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

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Abstract

This paper models land-use and irrigation water choices in a dynamic hydro-agro-economic model. We first confirm that the dynamic model leads to different results than a static model without pumping costs. We then apply our model to the Beauce area, which is one of the most important agricultural production areas in Europe. We show that dry wheather conditions lead to both more important decreases in water-table levels and losses in gross added value for the farmers. Next, we compare the performance of two regulatory policies: water restricions (quotas), which are currently in place, and increases in pumping costs (taxes), which are considered as an alternative. We show that restrictions outperform taxes with respect to hydrological criteria, while farmers' gross value added are comparable. Although they are relatively more performant than taxes, restrictions lead to important economic losses for the farmers.

Keywords: groundwater management; hydro-economic model; dynamic programming; land-use, irrigation, Beauce aquifer.

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1 Introduction

Most models of irrigation and land-use choice are static, i.e. they do not consider the evolution of the water resource (see for example Howitt 1995 [13] Heckelei 2002 [11], Heckelei and Wolff 2003 [12] or Graveline et al. 2012 [9]). Among the models that are dynamic, some deal with reservoir management (see for example Vedula and Kumar 1996 [23] or Evers et al. 1998 [6]), others consider the dynamics of agricultural yields (see for example Reynaud 2009 [20] or Knapp and Schwabe [14]), but they do not consider problems of groundwater mangament and in particular the consequence of a decrease in the water-table height on the costs of extractions. On the other hand, models that deal with the evolution of groundwater levels and resulting management costs, do not consider crop mangement, such as many dynamic models in resource economics (see for example Burt 1967 [2], Gisser and Sanchez 1980, Roseta Palma 2002 [22], Moreaux and Reynaud 2006 [19], or De Frutos Cachorro et al. 2014 [5]).

However, in many developed countries, piezometric measures are performed and aquifer levels can be considered to be common knowledge. Often, farmers can observe the levels of the water-table height and the resulting pumping costs and do consider these elements in their decision making. In addition, in some cases, collective groundwater management rules depend on aquifer levels, which are hence communicated to the farmers during the agricultural season. For all these reasons, it is interesting to consider a model that takes the evolution of the groundwater resource into account.

The aim of this paper is twofold: first, to construct a hydro-economic model, in which farmers chose crop allocation and irrigation water volumes while considering the state and the evolution of the groundwater aquifer. Second, we wish to assess the performance of different regulatory policies that are implemented in one of the most important agricultural areas in Europe, the Beauce aquifer.

Situated in the south-west of Paris, the Beauce aquifer extends over 9700 km^2 (see Lejars et al. [16]). It corresponds to the most important agricultural production region in France and one of the biggest cereal producing regions in Europe. With less than 600 mm of rainfall per year, it is also one of the driest regions in France (see Lejars et al. [16]).

As a consequence, about 50 % of the agricultural land is irrigated (Agreste [1]), using mainly water from the aquifer. The potentially important water demand materializes in individual withdrawals in the common groundwater resource, which has an average stock of 20 billion m^3 but quite important inter-annual variations, namely over the last thrirty years. The management of the Beauce aquifer is therefore an important issue which has been addressed through several governance schemes. In particular, since 1995 irrigation restrictions are dependent on the state of the aquifer and since 1999, individual irrigation quotas have been introduced, which are adjusted as a function of the state of the aquifer.

In this paper, we model irrigation and land-use choices of a representative field crops sugar-beet farm, which is one of the four main farm types in the study area. We estimate the water response of the underlying yield functions. In line with the wider literature, we use quadratic cost functions for operating expenses (see for example Carpentier and Letort [3]) and linear marginal cost functions for pumping costs, which are a function of pumping lift (see for example Gisser and Sanchez [8]). Depending on wheather conditions, yield responses and water-use by competitive sectors change, which in turn plays on the evolution of the water-table height and on pumping costs. We are interested in assessing how this farm-type adjusts to dry wheather conditions and what this implies for the aquifer. But more importantly, we aim at comparing different restriction policies: existing quota policies and increases in pumping costs, which can be assimilated to a tax policy.

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 performed to be able to apply the model to the Beauce study area. In Section 4, we present results for different scenarios, namely two climatic conditions (normal and dry year) and two types of policies to cope with dry conditions (restrictions and increases in pumping costs assimilated to a tax on water withdrawals). We show that the restriction policy outperforms the tax policy, although economic losses for the farmers are important. Finally, in Section 5 we present our conclusions and discuss some ideas for further research.

2 A Model of Irrigation and Land-Use Choice

2.1 The Model

In the following, we construct a two-period and k-crops model for a representative farm having a mean surface S. We call $t = 0$ the first time period (spring) and $t = 1$ the second time period (summer) for which decisions are taken. Each farmer choses the share of land for different crops, $\alpha_k(t)$, with $0 \leq \alpha_k(t) \leq 1$ and the total irrigation water volume for each crop $w_k(t)$. All farmers share the same acquifer which is described via the water table height, $H(t)$, the state variable. The water table evolves as a function of all the farmers' irrigation decisions. Parameter descriptions[1] are summarized in Table 1.

The (per hectare) yield response to water for each crop is given by the following function:

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

where y_k the yield and a_k, b_k and x_k positive parameters.

Each farmer aims at maximizing gross value added, v, given the price for each crop, p_k, and variable costs. For variable costs, we distinguish operating expenses, c_k^o, which depend on the surface allocated to each crop, from pumping costs, c^p, which depend on the water-table height and the water volume, $\tilde{w}(t)$, used by each farmer. Hence:

$$c_k^o = d_k \alpha_k(t) - \frac{e_k}{2} \alpha_k(t)^2, \tag{2}$$

$$c^p = (z - cH(t))\tilde{w}(t), \tag{3}$$

where d_k and e_k are positive parameters of operating expenses and z and c positive parameters of pumping costs (z measures the marginal costs of maximum possible lift and c the unit energy cost). The quadratic form of operating expenses is due to implicit managemnet costs associated with a given land allocation. As shown by Carpentier and Letort [3], 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 [12]. The per period water volume used by each farmer is given by:

$$\tilde{w}(t) = \sum_k \alpha_k(t) S w_k(t). \tag{4}$$

[1] For simplicity, we suppress the time indicator in the following whenever possible.

Value added is hence given by:

$$v = \sum_t \sum_k S \left\{ \alpha_k(t) \left[p_k y_k(w_k(t)) - c^p(w_k(t), H(t)) \right] - c_k^o(\alpha_k(t)) \right\}. \quad (5)$$

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 considered period, $r(t)$. The storage capacity of the aquifer is represented by the surface of the study area, S_b and the aquifer stock coefficient, η. The water table height in the second period thus depends on the water table height in the first period in the following way:

$$H(t+1) = H(t) + \frac{r(t) - (1-\sigma)\gamma W(t)}{\eta S_b}, \quad t = 0, 1. \quad (6)$$

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

$$W(t) = w^i(t) + w^j(t) + w^o(t), \quad (7)$$

where $w^i = M\tilde{w}$, with M the number of representative farms, $w^j(t)$ irrigation water volumes of other farms and $w^o(t)$ water extraction for other uses, namely drinking water and industrial uses.

In the following, we consider a model with three crops, of which two are grown in spring. Moreover, because there is one main summer crop, which is grown on a contractually fixed proportion of land, we assume in the following the case where the share of the summer crop is fixed. This also implies that the summer crop cannot be grown without irrigation. Hence, we have:

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

and consequently:

$$w_1(0) \geq 0, \quad w_2(0) \geq 0, \quad w_3(1) > 0.$$

Finally, we assume the value of the resouce by the end of the planning horizon, $V(T)$, 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 two agricultural seasons and the value of water at the end of these seasons is nil for the considered production process.

Parameter	**Description**
S	Mean Surface of Representative Farm
α_k	Share of Surface of Crop k (*decision variable*)
w_k	Water Volume Used for Crop k (*decision variable*)
H	Water table height (*state variable*)
y_k	Yield for Crop k
a_k	Coefficient 1 of Yield Water Response for Crop k
b_k	Coefficient 2 of Yield Water Response for Crop k
x_k	Intercept of Yield Water Response for Crop k
p_k	Price for Crop k
c_o	Operating Expenses for Crop k
c_p	Pumping Costs
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
v	Gross value added for Representative Farm
W	Total Water Extractions for all Water Uses
w^i	Irrigation Water Volume for all Representative Farms
w^j	Irrigation Water Used by all other Types of Farms
w^o	Water for Other Uses than Irrigation
$\tilde{w}$	Total Irrigation Water Volume for Representative Farm
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 of Study Area
H_0	Initial Water Table Height
$\bar{\alpha}$	Share of Surface Used for Summer Crop

Table 1: List of Parameters

The general problem for the farm is hence the following:

$$\max_{\{\alpha_k(t), w_k(t)\}} v \quad s.t. \quad (1) \quad \text{to} \quad (7) \quad \text{with} \tag{8}$$

$$H(0) \quad = \quad H_0, \tag{9}$$

$$\begin{aligned} V(T) &= constant, & (10)\\ \alpha_1(0) &+ \alpha_2(0) + \alpha_3(1) = 1, & (11)\\ \alpha_1(1) &= \alpha_2(1) = \alpha_3(0) = 0 \quad \Longrightarrow \quad w_1(1) = w_2(1) = w_3(0) = 0, & (12)\\ \alpha_3(1) &= \bar{\alpha}. & (13) \end{aligned}$$

2.2 Interior Solutions

We use the dynamic programming principle to solve the problem. Consequently, we have:

$$V(H(t)) = \max_{\left\{\substack{\alpha_1(t), \alpha_2(t) \\ w_1(t), w_2(t), w_3(t)}\right\}} S \sum_{k=1}^{3} \alpha_k(t)(p_k y_k(w_k(t)) - d_k - z w_k(t) + cH(t) w_k(t))$$
$$-S\frac{e_k}{2}\alpha_k^2(t) + \beta V(H(t+1)),$$

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

and constraints (9) to (13) above.

2.2.1 Land Use and Water Volumes in Summer

Let $V(H(2)) = V_T$ (constant), we have:

$$\pi(1) = S\bar{\alpha}(p_3(x_3 + a_3 w_3(1) - b_3 w_3(1)^2) - d_3 - z w_3(1) + cH(1) w_3(1)) - S\frac{e_3}{2}\alpha_3^2(1) \tag{14}$$

We first solve

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

The necessary condition of optimality is:

$$\frac{\partial \pi(1)}{\partial w_3(1)} = 0 \Leftrightarrow S\bar{\alpha}(p_3 a_3 - 2p_3 b_3 w_3(1) - z + cH(1)) = 0$$

hence:

$$w_3(1) = \frac{p_3 a_3 - z + cH(1)}{2p_3 b_3}, \tag{15}$$

with

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

$$\text{and} \quad \alpha_2(0) = 1 - \alpha_1(0) - \bar{\alpha}. \tag{16}$$

Note that $p_3 a_3 - 2p_3 b_3 w_3(1)$ is the marginal benefit derived from the summer-crop and $z - cH(1)$ is the marginal cost for water-use in summer. Hence, equation (15) describes the optimal irrigation water choice as the one which equalizes marginal benefit and marginal costs for the summer crop. Moreover, given the relation between the water table and irrigation water use, marginal costs for water use in summer depend on the optimal irrigation water choice in spring. Substituting (15) and (16) into (14), we can compute the maximum value of the resource in summer as a function of the choices in spring:

$$V(H(1)) = \pi^*(1) = F(\alpha_1(0), w_1(0), w_2(0)). \tag{17}$$

2.2.2 Land Use and Water Volumes in Spring

Next, we maximize the gains obtained in spring in $t = 0$. We have to solve:

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

with

$$\begin{aligned}
\pi(0) &= S\alpha_1(0)(p_1(x_1 + a_1 w_1(0) - b_1 w_1(0)^2) - d_1 - z w_1(0) + cH_0 w_1(0)) - S\frac{e_1}{2}\alpha_1(0)^2 \\
&+ S(1 - \alpha_1(0) - \bar{\alpha})(p_2(x_2 + a_2 w_2(0) - b_2 w_2(0)^2) - d_2 - z w_2(0) + cH_0 w_2(0)) \\
&- S\frac{e_2}{2}(1 - \alpha_1(0) - \bar{\alpha})^2 + \beta F(\alpha_1(0), w_1(0), w_2(0)).
\end{aligned}$$

One necessary condition of optimality is:

$$\frac{\partial \pi(0)}{\partial \alpha_1(0)} = 0 \Leftrightarrow P(1) - P(2) + \frac{\partial \pi(1)^*}{\partial \alpha_1} = 0, \tag{18}$$

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

$$P(1) = Sp_1(x_1 + a_1 w_1(0) - b_1 w_1^2(0)) - Sd_1 - Szw_1(0) + ScH_0 w_1(0) - Se_1\alpha_1(0), \tag{19}$$

$$P(2) = Sp_2(x_2 + a_2 w_2(0) - b_2 w_2^2(0)) - Sd_2 - Szw_2(0) + ScH_0 w_2(0) - Se_2(1 - \bar{\alpha} - \alpha_1(0)). \tag{20}$$

Equation (18) describes the optimal land-use share used for crop 1 in spring. Notice that this solution depends on the difference between the gains from crop 1 (equation (19)) and crop 2 (equation (20)) and the impact of the land-use choice in summer, α_1, on the value of the resource in summer $\frac{\partial F(\alpha_1(0), w_1(0), w_2(0))}{\partial \alpha_1}$ (see (17). Clearly, the greater the difference between the gains obtained from crop 1 and 2, and/or the more prudent irrigation behavior in summer, the greater the share chosen for crop 1.

The other conditions for a maximum are:

$$\frac{\partial \pi(0)}{\delta w_1(0)} = 0 \Leftrightarrow S\alpha_1(0)(p_1 a_1 - 2p_1 b_1 w_1(0) - z + cH_0) + \beta \frac{\partial \pi(1)^*}{\partial w_1(0)} = 0, \tag{21}$$

$$\frac{\partial \pi(0)}{\partial w_2(0)} = 0 \Leftrightarrow S\alpha_2(0)(p_2 a_2 - 2p_2 b_2 w_2(0) - z + cH_0) + \beta \frac{\partial \pi(1)^*}{\partial w_2(0)} = 0. \tag{22}$$

Following equations (21) and (22), 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.

At this point, we have a system of three equations:, (18), (21) and (22), with three unknowns which we can therefore determine: $\alpha_1^*(0)$, $w_1^*(0)$ and $w_2^*(0)$.

Finally, we have to substitute $\alpha_1^*(0)$, $w_1^*(0)$ and $w_2^*(0)$ into equation (15) to find $w_3^*(1)$ the optimal irrigation water choice for crop 3. We have described the optimal interior solution of the problem. In the next section, we will analyze possible corner solutions.

2.3 Corner solutions

We have to consider different cases, depending on whether restrictions on water use are imposed (or not). Without restrictions on water use, we have to consider the cases given

No Restriction	Values	Restriction	Values
Case 1	$\alpha_1(0) = 0 \Longrightarrow w_1 = 0$	Case 10	$S\alpha_1 w_1 = X \Longrightarrow w_2 = w_3 = 0$
Case 2	$\alpha_2(0) = 0 \Longrightarrow w_2 = 0$	Case 11	$S\alpha_2 w_2 = X \Longrightarrow w_1 = w_3 = 0$
Case 3	$w_1 = 0$	Case 12	$S\alpha_3 w_3 = X \Longrightarrow w_1 = w_2 = 0$
Case 4	$w_2 = 0$	Case 13	$S\alpha_1 w_1 + S\alpha_2 w_2 = X \Longrightarrow w_3 = 0$
Case 5	$w_3 = 0$	Case 14	$S\alpha_1 w_1 + S\alpha_3 w_3 = X \Longrightarrow w_2 = 0$
Case 6	$w_1 = w_2 = 0$	Case 15	$S\alpha_2 w_2 + S\alpha_3 w_3 = X \Longrightarrow w_1 = 0$
Case 7	$w_1 = w_3 = 0$	Case 16	$S\alpha_1 w_1 + S\alpha_2 w_2 + S\alpha_3 w_3 = X$
Case 8	$w_2 = w_3 = 0$		
Case 9	$w_1 = w_2 = w_3 = 0$		

Table 2: Possible Corner Solutions Depending On Restrictions on Water Use

in the left-hand side of Table 2. With retrictions on water use, we have to consider the cases given in the right-hand-side of Table 2. We solve the problem for the 17 possibles cases (16 and the interior solution). The optimum is given by the solution that maximizes V(H(0)).

2.4 A Particular Case: The Static Case

In order to evaluate the impact of the resource dynamics in the farmer's choice problem, we compute the optimal solution of the static problem, which we can compare to the dynamic solution. The static problem corresponds to a problem where all variables linked to the resource dynamics are ignored by the farmer. Substituting $z = c = 0$ in equations (15), (18), (21) and (22) of the preceding section, we get:

$$w_3^s(1) = \frac{a_3}{2b_3}. \tag{23}$$

The necessary conditions for a maximum in $t = 0$ are

$$\frac{\partial \pi(0)}{\partial \alpha_1(0)} = 0 \Leftrightarrow P^s(1) - P^s(2) = 0, \tag{24}$$

$$S\alpha_1(0)(p_1 a_1 - 2p_1 b_1 w_1(0)) = 0, \tag{25}$$

$$S(1-\alpha_1(0)-\bar{\alpha})(p_2a_2-2p_2b_2w_2(0))=0, \tag{26}$$

with the values of $P^s(1)$ and $P^s(2)$ defined in equations (19) and (20) when $z=c=0$.

We can distinguish three possible solutions for the static problem. Two corner solutions given by:

$$\alpha_1(0)=0 \Longrightarrow w_1(0)=0, \quad \alpha_2(0)=1-\bar{\alpha} \quad \text{and} \quad w_2(0)=\frac{a_2}{2b_2}, \quad \text{for the first,}$$

$$\alpha_2(0)=1-\alpha_1(0)-\bar{\alpha}=0 \Longrightarrow w_2(0)=0, \quad \alpha_1(0)=1-\bar{\alpha} \quad \text{and} \quad w_1(0)=\frac{a_1}{2b_1}, \quad \text{for the second,}$$

and the interior solution:

$$\alpha_1^s(0)=\frac{p_1(x_1+\frac{a_1^2}{4b1})-d_1-(p_2(x_2+\frac{a_2^2}{4b2}-d_2)+e_2(1-\bar{\alpha})}{(e_1+e_2)}, \tag{27}$$

where

$$\alpha_2^s(0)=1-\alpha_1^s(0)-\bar{\alpha}, \tag{28}$$

$$w_1(0)=\frac{a_1}{2b_1}, \tag{29}$$

$$w_2=\frac{a_2}{2b_2}. \tag{30}$$

Equation (27) gives the optimal solution of the share of land chosen for crop 1 in spring. This share depends on the difference of gains from crops 1 and 2 and the share of land used for crop 3 in summer ($\bar{\alpha}$ is given by assummption). The greater the difference in gains from crops 1 and 2, the greater is the share of land chosen for crop 1.

Finally, optimal solutions of irrigation water volumes for crops 1, 2 and 3 are described in equations (29), (30) and (23). Without pumping costs, optimal irrigation water volumes are chosen such that the marginal benefit from each crop is nil.

3 The Data of the Beauce Area

In this paper, we consider the "Beauce Centrale" area, which was defined by Lejars et al. [16]) and can be considered as representative of the whole Beauce region in terms of farm types. It comprises an aera of 300 600 ha of agricultural land (see Lejars et al. [17] for a map). In this section, we describe the agronomic, hydrogeological and economic data we

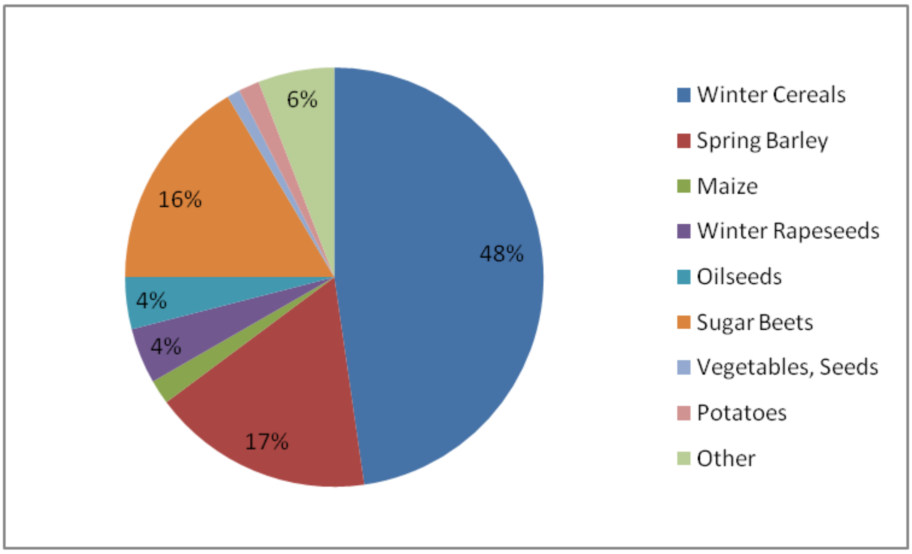

Figure 1: Representative Field Crops Sugar-Beets Farms in Study Area. Based on [15]

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 land-use data in 2010, Lejars et al.[15], [16], [15] identified four types of field crop farms in the study area. All of them grow an important part (over 45%) of winter crops (mainly wheat) but differentiate each other by the spring and summer crop they are specialized in: sugar-beet for the first group, rapeseed for the second, special crops for the third and maize for the fourth. In this study, we focus on the most numerous farm type in our study area, which are 679 famers specialized in field-crops and sugar-beet. Table 3 shows the results of the typology used Figure 1 shows the land-use of the representative Field Crops Sugar-Beets farm. The general agronomic data is summarized in Table 4.

Type	FC Special Crops	FC Rapeseed	FC Maize	FC Sugar Beet
Number of Farms	388	471	275	679
Mean surface (ha)	148	137	142	122

Data Source: RGA2010

Table 3: Types of Farms in Study Area, see Lejars et al. [15]

Parameter	**Description**	**Unit**	**Value**
S	Mean Surface of Representative Farm	ha	122
M	Number of Representative Sugar-Beets Farms	*unitless*	679
$\bar{\alpha}$	Share of Surface Used for Summer Crop	*unitless*	0.16
w_p^j	Water Needs in Spring by Farms other than FC-SB Farms	m^3	78
w_s^j	Water Needs in Summer by Farms other than FC-SB Farms	m^3	50

Table 4: Agronomic Parameter Values for Baseline Case, see [15]

Finally, note that the water needs by other farms also depend on the scenario considered. Parameter values are given in Table 5.

Parameter	**Unit**	**Baseline**	**Values Dry Years**		
			0% restrict.	40% restrict.	70% restrict.
w_p^j	10^6 m^3	78	97	47	26
w_s^j	10^6 m^3	50	56	38	41

Table 5: Irrigation Water Volumes in Spring w_p^i and Summer w_s^i for Other Farms than Field-Crops Sugar-Beet Depending on Climatic Scenario, see [15].

3.1.2 The Yield Response to Water

We compute the yield response to water based on simulation data from the agronomic Pilote Model (see for example Mailhol [18]). The data contains the water balance in the irrigation season (rain, real evapotranspiration (ETR) and irrigation at different dates) and yields, by crop and type of soil, over the period 1997-2001. We do regressions analysis by type of crop and type of soil for three types of wheather conditions: dry, normal and humid. Wheather conditions are defined as a function of efficient rainfall (rain minus real evapotranspriation) and computed for the most representative crop, i.e. wheat in spring and sugar-beet in summer. Wheather conditions are detailed in Table 6.

Rain minus ETR in mm	Dry Condition	Normal Condition	Humid Condition
Spring (Wheat)	<60	-60 to 35	>35
Summer (Sugar Beet)	<-220	-220 to -120	>-120

Table 6: Types of Wheather Conditions

The quadratic relationship between water and yields gives overall best results.[2] Regression results are given in the Appendix. The values of the regression coefficients are listed in in Table 7.

3.2 Hydrogeological Data

We use hydrogeological data from Graveline and Schomburkg [10] for the Beauce Centrale part of the aquifer. Graveline and Schomburkg consider a simulation model for six different hydrogeological areas. Simulation results are compared with observed data from the national data base ADES and show good results. For our study, [10] give the withdrawal coefficient, the return flow coefficent, the aquifer storage coefficient and water withdrawals for other uses than irrigation, see details in Table 8. Moreover, the total surface corresponds to the Beauce Centrale part area of the aquifer. The initial water table height is the one observed in Spring 2010. Water-table heights are measured in m NGF.[3] Finally,

[2] We also tested linear and cubic relationships.

[3] *Nivellement Général de la France* or General Levelling of France is the official levelling measure.

Parameters	Description	Unit	Values	
			Normal Year	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 7: Estimated Coefficients of Yield Function for Normal and Dry Year.

we set the net recharge in summer and spring to zero, as most of the recharge takes place in winter.

Parameter	Description	Unit	Value
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
S_b	Total surface of Study Area	km^2	3006.6
H_0	Initial Water Table Height	m (NGF)	92.81
r	Net Recharge in Summer and Spring	m^3/season	0

Table 8: Hydrogeologic Parameter Values for Baseline Case, see [10]

3.3 Economic Data

We use economic data from several sources: Prices for wheat and barley are taken from the national agency FranceAgriMer [7] prices for sugar-beet from sugar-beet producer organizations [4].

Operating expenses stem from the farm data-base network ROSACE [21]. Because we do not have enough data to regress farm surfaces on operating expenses, we attribute all operating expenses to the quadratic term, (see above and Carpentier and Letort [3] for explanation of the use of the quadratic function).

Parameter	**Description**	**Unit**	**Value**
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	1786
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 9: Economic Parameter Values for Baseline Case

Pumping costs correspond to energy costs necessary to pump the water to the topsoil. For typical pump capacities of around 50 m^3/h we need 0.136 kW to lift one m^3 one meter. Considering pump efficiencies of 85% 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[4] we hence have maximal (marginal) pumping costs of $z = 0,02912$ euros per m^3. Note that we do consider neither water taxes nor investments or payoffs for irrigation material. Therefore, our pumping costs correspond to a minimum bound.

[4]Considering the mean surface elevation at 150 m above sea level and the deepest point of the aquifer at 20 m above see level.

Next, the final value of the resource is set to an arbitrary constant, here zero. This satisfies our assumption that the implicit value of the resource by the end of the planning horizon is zero. Finally, the discount rate is set at 5% for each period considered.[5]

4 Model Results for the Beauce Area

4.1 Results for the Baseline Case: A Normal Year

Parameters	Description	Unit	Value
α_1	Wheat share	N/A	0.60
α_2	Barley share	N/A	0.24
α_3	Sugar Beet share	N/A	0.16
w_1	Water Volume for Wheat	m^3/ha	894
w_2	Water Volume for Barley	m^3/ha	1 059
w_3	Water Volume for Sugar Beet	m^3/ha	2167
$\tilde{w}$	Total Water Volume	m^3	138 781
V	Gross Annual Value Added	Euros	89 717
w^i	Total Water FC-SB Farms	10^6 m^3	94.23
H_1	Acquifer level by end of Spring	m	92.09
H_2	Acquifer level by end of Summer	m	91.67

Table 10: Baseline case: Normal year corresponding to 2010.

Table 10 shows the simulation results for the baseline case, a normal year corresponding to 2010. The representative sugar-beet farmer choses to allocate 60% of his land to wheat and 24% to barley production, 16% being used for sugar-beets. Wheat is irrigated with 894 m^3 per hectare, barley with 1059 m^3 per hectare, and sugar-beets with 2167 m^3 per hectare leading to a total water volume of 138 781 m^3 for one farm and 94.23 millions of m^3 for all the FC-SB farms. This reduces the water table height from the initial 92.81 m

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

above sea level (NGF) to 92.09 m by the end of spring and 91.67 m by the end of summer. Overall a representative farm generates a gross annual value added of 89 717 euros.

4.2 Results for a Dry Year Without Restrictions

Parameters	Description	Unit	Baseline	Dry Year
α_1	Wheat share	N/A	0.60	0.56
α_2	Barley share	N/A	0.24	0.28
α_3	Sugar Beet share	N/A	0.16	0.16
w_1	Water Volume for Wheat	m^3/ha	894	1 178
w_2	Water Volume for Barley	m^3/ha	1 059	1 147
w_3	Water Volume for Sugar Beet	m^3/ha	2167	1 954
$\tilde{w}$	Total Water Volume	m^3	138 781	157 800
V	Gross Annual Value Added	Euros	89 717	84 043
w^i	Total Water FC-SB Farms	10^6 m^3	94.23	107.15
H_1	Acquifer level by end of Spring	m	92.09	91.93
H_2	Acquifer level by end of Summer	m	91.67	91.49

Table 11: Dry Year Compared to Baseline Case.

Table 11 compares simulation results for a dry year to the baseline case. Because the share of the summer crop is fixed, 16% of land are still allocated to sugar-beets. Howerver, 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 droughts than barley, because yields are more responsive to water scarcity[6].

Next, total irrigation water volume increases by 19000 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

[6]Indeed, this can be illustrated as follows: consider optimal water volumes for wheat (894 m^3/ha) and barley 1059 m^3/ha in a normal year. If we use 894 m^3/ha of water for wheat in a dry year, the yield loss is 0.84 tons/ha compared to the normal year. If we use 1059 m^3/ha of water for barley in a dry year, the yield loss is only 0.16 tons/ha compared to a normal year.

m^3 /ha compared to 1059 m^3/ha for barley), while irrigation for sugar-beets is reduced. Wheat irrigation increases more (by 284 m^3 per hectare) than barley irrigation (88 m^3 per hectare), because yields for wheat in dry years are greater. Resulting total water volume of a representative farm has increased under the dry condition amounting to 157 800 m^3 (compared to 138 781 m^3 in the normal year). This leads to a more important decrease in the water table height, with 91.49 m NGF by the end of summer (compared to 91.67 m in the normal year). The most important part of this additional decrease is due to the withdrawals in spring, because of more intensive irrigation of spring crops. While the water table height was reduced by 0.72 m in a normal spring, it is reduced by 0.88 m in a dry spring, i.e. by 0.16 m. Finally, despite these adaptations, gross annual value-added for the representative farmer decreases slightly (by 5674 euros) from 89 717 euros in the normal year to 84 043 euros in a dry year. This can be explained by the decrease in yields.

4.3 Results for a Dry Year With Restrictions

Table 12 illustrates how the introduction of water restrictions changes the results. Following Lejars et al. [17], we consider two scenarios: a restriction of 40% of normal-year water volumes and the extreme case of a restriction of 70% of normal-year water volumes. Let us first compare a dry year with restrictions to a dry year without restrictions. Concerning land use allocation, we observe that stringent restrictions 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. As for the irrigation strategy, the farmer is now constraint to a smaller total water volume. The priority is given to the most performant crop: sugar-yield, for which water volumes do not change with water restrictions. On the other hand, volumes for wheat and barley are restricted in an important manner. With a restriction of 40 %, water volumes for wheat are reduced to 506 m^3 per hectare (compared to 1 178 m^3 per hectare without restrictions) and for barley to 319 m^3 per hectare (compared to 1 147 m^3 per hectare without restriction). Water volume for barley is more reduced than for wheat, because wheat is more sensitive to droughts. With a restrction of 70 %, barley is cultivated under dryland farming, and nearly the same conditions hold for wheat, for

Param.	Description	Unit	Dry Year	Rest. Values	
			Rest. 0%	Rest. 40%	Rest. 70%
α_1	Wheat share	N/A	0.56	0.54	0.52
α_2	Barley share	N/A	0.28	0.30	0.32
α_3	Sugar Beet share	N/A	0.16	0.16	0.16
w_1	Water Volume for Wheat	m^3/ha	1 178	506	55
w_2	Water Volume for Barley	m^3/ha	1 147	319	0
w_3	Water Volume for Sugar Beet	m^3/ha	1 954	1 954	1954
$\tilde{w}$	Total Water Volume	m^3	157 800	83 269	41 634
V	Gross Annual Value Added	Euros	84 043	72 346	55 486
w^i	Total Water FC-SB Farms	10^6 m^3	107.14	56.54	28.27
H_1	Acquifer level by end of Spring	m	91.93	92.39	92.65
H_2	Acquifer level by end of Summer	m	91.49	92.04	92.3

Table 12: Simulation Results for a Dry Year With Restrictions.

which a minimum amount of water is allocated.[7] Overall, total water volumes decreases to 56.54 millions of m^3 under the 40 % restriction and 28.27 millions of m^3 under the 70 % restriction for all the field-crop sugar-beet farms. Without surprise, restricting total water use has a beneficial effect on the water table height, which ends up at 92.04 m NGF in the 40 % restriction scenario and 92.3 m NGF in the 70 % restriction scenario. But these restrictions reduce gross annual value added compared to the case without restriction by about 11 700 euros (in the 40 % restriction case) and 28 600 euros (in 70 % restriction case). Such losses correspond to about 14 % and 34 % of the gross annual value added without restrictions.[8] This underlines the fact that restrictions, although efficient, have an important impact on the farmer's economic situation, even under the assumption that he has perfect forsight and adapts optimally to the dry situation.

Table 13 summarizes the results, showing the two restriction scenarios under dry condi-

[7]55 m^3 per hectare correspond roughly to one water turn.

[8]Lejars et al [15] found reductions of 10 % and 21 % of gross production under the same restriction scenarios.

tions with respect to the baseline case. We can confirm three general features of adaptation: first, land-use is changed by decreasing the share of the most sensitive crop and increasing the share of the less sensitive crop. Second, irrigation water volumes of all crops are reduced. Third, within each scenario, most important water volumes are allocated to the most productive summer crop and least important volumes to the less productive barley crop. In a dry year and when restrictions are in place, the economic loss for the farmer is important: a 40% restriction leads to a loss in gross annual value added of 19% (corresponding to 17 371 euros). A 70% restriction leads to a loss in gross annual value added of 38% (corresponding to 34 231 euros). Note however that the considered scenarios lead to extreme results regarding the water-table level. The aquifer level by the end of summer is even higher in the restriction cases than in the baseline case: 92.04 m NGF compared to 91.67 for the 40 % restriction and 92.3 for the 70 % restriction. Therefore, with restrictions, the water-table level increases by 0.37 m for the 40 % restriction and 0.63 m for a 70 % restriction case, with respect to the baseline case.

Param.	**Description**	**Unit**	**Baseline**	**Rest. Values**	
				Rest. 40%	Rest. 70%
α_1	Wheat share	N/A	0.60	0.54	0.52
α_2	Barley share	N/A	0.24	0.30	0.32
α_3	Sugar Beet share	N/A	0.16	0.16	0.16
w_1	Water Volume for Wheat	m^3/ha	894	506	55
w_2	Water Volume for Barley	m^3/ha	1 059	319	0
w_3	Water Volume for Sugar Beet	m^3/ha	2167	1 954	1954
$\tilde{w}$	Total Water Volume	m^3	138781	83 269	41 634
V	Gross Annual Value Added	Euros	89 717	72 346	55 486
w^i	Total Water FC-SB Farms	10^6 m^3	94.23	56.54	28.27
H_1	Acquifer level by end of Spring	m	92.09	92.39	92.65
H_2	Acquifer level by end of Summer	m	91.67	92.04	92.3

Table 13: Dry Year With Restrictions Compared to Baseline Case.

4.4 Results for Different Pumping Costs

Table 14 shows the consequence of an increase in pumping costs on optimal water and land-use choise. We represent two scenarios with increases of ten and twenty times the initial pumping costs of the baseline case.[9]

While land-use choice does not change, irrigation water volumes decrease. As before, the highest water volume is still allocated to sugar-beet, the second highest to wheat and the smallest to barley. With growing pumping costs, total water volume per farm decrease from 138 781 m^3 to 79 860 m^3 (110 815 m^3) considering an increase of costs by a factor of 20 (10 respectively). Total water volume used by representative farmers is hence reduced from 94.23 millions of m^3 to 54.22 millions of m^3 (75.24 millions of m^3 respectively). This leads again to important reductions in gross value added.

Param.	**Description**	**Unit**	**Baseline**	**Cost Values**	
				c^p x 10	c^p x 20
α_1	Wheat share	N/A	0.60	0.60	0.60
α_2	Barley share	N/A	0.24	0.24	0.24
α_3	Sugar Beet share	N/A	0.16	0.16	0.16
w_1	Water Volume for Wheat	m^3/ha	894	693	469
w_2	Water Volume for Barley	m^3/ha	1 059	743	392
w_3	Water Volume for Sugar Beet	m^3/ha	2167	1 965	1742
$\tilde{w}$	Total Water Volume	m^3	138 781	110 815	79 860
w^i	Total Water FC-SB Farms	10^6 m^3	94.23	75.24	54.22
H_1	Acquifer level by end of Spring	m	92.09	92.16	92.25
H_2	Acquifer level by end of Summer	m	91.67	91.75	91.85

Table 14: Simulation Results for Different Pumping Costs.

Note that we can also simulate the static case introduced in section 2.4, in which pumping costs are considered to be nil. Results are shown in Table 15. In this case,

[9] Although represented variations are high, these scenarios are still realistic as the initially used pumping costs was a lower bound.

irrigation water volumes chosen are greater than in the dynamic baseline case. More precisely, water volumes for wheat barley and sugar-beet incresase by 22, 35 and 23 m^3 per hectare respectively. The dynamic effect is relatively small in our example, because the Beauce aquifer covers a large surface and initial water table heights are not very far from the topsoil.

Param.	**Description**	**Unit**	**Baseline**	**Values c^p=0**
α_1	Wheat share	N/A	0.60	0.60
α_2	Barley share	N/A	0.24	0.24
α_3	Sugar Beet share	N/A	0.16	0.16
w_1	Water Volume for Wheat	m^3/ha	894	916
w_2	Water Volume for Barley	m^3/ha	1 059	1094
w_3	Water Volume for Sugar Beet	m^3/ha	2167	2190
$\tilde{w}$	Total Water Volume	m^3	138 781	141 905
V	Gross Annual Value Added	Euros	89 717	
w^i	Total Water FC-SB Farms	10^6 m^3	94.23	96.35
H_1	Acquifer level by end of Spring	m	92.09	92.08
H_2	Acquifer level by end of Summer	m	91.67	91.66

Table 15: Simulation Results for Static Case in Which Pumping Costs are Nil.

4.5 Results for a Tax on Pumping During a Dry Year

As shown above, a tax that increases the pumping costs can bring the farmer to more conservative water use. In order to be able to compare the tax to the restriction scenario, we have to compare both, the performance with respect to the water-table level and the loss in gross annnual value-added that the two policy scenarios trigger. In the following, we seek to define a tax on water pumping that leads to the same loss in gross value added as the above restriction policies and we compare the water-table levels that result. Table 16 shows the results. With a 13.9 fold increase in pumping costs, gross-value added is about the same as for 40 % restriction policy. With a 45.4 fold increase in pumping costs, gross-value added is about the same as for the 70% restriction policy.

Param.	Description	Unit	Baseline	Tax Values	
				c^p x 13,9	c^p x 45,4
α_1	Wheat share	N/A	0.60	0.56	0.54
α_2	Barley share	N/A	0.24	0.30	0.30
α_3	Sugar Beet share	N/A	0.16	0.16	0.16
w_1	Water Volume for Wheat	m^3/ha	894	947	385
w_2	Water Volume for Barley	m^3/ha	1 059	863	169
w_3	Water Volume for Sugar Beet	m^3/ha	2167	1 800	1 429
$\tilde{w}$	Total Water Volume	m^3	138 781	129 343	59 325
V	Gross Annual Value Added	Euros	136 487	72 350	55 421
w^i	Total Water FC-SB Farms	10^6 m^3	94.23	87.82	40.28
H_1	Acquifer level by end of Spring	m	92.09	92.00	92.20
H_2	Acquifer level by end of Summer	m	91.67	91.58	91.80

Table 16: Tax on Water Pumping in Dry Year.

4.6 Comparison of Tax and Restriction Scenarios in a Dry Year

Comparing tables 16 and 12 we observe the following results: with a 13.9 fold increase in pumping costs, gross value added is about the same as for 40 % restriction policy. With the restriction policy, the water table level is at 92.39 m by the end of spring and at 92.04 by the end of summer. The tax leads to water-table levels of 92.00 by the end of spring and 91.58 by the end of summer. Hence the restriction policy performs better. With a 45.4 forld increase in pumping costs, gross value added is about the same as for the 70 % restriction policy. With the restriction policy, the water table level ends up at 92.65 by the end of spring and 92.3 by the end of summer. The corresponding tax policy leads again to lower water-table levels of 92.20 by the end of spring and 91.80 by the end of summer. Overall, the restriction policy hence outperforms the tax policy. Note that the 45.4 tax policy leads to an end of the year aquifer level that is greater than in a normal summer.

This policy can thus be seen as an extreme case of tax policy, because the dry episode does not have any negative (but a positive) impact on the water-table level. The cost of the drought is completely born by the farmers.

5 Concluding Remarks

Both restrictions and increases in pumping costs do lead to lower total water use and higher water tables. However restrictions outperform the tax policy in our case. In section 4.5, we have considered the tax policy that leads to equivalent reductions in value-added as the restriction policies and we have compared resulting water-table levels. We could also compare the tax policy that leads to equivalent reductions in water-table levels and compare the coressponding economic loss. This is study is ongoing. Although restrictions are overall better performing than the tax policy, they lead to important economic losses for the farmers. For example, the 40 % restriction policy leads to losses of roughly 14% of gross annual value-added. Such restrictions may become more frequent in the context of climate change, which suggests that the agricultural sector has to cope with potential reductions in economic revenus in the coming decade.

Several extensions are possible to this work: First, we could assess how the farmer performs if he thinks being in a normal year but the year is actually dry. Likewise, we could asses the gap between a farmer preparing to a normal year being faced with restrictions in summer. Moreover, we could introduce uncertainty and show how the farmer can cope with it. Another line of developments could introduce several types of farmers and the interactions between them. For example, we could consider the field crops corn farms and the field crops sugar-beet farms and evaluate which sector is best adapted to dry conditions and different restriction policies.

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A Appendix

A.1 Regression Results

A.1.1 Yield-Water Response for Wheat

Table 17: Dry Wheather and Average/Profound Soil

Parameter	**Coefficient**	**Std.Error**	**t Value**	**P**$>|t|$
w	0.0051176	0.0012194	4.20	0.000
w squared	-2.14e-06	9.86e-07	-2.17	0.032
const.	7.144896	0.3032466	23.56	0.000

Number of observations: 125. Adjusted R-squared 0.3071

Table 18: Normal Wheather and Average/Profound Soil

Parameter	**Coefficient**	**Std.Error**	**t Value**	**P**$>|t|$
w	0.0031337	0.0005348	5.86	0.000
w squared	-1.71e-06	4.76e-07	-3.60	0.000
const.	9.415315	0.1214989	77.49	0.000

Number of observations: 173. Adjusted R-squared 0.2750

Table 19: Humid Wheather and Average/Profound Soil

Parameter	**Coefficient**	**Std.Error**	**t Value**	**P**$>|t|$
w	0.0029218	0.0008057	3.63	0.000
w squared	-2.06e-06	8.68e-07	-2.38	0.019
const.	10.42152	0.1525615	68.31	0.000

Number of observations: 117. Adjusted R-squared 0.1337

A.1.2 Yield-Water Response for Barley

Table 20: Dry Wheather and Average/Profound Soil

Parameter	**Coefficient**	**Std.Error**	**t Value**	**P**$>|t|$
w	0.004653	0.0007293	6.38	0.000
w squared	-1.99e-06	6.00e-07	-3.32	0.001
const.	5.876013	0.1789212	32.84	0.000

Number of observations: 119. Adjusted R-squared 0.5088

Table 21: Normal Wheather and Average/Profound Soil

Parameter	**Coefficient**	**Std.Error**	**t Value**	**P**$>|t|$
w	0.002735	0.0003649	7.50	0.000
w squared	-1.25e-06	3.57e-07	-3.50	0.001
const.	7.238088	0.0763662	94.78	0.000

Number of observations: 154. Adjusted R-squared 0.4916

Table 22: Humid Wheather and Average/Profound Soil

Parameter	**Coefficient**	**Std.Error**	**t Value**	**P**$>|t|$
w	0.0022922	0.0006509	3.52	0.001
w squared	-1.32e-06	7.32e-07	-1.80	0.075
const.	7.67778	0.1176547	65.26	0.000

Number of observations: 120. Adjusted R-squared 0.1910

A.1.3 Yield-Water Response for Sugar Beet

Table 23: Dry Wheather and Average/Profound Soil

Parameter	**Coefficient**	**Std.Error**	**t Value**	**P**$> \|t\|$
w	0.0554281	0.0048382	11.46	0.000
w squared	-0.0000141	2.83e-06	-4.97	0.000
const.	42.94781	1.710531	25.11	0.000

Number of observations: 212. Adjusted R-squared 0.7105

Table 24: Normal Wheather and Average/Profound Soil

Parameter	**Coefficient**	**Std.Error**	**t Value**	**P**$> \|t\|$
w	0.0325382	0.004551	7.15	0.000
w squared	-7.43e-06	2.88e-06	-2.58	0.010
const.	65.02174	1.462459	44.46	0.000

Number of observations: 309. Adjusted R-squared 0.4112

Table 25: Humid Weather and Average/Profound Soil

Parameter	**Coefficient**	**Std.Error**	**t Value**	**P**$> \|t\|$
w	0.0404101	0.0095222	4.24	0.000
w squared	-0.00002	8.91e-06	-2.25	0.028
const.	82.33762	2.109714	39.03	0.000

Number of observations: 74. Adjusted R-squared 0.3418