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Can the lack of coordination between an agricultural authority and a water agency generate inefficiencies?[1]

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Summary or abstract of the paper: The point of departure of this work is the situation occurring in the Crau area (South-East of France). In this region, organic farmers use surface water for irrigation and excess water percolates into an aquifer that is used as a source for local residents. In contrast to the standard framework, agricultural production thus increases groundwater levels. In this paper, using a dynamic model, we derive the myopic and socially optimal food and water consumption paths. The first aim is to bring to the fore that an intervention is needed and that, in such a specific case, the environment can be protected thanks to some "good" production incentives. We then analyze the problem of coordination that can occur when two distinct local authorities - an agricultural and a water one, optimize food production and water use. In order to do so, we use an open-loop Nash game. We furthermore add into the picture environmental externalities linked with irrigation water flows that can generate amenities when they replenish wetlands or negative externalities when they induce floods.

Keywords and JEL codes: externalities, agricultural policy, water policy, coordination of policies; H23, Q18, Q28.

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1 Introduction

The Crau area (South-East of France) is characterized by the fact that positive environmental externalities are generated from agricultural production to consumers. We know (see ANTEA (2001) and appendix A) that two-third of the aquifer inflows comes from agricultural irrigations .The main part of these irrigations are made without any chemical added since the major irrigated production of this area is one of hay that is a Certified Origin Product. The irrigation technology used comes from old practices: it is named border-check flood irrigation. With this technique, the surface water (distributed at a very low price because of deriving from a wet region) is simply allowed to run over the soil and to infiltrate.[1] Many people drink the groundwater coming from the stock replenished by agricultural irrigations. They also benefit from wetlands amenities that are maintained thanks to water runoffs. Indeed, the Crau area is located next to one of the biggest wetland in Europe: the Camargue.

One can observe that numerous information bulletins bringing to light the good agricultural practices in the Crau area are coedited by the local agricultural and environmental authorities. A first question is why? We know that this agricultural authority is implementing the agri-environmental policy and that it is not the environmental authority that is in charge of the water policy but a local water agency. Can the lack of coordination between a local agricultural authority and a local water agency introduce some inefficiencies? Where would this additional (with respect to more classical externalities) inefficiencies arise from? These are the questions that we want to address in this work.

From the best of our knowledge, the seminal conceptual framework concerned with interactions between environmental and agricultural policies was proposed by Lichtenberg and Zilberman (1986). They showed that the presence of revenue support programs cause striking alterations in the welfare effects of new regulations. Later on, Just and Antle (1990) demonstrated that the agricultural policies are structured so that undesirable environmental effects can be mitigated if policies are appropriately designed and administrated. Johnson, Wolcott and Aradhyula (1990) supported this view by emphasizing that the programs structure and the institutional setting are important conditioning factors. Finally, during the same debate in the American Economic Review papers and proceedings, Hrubovcak, Leblanc and Miranowski (1990) illustrated some of the difficulties of coordinating agricultural and environmental policies when altering agricultural chemical use.

[1] Sheep farming also plays a central role in this area since it interacts with hay production activity (grasslands) through the last cut of hay which is directly eaten by sheeps. In this region, vegetable and fruits are also grown up with the same irrigation technology.

But, as underlined by Just, Bust and Donoso (1991), these studies simply serve to *"better understand the interface of agricultural and resource policy"*. Following this point of view, Weinberg and Kling (1996) proposed to go further: they studied the opportunities to better coordinate the two types of policies. They concentrated on irrigation water policies in the West and policies for the control of drainage from irrigated agriculture. They specified a social objective in order to examine, both conceptually and empirically, the welfare losses associated with uncoordinated policy making. More recently, Gomez-Limon, Arriaza and Berbel (2002), within the framework of the European water framework directive and common agricultural policies, examine the relationships between these policies. Their empirical work, applied to a case study in central Spain, shows that the two policies must be coordinated in order to meet socioeconomic goals (farmers' income and labour demand) and environmental protection (water-use efficiency).

The papers previously quoted are primarily concerned with agricultural production externalities, these latter one possibly being either positive or negative. In our work, we want to concentrate on a less studied case corresponding to the situation occurring in the Crau area: the one in which environmental amenities are jointly produced by the agricultural sector (including both livestock and crop farming). For this purpose, we will concentrate on the strong links between the aquifer level and food agricultural production. Our basic problem will be formally identical to artificial recharge of an aquifer (see Supalla and Comer, 2007), except that in our case recharge involves a net benefit rather than a net cost. The literature on conjunctive use of ground and surface water, first analyzed by Brown and McGuire (1967) is closely related as well, as is the literature on optimal drainage management (where recharge from irrigation water is a bad rather than a good).

Furthermore, from the best of our knowledge, most of papers interested in agricultural and environmental policies coordination concentrate on basic optimization models, without any consideration of the interactions between the authorities. In our paper, focusing on the french context characterized by two distinct authorities, we propose to add a strategic component: we will consider the interactions between a local water agency and a local agricultural authority, both of them having environmental concerns in mind. The water agency will be in charge of the regulation of the resource extraction and the agricultural one of the organic production of food. The literature on the economics of groundwater includes some differential games related to the individual extraction in which both closed-loop and open-loop information structures are considered (see for instance, Rubio and Casino, 2001). A closed-loop information is more appropriated for individual extractions since when they exploit the resource, agents have an information on the level of the aquifer through the costs induced. It is not the case for authorities who are not in charge of the aquifer monitoring and who are not collaborating. It is why we propose to analyze the authorities interactions as one corresponding to an open-loop information structure. The groundwater considerations that adds some interesting dynamic into the coordination problem.

Our argument will be organized in the following way. We begin with the presentation of our dynamic model in section 2. Section 3 is devoted to the characterization of the environmental externalities of organic food and groundwater consumption. Section 4 brings to the fore the inefficiencies of Uncoordinated Water and Agricultural Internalizing policies (UWAIP). We will finally conclude and propose some potential extensions.

2 The model

Since we do not want to enter into the debate related to the conjunctive use of water resources, we assume that an equilibrium with respect to the choice of the water resource had already been reached: groundwater will be consumed for domestic uses and the crops will be grown up thanks to surface water irrigations. This is in phase with the Crau current situation.

2.1 The simplified hydrological model

As a first step, we propose to consider a small closed economy working as the Crau economy: it is composed of consumers and producers who are located above an aquifer. At time t, the first one consume an amount g_t of groundwater for domestic use (this water is assumed to be clean: it is drinkable without the need of any treatment) and an amount f_t of agricultural food (meat, vegetables and fruits). The latter one is assumed to be sold on a pure and perfect competitive market by homogeneous atomistics farmers and the first one by a distribution agency. Also considering homogeneous consumers, we will reason on a representative consumer and a representative producer.

As in the Crau case study, the production of food generates a by-product: percolations of an amount bf_t of surface water to the aquifer. For clarity sake, a fixed linear relation between the amount of agricultural food produced and the aquifer height is assumed. Crops are supposed to be grown up in a traditional organic way.

The water table is described as a function of time which is obtained, as in most of the papers of the literature on the subject, by equating "rate in" minus "rate out" with the impact on the water table height, $\dot{h}(t) := \dot{h}_t$ where $h_t \in]0,1[\ \forall t \neq 0$ is a percentage of height.[2] The aquifer

[2] $h_t \in]0,1[$ means that we will focus on the interior solutions.

height motion is thus described by the following differential equation:

$$\dot{h}_t = bf_t - g_t \tag{1}$$

where $b > 0$. Our major contribution with respect to the literature about groundwater economics lies in the fact that the aquifer recharge is endogenous here and does not consist in a given parameter, as usually postulated.

We also assume that the initial groundwater height is equal to its natural hydrologic equilibrium: $h_0 = 1$. Rubio and Casino (2001) define this level as the one *"corresponding to the maximum water table elevation at which the water reserves coincide with the storage capacity of the aquifer"*. They added that with such an assumption, *"the human activity, justified by economic parameters, consists of mining the aquifer until an economic hydrologic equilibrium has been reached"*.

2.2 The producers

Food and groundwater are the two market goods considered in our economy.

2.2.1 The representative groundwater distribution supplier

Drinkable water distribution is generally associated with strong and expensive networks of canals and pipes. The presence and the importance of the costs associated with such networks can be the origin of natural monopoly situations that one can observe in France. It is why the water distribution is generally delegated by local authorities to a private firm through an auction mechanism: the networks building investments are made by this authority (thanks to lump-sum taxes imposed to consumers for instance) and the private firm is in charge of operating and maintaining costs. The government then chooses the firm proposing the cheapest price.

Considering atomistics and homogeneous firms makes them compete on a pure and perfect market in order to win the water distribution task. But we do not want to model this mechanism here. We will rather focus on its outcome which is a groundwater unit price at time t, π_t, equal to its marginal cost at time t:

$$\pi_t(h_t) = \kappa(h_t)$$

where the marginal cost $\kappa(h_t)$ is a decreasing function since a low height is associated with high energy needs and thus high pumping costs.[3]

[3] We could have had equivalently assumed that the groundwater is sold at a price equal to the marginal cost of extraction.

In order to fully characterize and compare the solutions of the dynamic optimal control problems that we are going to study, we need to specify all our functions. The total cost of groundwater distribution at time t, $\kappa(h_t)g_t$, will be assumed to depend on both the amount of water extracted and on the pumping lift rate $(1 - h_t)$, in a linear way. The marginal cost of pumping groundwater will thus take the following form:

$$\kappa(h_t) := \kappa - h_t$$

It is thus assumed to be composed of:

- a fixed part $\kappa > 0$ due to the hydrologic cone (the depth of the aquifer next to the pumping system is lower than elsewhere),
- another part negatively proportional to the groundwater height due to the energy needed in order to pump water.

κ corresponds to the aquifer height from which extraction costs are null.

2.2.2 The representative organic farmer

The organic agricultural production is assumed to be sold on a pure and perfect competitive market. The production costs, $c(f_t)$, are assumed proportional to the amount of food produced:

$$c(f_t) := cf_t$$

where $c > 0$. At the equilibrium of the market, the unit price of the food is equal to its marginal cost such that:

$$p_t = c$$

Since the marginal costs of this producer are equal to their average one, considering a pure and perfect competitive markets means that, at the equilibrium, his profits are null.

2.3 The representative consumer

The consumer is assumed to consume an amount f_t of food and g_t of groundwater at time t. For clarity sake, the utility generated from this consumption is assumed fully separable in both goods: $u(f_t)$, resp. $v(g_t)$, denotes the willingness to pay for food, resp. for groundwater consumption. Furthermore, the complete utility function will be written as: $U(f_t, g_t, h_t) = u(f_t) + v(g_t) + e(h_t) + W(f_t, g_t, h_t)$ where:

- $W(f_t, g_t, h_t)$ represent the wealth of the consumer;
- and $e(h_t)$ is an indicator of this consumer's environmental preferences for wetlands. These preferences carry on wetlands level that is assumed to be fully determined by the aquifer height, h_t.

If we remind that the market prices are set at their competitive level (given by the marginal costs of the goods), the surplus from food, $s(f_t)$, and groundwater, $\sigma(g_t)$, consumption are given by the following expressions:

$$\begin{aligned} s(f_t) &= u(f_t) - cf_t \\ \sigma(g_t, h_t) &= \upsilon(g_t) - \kappa(h_t)g_t \end{aligned}$$

More specifically, for the purpose of the computations, the utility from the consumption of both goods will be assumed quadratic (and thus concave): $\upsilon(g_t) := \alpha g_t - \frac{1}{2}g_t^2$ and $u(f_t) := af_t - \frac{1}{2}f_t^2$ where $\alpha, a > 0$, and quasi-linear in money.[4] Hence, if we assume that the consumer is exogenously endowed with a constant income I[5] through time, his wealth after goods consumption is: $W(f_t, g_t, h_t) := I - cf_t - \kappa(h_t)g_t$. For clarity sake and because of not modifying our results, the income variable I will be omitted. The consumption of food generating the maximum amount of surplus, $s(f_t)$, is assumed strictly positive: $d := a - c > 0$. Furthermore, when the aquifer tends to be empty ($h_t \to 0$), there is a choke price and the demand for groundwater must go to zero. Thus it is reasonable to assume that $\alpha - \kappa := 0$.

Concerning the environmental preferences of the consumer, we assume that a higher groundwater stock increases wetlands capacity of generating biodiversity and hence amenities. But, in a more general case than the Crau one, it can not be true for every heights of the stock since the consumer can also suffer from water-floods. So, we are going to assume that there is a physical threshold of the groundwater stock height, $\bar{h} \in]0, 1[$, for which neither an increase nor a decrease of the aquifer height affects the consumer utility. When the groundwater stock is higher than this threshold, water-floods are assumed to be more likely to occur, hence inducing a decrease of the consumer's utility with the aquifer height. These environmental concerns are captured by the function $e(h_t)$ which properties can formally be summed up as:

[4] Since these functions are increasing with the first units and decreasing with the last one, the position of the maximum is of importance. It is why it would have been more correct to rather reason on the functions $\upsilon(g_t) := Max\left\{\alpha g_t - \frac{1}{2}g_t^2, \frac{1}{2}\alpha^2\right\}$ and $u(f_t) := Max\left\{af_t - \frac{1}{2}f_t^2, \frac{1}{2}a^2\right\}$. But since parameters a and α can always be chosen sufficiently high in order to check the "good position" of the maximum, we will work on the simpler functions proposed in the text.

[5] We can consider that the building costs needed by the government to construct the groundwater distribution networks are deducted from this amount, through a lump-sum tax for instance.

- P1: $e^{'}(h_t) > 0$ for $h_t < \bar{h}$,[6]

- P2: $e^{'}(h_t) < 0$ for $h_t > \bar{h}$.

It is why we decided to specify this function as: $e(h_t) := -\frac{1}{2}\left(h_t - \bar{h}\right)^2$. It is important to mention that despite the fact that we constructed a very basic hydrological modelling (presupposing an infinite storage capacity of the aquifer) that is widely assumed in the literature, the property P2 reduces the incentives to increase the aquifer height indefinitely.

Finally, the expressions used in order to fully characterize and compare our dynamic solutions will be the following one:

$$
\begin{aligned}
U(f_t, g_t, h_t) &= -\frac{1}{2}g_t^2 + h_t g_t + df_t - \frac{1}{2}f_t^2 - \frac{1}{2}\left(h_t - \bar{h}\right)^2 \\
\sigma(g_t, h_t) &= -\frac{1}{2}g_t^2 + h_t g_t \\
s(f_t) &= df_t - \frac{1}{2}f_t^2
\end{aligned}
$$

2.4 The interactions between a local agricultural authority and a local water agency

In France, policies aiming at internalizing environmental externalities are usually delegated to two different authorities that are generally local: a water authority and an agricultural one. Furthermore, these policies are rarely coordinated in the sense that each authority is pursuing a distinct objective: maximizing the present value of the consumer's surplus stream with respect to food consumption for the agricultural authority and to groundwater use for the water one, both taking into account the consumer's environmental concern. We will refer to such a setting as one of Uncoordinated Water and Agricultural Internalizing Policies (UWAIP).

It is the most realistic to assume that the authorities' decisions depend on time and on the initial level of the stock since none of both is in charge of the aquifer level monitoring[7] and hence have access to information about the depth of the water table at each time. Furthermore, only the agricultural authority is monitoring food consumption and only the water agency is monitoring groundwater consumption. As a consequence, aquifer levels can not be inferred from these variables in the model. In a dynamic setting, it is the open-loop information structure that corresponds to such a situation. In the resulting open-loop Nash equilibrium (which will be denoted with the superscript *ol*) the authorities commit themselves at the moment of starting to an entire temporal path of groundwater consumption for the water one and of food consumption

[6] The superscript $'$ will denote the derivative with respect to the function argument.

[7] In France, it is the BRGM (Bureau de Recherche en Géologie Minière) that is in charge of this monitoring.

for the agricultural one, the consumption path chosen by the other being given and incorporated into the groundwater height motion.

In the more general case, the agricultural authority puts a weight $0 \leq w \leq 1$ on environmental concerns and the water one another one denoted $0 \leq \omega \leq 1$. Why would the authorities put different weights on these concerns? Precisely because they do not coordinate on this goal.

Definition 1 *The equilibrium paths of groundwater and food consumption $\left\{g^{ol}(h_t), f^{ol}(h_t)\right\}$ in an UWAIP setting are given by the simultaneous maximizations of the present value of the consumer's surplus with respect to (i) food and to (ii) groundwater consumption, both programs taking into account the consumer's preferences for environmental concerns in a weighted way:*

(i)

$$\begin{aligned} & \max_{f_t} \int_0^\infty \left[s\left(f_t\right) + we\left(h_t\right)\right] \exp(-rt)dt \\ s.t. \quad : \quad & \dot{h}_t = bf_t - \bar{g}_t \text{ with } h_0 = 1 \end{aligned}$$

where $\bar{g}_t$ is the optimal groundwater consumption path chosen by the water authority;

(ii)

$$\begin{aligned} & \max_{g_t} \int_0^\infty \left[\sigma(g_t, h_t) + \omega e\left(h_t\right)\right] \exp(-rt)dt \\ s.t. \quad : \quad & \dot{h}_t = b\bar{f}_t - g_t \text{ with } h_0 = 1 \end{aligned}$$

where $\bar{f}_t$ is the optimal food consumption path chosen by the agricultural authority.

3 The inefficiencies of food and groundwater consumption in a situation with no optimal control

In dynamic settings concerned with natural resources management, agents are usually assumed to be a too small part of the whole in order to be able to consider the impact of their decision on the resource stock. So, in what we name the myopic competitive case (that will be denoted with the superscript m), our representative consumer will not take into account the impact of his consumption choices on the hydrologic system. We will show that this leads to inefficiencies with respect to a central planner program (which solution will be denoted with the superscript $*$).

Definition 2 *The myopic competitive equilibrium paths of groundwater and food consumption* $\{g_t^m(h_t), f_t^m\}$ *are given by the maximization of the consumer's utility at each time* t*:*

$$\{g_t^m(h_t), f_t^m\} \in \arg\max_{f_t, g_t} U(f_t, g_t, h_t)$$

The necessary FOC (First Order Conditions) of this problem give the short-run demand functions for groundwater and food:

$$\begin{aligned} \upsilon'(g_t) &= \kappa(h_t) \\ u'(f_t) &= c \end{aligned}$$

These equations illustrate a classical result according to which, at each time t, the myopic competitive allocation of groundwater and food are such that the private marginal utility of each one consumption equals its private marginal cost.

Proposition 1 *Within the framework of our specific functional forms*[8]*, the myopic competitive intertemporal paths can be written as:*

$$\begin{aligned} h_t^m &= g_t^m = h_e^m + (1 - h_e^m)\exp(-t)\ \forall t \\ f_t^m &= f_e^m = d\ \forall t \end{aligned}$$

where the aquifer height at the steady state is denoted $h_e^m = bd$*.*

Proposition 1 tells us that at the steady state of this myopic competitive setting, which is denoted by subscript e and for which $t \to \infty$, we observe that the amount of groundwater consumed, g_e^m, is equal to the by-product, bd, generated when the food utility function is maximized, i.e. it is equal to the aquifer inflows. If we remind that the initial groundwater height is always higher than the steady state one since it is equal to one, we have that:

- the aquifer stock is decreasing along time and so is the amount of groundwater consumed;
- the myopic competitive demand of food is the same one at each time and so are the percolations to the aquifer induced by this food production.

We now move to the characterization of an efficient consumption path. In such a setting, it is as if a central planner was choosing the optimal paths of food and groundwater to consume,

[8] *Since we focus on the interior solutions, we implicitly restrict our parameters in such a way that* $bd < 1$*. Furthermore, if parameters* b *and* d *are too small, this can lead to a negative utility because of the externalities hence becoming too severe.*

knowing perfectly the impacts of these consumptions on the aquifer height.

Definition 3 *The optimal paths of groundwater and food consumption* $\{g_t^*(h_t), f_t^*(h_t)\}$ *are given by the maximization of the present value of the consumer's utility stream:*

$$\max_{f_t,g_t} \int_0^\infty U(f_t, g_t, h_t)\exp(-rt)dt$$
$$s.t. \quad : \quad \dot{h}_t = bf_t - g_t \text{ with } h_0 = 1$$

where $0 < r < 1$ *is the discount factor.*

In order to solve this problem, we are going to use the maximum principle. Let H denotes the current value Hamiltonian of this problem:

$$H(h_t, g_t, f_t, \mu_t) = \upsilon(g_t) - \kappa(h_t)g_t + u(f_t) - cf_t + e(h_t) + \mu_t(bf_t - g_t)$$

The efficient solution thus satisfies the conditions:

$$\begin{array}{ll} \upsilon'(g_t) = \kappa(h_t) + \mu_t & \dot{h}_t = bf_t - g_t \\ u'(f_t) + b\mu_t = c & \frac{\dot{\mu}_t}{\mu_t} = r + \kappa'(h_t)\frac{g_t}{\mu_t} - e'(h_t)\frac{1}{\mu_t} \end{array}$$

which, along with the following transversality condition[9], are necessary:

$$\lim_{t\to\infty} \exp(-rt)\mu_t = 0$$

With this general formulation, the shadow price of the groundwater stock, μ_t, reflects the opportunity costs (resp. benefits) associated with the unavailability (resp. availability) in the future of any unit of water consumed (resp. which is percolating) in the present. Its rate of variation along time, $\frac{\dot{\mu}_t}{\mu_t}$, reflects the externalities that a myopic competitive solution fails to internalize with respect to a central planner solution:

- $\kappa'(h_t)\frac{g_t}{\mu_t}$ is the so-called negative pumping cost externality (see Provencher and Burt, 1993);
- when the aquifer height is higher than $\bar{h}$, the negative water-flood externality linked with the water flows lies in $-e'(h_t)\frac{1}{\mu_t}$;
- when the aquifer height is lower than $\bar{h}$, $-e'(h_t)\frac{1}{\mu_t}$ reflects a positive environmental externality that is related to the amenities generated by wetlands.

[9] This transversality condition can seem unusual without reminding that we assumed that $h_t \in]0, 1[\forall t \neq 0$.

There is a market for the pumping cost externality, through the price of the groundwater, $\kappa(h_t)$, but there is none for the two other one since $e(h_t)$ represents an environmental preference. It is why we named the externalities described in the two last bullet items environmental externalities.

r reflects the discounting effect due to the myopic assumption.

Proposition 2 *Using our specific functional forms*[10]*, the efficient intertemporal paths can be written as:*

$$\begin{aligned} \mu_t^* &= \frac{\bar{h}}{r+1},\ f_t^* = d + \frac{b\bar{h}}{r+1}\ \forall t \\ h_t^* &= h_e^* + (1-h_e^*)\exp(-t) \\ g_t^* &= g_e^* + (1-h_e^*)\exp(-t) \end{aligned}$$

where $g_e^* = bd + \frac{\bar{h}b^2}{r+1}$ *and* $h_e^* = bd + \frac{\bar{h}\left(b^2+1\right)}{r+1}$.

We directly deduce from proposition 2 that:

- the shadow price of the groundwater stock is positive and constant along time;
- the efficient amount of food consumed is the same one at each period of time and it is increasing with the shadow price of the groundwater stock, in a way proportional to the percolation coefficient,
- the efficient paths of groundwater consumption and aquifer height are decreasing along time and the efficient paths of groundwater consumed is related to the shadow price of the aquifer in a negative way: the resource extraction is slowed down with respect to the myopic competitive case.

The sign of the shadow price, μ_t^*, means that our specifications make the externalities at work offset in such a way that only incentives to increase the aquifer height, h_t, remains at the optimal solution. As a consequence, groundwater consumption is dishearten and food consumption fostered (see the first order conditions). The shadow price only represents a discounting effect, r, proportional to the physical aquifer height, $\bar{h}$, that does not induce a decrease of the consumer's utility.

Finally, in order to investigate the inefficiency of the myopic competitive solution within the framework of our specifications, we now propose to compare it with the efficient one.

[10] *We need to impose the following restriction on our parameters in order to avoid that the aquifer overflows:* $d < \frac{r+1-\bar{h}\left(b^2+1\right)}{b(r+1)}$. *Notice that this condition is stronger than the one needed in the myopic competitive case,* $bd < 1$.

Proposition 3 *The comparisons of the efficient and myopic competitive intertemporal solutions tell us that:*

(i) the efficient aquifer height is always higher,

(ii) the efficient volume of groundwater consumed can also be higher after a transition phase during which it is lower,

(iii) the efficient amount of food consumed is always higher,

(iv) all the differences are increasing along time except the one in food consumption which is temporally constant.

The possibility of having an efficient volume of groundwater consumed higher than in the myopic case, the efficient aquifer height being always higher, (see (i) and (ii)) is quite different from classical results of the literature about the economics of groundwater management. It furthermore underlines the interest of conducting a dynamic analysis within our framework. It is the fact that the amount of food consumed (and hence the percolations to the aquifer) is also controlled in the efficient case that makes it possible to consume higher amounts of groundwater without reducing the aquifer height. The beginning date of this phase, $t = -\ln \frac{b^2}{1+b^2}$, is increasing with the percolation coefficient.

4 The additional inefficiencies that UWAIP can introduce

In an UWAIP (Uncoordinated Water and Agricultural Internalizing Policies) setting, when they maximize the present value of the consumer's surplus, the authorities also take into account the environmental concerns of the consumers. But according to the weight put by each one of these administrations on these preferences, the inefficiencies due to the lack of coordination between both can differ. It is in order to better understand these inefficiencies that, after having presented the general case, we will study four special cases in details: $(w, \omega) = (0, 1)$, $(w, \omega) = (1, 1)$, $(w, \omega) = (1, 0)$ and $(w, \omega) = (\frac{1}{2}, \frac{1}{2})$

4.1 The general case

This double problem stated in definition 1 can be solved using the maximum principle; it admits two current value Hamiltonians:

$$\begin{aligned} H_f(h_t, f_t, p_t) &= s(f_t) + we(h_t) + p_t(bf_t - \bar{g}_t) \\ H_g(h_t, g_t, \lambda_t) &= \sigma(g_t, h_t) + \omega e(h_t) + \lambda_t\left(b\bar{f}_t - g_t\right) \end{aligned}$$

where λ_t is the shadow price of the aquifer taken into account by the water authority and p_t the one by the agricultural authority. The necessary conditions are the following one:

$$\begin{array}{ll} \upsilon^{'}(g_t) = \kappa(h_t) + \lambda_t & u^{'}(f_t) + bp_t = c \\ \dot{h}_t = bf_t - g_t & \\ \frac{\dot{\lambda}_t}{\lambda_t} = r + \kappa^{'}(h_t)\frac{g_t}{\lambda_t} - e^{'}(h_t)\frac{\omega}{\lambda_t} & \frac{\dot{p}_t}{p_t} = r - e^{'}(h_t)\frac{w}{p_t} \\ \lim\limits_{t\to\infty} \exp(-rt)\lambda_t = 0 & \lim\limits_{t\to\infty} \exp(-rt)p_t = 0 \end{array} \tag{2}$$

The difference between this UWAIP case and the efficient one is the main point of the paper. It lies in the presence of two shadow prices. We can furthermore mention that the rate of variation along the time of the shadow price taking into account by the water administration is the same one as in the efficient case. But it is not true for the one considered by the agricultural authority since it only concentrates on environmental effects, through $e(h_t)$, and not on the one linked with the pumping costs.

Proposition 4 *Using our specifications*[11]*, the uncoordinated intertemporal paths can be written as:*

$$\begin{array}{ll} f_t^{ol} = f_e^{ol} + \frac{bw\left(1-h_e^{ol}\right)}{\rho-r}\exp(\rho t) & g_t^{ol} = g_e^{ol} + \frac{\left(1-h_e^{ol}\right)(r-\rho+\omega)}{r+1-\rho}\exp(\rho t) \\ h_t^{ol} = h_e^{ol} + \left(1-h_e^{ol}\right)\exp(\rho t) & \\ p_t^{ol} = p_e^{ol} + \frac{w\left(1-h_e^{ol}\right)}{\rho-r}\exp(\rho t) & \lambda_t^{ol} = \lambda_e^{ol} + \frac{(1-\omega)\left(1-h_e^{ol}\right)}{r+1-\rho}\exp(\rho t) \end{array}$$

where $g_e^{ol} = \frac{br\left[d(r+\omega)+b\bar{h}w\right]}{wb^2(r+1)+r(r+\omega)}$, $f_e^{ol} = \frac{r\left[d(r+\omega)+b\bar{h}w\right]}{wb^2(r+1)+r(r+\omega)}$, $h_e^{ol} = \frac{b(r+1)\left(dr+\bar{h}wb\right)+r\bar{h}\omega}{wb^2(r+1)+r(r+\omega)}$, $p_e^{ol} = \frac{w\left[-bd(r+1)+r\bar{h}\right]}{wb^2(r+1)+r(r+\omega)}$, $\lambda_e^{ol} = \frac{rbd(1-\omega)+\bar{h}\left(wb^2+\omega r\right)}{wb^2(r+1)+r(r+\omega)}$ *and* $\rho < 0$.

It is first interesting to mention that the shadow price of the groundwater stock taken into account by the water authority is always positive in this general UWAIP setting. This means that she always (whatever the weights are) gives incentives to reduce the amount of groundwater consumed, with respect to a myopic competitive solution.

Furthermore, it is easy to check that the amount of groundwater consumed and the aquifer height are decreasing along time. On the contrary, the amount of food consumed is increasing along time; the shadow price taken into account by the agricultural policy can be either positive or negative, hence possibly inducing either a decrease or an increase of food consumption with respect to the myopic competitive case. Our main claim is that the coordination problem lies

[11] *When $p_t^{ol} < 0$, since the agricultural authority has no incentive to slow down the decrease of food consumption, we have to restrict our parameters such that $f_e^{ol}(r-\rho) > bw\left(1-h_e^{ol}\right)$ in order to check that this consumption is positive all along the path. Finally, we also need to restrict our parameters values in order to insure that the aquifer never overflow by imposing $h_e^{ol} < 1$.*

here. It is why we now propose to investigate it in further details through a detailed analysis of the inefficiencies of specific UWAIP settings.

4.2 The pure water policy setting: $(w, \omega) = (0, 1)$

When $\omega = 1$ and $w = 0$, the agricultural authority does not take environmental concerns into account but the water authority does. Furthermore, since the consumer's surplus with respect to food consumption does not depend on the groundwater table level, the consumption of food is the same one as in the myopic competitive one. In such a virtual setting, the agricultural authority is useless. It is why we named this specific case a pure water policy setting.

Proposition 4 directly gives us the stable intertemporal paths leading to the stationary equilibrium, $(g_e^a, h_e^a, \lambda_e^a)$, in the pure water policy setting as:

$$\begin{aligned} \lambda_t^a &= \frac{\bar{h}}{r+1} \; \forall t \\ h_t^a &= h_e^a + (1 - h_e^a)\exp(-t) \\ g_t^a &= g_e^a + (1 - h_e^a)\exp(-t) \end{aligned}$$

where $g_e^a = bd$ and $h_e^a = bd + \frac{\bar{h}}{r+1}$.

We observe that in such a setting, the shadow price of the aquifer is constant along time and equal to the efficient one since the same quantity effect is remaining.

Proposition 5 *The comparison of these pure water policy setting paths and steady states,*

(i) with the myopic competitive one, tells us that they are always higher or equal,

(ii) and with the efficient one, that they are always lower.

So, even if this pure water policy setting can induce a welfare increase with respect to a myopic competitive situation, it is always worse than an efficient solution, as defined previously.

One additional interesting result (see the proof of (i) of proposition 5) is that, at the steady states of the myopic competitive and pure water policy settings, the consumptions are the same one although the aquifer heights are different. This comes from the fact that, at each time before the steady state, the amount of groundwater consumed in the myopic competitive setting is strictly higher than the one consumed in the pure water policy setting.

4.3 The addition of agri-environmental considerations: $(w, \omega) = (1, 1)$

In practice, we know that an appropriate control of the agricultural production can induce positive effects on the environment. It is the idea behind agri-environmental schemes consisting in financing agricultural production that is good for the environment. We also know that, in

France, it is the agricultural authority that is in charge of this scheme. The differential game presented in definition 1 is now going to be fully played by our two distinct authorities. As a first step, in this subsection, we assume that each authority is taking into account the full environmental preferences of the consumers: $(w, \omega) = (1, 1)$. We will refer to such a case as the agri-environmental policy setting and it will be denoted with the superscript ae.

We then directly deduce the paths leading to the new stationary equilibrium $(g_e^{ae}, h_e^{ae}, \lambda_e^{ae}, p_e^{ae})$ characterizing the agri-environmental policy setting as:

$$\begin{array}{ll} f_t^{ae} = f_e^{ae} + \frac{b(1-h_e^{ae})}{\phi - r} \exp(\phi t) & g_t^{ae} = g_e^{ae} + (1 - h_e^{ae}) \exp(\phi t) \\ h_t^{ae} = h_e^{ae} + (1 - h_e^{ae}) \exp(\phi t) & \\ p_t^{ae} = p_e^{ae} + \frac{1-h_e^{ae}}{\phi - r} \exp(\phi t) & \lambda_t^{ae} = \frac{\bar{h}}{r+1} \ \forall t \end{array}$$

where $g_e^{ae} = \frac{br\left[d(r+1)+b\bar{h}\right]}{(r+1)(r+b^2)}$, $f_e^{ae} = \frac{r\left[d(r+1)+b\bar{h}\right]}{(r+1)(r+b^2)}$, $h_e^{ae} = \frac{b(r+1)\left(dr+b\bar{h}\right)+r\bar{h}}{(r+1)(r+b^2)}$, $p_e^{ae} = \frac{-bd(r+1)+r\bar{h}}{(r+1)(r+b^2)}$ and $\phi = -\frac{1}{2} + \frac{1}{2}r - \frac{1}{2}\sqrt{1 + 2r + r^2 + 4b^2}$.

In such an agri-environmental policy setting, the shadow prices of the aquifer taken into account by the water and by the agricultural administrations differ in such a way that:

- the one of the water authority is constant along time and equal to the efficient one (and consequently to the one corresponding to the pure water policy setting): this authority gives incentives to increase the aquifer height;
- the one of the agricultural authority evolves along time according to the aquifer height, in a way strongly dependant on the value of $\bar{h}$ since the agricultural authority internalizes the wetlands and water-flood externalities but not the pumping cost one.

Proposition 6 *(i) In an agri-environmental policy setting, the shadow price of the aquifer taken into account by the agricultural authority is always lower than the one of the efficient case. It can furthermore either be positive or negative since, depending on the parameters values, the water-flood externality can be considered as being less significant than the wetlands one, or the opposite.*
(ii) The amount of food consumed in an agri-environmental policy setting can either be lower or higher than the one obtained in a pure agricultural setting, depending on the sign of p_e^{ae}. But it is always lower than the efficient one.

Because of the exponential functions, comparisons of the groundwater consumption and aquifer height equilibrium paths between the agri-environmental policy settings and the one previously obtained are less obvious. We thus propose to further work on numerical examples. If we consider the situation in which $p_t^{ae} < 0 \ \forall t$ that is more likely to occur since it corresponds to a larger set of parameters, the simulations example stated in appendix I tells us that there are some parameters sets for which the agri-environmental policy setting is worse than the pure water policy one, all along the paths. Furthermore, appendix J shows that the agri-environmental policy setting equilibria are lower than the one of the efficient setting at each time if the shadow price of the agricultural authority is negative and that the two solutions becomes very similar if the set of parameters induces a possible positivity of this shadow price. But if we remind that the amount of food consumed in an agri-environmental policy setting is always lower than the efficient one, we can conclude that the agri-environmental policy setting is always inefficient. This conclusion can be checked by computing the Net Present Value (NPV) of future utility stream in the two case: $NPV^* - NPV^{ae} = 5,01$ for the set of parameters for which $p_t^{ae} < 0 \ \forall t$ and $NPV^* - NPV^{ae} = 0,001$ for the other set.[12]

4.4 Two other special cases: $(w, \omega) = (1, 0)$ and $(w, \omega) = (\frac{1}{2}, \frac{1}{2})$

We propose here to check if other special cases of the UWAIP setting are also inefficient. The two other settings to study are:

(i) the one where only the agricultural authority is internalizing the environmental externalities (the water authority only concentrates on the pumping cost externality), denoted with the superscript w: $(w, \omega) = (1, 0)$;

(ii) and the one where both authorities internalize them in equal share, denoted with the superscript s: $(w, \omega) = (\frac{1}{2}, \frac{1}{2})$.

Since the comparisons with the myopic and efficient cases are as difficult as in the agri-environmental policy setting (because of the exponential functions), we will directly work on simulations. For this purpose, we will run the NPV and compare them in the efficient, the myopic and the various UWAIP cases for different sets of parameters[13]. Values are summed up in appendix K.

The main result is that any of the UWAIP cases studied is efficient although UWAIP settings are welfare improving with respect to the myopic competitive case. The exception pointed out by our simulation is the case (i) where the water authority does not take into account environmental concerns and where the NPV can be worse than the myopic competitive one, specially for a low value of the aquifer height threshold, $\bar{h}$. The sensibility of this case with respect to this threshold is of special interest since we also observe that all the differences increase with $\bar{h}$ except the one

[12] The reader can be surprised of these very low values but it is due to the scale chosen: the NPV are also very low.

[13] The set of parameters inducing an interior solution will be different from the one previously chosen since the condition insuring that the aquifer never overflows becomes stronger in the w case than in the efficient one. Futhermore, with the new set of parameters chosen, the real eigenvalue ρ is going to possibly become complex because of the square root it contains. But the imaginary parts will be neglected because of being next to zero.

related to this case: they are decreasing for the set of parameters such that $p_t^{ae} < 0 \; \forall t$ and there is no clear trend for the other set.

The sensibility of case (i) to the aquifer height threshold shows us that the inefficiencies do not only come from the lack of coordination of the authorities on environmental externalities. The pumping cost one is also crucial. Indeed, in this case where only the agricultural authority is internalizing the environmental externalities, if, for instance, she has to give incentive to consume more food in order to increase aquifer replenishment and hence height, the water authority will refrain groundwater consumption fewer because of only internalizing pumping cost externalities. And the aquifer height will remain low. The two authorities will then make incentives in opposite ways because of pursuing conflicting goals.

In other words, the inefficiencies of UWAIP do not only come from the lack of coordination of agricultural and water administrations on environmental goals, $e(h_t)$, but also from the fact that an authority in charge of the agricultural policy generally do not aim at internalizing pumping cost externalities which are under the jurisdiction of another authority: the water one.[14] We explained that in the efficient case, the various externalities identified in our model offset in such a way that only incentives to increase the aquifer height remain. But if various authorities aim at internalizing each of them without taking into account this compensation phenomena, the output can not be efficient.

5 Conclusion

When an aquifer is replenished thanks to organic agricultural activities and that the groundwater is consumed in order to satisfy domestic uses, like in the Crau area, a pumping cost externality is occurring. If one add into the picture the fact that water flows due to irrigation can generate either positive (wetlands amenities) or negative (water-floods) externalities, what we named environmental externalities occur. All these externalities can go in opposite ways and can offset in such a way that there is either a need for incentives to increase the aquifer height or for incentives to decrease this height. In order to be fully in phase with the Crau case study, we proposed to concentrate on a specific framework in which the optimal solution is characterized by only a need for incentives to increase the groundwater stock.

In a such a setting, the absence of intervention lead to inefficiencies. It is why authorities usually aim at internalizing these externalities through the control of agricultural production and groundwater consumption. In France, two distinct local authorities are in charge of these

[14] This phenomena can easily be checked by looking at the rate of variation of the shadow prices in equation 2.

controls. We proposed to model such a situation as an open-loop Nash game played between these authorities. We shew that, in such a context, some inefficiencies are still remaining since the agricultural authority does not take into account the pumping cost externality. Our main point relies on this outcome.

All our solutions are summed up in the synoptic table of results presented in figure 2 (see the appendix F).

Even if our model is very specific because of being in phase with the Crau case study, it could be extended in order to investigate the more general question of the coordination of the Common Agricultural Policy (CAP) and the Water Framework Directive (WFD) implementation in the European Union. Indeed, our work shows that an open-loop Nash game can constitute an interesting way of modelling such a problem. In an even more general perspective, this framework can also be helpful in studying the problem of the coordination of various authorities intervention.

Furthermore, as a first step, we proposed to consider a closed economy. Considering the more general question of the coordination of the CAP and of the WFD, it would have been more appropriate to work within the framework of an open economy. The study of the global implications of the authorities intervention would thus have been of major interest.

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APPENDIX

A The Crau aquifer pumping lifts for one representative monitoring point

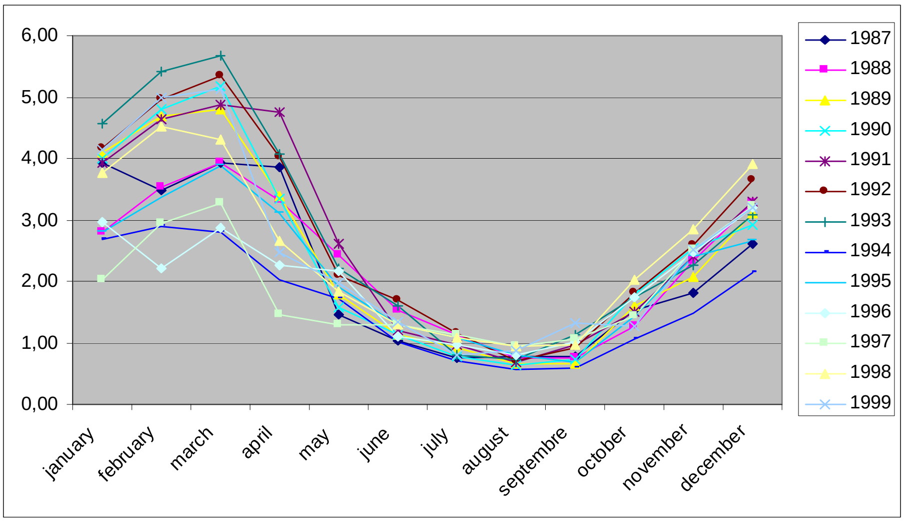


Figure 1: The Crau aquifer pumping lifts

This figure illustrates that, in the Crau area, pumping lifts are lower in the dry season than in the wet one: the groundwater stock is higher in the summer because irrigations are occurring in the dry periods.

B Proof of proposition 1

In order to fully characterize the solution, we solve the problem stated in definition 2 by using our functional forms. The necessary FOC, which are also sufficient, give us the short-run demand functions for groundwater and food as:

$$\begin{aligned} g_t^m &= h_t^m \\ f_t^m &= d \end{aligned}$$

We then need to study the long-run demand functions: the paths which are leading to the myopic competitive steady state (f_e^m, g_e^m, h_e^m), characterized by $\dot{h}_t^m = 0$. It thus remains to solve, with respect to h_t, the following differential equation governing the change in the water table over time in the myopic competitive setting :

$$\dot{h}_t^m = bd - h_t^m$$

Thanks to a standard computation and if we remind that we assumed that $h_0 = 1$, the myopic competitive intertemporal optimal path can then be written as:

$$\begin{aligned} h_t^m &= g_t^m = h_e^m + (1-h_e^m)\, e^{-t}\ \forall t \\ f_t^m &= f_e^m = d\ \forall t \end{aligned}$$

where $h_e^m = bd$.

C Proof of proposition 2

In order to solve the problem stated in definition 3, we are going to use the maximum principle. Let H denotes the current value Hamiltonian of this problem:

$$H(h_t, g_t, f_t, \mu_t) = -\frac{1}{2}g_t^2 + h_t g_t + df_t - \frac{1}{2}f_t^2 - \frac{1}{2}\left(h_t - \bar{h}\right)^2 + \mu_t\left(bf_t - g_t\right)$$

According to the maximum principle, the efficient solution $(h_t^*, g_t^*, f_t^*, \mu_t^*)$ satisfies the following necessary conditions:

$$\begin{aligned} g_t^* &= h_t^* - \mu_t^* & \dot{h}_t^* &= bf_t^* - g_t^* \\ f_t^* &= d + b\mu_t^* & \dot{\mu}_t^* &= r\mu_t^* - \left(g_t^* - h_t^* + \bar{h}\right) \\ & & \lim_{t\to\infty} & \exp(-rt)\mu_t^* = 0 \end{aligned}$$

Remark 1 *Using the Arrow sufficiency theorem, it is obvious to check that these conditions are also sufficient since $\partial_{hh}H^* = 0$, where H^* denotes the maximized Hamiltonian corresponding to the efficient setting.*

In order to fully characterize the efficient paths, we then solve the following dynamic system:

$$\begin{pmatrix} \dot{h}_t^* \\ \dot{\mu}_t^* \end{pmatrix} = \begin{pmatrix} bd \\ -\bar{h} \end{pmatrix} + \underbrace{\begin{pmatrix} -1 & b^2+1 \\ 0 & r+1 \end{pmatrix}}_{A^*} \begin{pmatrix} h_t^* \\ \mu_t^* \end{pmatrix}$$

Since $\det A^* = -r - 1 < 0$, we deduce from the trace/determinant criteria that the path leading to the efficient steady state (g_e^*, h_e^*, μ_e^*) characterized by $\dot{h}_t^* = 0$ and $\dot{\mu}_t^* = 0$, is unstable except on the stable trajectories which directions are given by the eigenvector $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$ associated to the eigenvalue -1 which is satisfying the transversality condition $\lim_{t\to\infty} e^{-rt}\mu_t^* = 0$. The steady state is thus a saddle point.

After some simple computations, the stable intertemporal efficient paths are given by the following system:

$$\begin{aligned} \mu_t^* &= \frac{\bar{h}}{r+1},\ f_t^* = d + \frac{b\bar{h}}{r+1}\ \forall t \\ h_t^* &= h_e^* + (1-h_e^*)\exp(-t) \\ g_t^* &= g_e^* + (1-h_e^*)\exp(-t) \end{aligned}$$

where $g_e^* = bd + \frac{\bar{h}b^2}{r+1}$ and $h_e^* = bd + \frac{\bar{h}\left(b^2+1\right)}{2r+1}$.

D Proof of proposition 3

Some simple computations on the previous results tell us that:

$$
\begin{aligned}
&f_t^* - f_t^m = b\mu_e^* > 0 \ \forall t \\
&h_t^* - h_t^m = \left(b^2+1\right)\mu_e^* \left(1-\exp(-t)\right) > 0 \ \forall t \neq 0 \\
&g_t^* - g_t^m = b^2\mu_e^* \left(1-\exp(-t)\right) - \mu_e^* \exp(-t) < 0 \text{ for } t < -\ln \tfrac{b^2}{1+b^2} \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad > 0 \text{ for } t > -\ln \tfrac{b^2}{1+b^2}
\end{aligned}
$$

E Proof of proposition 4

The double problem stated in definition 1 can be solved using the maximum principle; it admits two current value Hamiltonians:

$$
\begin{aligned}
H_f(h_t, f_t, p_t) &= df_t - \frac{1}{2}f_t^2 - \frac{w}{2}\left(h_t - \bar{h}\right)^2 + p_t\left(bf_t - \bar{g}_t\right) \\
H_g(h_t, g_t, \lambda_t) &= -\frac{1}{2}g_t^2 + h_t g_t - \frac{\omega}{2}\left(h_t - \bar{h}\right)^2 + \lambda_t\left(b\bar{f}_t - g_t\right)
\end{aligned}
$$

According to the maximum principle, the solution $(h_t^{ol}, g_t^{ol}, f_t^{ol}, \lambda_t^{ol}, p_t^{ol})$ satisfies the following necessary conditions:

$$
\begin{aligned}
&g_t^{ol} = h_t^{ol} - \lambda_t^{ol} && f_t^{ol} = d + bp_t^{ol} \\
&\dot{h}_t^{ol} = bf_t^{ol} - g_t^{ol} && \\
&\dot{\lambda}_t^{ol} = r\lambda_t^{ol} - \left[g_t^{ol} - \omega\left(h_t^{ol} - \bar{h}\right)\right] && \dot{p}_t^{ol} = rp_t^{ol} - \left[-w\left(h_t^{ol} - \bar{h}\right)\right] \\
&\lim_{t\to\infty} \exp(-rt)\lambda_t^{ol} = 0 && \lim_{t\to\infty} \exp(-rt)p_t^{ol} = 0
\end{aligned}
$$

Remark 2 *Using the Arrow sufficiency theorem, it is obvious to check that these conditions are also sufficient if and only if $\omega = 1$. Indeed, in such a setting, we can check that $\partial_{hh}H_f^{ol} = -w$ and $\partial_{hh}H_g^{ol} = 0$, where H_f^{ol} and H_g^{ol} denote the maximized Hamiltonian in the open-loop setting corresponding respectively to the agricultural and water authorities' maximization problem.*

We have then the following dynamic system to solve:

$$
\begin{pmatrix} \dot{h}_t^{ol} \\ \dot{p}_t^{ol} \\ \dot{\lambda}_t^{ol} \end{pmatrix} = \begin{pmatrix} bd \\ -w\bar{h} \\ -\omega\bar{h} \end{pmatrix} + \underbrace{\begin{pmatrix} -1 & b^2 & 1 \\ w & r & 0 \\ -1+\omega & 0 & r+1 \end{pmatrix}}_{A^{ol}} \begin{pmatrix} h_t^{ol} \\ p_t^{ol} \\ \lambda_t^{ol} \end{pmatrix}
$$

The characteristic polynomial of the matrix A^{ol} is a cubic-root one: $-\rho^3 + 2r\rho^2 + \rho\left(r - r^2 + wb^2 + \omega\right) - r^2 - wrb^2 - wb^2 - \omega r$. A^{ol} has thus three eigenvalues denoted ρ, ρ_1 and ρ_2. We then directly deduce from Cardan's formula and $r < 1$ that there are one real, ρ, and two complex eigenvalues, one being the conjugate of the other ($\rho_1 := a + ib$ and $\rho_2 := a - ib$, for instance):

$$
\left(-r^2 - wrb^2 - wb^2 - \omega r\right)^2 + \frac{4}{27}\left(r - r^2 + wb^2 + \omega\right)^3 > 0
$$

We furthermore know that:

$$
\det A^{ol} = \rho\rho_1\rho_2 = -r^2 - wrb^2 - wb^2 - \omega r < 0
$$

Since $\rho_1\rho_2 = a^2 + b^2 > 0$, the real eigenvalue is always negative. Furthermore, we know from

$$trA^{ol} = \rho + \rho_1 + \rho_2 = 2r > 0$$

that $a > r$. As a consequence, there exists a unique eigenvalue with a negative real part satisfying the transversality conditions $\lim_{t\to\infty} e^{-rt}\lambda_t^{ol} = 0$ and $\lim_{t\to\infty} e^{-rt}p_t^{ol} = 0$: it is the real negative one ρ. But it is important to mention that since this eigenvalue contains a square root, according to the values of our parameters, it can be either real or complex.

So, the path leading to the general UWAIP stationary equilibrium $\left(g_e^{ol}, h_e^{ol}, \lambda_e^{ol}, p_e^{ol}\right)$, is unstable except on the stable trajectories which directions are given by the eigenvector associated to the negative eigenvalue: $\begin{pmatrix} 1 \\ \frac{w}{\rho-r} \\ \frac{1-\omega}{r+1-\rho} \end{pmatrix}$. The stationary equilibrium is thus also a saddle point in this setting. After some simple computations, the stable intertemporal paths of the other variables can be deduced as:

$$\begin{array}{ll} f_t^{ol} = f_e^{ol} + \frac{bw\left(1-h_e^{ol}\right)}{\rho-r}\exp(\rho t) & g_t^{ol} = g_e^{ol} + \frac{\left(1-h_e^{ol}\right)(r-\rho+\omega)}{r+1-\rho}\exp(\rho t) \\ h_t^{ol} = h_e^{ol} + \left(1-h_e^{ol}\right)\exp(\rho t) & \\ p_t^{ol} = p_e^{ol} + \frac{w\left(1-h_e^{ol}\right)}{\rho-r}\exp(\rho t) & \lambda_t^{ol} = \lambda_e^{ol} + \frac{(1-\omega)\left(1-h_e^{ol}\right)}{r+1-\rho}\exp(\rho t) \end{array}$$

where $g_e^{ol} = \frac{br\left[d(r+\omega)+b\bar{h}w\right]}{wb^2(r+1)+r(r+\omega)}$, $f_e^{ol} = \frac{r\left[d(r+\omega)+b\bar{h}w\right]}{wb^2(r+1)+r(r+\omega)}$, $h_e^{ol} = \frac{b(r+1)\left(dr+\bar{h}wb\right)+r\bar{h}\omega}{wb^2(r+1)+r(r+\omega)}$, $p_e^{ol} = \frac{w\left[-bd(r+1)+r\bar{h}\right]}{wb^2(r+1)+r(r+\omega)}$ and $\lambda_e^{ol} = \frac{rbd(1-\omega)+\bar{h}\left(wb^2+\omega r\right)}{wb^2(r+1)+r(r+\omega)}$.

F Synopsis of results

	Efficient	Myopic competitive	UWAIP	
Optimization problem	$\max_{f_t,g_t}\int_0^\infty U(f_t,g_t,h_t)e^{-rt}dt$ $s.t.: \dot{h}_t = bf_t - g_t, h_0 = 1$	$\max_{f_t,g_t} U(f_t,g_t,h_t)$	$\max_{g_t}\int_0^\infty [\sigma(g_t,h_t)+\omega e(h_t)]e^{-rt}dt$ $s.t.: \dot{h}_t = b\bar{f}_t - g_t, h_0 = 1$	$\max_{f_t}\int_0^\infty [s(f_t)+we(h_t)]e^{-rt}dt$ $s.t.: \dot{h}_t = bf_t - \bar{g}_t, h_0 = 1$
Food consumption				
Path	$d+\frac{b}{2(r+1)}\forall t$	d $\forall t$	$f_e^{ol}+\frac{bw(1-h_e^{ol})}{\rho-r}e^{\rho t}$	
Steady state			$\frac{r[d(r+\omega)+b\bar{h}w]}{wb^2(r+1)+r(r+\omega)}$	
Groundwater consumption				
Path	$g_e^*+(1-h_e^*)e^{-t}$	$h_e^m+(1-h_e^m)e^{-t}$	$g_e^{ol}+\frac{(1-h_e^{ol})(r-\rho+\omega)}{r+1-\rho}e^{\rho t}$	
Steady state	$bd+\frac{b^2}{2(r+1)}$	bd	$\frac{br[d(r+\omega)+b\bar{h}w]}{wb^2(r+1)+r(r+\omega)}$	
Aquifer height				
Path	$h_e^*+(1-h_e^*)e^{-t}$	$h_e^m+(1-h_e^m)e^{-t}$	$h_e^{ol}+(1-h_e^{ol})e^{\rho t}$	
Steady state	$bd+\frac{b^2+1}{2(r+1)}$	bd	$\frac{b(r+1)(dr+\bar{h}wb)+r\bar{h}\omega}{wb^2(r+1)+r(r+\omega)}$	
Shadow prices				
Path	$\frac{1}{2(r+1)}\forall t$	$0\forall t$	$\lambda_e^{ol}+\frac{(1-\omega)(1-h_e^{ol})}{r+1-\rho}e^{\rho t}$	$p_e^{ol}+\frac{w(1-h_e^{ol})}{\rho-r}e^{\rho t}$
Steady state			$\frac{rbd(1-\omega)+\bar{h}(wb^2+\omega r)}{wb^2(r+1)+r(r+\omega)}$	$\frac{w[-bd(r+1)+r\bar{h}]}{wb^2(r+1)+r(r+\omega)}$

Figure 2: Synopsis of results

G Proof of proposition 5

Simple computations lead to the following results:

(i)

$$
\begin{aligned}
f_t^a - f_t^m &= 0\ \forall t,\ g_e^a - g_e^m = 0 \\
h_t^a - h_t^m &= \lambda_e^a\left(1-\exp(-t)\right) > 0\ \forall t \neq 0 \\
g_t^a - g_t^m &= -\lambda_e^a \exp(-t) < 0\ \forall t \nrightarrow \infty
\end{aligned}
$$

(ii)

$$
\begin{aligned}
h_t^a - h_t^* &= -b^2\mu_e^*\left(1-\exp(-t)\right) < 0\ \forall t \neq 0 \\
g_t^a - g_t^* &= -b^2\mu_e^*\left(1-\exp(-t)\right) < 0\ \forall t \neq 0 \\
f_t^a - f_t^* &= -b\mu_e^* < 0\ \forall t
\end{aligned}
$$

H Proof of proposition 6

(i) According to our assumptions, $\frac{1-h_e^{ae}}{\phi-r} < 0$ and

$$\mu_t^* - p_t^{ae} = \frac{bd\,(r+1)+\bar{h}b^2}{(r+1)\,(r+b^2)} - \frac{1-h_e^{ae}}{\phi-r}\exp(\phi t) > 0\ \forall t$$

Furthermore, since $p_t^{ae} = p_e^{ae} + \frac{1-h_e^{ae}}{\phi-r}\exp(\rho t)$ and $p_e^{ae} = \frac{-bd(r+1)+r\bar{h}}{(r+1)\left(r+b^2\right)}$,

- $bd\,(r+1) > r\bar{h} \Rightarrow p_t^{ae} < 0\ \forall t$,
- $bd\,(r+1) < r\bar{h} \Rightarrow p_t^{ae} > 0\ \forall t > \frac{1}{\phi}\ln\frac{p_e^{ae}(r-\phi)}{1-h_e^{ae}}$.

(ii) The comparison between the amounts of food consumed in an agri-environmental setting and in a pure agricultural one,

$$f_t^{ae} - f_t^a = bp_e^{ae} + \frac{b\,(1-h_e^{ae})}{\phi-r}\exp(\phi t)$$

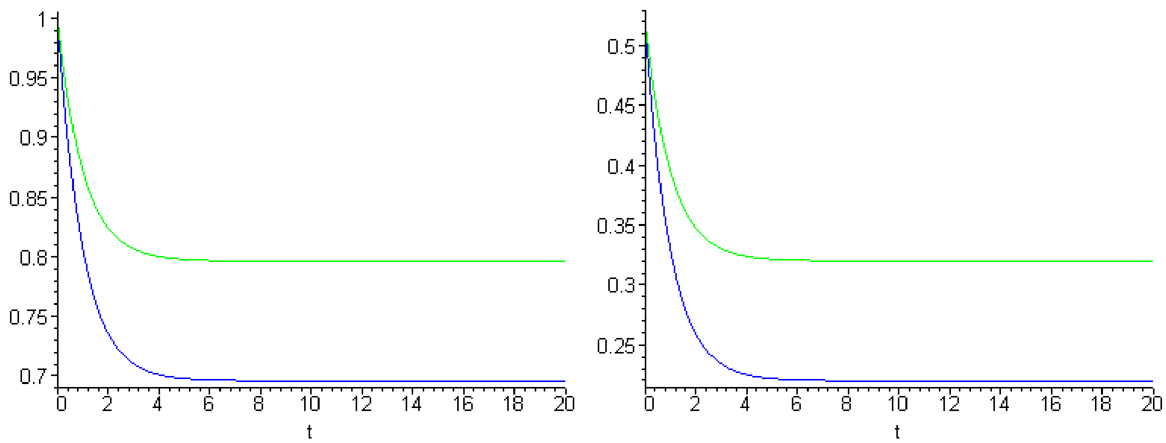
leads us to two different cases:

- $p_e^{ae} < 0 \Rightarrow f_t^{ae} - f_t^a < 0\ \forall t$;
- $p_e^{ae} > 0 \Rightarrow f_t^{ae} - f_t^a > 0\ \forall t > \frac{1}{\phi}\ln\frac{p_e^{ae}(r-\phi)}{1-h_e^{ae}}$.

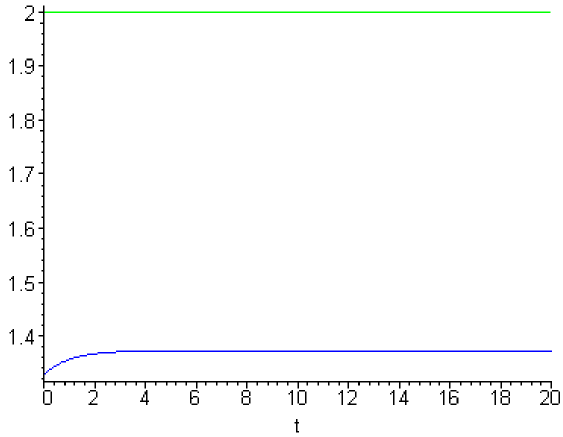
Finally, comparing the amount of food consumed in the agri-environmental setting with the efficient one leads to:

$$f_t^* - f_t^{ae} = \frac{b^2\left(dr+d+b\bar{h}\right)}{(r+1)\,(r+b^2)} - \frac{b\,(1-h_e^{ae})}{\phi-r}\exp(\phi t) > 0\ \forall t$$

I Numerical example for which an agri-environmental policy setting is worse than a pure agricultural one at each period of time



Aquifer height paths — Groundwater consumption paths

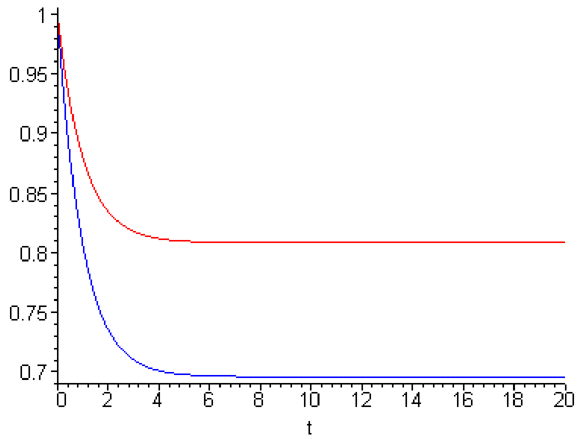


Food consumption paths

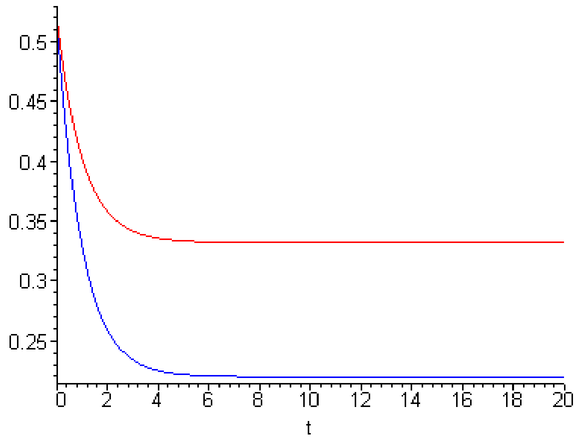
b=0,16 d=2 (i.e. $p_t^{ae} < 0\ \forall t$) r=0,05 and $\bar{\text{h}}$=1/2

The green color is for the pure agricultural policy setting and the blue one for an agri-environmental one.

J The inefficiency of an agri-environmental setting



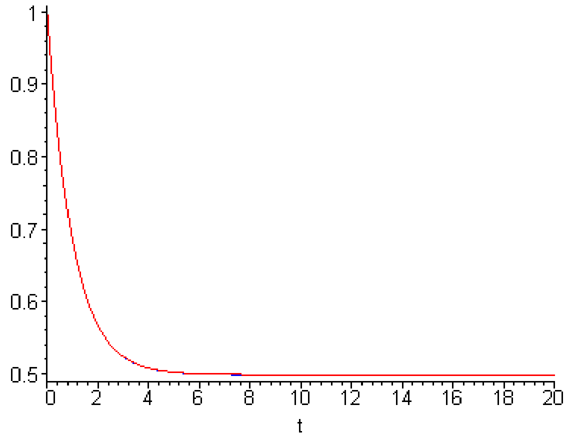
Aquifer height paths



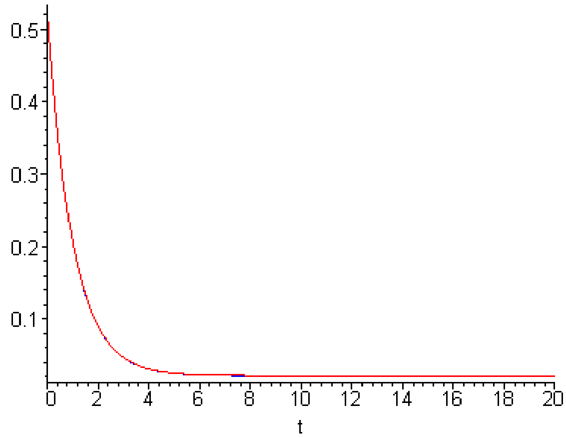
Groundwater consumption paths

b=0,16 d=2 (i.e. $p_t^{ae} < 0\ \forall t$) r=0,05 and $\bar{\text{h}}$=1/2

The red color is for the efficient setting and the blue one for an agri-environmental policy one.



Aquifer height paths



Groundwater consumption paths

b=0,018 d=1,2 (i.e. $p_t^{ae} > 0 \ \forall t > 2,39$) r=0,05 and $\bar{\text{h}}$=1/2

K NPV computations

	$\bar{h} = \frac{3}{8}$	$\bar{h} = \frac{1}{2}$	$\bar{h} = \frac{3}{4}$
$NPV^* - NPV^m$	1,31	2,33	5,23
$NPV^* - NPV^a$	0,03	0,06	0,13
$NPV^a - NPV^m$	1,27	2,27	5,10
$NPV^* - NPV^{ae}$	0,87	0,90	0,97
$NPV^{ae} - NPV^m$	0,44	1,43	4,26
$NPV^* - NPV^w$	5,59	5,18	4,45
$NPV^w - NPV^m$	-4,28	-2,86	0,78
$NPV^* - NPV^s$	0,88	0,90	0,96
$NPV^s - NPV^m$	0,43	1,42	4,27

r=0,05 b=0,16 d=0,8 : $p_t^{ae} < 0 \ \forall t$

	$\bar{h} = \frac{3}{8}$	$\bar{h} = \frac{1}{2}$	$\bar{h} = \frac{3}{4}$
$NPV^* - NPV^m$	1,27	2,27	5,10
$NPV^* - NPV^a$	0	0	0
$NPV^a - NPV^m$	1,27	2,27	5,10
$NPV^* - NPV^{ae}$	0	0	0
$NPV^{ae} - NPV^m$	1,27	2,27	5,10
$NPV^* - NPV^w$	0,39	0,15	0,45
$NPV^w - NPV^m$	0,88	2,11	4,65
$NPV^* - NPV^s$	0,01	0,01	0
$NPV^s - NPV^m$	1,26	2,26	5,10

r=0,05 b=0,018 d=1,2