

Table 1. Output prices and unit production costs

	Corn		Sunflower		Soy	
	Irrigated	Non-irrigated	Irrigated	Non-irrigated	Irrigated	Non-irrigated
Average output price (euros/kg)	0.095	0.095	0.21	0.21	0.19	0.19
Decoupled payment (euros/ha)	346	230	346	230	346	230
Coupled payment (euros/ha/kg)	115.4	76.7	115.4	76.7	115.4	76.7
Unit production cost (euros/ha)	530	400	347	227	315	228
Unit water cost (euros/mm/ha)	0.640	0.640	0.640	0.640	0.640	0.640

Sources: Arvalis, Institut du Végétal.

To establish this relationship, we first use a crop growth model to generate a set of experimental data (irrigation vector/crop yield). We have used the crop growth model STICS developed by Brisson *et al.* (2002) and adapted to our context in Poupa (2006). The STICS simulations allow us to build a dataset giving for each crop, each climate realization and each vector of irrigation the corresponding yield. The next step consists in estimating the crop yield function based on this dataset. Simple quadratic forms have been estimated based on these databases. All the crop yield functions (climate \times year) have been estimated using Stata. We get a good fit of the quadratic approximations with adjusted R^2 greater than 0.9 for all climatic years and all crops. This means that the quadratic form offers enough flexibility for approximating the unknown yield functions. Moreover, most of the estimated parameters are significant at 1%.

2. Characterizing the optimum

In this section, we characterize the optimal decisions of a farmer that may produce corn, sunflower and soy. We particularly focus on the impact of climatic uncertainty resolution on the optimum by distinguishing three cases: a late resolution corresponds to $\bar{t} = 9$ (30 August), an early resolution to $\bar{t} = 1$ (10 June) and an average resolution to $\bar{t} = 4$ (10 July) (Table 2).

Table 2. Characteristics of the optimum and resolution of climatic uncertainty

Resolution of climatic uncertainty	Expected utility of total profit [†]	Expected unit profit [†] (euros/ha)	Optimal decisions				
			Crop	Sowing date	Land irrigation	Land share	Expected use of water (mm/ha)
Late	-0.053	690.1	Corn	15/05	Irrigated	0.723	158
			Sunflower	30/04	Irrigated	0.277	87
Average	-0.036	682.8	Corn	15/05	Irrigated	0.649	98
			Sunflower	30/04	Irrigated	0.351	27
Early	-0.029	765.8	Corn	15/05	Irrigated	0.820	113
			Sunflower	30/04	Irrigated	0.180	22

[†]Total profit including decoupled payment.

First, it should be noticed that it is optimal for the farmer to produce corn and sunflower although the expected profit from sunflower is lower than the expected profit from corn. This decision results from a strategy of risk diversification. Second, an early resolution of climate uncertainty is always preferable to a late one and the gain to be expected (both in terms of expected utility and expected total profit) is significant. Third, the crop portfolio appears to be quite stable with respect to the resolution of the climatic uncertainty. Hence, in the three cases we have considered, a farmer only produces corn and sunflower with irrigation. The optimal sowing date

is not affected by the time at which the climatic uncertainty is resolved. Finally, land shares are similar in the three scenarios of climate uncertainty resolution.

The timing of the climate uncertainty resolution has however a more important impact on water consumption. If uncertainty is resolved at the first period, the quantity of water used for irrigating corn is 113 mm/ha, compared to 158 mm/ha in the case of a late resolution. With a late resolution of climatic uncertainty, the farmer uses more water. This may be viewed as a precautionary behaviour.

3. The value of an early resolution of climate uncertainty

An interesting question that emerges from the previous analysis is to determine the value for the farmer of an early resolution of climate uncertainty. In other words, we wish to determine the level of the risk premium a farmer is ready to pay for being in a situation where the climatic uncertainty is resolved earlier.

First, we have computed the amount of money a farmer is ready to pay in order to remain in a situation with an early resolution of climatic uncertainty compared to a late one. The risk premium is estimated to be 80.3 euros/ha which represents around 10% of the profit/ha in the case of an early resolution of the climatic risk. Second, if we compare an early resolution of climatic uncertainty to an average one, the risk premium is equal to 27.3 euros/ha. This lower value is consistent with the fact that an average resolution is always preferred by the farmer to a late resolution of the climatic uncertainty. Those values confirm the fact that the timing of climatic uncertainty resolution is an important determinant of the risk premium. Such determinants should be taken into account by an assurance wishing to propose climatic assurance contracts.

IV – Regulating agricultural water demands

In this last section, we analyze the impact of some instruments that can be used by public authorities for regulating water use. We will in particular assess the impact of those instruments both on land use choice and on intra-annual water use.

1. Changes in the water price

A possible way to regulate agricultural water demands is to increase (or to decrease) the water price in order to transmit to final users a signal of water scarcity. The initial unit price of water is 0.64 euros/mm/ha (corresponding to 6.4 cents per m³). In what follows, we derive the optimal crop portfolio of the farmer and the resulting water consumption if the water price is modified by a given multiplicative coefficient (from 0.5 for a decrease by 50% to 3 for an increase by 200%).

In Fig. 1, the benchmark case (price multiplying coefficient equal to 1) results in allocating 72.3% of the available land to an irrigated corn with a sowing date equal to 15th May and to allocate the remaining land to an irrigated sunflower. Facing a unit water price reduction (price multiplying coefficient equal to 0.5 or 0.75), the optimal land use strategy is to allocate more land to corn. On contrary, as the unit water price increases, more land is allocated to sunflower. From a unit water price equal to 1.12 euros/mm/ha (price multiplying coefficient equal to 1.75), soy enters into the optimal farmer crop portfolio.

Table 3 gives the expected water consumption as a function of the water price. The main result is that modifying the water price has a significant impact on the annual water consumption.

In Fig. 2, we have represented the expected intra-annual water use for the benchmark case (multiplicative coefficient equal to 1) and for a water price multiplied by two and three. For the last four slots, as expected, the price increase results in a decrease in the water used.

Interestingly, we observe a non-linear relationship between the price and the water consumption for the second slot, and even an increasing relationship for the fifth slot. The fact that, facing a uniform price increase, the farmer increases the water consumption at the fifth slot can be understood based on agronomical consideration. This slot corresponds to the period of corn silking in Southwest of France, period known as critical in terms of hydric stress.

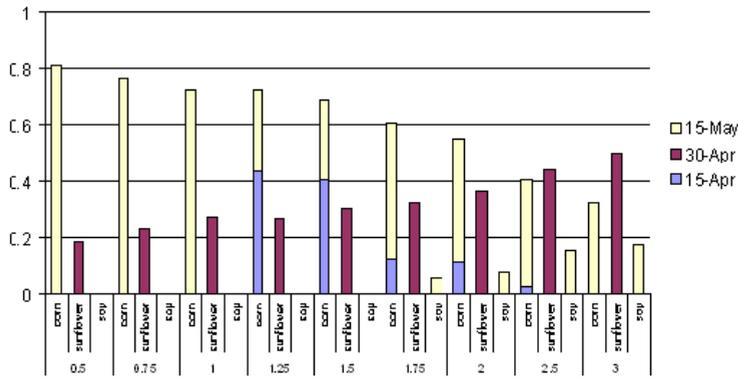


Fig. 1. Impact of water price on optimal land use shares (late resolution of uncertainty).

Table 3. Impact of water price on annual water use

Unit water price in euros/mm/ha	0.32	0.48	0.64	0.80	0.96	1.12	1.28	1.60	1.92
Multiplicative coefficient	0.5	0.75	1	1.25	1.5	(1.75)	2	2.5	3
Expected water consumption in mm/ha	163.4	150.6	138.3	129.6	113.2	80.9	68.8	45.3	32.5

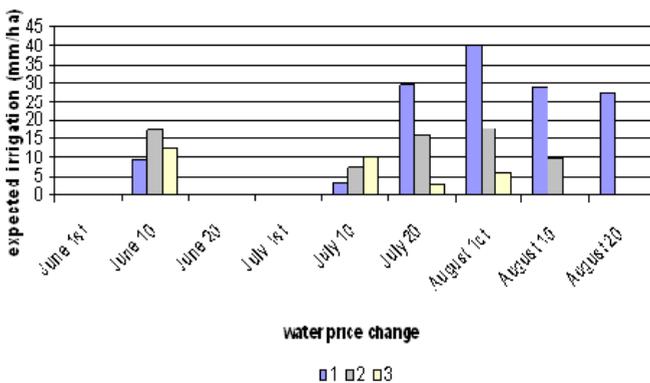


Fig. 2. Impact of water price on intra-annual water use.

The main result here is that modifying the water price has a non-uniform impact on the intra-annual water consumption. Compared to the benchmark case, the price increase may result in

an increase in the water consumption at some slots. From a policy point of view, this is particularly important since the water consumption increase may occur at a period of time where the pressure on the resource is very high due to competitive users.

2. Implementing peak prices

We wish now to evaluate the impact of implementing peak water pricing. In the context of agricultural water use, the main motivation for implementing peak prices is that the social value of water is likely to vary according the period of the year. As a result, it makes economic sense to charge more at these times since the opportunity cost of water consumption is higher.

The peak period we have considered corresponds to slots 5 to 7 (from 10 July to 10 August). For these periods, we have simulated a multiplicative price coefficient varying from 1.25 to 3.

In the benchmark case (Table 4), the expected water consumption during the peak period represents 53% of the expected annual water consumption. Increasing the peak price by 25% does not result in a significant change in the average expected water use (138 mm/ha) or in the share of the peak water use to total water use (around 50%). From a peak price increase of 50%, a process of reallocating water from the peak period toward adjacent decades starts. Implementing peak price allows to reallocate water from the peak period toward the off-peak period at a reasonable cost for the farmer (measured in term of expected utility loss).

Table 4. Impact of peak pricing (late climatic uncertainty resolution)

Peak price coefficient	Expected utility of total profit	Average water use (mm/ha)	Share of peak water use (%)	Irrigation date								
				June			July			August		
				1	10	20	1	10 [†]	20 [†]	1 [†]	10	20
1	-0.053	138.5	53	0.0	9.2	0.0	0.0	3.5	29.5	40.0	28.9	27.4
1.25	-0.056	138.3	49	0.0	21.5	0.0	2.1	2.6	26.6	38.4	26.0	21.2
1.5	-0.061	130.8	41	0.0	21.8	0.0	5.4	1.0	20.3	31.7	29.4	21.0
1.75	-0.062	122.4	27	0.0	29.1	0.0	10.9	0.0	17.6	16.1	34.6	14.2
2	-0.065	114.4	21	0.0	28.3	0.0	11.7	0.0	11.3	12.8	35.9	14.3
2.25	-0.067	107.4	15	0.0	27.2	0.0	12.8	0.0	5.8	9.9	37.6	14.1
2.5	-0.068	102.6	11	0.0	26.6	0.0	13.4	0.0	3.0	8.3	37.2	14.1
2.75	-0.069	98.4	8	0.0	26.0	0.0	14.0	0.0	1.3	6.1	36.6	14.3
3	-0.069	96.2	6	0.0	25.7	0.0	14.3	0.0	0.5	4.9	36.5	14.4

[†]Peak period (10 July, 20 July, 1 August).

The main result is here that implementing peak water prices has a moderate impact on annual water use and on the expected utility of the farmer but a significant impact of intra-annual water use. Peak pricing appears to be an interesting instrument for a public authority wishing to transmit to farmers some incentives to reallocate water use from the peak-period towards the off-peak period. The social gains to be expected from peak pricing include the water saved during the peak period which is now available for alternative uses. One should however take into account the cost of installing meters in order to measure water consumption during the peak and the off-peak periods.

V – Conclusion

We have proposed a framework allowing to optimize land allocation across crops and intra-annual water use for a farmer facing both climate and price uncertainty. Agricultural production

technologies are represented through climate-contingent crop yield functions estimated using data generated by a biophysical crop growth model. These crop yield functions are then integrated into a decision model under uncertainty allowing to optimize both land and water use. An empirical application has been developed for a region located in Southwest of France. We have shown that the timing of climatic uncertainty is a significant determinant of farmer optimal decisions.

We have also assessed the impact of various economic instruments aiming at regulating intra-annual water use by farmers. We have in particular shown that peak pricing appears to be an interesting instrument for a public authority wishing to transmit to farmers some incentives to reallocate water use from the peak-period towards the off-peak period.

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