A dynamic model of irrigation and land-use choice: application to the Beauce aquifer in France*

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Abstract

We set up a model of land-use and irrigation water choices to assess the impact of dry weather conditions and possible restriction policies on farmers' payoffs in the Beauce area in France. Given the informational context, we construct a dynamic two-period model in which farmers make conjectures on the water abstraction by other users and take into account variations in the height of the water-table. We solve the problem using dynamic programming. We simulate different restriction policies, proposed in the literature and tested in the field. We show that these restrictions, although efficient with respect to hydrological criteria, result in serious economic losses for the farmers.

Keywords: groundwater management; hydro-agro-economic model; dynamic programming; irrigation; Beauce aquifer.

JEL: C61, Q15, Q25

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1 Introduction

In the second half of the 20th century, the increasing use of tube wells and mechanical pumps has led to significant groundwater depletion in many parts of the world (Shah et al. 2007). With the help of irrigation, high performance agricultural production areas have been created above aquifers, contributing to the growing pressure on groundwater resources (Shah et al. 2007). As a consequence, water managers need to counteract dropping groundwater levels to secure water for other uses as well as for future generations. To do so, they may rely on institutions (Ostrom 1990), regulatory tools (Pérez-Blanco and Gómez 2014) or economic instruments, such as pricing and water markets (see for example Easter et al. 1999, Koundouri 2004).

In this article, we focus on the Beauce area, one of the most important agricultural production regions in France, and one of the biggest cereal producing regions in Europe. Not only is the Beauce aquifer a typical example of an aquifer depleted by individual pumping for irrigation, but it is also an interesting example because of the restriction policies already in place. Restrictions in the Beauce area are proportional reductions in farmers' individual quotas and are contingent on the aquifer level. Less precipitation and increasing water demand may render potentially drastic restriction policies necessary (Lejars et al. 2012a,c). The aim of this paper is to evaluate the impact of different restriction policies on farmers' land allocation and irrigation decisions under dry weather conditions.

Similar to the work of Madani and Dinar 2012, we make rather unusual but realistic assumptions about the informational context in which farmers take their decisions. Concerning the time horizon, farmers are assumed to be neither completely myopic, i.e. maximizing their instantaneous welfare, nor completely farsighted, i.e. taking the long-term outcomes of payoffs and resources into account. Concerning the actions of other resource users, they are neither completely smart, i.e. learning about the behavior of other users, nor are they completely ignorant of other resource users' water abstractions.[1]

Completely myopic agents justify the use of static models, and such agents have been extensively used in programming models explaining optimal crop choices (see for example Howitt 1995, Heckelei 2002, Heckelei and Wolff 2003, Graveline et al. 2012 or Graveline and Mérel 2014). Good knowledge of future changes in the resource and farsighted agents justify the use of dynamic resource models, explaining the optimal choice of water use over

[1]Madani and Dinar distinguish four possible types of behavior in a non-cooperative common pool resource (CPR) management problem. They state: "ignorant myopic management and smart non-myopic management institutions reflect two extreme cases of anti-ideal and ideal types of users, respectively. Based on the current conditions of the CPRs in practice,[...] it is reasonable to claim that most CPR users adopt the institutions which are in between the two extremes".

time, and have been extensively used in the resource economics literature (see for example Burt 1967, Gisser and Sánchez 1980, Roseta-Palma 2002, Moreaux and Reynaud 2006, or De Frutos Cachorro et al. 2014).[2]

In this paper, we construct a model in which farmers choose crop allocation and irrigation water volumes. Individual farmers do not consider long-term changes in the resource and are therefore modelled as decision makers with a limited planning horizon. However, when taking their decisions in spring, farmers consider the potential impact of restrictions not only on the spring crop but also on the summer crop. They are hence farsighted over two periods. In addition, farmers in the Beauce area can observe the level of the resource and make conjectures about the total abstraction volume made by other resource users, based on information from the previous years. In contrast to other hydro-economic models in the literature (see for example Britz et al. 2013, Erfani et al. 2014), we presume the farmers have imperfect information on other users' actions but do make some best guesses about their water abstractions. In addition, there is no formal water market that can adjust water demand and supply (but see Erfani et al. 2014 for a model including water markets). Because farmers are somewhat farsighted when restrictions are in place and because they can monitor changes in the resource over the year, we construct a dynamic two-period hydro-agro-economic model.

Situated south-west of Paris, the Beauce aquifer extends over 9700 km^2 (see Lejars et al. 2012b). With less than 600 mm of rainfall per year, it is one of the driest regions in France (see Lejars et al. 2012b). As a consequence, about 50% of the agricultural land is irrigated (MAAF 2012), mainly with water from the aquifer. The aquifer is also a crucial resource for drinking water in the region. The management of the Beauce aquifer is therefore an important issue that has been addressed through several governance schemes. In particular, since 1995, irrigation restrictions depend on the state of the aquifer and since 1999, individual irrigation quotas have been introduced, which are adjusted every spring through a reduction coefficient calculated as a function of the state of the aquifer.[3]

Future weather conditions may render drastic restrictions necessary. This is why Lejars et al. 2012c discussed the potential impact of restrictions representing 40% and 70% of quota in force today. In this paper, we first assess how the farmers adjust to dry weather conditions and what this implies for the aquifer. We then introduce restrictions of 20%, 40 % and 70 % of individual quotas under dry conditions in our model. While Lejars et

[2] Other dynamic models exist, e.g. on reservoir management (see for example Vedula and Nagesh Kumar 1996 or Evers et al. 1998), or on the dynamics of agricultural yields (see for example Reynaud 2009 or Knapp and Schwabe 2008), but they do not deal with groundwater management and particularly with the consequence of a drop in the height of the water-table for the cost of extraction.

[3] The aquifer has an average stock of 20 billion m^3 but has been subject to quite high inter-annual variations over the last 30 years (see Coz 2000).

al. (2012c) studied such restrictions in focus groups with farmers, we test the impact of such restrictions in an analytical model. Similar stringent restrictions have been found to be necessary in other regions of Europe. For example, Pérez-Blanco and Gómez 2014 reported that drought management plans in the Guadalquivir river basin in Spain lead to restrictions of 30% when the drought alert index is reached and up to 70% in emergency situations. Our study shows that, although restrictions are efficient in preserving water-table levels, they result in serious economic losses for farmers, representing almost one third of gross annual value added in the most extreme scenario.

The paper is organized as follows. In Section 2, we present the hydro-agro-economic model and the solution approach we use. In Section 3, we describe the existing data and the transformations we undertook to be able to apply the model to the Beauce study area. We model choices of a representative farm specialized in field crops and sugar beet production, which is one of the four main farm types in the study area. We estimate the water response of the underlying yield functions. We also consider how yield responses and water-use by competitive sectors change, depending on weather conditions. In Section 4, we present the baseline-case, a normal year corresponding to 2010, and results for different scenarios, namely a dry year with no policy intervention, and four policy-scenarios, in which quotas and restrictions are used to cope with dry conditions. In Section 5, we discuss the impact of some key parameters of our model. Finally, in Section 6 we present our conclusions and ideas for further research.

2 A Model of Irrigation and Land-Use Choice

2.1 The Model

We consider a two-period and k-crop model for a representative farm with a surface area S. We call $t = 0$ the first time period (spring) and $t = 1$ the second time period (summer) for which decisions are taken. At the beginning of spring, the farmer chooses the share of land, $\alpha_k(t)$, with $0 \leq \alpha_k(t) \leq 1$ and the (per hectare) irrigation water volume, $w_k(t)$, for each crop k and each period t. These are the decision variables. M represents the number of representative farmers in the study area, which covers a total surface area of S_b hectares. These farmers share the same aquifer, which is described by the height of the water-table, $H(t)$, which is the state variable. The water-table changes as a function of all the farmers' irrigation decisions (see equation (5)). In the following, we describe all the parameters and variables of the model which are also described in table 1.[4]

[4]For the sake of simplicity, whenever possible, we suppress the time indicator in the following.

Name	Description
S	Mean surface area of representative farm
α_k	Share of surface area of crop k (*decision variable*)
w_k	Water volume (per hectare) used for crop k (*decision variable*)
H	Water-table height (*state variable*)
y_k	Yield water response (per hectare) of crop k
a_k	Coefficient 1 of yield water response of crop k
b_k	Coefficient 2 of yield water response of crop k
x_k	Intercept of yield water response of crop k
p_k	Price of crop k
c_k^o	Operating expenses (per hectare) for crop k
c_k^p	Pumping costs (per hectare) for crop k
d_k	Coefficient 1 of operating expenses for crop k
e_k	Coefficient 2 of operating expenses for crop k
z	Cost parameter for maximum pumping height
c	Unit energy cost per volume pumped
π	Gross value added (per period) for representative farm
β	Discount rate
$\tilde{w}$	Total volume of irrigation water for representative farm
w^j	Irrigation water used by all other types of farms
w^o	Water for other uses than irrigation
W	Total water extractions for all water uses
M	Number of representative farms
r	Net average recharge in one period
σ	Return flow coefficient
γ	Withdrawal coefficient
η	Aquifer stock coefficient
S_b	Total surface are of study area
H_0	Initial height of water-table
$\bar{\alpha}$	Share of surface are used for summer crop
$\bar{w}$	Minimum amount of water applied to the summer crop

Table 1: List of Variables and Parameters

First, the (per hectare) yield response to water, y_k, for each crop, is given by:

$$y_k(w_k) = a_k w_k - b_k w_k^2 + x_k, \tag{1}$$

where a_k, b_k and x_k are positive parameters.

Each farmer aims to maximize the present value of gross values added, $\sum_t \beta^t \pi(t)$, given the price for each crop, p_k, the discount rate, β, and variable costs. For per hectare variable costs, we distinguish operating expenses, c_k^o, which depend on the share of surface area allocated to each crop, from pumping costs, c_k^p, which depend on the water-table height and on the per hectare water volume used for each crop. Hence:

$$\begin{aligned} c_k^o(\alpha_k) &= d_k \alpha_k + \frac{e_k}{2}\alpha_k^2, && (2)\\ c_k^p(w_k, H) &= (z - cH) w_k, && (3) \end{aligned}$$

where d_k and e_k are positive parameters of operating expenses, and z and c positive parameters of the cost of pumping. In particular, the quadratic form of operating expenses is due to implicit management costs associated with a given land allocation. As shown by Carpentier and Letort 2012, quadratic costs occur because of the constraints associated with quasi-fixed inputs (machinery and labor peak loads) and crop rotations (see also Heckelei and Wolff 2003). Concerning the pumping cost function, z measures the marginal costs of maximum possible lift and c the unit energy cost (see for example Gisser and Sánchez 1980). Thus, Gross Value Added in period t is given by:

$$\pi(t) = \sum_k S\left\{\alpha_k(t)\left[p_k y_k(w_k(t)) - c_k^p(w_k(t), H(t))\right] - c_k^o(\alpha_k(t))\right\}. \tag{4}$$

The water-table height decreases with total extractions, W, corrected by the withdrawal coefficient γ, and increases according to the return flow coefficient σ and the net recharge over the period concerned, $r(t)$. The storage capacity of the aquifer is represented by the surface area of the study area, S_b and the aquifer stock coefficient, η. The height of the water-table in the second period thus depends on the height of the water-table in the first period in the following way:

$$H(t+1) = H(t) + \frac{r(t) - (1-\sigma)\gamma W(t)}{\eta S_b}, \quad t = 0, 1. \tag{5}$$

Total extractions are the sum of extractions by representative farms and other extractions:

$$W(t) = M\tilde{w}(t) + w^j(t) + w^o(t), \tag{6}$$

with

$$\tilde{w}(t) = S\sum_k \alpha_k(t) w_k(t), \tag{7}$$

the total water volume used by each farmer, $w^j(t)$ irrigation water volumes of non-representative farms and $w^o(t)$ water extraction for other uses, namely drinking water and industrial uses.

We consider that the representative farm does not know the value added of the other players who share the aquifer. However, the farmer guesses the volume used by other water users, for example, based on the total amount of water used in a previous agricultural campaign. Finally, we assume that the value of the resource at the end of the planning horizon, $V(H(2))$, is constant. This means that the implicit price of the water resource at that time is zero. The farmer's planning horizon is indeed only one agricultural campaign with two irrigation periods and the value of water at the end of these seasons is nil for the production process considered here.

The general problem for the representative farmer is hence the following:

$$V(H_0) = \max_{\{\alpha_k(t)\geq 0, w_k(t)\geq 0\}} \quad \sum_t \beta^t \pi(t) \quad s.t. \quad (1) \quad \text{to} \quad (7) \quad \text{with} \tag{8}$$

$$H(0) \quad = \quad H_0, \quad V(H(2)) = V_T(\text{constant}), \quad \text{and} \quad \sum_k \alpha_k = 1. \tag{9}$$

We use the dynamic programming principle to solve the problem. Consequently, we have to solve the Hamilton-Jacobi-Bellman equation:

$$V(H(t)) = \max_{\{\alpha_k(t)\geq 0, w_k(t)\geq 0\}} \pi(t) + \beta V(H(t+1)),$$

where,

$$H(t+1) \quad = \quad H(t) + \frac{r(t) - (1-\sigma)\gamma\left[M\sum_k \alpha_k(t) S w_k(t) + w^j(t) + w^o(t)\right]}{\eta S_B}, \quad t = 0, 1.$$

$\pi(t)$ described in (4) and constraints (9) above.

2.2 A Simpler Case

In the following, we consider a simpler case representing a typical situation in the Beauce area. We use a model with three crops, of which two are grown in spring. Because there is only one main summer crop, which is grown on a contractually fixed proportion of land, in the following, we assume the case where the share of the summer crop is fixed. The contract also implies that the summer crop cannot be grown without a minimum amount of irrigation. Hence, we have:

$$\alpha_1(0) \geq 0, \quad \alpha_2(0) \geq 0, \quad \alpha_3(1) = \bar{\alpha},$$

and consequently:

$$w_1(0) \geq 0, \quad w_2(0) \geq 0, \quad w_3(1) \geq \bar{w},$$

and

$$\alpha_1(1) = \alpha_2(1) = \alpha_3(0) = w_1(1) = w_2(1) = w_3(0) = 0.$$

2.2.1 Land Use and Water Volumes in Summer

We can now solve the dynamic programming problem using backward induction. As $V(H(2)) = V_T$ (constant), we have:

$$\pi(1) = S\bar{\alpha}(p_3(x_3 + a_3w_3(1) - b_3w_3(1)^2) - d_3 - zw_3(1) + cH(1)w_3(1)) - S\frac{e_3}{2}\bar{\alpha}^2 \quad (10)$$

We first solve

$$V(H(1)) = \max_{w_3(1)} \pi(1) + \beta V_T.$$

The necessary condition of optimality is:

$$\frac{\partial \pi(1)}{\partial w_3(1)} = 0 \Leftrightarrow S\bar{\alpha}(p_3a_3 - 2p_3b_3w_3(1) - z + cH(1)) = 0 \quad (11)$$

hence:

$$w_3(1) = \frac{p_3a_3 - z + cH(1)}{2p_3b_3}, \quad (12)$$

with

$$H(1) = H_0 + \frac{r(0) - (1-\sigma)\gamma(MS(\alpha_1(0)w_1(0) + \alpha_2(0)w_2(0)) + w^j(0) + w^o(0))}{S_B\eta},$$

$$\text{and} \quad \alpha_2(0) = 1 - \alpha_1(0) - \bar{\alpha}. \quad (13)$$

Note that $p_3a_3 - 2p_3b_3w_3(1)$ is the marginal benefit derived from the summer crop and $z - cH(1)$ is the marginal cost of water-use in summer. Hence, equation (12) describes the optimal irrigation water choice as the one that equalizes marginal benefit and marginal costs for the summer crop. Moreover, given the relation between the water table and irrigation water-use (see equation (13)), marginal costs for water use in summer depend on the optimal irrigation water choice in spring. Substituting (12) and (13) in (10), we can compute the maximum value of the resource in summer as a function of the choices made in spring:

$$V(H(1)) = \pi^*(1) + \beta V_T. \quad (14)$$

2.2.2 Land Use and Water Volumes in Spring

Next, we maximize the value of the resource in spring in $t = 0$. We have to solve:

$$V(H(0)) = \max_{\substack{\alpha_1(0) \\ w_1(0), w_2(0)}} \pi(0) + \beta V(H(1))$$

with

$$\pi(0) = S\alpha_1(0)(p_1(x_1 + a_1w_1(0) - b_1w_1(0)^2) - d_1 - zw_1(0) + cH_0w_1(0)) - S\frac{e_1}{2}\alpha_1(0)^2$$
$$+S(1-\alpha_1(0)-\bar{\alpha})(p_2(x_2+a_2w_2(0)-b_2w_2(0)^2)-d_2-zw_2(0)+cH_0w_2(0))-S\frac{e_2}{2}(1-\alpha_1(0)-\bar{\alpha})^2, \quad (15)$$

and $V(H(1))$ described in (14). One necessary condition of optimality is:

$$\frac{\partial \pi(0)}{\partial \alpha_1(0)} + \beta \frac{\partial \pi(1)^*}{\partial \alpha_1(0)} = 0 \Leftrightarrow P(1) - P(2) + \beta \frac{\partial \pi(1)^*}{\partial \alpha_1(0)} = 0, \tag{16}$$

with P(1) and P(2) the value added from crops 1 and 2:

$$P(1) = Sp_1(x_1 + a_1 w_1(0) - b_1 w_1^2(0)) - Sd_1 - Szw_1(0) + ScH_0 w_1(0) - Se_1 \alpha_1(0), \tag{17}$$

$$P(2) = Sp_2(x_2 + a_2 w_2(0) - b_2 w_2^2(0)) - Sd_2 - Szw_2(0) + ScH_0 w_2(0) - Se_2(1 - \bar{\alpha} - \alpha_1(0)). \tag{18}$$

Equation (16) describes the optimal share of land-use used for crop 1 in spring. Notice that this solution depends on the difference between the gains from crop 1 (equation (17)) and crop 2 (equation (18)) and the impact of the choice of land-use in spring, $\alpha_1(0)$, on the discounted value of the resource in summer $\beta \frac{\partial \pi^*(1)}{\partial \alpha_1(0)}$ (see (14)). Clearly, the greater the difference between the gains obtained from crop 1 and 2, and/or the smaller the irrigation volume used in summer, the greater the share chosen for crop 1.
The other conditions for a maximum are:

$$\frac{\partial \pi(0)}{\delta w_1(0)} + \beta \frac{\partial \pi(1)^*}{\partial w_1(0)} = 0 \Leftrightarrow S\alpha_1(0)(p_1 a_1 - 2p_1 b_1 w_1(0) - z + cH_0) + \beta \frac{\partial \pi(1)^*}{\partial w_1(0)} = 0, \tag{19}$$

$$\frac{\partial \pi(0)}{\partial w_2(0)} + \beta \frac{\partial \pi(1)^*}{\partial w_2(0)} = 0 \Leftrightarrow S\alpha_2(0)(p_2 a_2 - 2p_2 b_2 w_2(0) - z + cH_0) + \beta \frac{\partial \pi(1)^*}{\partial w_2(0)} = 0. \tag{20}$$

Following equations (19) and (20), optimal irrigation water volumes for crop 1 (crop 2 respectively) depend on the share of land used for crop 1 (crop 2), the difference between marginal benefits and costs of water use for crop 1 (crop 2) and the value of the resource in summer given the irrigation water choice for crop 1 (crop 2) in spring.

We have a system of three equations: (16), (19) and (20), with three unknowns which we can therefore determine and find $\alpha_1^*(0)$, $w_1^*(0)$ and $w_2^*(0)$. Finally, we have to substitute $\alpha_1^*(0)$, $w_1^*(0)$ and $w_2^*(0)$ in equation (12) to find $w_3^*(1)$ the optimal irrigation water choice for crop 3.

At this point, we have only described the optimal interior solution of the problem. In order to take into account corner solutions, we need to consider different cases, depending on whether or not water use quotas and restrictions are implemented (see table 2). Quotas reduce the total water amount available. They can be reduced by a coefficient ω ($0 < \omega \leq 1$), depending on the water-table level at the beginning of the irrigation season. Without quotas or restrictions, we have to consider the 15 cases in Table 2. If quotas and restrictions are implemented, we have to consider the additional constraint

$$S\alpha_1 w_1 + S\alpha_2 w_2 + S\bar{\alpha} w_3 = \omega X \tag{21}$$

for all cases, except cases 9, 14, 15 and the specific reduction coefficient. The optimum is given by the solution (corner or interior solutions) that maximizes V(H(0)).

Cases	Values
Case 1	$\alpha_1 = 0 \Longrightarrow w_1 = 0$
Case 2	$\alpha_2 = 0 \Longrightarrow w_2 = 0$
Case 3	$w_1 = 0$
Case 4	$w_2 = 0$
Case 5	$w_3 = \bar{w}$
Case 6	$w_1 = w_2 = 0$
Case 7	$w_1 = 0$ and $w_3 = \bar{w}$
Case 8	$w_2 = 0$ and $w_3 = \bar{w}$
Case 9	$w_1 = w_2 = 0$ and $w_3 = \bar{w}$
Case 10	$w_1 = w_2 = \alpha_1 = 0$
Case 11	$w_1 = w_2 = \alpha_2 = 0$
Case 12	$w_1 = \alpha_1 = 0$ and $w_3 = \bar{w}$
Case 13	$w_2 = \alpha_2 = 0$ and $w_3 = \bar{w}$
Case 14	$w_1 = w_2 = \alpha_1 = 0$ and $w_3 = \bar{w}$
Case 15	$w_1 = w_2 = \alpha_2 = 0$ and $w_3 = \bar{w}$

Table 2: Possible Corner Solutions.

3 Data on the Beauce Area

Our study area, the "Central Beauce" area, which was defined by Lejars et al. 2012b, occupies an area of 300 600 ha of agricultural land and can be considered as representative of the whole Beauce region in terms of farm types. The Beauce region is one of the driest regions in France, with less than 600 mm rainfall per year. More than half the farms depend on individual water extractions from the Beauce aquifer. Since 1999, the aquifer has a well-established volumetric management system consisting in individual irrigation quotas, which are adjusted each year by a reduction coefficient as a function of water-table levels and are communicated to farmers at the beginning of the irrigation season, (see Petit 2002). Farmers can observe the water-table level in their wells or they can learn about the water-table level from the water-basin manager and official statistics. In addition, each spring, they are informed whether additional restrictions will be introduced in the region. Whether restrictions apply or not depends on the level of the aquifer. Severe restrictions apply when the crisis threshold is reached and some restrictions may even apply earlier, when the alert threshold is reached. In 2010, the crisis threshold was at 110.75 m NGF[5], the alert threshold at 112.19 m NGF. Relatively high variability of water-table levels led to variations in restrictions ranging from 4.5% to 55% from 1999 to the present (see Bouarfa

[5]Nivellement Général de la France (NGF) or General Levelling of France is the official levelling measure.

et al. 2011 or Lejars et al. 2012c). In the future, severe restrictions could be necessary under certain climate change assumptions (Lejars et al. 2012c). Following Lejars et al., we test restrictions corresponding to 40% and 70% reductions in individual quotas.

In what follows, we describe the agronomic, hydro-geological and economic data we use to inform our model of irrigation and land-use choice. Our baseline case is the year 2010, which corresponds to a year with normal precipitation in the study area. We also consider a scenario of a dry year, with and without restrictions on irrigation water use, for which some of the parameters change.

3.1 Agronomic Data

3.1.1 Types of Farms

Based on RGA[6] land-use data in 2010, Lejars et al. 2012a,b,c, identified four types of field crop farms in the study area. All of them cultivate over 45% of winter crops (mainly wheat) but differ from each other in the spring or summer crops in which they specialize: sugar beet in the first group, rapeseed in the second, special crops in the third, and maize in the fourth. Here, we focus on the most common type of farm in our study area, which accounts for 679 farmers specialized in field-crops and sugar beet. Land-use of the representative field crops sugar beet farm consists mainly of winter cereals, winter barley and sugar beet, with 48%, 17% and 16% of the land-use share respectively. The general agronomic data is available in the first part of table 3 and Figure 1.

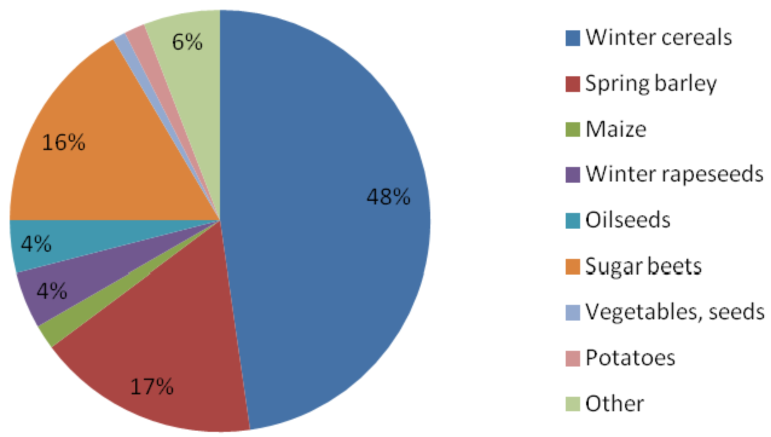

Figure 1: Representative field crops sugar beets farms in the study area.

[6]The General Agricultural Census (French acronym RGA for Recensement Général de l'Agriculture) is a survey conducted every ten years that updates knowledge of the farming sector: number of farms, allocation of farm land...

Parameters	Description	Unit	Value
S	Surface area of representative farm	ha	122
M	Number of representative sugar beet farms	*unitless*	679
$\bar{\alpha}$	Share of surface area used for summer crop	*unitless*	0.16
$\bar{w}$	Minimum amount of water applied to the summer crop	m^3/ha	1 300
γ	Withdrawal coefficient	*unitless*	1.1
σ	Return flow coefficient	*unitless*	0
η	Aquifer storage coefficient	*unitless*	0.08
w^o	Water for other uses than irrigation	million m^3	13.78
w_p^j	Water needs by other farms in spring	10^6 m^3	78
w_s^j	Water needs by other farms in summer	10^6 m^3	50
S_b	Total surface area of study area	km^2	3 006.6
H_0	Initial water-table height	m	92.81
r	Net recharge in summer and spring	m^3/season	0
p_1	Price crop 1 (soft wheat)	€/ton	109
p_2	Price crop 2 (barley)	€/ton	95.85
p_3	Price crop 3 (sugar beet)	€/ton	25.41
d_1	Coeff 1 operat. expenses crop 1	€/ha	0
d_2	Coeff 1 operat. expenses crop 2	€/ha	0
d_3	Coeff 1 operat. expenses crop 3	€/ha	0
e_1	Coeff 2 operat. expenses crop 1	€/ha	908
e_2	Coeff 2 operat. expenses crop 2	€/ha	780
e_3	Coeff 2 operat. expenses crop 3	€/ha	1 786
z	Maximum pumping cost	€/m^3	0.02912
c	Marginal pumping cost	€/m^3*m	0.000224
V_T	Final value of resource	€	0
β	Discount rate per period	*unitless*	0.05

Table 3: Agronomic, hydrogeologic and economic parameter values for the baseline case.

3.1.2 Yield Response to Water

We compute the yield response to water based on simulation data from the agronomic PILOTE Model (see Mailhol et al. 2011). The data accounts for the water balance in the irrigation season (rain, real evapotranspiration (ETR) and irrigation at different dates) and for the yields of different types of crops and soil, for the period 1997-2001. We aggregate data using different regressions according to the type of crop, the type of soil and weather conditions. Regression results are given in Tables 10-12 in the Appendix. We focus on results for average/deep soil, which is the most common soil found on specialized sugar beet farms, and on normal and dry weather conditions. Weather conditions are defined as a function of efficient rainfall (rain minus real evapotranspiration) and computed for the most representative crop in each irrigation season, i.e. wheat in spring and sugar beet in summer. In spring, dry conditions correspond to an ETR $\leq$ -60 mm and normal conditions to an ETR between -60 mm and 35 mm. In summer, the dry condition corresponds to an ETR $\leq$ -220 mm and normal conditions to an ETR between -220 mm and -120 mm.

We find that the quadratic relationship between water and yields gives the overall best results, which is in line with results in the literature (see for example Bozkurt et al. 2006 or Ali 2011 for a survey). We also tested linear and cubic relationships but the fit was less good. Note that we use simulated data as the basis for our regressions. All the scenarios we use are assumed to be equiprobable. We can therefore compare the goodness of fit of different model specifications. The values of the regression coefficients are listed in table 4.

Coefficients	**Description**	**Unit**	**Values**	
			in a normal year	**in a dry year**
x_1	Intercept for wheat	ton/ha	9.415315	7.144896
x_2	Intercept for barley	ton/ha	7.238088	5.876013
x_3	Intercept for sugar beet	ton/ha	65.02174	42.94781
a_1	coef. 1 for wheat	ton/m^3	0.0031337	0.0051176
a_2	coef. 1 for barley	ton/m^3	0.002735	0.004653
a_3	coef. 1 for sugar beet	ton/m^3	0.0325382	0.0554281
b_1	coef. 2 for wheat	ton.ha/m^3.m^3	0.00000171	0.00000214
b_2	coef. 2 for barley	ton.ha/m^3.m^3	0.00000125	0.00000199
b_3	coef. 2 for sugar beet	ton.ha/m^3.m^3	0.00000743	0.0000141

Table 4: Estimated Coefficients of Yield Function for Normal and Dry Year.

3.2 Hydro-geological Data

We use hydro-geological data from Graveline 2013 for the Central Beauce part of the aquifer. For our study, the withdrawal coefficient, the return flow coefficient, the aquifer storage coefficient come from Graveline 2013 and water withdrawals for other uses than irrigation from Lejars et al. 2012b. The water needs of other types of farms in spring and summer come from Lejars et al. 2012a and the total surface area corresponds to the Central Beauce part of the aquifer. The initial water table height for the baseline scenario is the one recorded in Spring 2010.[7] The initial water-table height in our example is thus 0.62 m above the alert threshold. Next, we set the net recharge in summer and spring to zero, as most recharge takes place in winter. Finally, water-table heights and withdrawals by other types of farms vary with the scenario. A summary of all these values is presented in the second part of table 3 and in table 5. All initial water-table heights for restriction scenarios are under the crisis threshold of 110.75 m NGF. A realistic assumption is that higher restriction scenarios go with lower initial water-table heights.

Parameters	Dry year	Quota	20% restrict.	40% restrict.	70% restrict.
H_0	92.81	92.81	74.25	55.67	27.84
w_p^j	97	78	61	47	26
w_s^j	56	50	36	38	41

Table 5: Initial water-table levels H_0 (in m) and irrigation water volumes (in 10^6 m^3) for other farms in spring, w_p^j, and summer, w_s^j, depending on weather and restriction scenarios.

3.3 Economic Data

We use economic data from several sources, which are summarized in the thrird part of table 3. Prices for wheat and barley come from the national agency FranceAgriMer (2012) and price of sugar beet from sugar beet producer organizations (CGB 2009). Operating expenses come from the farm data-base network ROSACE (2010). Because we do not have enough data to regress operating expenses on farm area, we attribute all operating expenses to the quadratic term. Pumping costs correspond to the cost of energy required to pump water to the topsoil. For typical pump capacities of around 50 m^3/h, 0.136 kW is required to lift one m^3 one meter. Considering pump efficiencies of 85%[8] and energy costs of 0.07 euros/kWh, we obtain marginal pumping costs of 0.000224 euros/m^3*m. For the largest potential pumping distance (considering the mean surface elevation to be 150 m above sea level and the deepest point of the aquifer to be 20 m above sea level) we obtain maximal (marginal) pumping costs of $z = 0.02912$ euros per m^3. Note that we do not consider neither water taxes or investments or payoffs for irrigation equipment. Therefore, our pumping costs correspond to a minimum bound. The final value of the resource is set to zero. Indeed, individual farmers do not internalize the consequences of long-term changes in the water-table. Finally, the discount rate is set at 5% for each period considered.[9]

[7] Water-table heights are measured in meters. Referring to the General Levelling of France, 92.81 m corresponds to 112.81 m NGF because the bottom of the water table is 20 m NGF.

[8] Personal communication from an expert in the field. Pump efficiencies in the Beauce area are high compared to those in other areas.

[9] This corresponds to a double-digit annual discount rate. Empirically elicited discount rates may be even higher.

4 Model Results for the Beauce Area

4.1 Results for the Baseline Case: A Normal Year

Variables	Description	Unit	Baseline	Dry Year
α_1	Share for wheat	*unitless*	0.60	0.56
α_2	Share for barley	*unitless*	0.24	0.28
w_1	Volume of water for wheat	m^3/ha	894	1 178
w_2	Volume of water for barley	m^3/ha	1 059	1 147
w_3	Volume of water for sugar beet	m^3/ha	2 167	1 954
$\tilde{w}$	Total water volume	m^3	138 782	157 800
$V(H(0))$	Gross annual value-added	Euros	89 717	84 043
$M\tilde{w}$	Total water of sugar beet farms	10^6 m^3	94.23	107.15
H_1	Aquifer level by end of spring	m	92.09	91.93
H_2	Aquifer level by end of summer	m	91.67	91.49
$H_0 - H_2$	Decrease in the aquifer level	m	1.14	1.32

Table 6: Dry year compared to baseline case.

Table 6 (second last column) shows the results of the simulation of the baseline case, a normal year corresponding to 2010. The representative sugar beet farmer chooses to allocate 60% of his/her land to wheat and 24% to barley, 16% being used for sugar beet by assumption. Wheat is irrigated with 894 m^3 per hectare, barley with 1 059 m^3 per hectare, and sugar beets with 2 167 m^3 per hectare, leading to a total water volume of 138 782 m^3 for one farm and 94.23 million m^3 for all the field-crop sugar beet farms. This lowers the height of the water-table from the initial 92.81 m to 92.09 m by the end of spring and to 91.67 m by the end of summer. Note that this water-table level (which corresponds to 111.67 m NGF) is above the crisis threshold (110.75 m NGF) that would lead to severe restrictions. Overall, a representative farm generates a gross annual value added of 89 717 euros.

4.2 Results for a Dry Year

Table 6 compares simulation results for a dry year with the baseline case. Because the share of the summer crop is fixed, 16% of land is still allocated to sugar beet, that is $\bar{\alpha} = 0.16$. However, the allocation of spring crops changes: compared to the baseline case, the representative farmer chooses to allocate less land to wheat (56% compared to 60%) and more to barley (28% compared to 24%). The intuition behind this change is that wheat is more sensitive to drought than barley, because yields are more responsive to water scarcity. This can be checked by computing the marginal productivity of water (MPW) at optimal values, in normal and dry years. First, the MPW value for wheat decreases by around 70 euros/m^3 per ha while the MPW for barley decreases by only around 13 euros/m^3. Moreover, the difference in MPW between wheat and barley is around 346 euros/m^3 per ha in a normal year and 288 euros/m^3 per ha in a dry year. This explains the change in the farmers' choice of land-use.

Next, total irrigation water volume increases by 19 000 m^3. This is due to an increase in both wheat and barley irrigation (1178 m^3/ha compared to 894 m^3/ha for wheat, 1147 m^3 /ha compared to 1059 m^3/ha for barley), while irrigation for sugar beets is reduced. The resulting total water volume of a representative farm increases in dry conditions and amounts to 157 800 m^3 (compared to 138 782 m^3 in the normal year). This leads to a bigger drop in the water-table, to 91.49 m by the end of summer (compared to 91.67 m in the normal year), which corresponds to a drop of 1.32 m. Most of this additional decrease is due to withdrawals in spring. While in a normal spring, the water-table height was reduced by 0.72 m, in a dry spring, it is reduced by 0.88 m, i.e. by 0.16 m. Finally, despite these adaptations, gross annual value-added for the representative farmer decreases only slightly (by 5 674 euros) from 89 717 euros in the normal year to 84 043 euros in a dry year.

4.3 Results for a Dry Year With Restriction Policies

We now introduce restriction policies. In the study area, individual quotas are in place. We first analyze the case in which the quota restricts the water volume to amounts in a normal year. Quotas can be changed into restrictions in dry years when the level of the aquifer is low. Table 7 illustrates how the introduction of these policies changes the results. We consider four scenarios: the use of quotas alone and restrictions corresponding to 20%, 40% and 70% of the quotas. Lejars et al. 2012c considered the 40% and the 70% restrictions as possible for future water policies. Graveline and Mérel 2014 considered 10% and 30% as policy scenarios in a model on the Beauce aquifer. We hence add the 20% restriction as a less extreme scenario. In all our restriction scenarios, the initial water-table levels are set below the crisis threshold, justifying policy intervention.

Let us first compare results for a dry year without restrictions to results for a dry year with restriction policies (see Tables 6 and 7). Concerning land use allocation, the use of policies lead to lower land-use shares allocated to wheat and higher shares to barley. Land-use shares of sugar beet are fixed and hence not adjusted. Concerning the irrigation strategy, when restriction policies are implemented, the farmer has access to a smaller total water volume. Priority is then given to the contractual summer crop: sugar beet, for which a minimum amount of irrigation is required by contract, see Bouarfa et al. 2011. Optimal results show that volumes for wheat and barley are greatly reduced. With a

Var.	Description	Unit	Restriction Policies			
			Quota	20%	40%	70%
α_1	Share for wheat	*unitless*	0.56	0.56	0.55	0.53
α_2	Share for barley	*unitless*	0.28	0.28	0.29	0.31
w_1	Volume of water for wheat	m^3/ha	1 121	870	621	251
w_2	Volume of water for barley	m^3/ha	1 077	768	460	3
w_3	Volume of water for sugar beet	m^3/ha	1 300	1 300	1 300	1 300
$\tilde{w}$	Total water volume	m^3	138 782	111 025	83 269	41 634
$V(H(0))$	Gross annual value added	Euros	83 811	81 090	75 360	61 175
$M\tilde{w}$	Total water of sugar beet farms	10^6 m^3	94.23	75.39	56.54	28.27
$H_0 - H_2$	Decrease in the aquifer level	m	1.14	0.91	0.77	0.56

Table 7: Results of simulation for a dry year with restrictions.

restriction of 20% (respectively 40%) the volume of water for wheat is reduced to 870 (respectively 621) m^3 per hectare (compared to 1 178 m^3 per hectare without restrictions) and for barley to 768 (respectively 460) m^3 per hectare (compared to 1 147 m^3 per hectare without restriction). The volume of water for barley is reduced more than for wheat, as wheat requires more water than barley. This is in line with results reported by Graveline and Mérel 2014. With a restriction of 70%, barley is cultivated under dryland farming conditions. Indeed, an amount of 3 m^3 per hectare is negligible as the volume applied in one water turn corresponds roughly to 55 m^3 per hectare. Overall, water volume reductions are quite important, ranging for instance between 26% and 33% of dry year amounts in the 20% restriction scenario. Graveline and Mérel 2014 find water volume reductions that are smaller than 9% for a 30% restriction scenario (intensive margin) but report the move to less water intensive crops (extensive margin) already for 10% and 30% restrictions scenarios. Overall, total water volumes decrease to 28.27 (75.39 and 56.54) million m^3 in the 70% (20% and 40%) restriction scenarios. Not surprisingly, restricting total water use has a beneficial effect on the height of the water-table, which drops by about 0.91 m (0.77 m) with a restriction of 20% (respectively 40%) and by only 0.56 m in the most extreme scenario. Restrictions lead to changes in water-table levels of 1-2%. However, such apparently slight variations correspond to large volumes of water, between 0.2 and 0.4 million m^3.[10] Moreover, repeated withdrawals of 1-2% can lead to substantial drops in the water-table level over longer time horizons - except when winter recharge is high. On the other hand, restrictions reduce gross annual value added: compared to the case in which only quotas apply, gross annual value added is reduced by about 2 721 euros

[10]For comparison, the distance between the alert threshold and the crisis threshold, which is 1.44 m corresponds to a 1.28% drop in water-table levels.

in the least restrictive scenario, 8 451 euros with a 40% restriction, and 22 637 euros with a 70% restriction. Such losses correspond to 3%, 10% and 27% of the gross annual value added compared with when only quotas apply. For comparison, Lejars et al. 2012a found reductions of 10% and 21% of gross production under the 40% and 70% restriction scenarios, which is very close to our results. In contrast, Graveline and Mérel 2014 report very moderate reductions in profits for the 30% restriction scenario of a regional Beauce model. In line with our results, Reynaud 2009 or Bouarfa et al. 2011 find again important revenue reductions in their respective case studies. This underlines the fact that although restrictions adequately preserve groundwater levels, they have a significant impact on the farmer's economic situation in the short term, even assuming that he/she adapts optimally to the dry situation. A policy maker could thus count on abundant winter recharge (which can exceed 1.5 m in wet years) to avoid too high economic losses for farmers, (see Bruand et al. 1997 for data on recharge).

To summarize, we can confirm three general features of adaptation in the face of drought and restriction policies: first, land-use is affected by a reduction in the share of the most sensitive crop and an increase in the share of the less sensitive crop. Second, the total volume of irrigation water for all crops is reduced. Third, in each scenario, lowest water volumes are allocated to the less productive barley crop, higher volumes to the more water sensitive wheat crop and highest volumes to the contractual summer crop. We can also summarize the economic impacts of our simulations. The combined effect of a dry year and restrictions leads to very serious economic losses for the farmers: for example 10% (16%) of gross annual value added with a 20% (40%) restriction, corresponding to 8 627 euros (14 357 euros). The quota only policy leads to a loss of 7% of gross annual value added (or 5 906 euros). The 70% restriction in quota volumes would lead to a 32% loss of gross annual value added. Concerning the level of the aquifer, restriction policies show lower aquifers than the baseline case, because initial aquifer levels were intentionally set very low when stringent restrictions are in place. By assumption, there is no recharge in spring and summer, and hence no restriction can enable recovery of the resource within a year. However, we can measure the performance of different restriction policies with respect to the drop in water-table levels they trigger. We can see that the more stringent the restriction, the smaller the drop in the aquifer level during the irrigation campaign. This confirms the importance of the implementation of restriction policies to preserve the resource.

5 Discussion of Key Parameters

Finally, we need to analyze the importance of different parameters in the simulation results.[11] One major limit of the model is the lack of information to estimate the quadratic function that represents operating costs. As final results could be driven by the choice of this cost function, we designed some scenarios with different operating cost parameters. These different scenarios are simulated in such a way that the marginal unitary cost per crop is the same, as can be seen in Table 8.

Var.	**Baseline**		**Scenario 1**		**Scenario 2**	
	$d_1 = 0$	$e_1 = 908$	$d_1 = 908/3$	$e_1 = 2 * 908/3$	$d_1 = 908/2$	$e_1 = 908/2$
	$d_2 = 0$	$e_2 = 780$	$d_2 = 780/3$	$e_2 = 2 * 780/3$	$d_2 = 780/2$	$e_2 = 780/2$
	$d_3 = 0$	$e_3 = 1786$	$d_3 = 1786/3$	$e_3 = 2 * 1786/3$	$d_3 = 1786/2$	$e_3 = 1786/2$
α_1	0.60		0.68		0.73	
α_2	0.24		0.18		0.11	
w_1	894		894		894	
w_2	1 059		1 059		1 059	
w_3	2 167		2 167		2 167	
$\tilde{w}$	138 782		137 431		136 082	
$V(H(0))$	89 717		67 266		56 504	
$M\tilde{w}$	94.23		93.32		92.4	
$H_0 - H_2$	1.14		1.14		1.14	

Table 8: Results accounting for different operating costs for each crop.

We observe significant changes in the share of land allocated to each crop and in the gross value added obtained by each farmer. For example, in scenario 2 in which the marginal unitary cost for each crop is shared equally between the linear and quadratic parameters, the share of land allocated to wheat (respectively to barley) increases (respectively decreases) by 13 points compared with the baseline scenario. Moreover, the gross value-added decreases by 33 213 euros from the baseline scenario to the second scenario, which corresponds to an economic loss of 37%. However, the simulation results provide some hints for the validation of our model. First, total volumes of water used by the farm do not vary significantly between scenarios (less than 2%). This implies that changes in water-table levels are very low between scenarios. Concerning economic outputs, the values in the baseline scenario are more realistic, as reported in the different studies conducted in the study area (cf. Lejars et al. 2012b,c).

Next, in our analysis, we use estimated parameter values, a_k, b_k and x_k, which contain

[11] We thank two anonymous referees for discussions on an earlier version of this section.

Variables	Description	Unit	Baseline	Dry Year	T-test
α_1	Share for wheat	*unitless*	0.60	0.58	**
			(0.07)	(0.17)	
α_2	Share for barley	*unitless*	0.24	0.26	**
			(0.07)	(0.17)	
w_1	Water volume for wheat	m^3/ha	986	1 440	**
			(409)	(764)	
w_2	Water volume for barley	m^3/ha	1 174	1 401	**
			(454)	(580)	
w_3	Water volume for sugar beet	m^3/ha	2 225	2 026	**
			(608)	(436)	
$\tilde{w}$	Total water volume	m^3	154 392	196 985	**
			(40 809)	(73 219)	
$V(H(0))$	Gross annual value-added	Euros	92 381	98 937	**
			(8 033)	(36 044)	
H_1	Aquifer level at the end of spring	m	92.04	91.81	**
			(0.12)	(0.23)	
H_2	Aquifer level at the end of summer	m	91.62	91.37	**
			(0.13)	(0.23)	

Table 9: Mean simulated values (with standard errors) and 95% confidence intervals in the T-test comparing sample means. (**) indicates cases where H0 of equal means is rejected.

uncertainty. We therefore conduct a sensitivity analysis with respect to these parameter values. More precisely, we draw 10000 parameter values in a normal law with standard errors as estimated in the regressions shown in Tables 10-12. Results for normal and dry year scenarios[12] are given in Table 9.

We can see that land-use changes, as described in our example based on the year 2006, are robust to changes in parameters. Likewise, volumes of water increase for wheat and barley and decrease for the summer crop in the dry scenario, like in our example. Moreover, at the end of spring and summer, the levels of the aquifer are significantly lower under dry conditions than in a normal year. However, gross annual value added according to the uncertainty analysis is greater in a dry year than in a normal year, in contrast to our example. This is probably due to a greater decrease in the yield of the contractual summer crop in our example. Results for the total water volumes are also robust as there is an increase in the dry scenario compared to the normal scenario. The implementation of restriction policies in dry years are then justified.

Finally, we ran other simulations with different values for prices, pumping costs and parameters of the dynamics of the resource.[13] For example cereal crop prices are key parameters in the economic model. Increasing the price of barley above that of wheat leads to a significant decrease in the share of land allocated to wheat (- 20 points). Doubling cereal prices leads to higher revenues (+ 128 points), but does not influence the state of the aquifer at the end of summer. Doubling the price of sugar beet leads to higher irrigation water volumes used for this crop. Results are less sensitive to an increase in pumping costs. Pumping costs have to be multiplied by at least ten to result in significant changes in the water volumes used and revenues obtained. Finally, a variation in hydrological parameters, for example in water volumes applied by other users or the total surface area of the study area, does not impact individual irrigation and land-use choices but plays an important role in aquifer levels.

6 Conclusion

In this paper, we assess the impact of dry weather conditions and restriction policies in the Beauce aquifer in France. To this end, we built a dynamic hydro-agro-economic model to simulate the choice of land-use and irrigation volumes made by farmers. We needed a dynamic model because we wanted to assess restriction policies that apply in spring and in summer, but which the farmers learn about and take into account at the beginning of spring. The dynamic effect is not very large in our model, because pumping costs are

[12] Sensitivity analyses have also been made for results of the dry year scenarios with restriction policies in Table 6. Results of these analyses are available from authors upon request.

[13] More detailed results are available upon request.

very low and the aquifer is very large. If the model were to be used in other study areas, the dynamic effect would be increasingly relevant. However, with large surface areas, like Central Beauce, small drops in the level of the water-table lead to major reductions in water volumes and may harm the whole agricultural sector. Specifically, the estimated 1% to 2% drops in the level of the water table during the irrigation period correspond to water volumes of between 0.2 and 0.4 million m^3. The main contribution of the paper is assessing the impact of dry weather conditions and water restrictions on farmers' decisions concerning optimal land-use and irrigation. We first consider a dry year scenario, in which there is an increase in water demand. We then consider a dry year scenario with different restriction policies. We show that, first, land-use strategies in the face of droughts consist in decreasing the share of the most sensitive crop and increasing the share of the less sensitive crop. Second, total irrigation water volumes may increase in absence of restrictions but are reduced when restrictions are implemented. Third, in the case of restrictions, water volumes are reduced in quite important proportions (with reduction greater than 26%). Fourth, with restrictions, lowest water volumes are allocated to the less productive barley crop, higher volumes to the more water sensitive wheat crop and highest volumes to the contractual summer crop. Lastly, we show that the combined effect of a dry period and restriction policies results in significant losses for farmers, which can reach 16% of gross value-added for a high but not implausible 40% limitation on water use and up to 32% for drastic restrictions of 70%. The order of magnitude of these losses is in line with other studies on the Beauce aquifer, see for example Bouarfa et al. 2011 or Lejars et al. 2012a. Hence, the implementation of restriction policies comes at a cost, which our model can assess. To conclude, although restriction policies are a satisfactory way of preserving water-table levels, they can lead to serious economic losses for farmers in the short term. To avoid such losses to farmers, a policy maker could count on abundant winter recharge. In wet winters, recharge can exceed 1.5 m (see Bruand et al. 1997), which results in higher water-table levels the following spring than initial levels, whatever the restriction scenario considered in the current year. However, as the Beauce aquifer is characterized by low winter recharges, this scenario is rather unlikely. Our results thus imply important future challenges for policy makers in our study area.

Several extensions of this work are possible: First, we could improve the dynamic model by considering more than two periods and a more complex crop rotation system. In addition, we could introduce uncertainty and show how a farmer can cope with it. Moreover, we could assume farmers are risk averse, for example by including farmers who minimize the variance of outcomes. Finally, we could introduce different types of farmers and the interactions between them, and focus especially on how they learn about their respective behaviors.

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Appendix

Table 10: **Yield-water response for wheat and average/deep soil**

Dry weather conditions

Variable	**Coefficient**	**Std.error**	**t Value**	**P**$>|t|$	**95% Conf. interval**
w	0.0051176	0.0012194	4.20	0.000	[0.0027036, 0.0075315]
w squared	-2.14e-06	9.86e-07	-2.17	0.032	[-4.09e-06, -1.87e-06]
const.	7.144896	0.3032466	23.56	0.000	[6.544589, 7.545203]

Number of observations: 125. Adjusted R-squared 0.3071

Normal weather conditions

Variable	**Coefficient**	**Std.error**	**t Value**	**P**$>|t|$	**95% Conf. interval**
w	0.0031337	0.0005348	5.86	0.000	[0.0020779, 0.0041895]
w squared	-1.71e-06	4.76e-07	-3.60	0.000	[-2.65e-06, -7.71e-07]
const.	9.415315	0.1214989	77.49	0.000	[9.175474, 9.655156]

Number of observations: 173. Adjusted R-squared 0.2750

Table 11: Yield-water response for barley and average/deep soil

Dry weather conditions

Variable	Coefficient	Std.error	t Value	P> $\|t\|$	95% Conf. interval
w	0.004653	0.0007293	6.38	0.000	[0.0032086, 0.0060974]
w squared	-1.99e-06	6.00e-07	-3.32	0.001	[-3.18e-06, -8.01e-07]
const.	5.876013	0.1789212	32.84	0.000	[5.521637, 6.231389]

Number of observations: 119. Adjusted R-squared 0.5088

Normal weather conditions

Variable	Coefficient	Std.error	t Value	P> $\|t\|$	95% Conf. interval
w	0.002735	0.0003649	7.50	0.000	[0.002014, 0.0034559]
w squared	-1.25e-06	3.57e-07	-3.50	0.001	[-1.95e-06, -5.44e-07]
const.	7.238088	0.0763662	94.78	0.000	[7.087203, 7.388972]

Number of observations: 154. Adjusted R-squared 0.4916

Table 12: Yield-water response for sugar beet and average/deep soil

Dry weather conditions

Variable	Coefficient	Std.error	t Value	P> $\|t\|$	95% Conf. interval
w	0.0554281	0.0048382	11.46	0.000	[0.00458902, 0.064966]
w squared	-0.0000141	2.83e-06	-4.97	0.000	[-0.0000196, -8.48e-06]
const.	42.94781	1.710531	25.11	0.000	[39.57571, 46.31992]

Number of observations: 212. Adjusted R-squared 0.7105

Normal weather conditions

Variable	Coefficient	Std.error	t Value	P> $\|t\|$	95% Conf. interval
w	0.0325382	0.004551	7.15	0.000	[0.023583, 0.0414934]
w squared	-7.43e-06	2.88e-06	-2.58	0.010	[-0.0000131, -1.75e-06]
const.	65.02174	1.462459	44.46	0.000	[62.14399, 67.89948]

Number of observations: 309. Adjusted R-squared 0.4112