Protecting biodiversity on farm land: Which type of agri-environmental measure does it better?[*]

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Abstract

Much biodiversity is found in farm land. However, there is usually a trade-off between farm land productivity and sustainability of natural resources. Biodiversity conservation in agricultural land usually requieres to carry on a serie of conservationist practices that are costly. Therefore, farmer's participation in conservationist programs requires economic incentives. Our goal is to identify which is the most approppriated policy design for garanteeing both the sustainability of the natural resources and economic efficency. We provide a model where a natural resource is affected by the cultivation practices of two types of farmers, conservationist and non-conservationist, who adjust their farming practices in response to persistent differential payoffs. We show that partnership subsidies are better than individual constant subsidies protecting natural resources.

Keywords: natural resource, cooperation, sustainable management, evolutionary framework.

JEL: Z13, Q20, D62

1 Introduction

Sometimes farm production and sustainability of natural resource are at odds. There is usually a trade-off between farm productivity and sustainability of natural resources. The first usually implies to increase irrigation and/or to intensively use fertilizers, pesticides and phytosanitary products that jeopardize the preservation of natural environments. Since the publication of Carson's Silent Spring in 1962 this relationship between chemical pesticides, agribusiness and the environment has prompted vigorous and controversial debate.[1] Other times, however, farming has been a major grantor of the sustainability of biodiversity since often farming traditions have resulted in the development and preservation of habitats able to sustain a large span of wild species (Bignal and McCracken, 1996, and 2000 and Farina, 1997). Nevertheless, in general intensification in agriculture has caused biodiversity losses (Buckwell and Armstrong-Brown, 2004 and Young *et al.,* 2005) and most developed countries have enacted some natural resources preservation programs to protect biodiversity and the natural environment from such farming practices and foregone land intensification.

Accordingly, the EU legal framework have enacted two major Directives to preserve Europe most valuable species, the Habitats Directive and the Birds Directive.[2] These two Directives provide mechanisms for the conservation of natural habitats and wild fauna and flora, including special protection areas for birds. Natura 2000 network is an instrument created by the European Union to protect these areas. Natura 2000 is a biodiversity preservation sites network created to protect and ensure the conservation of protected species and of habitats of interest.

[1] See for example Eicnher and Pethig (2006), Borge and Skonhoft (2009), Polasky and Segerson (2009), Espinosa-Goded et. al. (2010), Levin *et al.* (2013) and William and Xepapadeas (2014)

[2] The Habitats Directive is Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Birds Directive is Directive 79/409 / EEC of 2 April 1979 on the conservation of wild birds.

It comprises all EU state members. Every state member has to appoint their Natura 2000 sites according to the European Habitats and Birds Directive, and has to maintain such sites in a favorable state of conservation. The Natura 2000 network identifies areas of special interest where natural resource should be preserved, the preservation of these areas results on the provision of environmental public goods, such as biodiversity protection, habitat conservation, and landscape preservation.

Farmland is crucially important for the Natura 2000 network since 40% of the total area included in this network is agricultural land, furthermore a large number of species and habitats protected under the Habitats and/or the Birds Directive depend on agricultural land.[3] Some of the farmland included in Natura 2000 is located in marginal farming areas, with low intensity farming systems consistent with the conservation of habitats and species.[4] However, other protected species are found in areas that are already intensively managed and highly productive or in areas that could become so through out the implementation of some modernization projects, such as the development of irrigation projects or the introduction of intensive farming practices. In such cases, farmers often resist the incorporation of their land in the network or once had been include they refuse to comply with the conservation plans designed by the regulatory authorities.[5] Protecting these Natura 2000 sites usually leads to develop conservation plans oriented to the protection of the natural environment that usually results in setting some limits to the agricultural practices. These restrictions usually increase production cost or/and reduce farmers profits making more difficult for farmers to comply with them.

[3] See European Commission, 2014.

[4] See Oppermann *et al.*, 2012

[5] For example, the controversy generated by the Natura 2000 areas located in the Segarra-Garriga channel project. (Reguant and Lletjós, 2014). And the opposition of local land users to the Natura 2000 perimeter in Étang de Mauguio, France (Bouwma *et al*, 2010).

Furthermore and quite often, farmers who harvest on Natura 2000 sites work under difficult economic conditions. Usually they are small owners that have to manage their harvests under every day more difficult competitive conditions. Often these farmers are highly vulnerable and face global economic pressures that can lead to the abandonment of the low intensity farming practices or to the abandonment of the agricultural activity all together (IEEP and Veenecology, 2005; Keenleyside and Tucker, 2010). In these cases compatibility between conservation and profitability of the farm is compromised and therefore it is necessary to find ways of introducing economic incentive to modify agricultural practices and enable their economic sustainability while also enabling the sustainability of habitats and biodiversity.

To make compatible habitat preservation with economically sustainable agricultural practices, the EU has issued a set of measures aimed on supporting farmer's activity in Natura 2000 areas through agri-environmental schemes. The most important source of funding is the European Agricultural Fund for Rural Development (EAFRD)[6] that funds a large part of the Common Agricultural Policy (CAP), particularly the Pillar II, aimed on rural development. Each Member State must develop their Rural Development Plan (RDP) to promote rural development and ensure the conservation of biodiversity, particularly in Natura 2000 areas, most of these payments must be distributed by hectare and year.[7] The EAFRD also includes the Leader funds that aim to capitalize on a common identity through the creation of partnerships. Leader finances Local Action Groups (LAGs) and promotes sustainable development projects on small scale. Thus, Leader funds promote cooperation among farmers to carry out

[6] It was approved by Regulation (EC) 1305/2013 of the European Parliament and of the Council of 17 December

[7] According to the Regulation (EC) 1305/2013. For examples of funding see annexes of IEEP and Veenecology, 2005.

projects that combine resource conservation and land use (See European Commission, 2014). Moreover, the Pillar I of the CAP is financed by the European Agricultural Guidance and Guarantee Fund (EAGGF) that is a major source of direct payments per hectare subject to conditionalities. The Pillar I can, especially, give support to the economic viability of farms with low intensity systems, as it happen, in some cases, in agricultural land within Natura 2000. [8]

Furthermore, agri-environmental schemes can also consider payment systems that rely on the environmental services provided by farmers. Farmers who are located in Natura 2000 sites generate environmental services such as biodiversity or landscapes conservation and carbon sequestration (Swinton *et al.*, 2007, Smith and Sullivan, 2014) and therefore farmers could be rewarded through result-based agri-environment schemes such as payments for environmental services (PES). The large the environmental service farmers are able to generate, the larger the payments that they receive (Keenleyside *et al.,* 2014).[9] But these type of subsidy are not wide spread in the EU.

After reviewing these programs it is clear that most of these agri-environmental schemes are carried on through direct payments per hectare and are subject to conditionality. That is,

[8] There are other instruments which can be used to finance Natura 2000. The most important is the Life Program, created by the EU to support environmental projects, nature conservation and climate actions. Over half of the budget destined to the environment subprogram, is spent on actions to nature and biodiversity, with particular attention to Natura 2000. It is possible to find another funding measures for Natura 2000 in the European Structural and Investment Funds (ESIFs). Within the ESIFs there are the already mentioned EAFRD, and also the European Regional Development Fund (ERDF), the European Social Fund (ESF) and the Cohesion Fund (CF), which can be useful in financing agricultural areas in Natura 2000. Although the use of these funds in Natura 2000 areas is reduced and their major goal is not biodiversity preservation, we can find some examples such as the use of ERDF in Natura 2000 to develop the TIDE project (Tidal River Development, 2010-2013). Both LIFE and Structural Funds are usually tied to projects with a predetermined timeframe. The common objective of these funds is to promote social and economic development in disadvantaged areas, sectors or groups, trying to reduce economic and social differences through integration projects (Farmer, 2011).

[9] In some cases, the states have been developed policies focused on rewarding farmers for the generation of environmental services through payment schemes based on the market, such as the Bush Tender in Australia (Crowe *et al.*, 2008) or the Conservation Reserve Program in the United States (Mishra and Khanal, 2013).

only farmers that comply with the regulations receive a per hectare payment. These payments are not result-based they only take into account if farmers has complied with the environment protecting practices.[10] Furthermore, Leader and Life programs not only preserve the environment but also promote cooperation and partnership among farmers to develop projects that combine natural resources conservation and land use. In our model we analyze and compare the performance of two types of agri-environmental schemes in an evolutionary framework. First, we consider a fixed payment per hectare subject to conditionality. This type of payment are the most widely spread. Farmers are offered a payment for a set of management actions that are thought to increase biodiversity independently of the results obtained. Second, we introduce payment schemes that represent a fixed payment by project or goal.[11] The final payment per participating farmer will depend on the number of conservationist farmers participating in the project. The larger the number of conservationists farmers the lower the individual payment received by a cooperative agent. These programs are subject to conditionality but the payments per hectare change with the number of cooperative agents. Our goal is to compare the performance of these two types of measures, and to contribute to the joint analysis of the economic viability and the capacity of recovering a natural resource of these two agri-environmental measures.

We analyze from a theoretical perspective the performance of these two different types of agri-environmental measures with the goal of ensuring the maintenance of a sustainable growth of natural resources in agricultural systems. In particular, we claim that, for a given

[10] On the other hand, schemes can be result-based. In these cases the payment received by farmers depends on the degree of habitat or specie recovery. These type of programs present similarities to PES as agents are paid depending on the environmental service provided.

[11] We do not aim to reprocude Leader and Life programs because in such cases there is the participation of other types of agents.

budget, agri-environmental schemes that relay on agents partnership are better suited to preserve natural resources, that are highly sensitive to farmers actions. For resources with a low sensitivity to farmers actions agri-environmental schemes independent of the number of cooperative agents can attain the same results and the resource be recovered. The aim is to identify economic mechanisms that encourage environmentally friendly agricultural practices, which are truly able to preserve the natural resources on farm lands.

The evolutionary approach differs from standard non-cooperative game theory as it is not a game where agents use best-replies. While the agents in our setting act in their own self interest they are myopic. We assume that individuals select a set of management actions such as the level of fertilizer, pesticide and phytosanitary inputs use and respond to differences in payoff by modifying their choices. In order to prevent sudden changes in behavior patterns, we adopt the assumption that the weight of the population shifts gradually towards the group whose payoff is above the average, that is, we assume the evolution of the composition of the population is described by the replicator dynamics. Unlike agents in non-cooperative games, they do not have a contingency plan that dictates their best response to the strategies of other players. Our approach does, however, enable us to focus on aggregate outcomes - such as the composition of society and the evolution of the stock of natural resources - more easily than with standard game theory.

This evolutionary approach has been widely used to analyze resource management under common property regimes where a set of agents jointly exploit a natural resource (Brandt *et al.,* 2003; Noailly, 2003; Oses-Eraso and Viladrich-Grau, 2007; Blanco *et al*, 2009; De silva *et al.*, 2010; Sigmund *et al.,* 2011). Instead we consider a situation where each agents exploit its own farmland in a resource preservation area such as Natura 2000. In our case each farmer selects the level of inputs used during its production process where both inputs and land are privately own.[12] Farmers' goals is to maximize individual profits and choose the level of non-enviromentally friendly inputs used during its farming activity. The use of these non-environmentally friendly inputs results in damages on a population of an endangered specie of birds. We assume that this specie of birds is a non-excludable and non-rival good, it also results in a negative externality for farmers.

The paper is organized as follows. In the next two sections, we present our model, and describe the dynamics of the resource stock and the farmers behavior. In section 4, we are concerned with the dynamics of the combined system: that is, we consider the dynamics of farmer behavior together with the sustainability of the natural resource. We analyze the policy measures that can provide, in equilibrium, both a sustainable management of the natural resource and an economically sustainable agricultural activity. We show that these equilibria can be obtain with a stable heterogeneous equilibrium - i.e. one in which conservationist and non-conservationist farmers coexist. In section 5, we show a simulation example and in Section 6 we present our conclusions.

2 The model

2.1 Resource Stock Dynamics

We consider a model where a farming land area L_Z provides habitat for an endangered specie of birds, B, a steppe bird.[13] We represent the natural evolution of the bird population with the classic growth model, where the dynamics of the stock depends on its natural rate of growth,

[12] See Blanco *et al.,* 2009 for a similar application of replicator dynamics on private properties.
[13] We assume that the extension of the farming land L_Z is fixed.

which is a function of the resource stock level, B. The rate of replenishment is represented by the differentiable function $F(B)$. We assume that this function satisfies the usual assumptions describing the dynamics of renewable resources and that its graph is bell-shaped, as shown in Fig 1a.[14] Let $\overline{B}$ be the maximum stock of birds that the environment is able to support, and $\underline{B}$ the volume below which growth via renewal is impossible, both stock levels depend on L_Z. At these values, $F(\underline{B}) = F(\overline{B}) = 0$. For stock levels between $\underline{B}$ and $\overline{B}$, $F''(B) < 0$ and the resource grows at a positive rate, $F(B) > 0$; this growth reaches its only maximum at B^M, $\underline{B} < B^M < \overline{B}$. Also for stock levels $B < \underline{B}$, $F(B) < 0$ and for stock levels $B > \bar{B}$ $F(B) = 0$. We consider that area L_Z has been included in a natural resource protection network.[15] A set of $N = \{1, \ldots, n\}, n \geq 2$ farmers cultivate land in this area. Each farmer determines the individual amount of non-environmentally friendly inputs x_i (such as pesticides and phytosanitary products) used during the harvesting process. We further assume that farming activities, such as the use of these inputs, can damage the bird habitat and therefore can threaten the conservation of the population of birds. We represent this situation with a so called wipe out function, that depends on the stock level, B, and on the total level on non-environmentally friendly inputs used, X. The amount of non-environmentally friendly inputs used $X = \sum_{i=1}^{N} x_{it}$ is jointly determined by the N farmers that own agricultural land in L_Z. The wipe out function per unit of time is represented as $W(B, X)$, where W is a twice-continuously differentiable function; also $W(0, X) = W(B, 0) = 0$ and $\frac{\partial W}{\partial B} \geq 0$, $\frac{\partial^2 W}{\partial B^2} \leq 0$, $\frac{\partial W}{\partial X} \geq 0$, $\frac{\partial^2 W}{\partial X^2} \leq 0$, $\frac{\partial^2 W}{\partial B \partial X} \geq 0$, and $\frac{\partial (W/X)}{\partial B} \geq 0$. The evolution of the resource stock depends on this wipe out function. Therefore, the resource stock changes at a rate equal to the difference

[14] This resource dynamics is similar to the resource dynamics of Osés-Eraso and Viladrich-Grau (2007), we fully describe it here to ease the reader job see this paper for further details.

[15] For example, such as Natura 2000 in Europe.

between the renewal and the wipe out rate:

$$\dot{B} = F(B) - W(B, X) \tag{1}$$

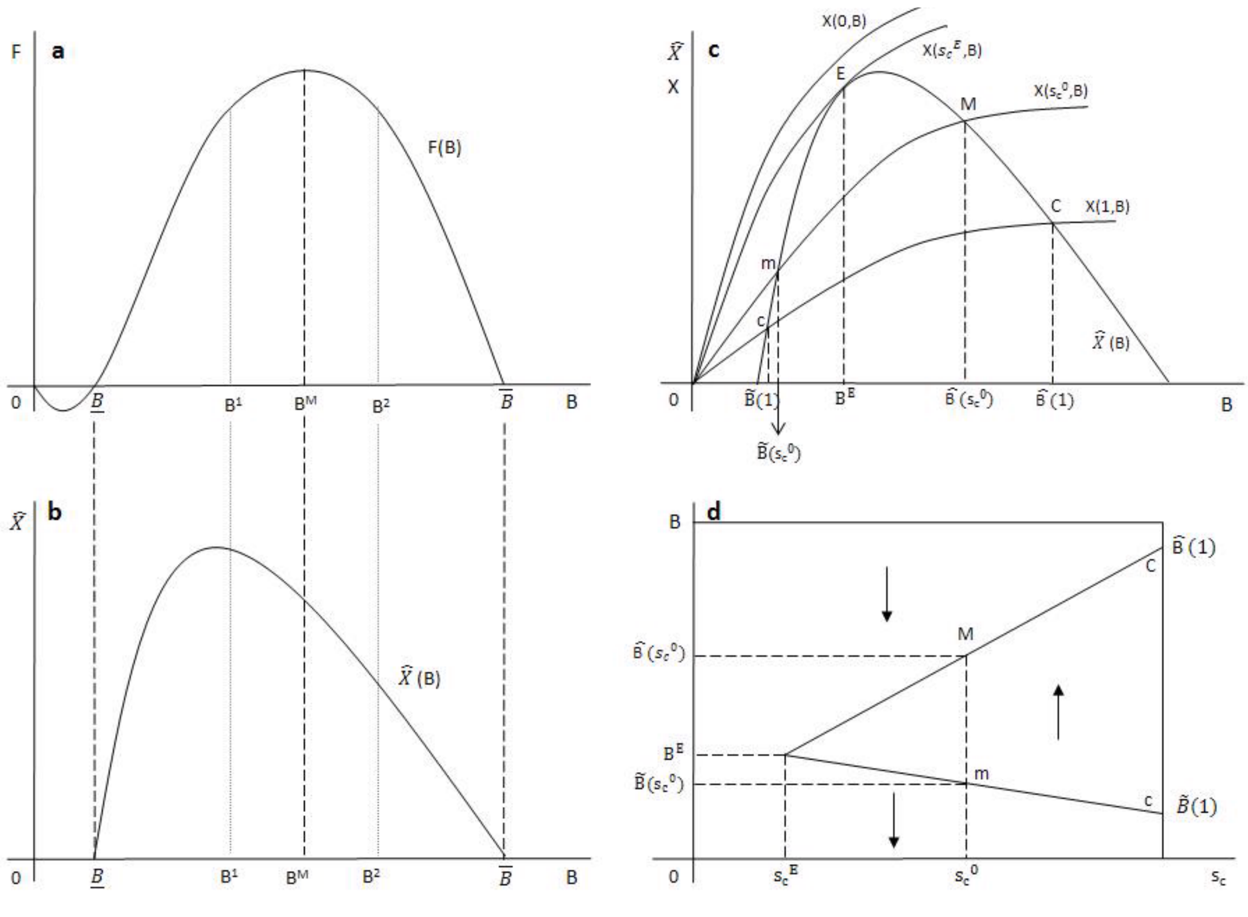

Fig 1. Natural resource dynamics

2.2 Equilibrium conditions of the Resource Stock Dynamic

Let us first consider the equilibrium condition for equation 1. A natural resource is in equilibrium when its stock level remains constant over time, that is, when the rate of extraction is equal to the rate of renewal, $\dot{B} = 0$. We assume that for any stock of birds, $\underline{B} \leq B \leq \bar{B}$, there will exist a non-environmentally friendly level of inputs, X, such that the wipe out rate,

$W(B, X)$, coincides with the rate of renewal, $F(B)$, that is, $\dot{B} = 0$. If this were not the case, the resource would be inexhaustible. We represent this equilibrium level by the function $\widehat{X}(B)$, as seen in Fig.1b.

Further, note that when the stock level is greater than B^M, the non-environmentally friendly input level $\widehat{X}(B)$ is a decreasing function of resource stock B.[16] On the other hand, however, when stocks are lower than B^M the non-environmentally friendly input level, $\widehat{X}(B)$ may be either increasing or decreasing function of B,[17] see Fig. 1b. Let B_1 and B_2 be two different stock levels such that $B_1 < B^M < B_2$ and $F(B_1) = F(B_2)$, the growth rate is equal for both stock levels, therefore the extraction rate that allows to maintain the stock must be the same in both situations. However B_2 is larger than B_1, the larger the number of units of a resource the easier will be to hunt a given amount, and therefore to hunt the same number of units less effort will be necessary. It is easier to hunt a given number of resource in B_2 than in B_1. This argument will hold for values of B arbitrarily close to B^M. Therefore,it can be seen in Figure 1.b that $\widehat{X}(B)$ for stock levels B such that $B^m < B < B^M$, $\widehat{X}(B)$ would be a decreasing function of B. For stocks in short supply, $B < B^m$ we assume $\widehat{X}(B)$ to be an increasing function of stock. Note that the equilibrium level $\widehat{X}(B)$, in which the rate of extraction is equal to the rate of renewal, does not necessarily coincide with the total amount of non-environmentally friendly input used by the community. Consider a situation where

[16] We can obtain this result by applying the implicit function theorem to the resource stock equilibrium condition, $F(B) = W(B, X)$, that is, $\frac{d\widehat{X}}{dB} = \frac{\frac{dF}{dB} - \frac{\partial W}{\partial B}}{\frac{\partial W}{\partial X}}$. When the resource stock is such that $B > B^M$, then $\frac{dF}{dB} < 0$. Recall also that the rate of extraction is an increasing function of non-environmentally friendly inputs level, X and of resource stock B, that is, $\frac{\partial W}{\partial B} > 0$, $\frac{\partial W}{\partial X} > 0$. Then, $\frac{d\widehat{X}}{dB} < 0$, which implies that non-environmentally friendly input level $\widehat{X}$ is a decreasing function of the resource stock whenever $B > B^M$.

[17] When the resource stock is such that $B < B^M$, the rate of replenishment is an increasing function of B, $\frac{dF}{dB} > 0$. Then $\widehat{X}$ (applying the results obtained in the previous footnote) would be an increasing function of B, $\frac{d\widehat{X}}{dB} > 0$, if $\frac{dF}{dB} > \frac{\partial W}{\partial B}$. Similarly, $\widehat{X}$ is a decreasing function of B, $\frac{d\widehat{X}}{dB} < 0$ if $\frac{dF}{dB} < \frac{\partial W}{\partial B}$.

everybody behaves as a conservationist, that is, where the non-environmentally friendly input level is equal to $X(1, B) = nx_c(B)$. The population composition is invariant with respect to B throughout $X(1, B)$. This situation is represented in Fig. 1c.

When the volume of non-environmentally friendly inputs $X(1, B)$, used by the community intersects the equilibrium function, $\widehat{X}(B)$, we obtain the corresponding equilibrium points of the resource stock dynamic represented by equation 1. Then the level of non-environmentally friendly inputs used by the community , $X(1, B)$, is such that the rate of extraction is equal to the rate of natural renewal. Points C and c in Fig. 1c are equilibrium points in this situation; the proportion of conservationist farmers is $s_c = 1$ and the corresponding equilibrium levels of the resource stock are labeled as $\widehat{B}(1)$ and $\widetilde{B}(1)$, respectively.[18]

The argument could be repeated for the case in which all agents were non conservationists $X(0, B) = nx_{nc}(B)$.[19] Also we suppose that there is $s_c = s_c^E \in (0, 1)$, so that $X(1, B) < X(s_c^E, B) < X(0, B)$ for every level of B and where $X(s_c^E, B)$ is tangent to $\widehat{X}(B)$ at B^E, that is $s_c^E \in (0, 1)$ such that $X(s_c^E, B^E) = \widehat{X}(B^E)$, see Fig.1c where point E is a semistable equilibrium point of the resource dynamics. For $s_c < s_c^E$ the resource B would be brought to extinction and for $s_c > s_c^E \in (0, 1)$, there could exist s_c^0 so that $X(1, B) < X(s_c^0, B) < X(0, B)$ for every level of B. Therefore, $X(s_c^0, B)$ intersects $\widehat{X}(B)$ at a stock level between $\widetilde{B}(s_c^E)$ and $\widetilde{B}(1)$ and also at a stock level between $\widehat{B}(s_c^E)$ and $\widehat{B}(1)$. That is, for each level of social capital s_c^0 we have two resource stock equilibria $\widehat{B}(s_c^0)$ and $\widetilde{B}(s_c^0)$; corresponding to the equilibrium points M and m, in Fig. 1c, respectively.[20] Not all intersection points determine stable equilibria,

[18] We asume that $X(B)$ is an increasing function of B. The conditions for the stability of an equilibrium are presented later in Lemma 1. They would also be satisfied if $X(B)$ is a decreasing or constant, function of B.

[19] In this case there woulld also be two equilibrium points, one stable and another unstable with stock levels $\hat{B}(0)$ and $\widetilde{B}(0)$, respectively.

[20] These would be isolated points except for the case that $X(s_c^0, B)$ and $\widehat{X}(B)$ have the same shape for some range of B.

however, as Lemma 1 shows.

Lemma 1 *An equilibrium point* (s_c^*, B^*) *such that* $s_c^* > s_c^E \in (0,1)$ *of the resource stock dynamics is asymptotically locally stable (unstable) if* $\frac{\partial X(s_c^*,B^*)}{\partial B} > \frac{d\widehat{X}(B^*)}{dB}$ $\left(\frac{\partial X(s_c^*,B^*)}{\partial B} < \frac{d\widehat{X}(B^*)}{dB}\right)$. *An equilibrium point such as* (s_c^*, B^*) *where* $\widehat{B}(sc^E) = \widetilde{B}(sc^E) = B^E$ *is an undetermined equilibrium point of the natural resource stock. Finally, if* $s_c^* < s_c^E \in (0,1)$ *the unique asymptotically locally stable equilibrium point is* $B = 0$.

Points C, and M in Fig. 1c represent stable equilibria, while the unstable equilibria are represented with lower case letters. From this figure we can see the differences between them. For a stable equilibrium point such as M, if $B > \widehat{B}(s_c^0)$ then $X(s_c^0, B) > \widehat{X}(B)$ and $\dot{B} < 0$, the resource stock decreases towards the equilibrium level, $\widehat{B}(s_c^0)$. Similarly, if $B < \widehat{B}(s_c^0)$ then $X(s_c^0, B) < \widehat{X}(B)$ and $\dot{B} > 0$, the resource stock increases towards equilibrium.[21] However, this is not the case if we consider an unstable equilibrium such as m; if $B > \widetilde{B}(s_c^0)$, then $X(s_c^0, B) < \widehat{X}(B)$ and $\dot{B} > 0$, the resource stock diverges away from $\widetilde{B}(s_c^0)$ and a similar situation occurs for $B < \widetilde{B}(s_c^0)$. We also represent these equilibria in the phase diagram of Fig. 1d, where $\widehat{B}(s_c)$ and $\widetilde{B}(s_c)$ describe the relation between the stock of the resource and the composition of population in the stable equilibria and the unstable equilibria, respectively. Lemma 2 describes these relations:

Lemma 2 $\widehat{B}(s_c)$ $(\widetilde{B}(s_c))$ *is an increasing (decreasing) function of* s_c.

[21] Note that, depending on the relative position of $B_{\min}$ other equilibrium cases are possible, for all these cases the conditions for stable equilibrium stated in Lemma 1 would continue to hold. Fig. 2 illustrates some possible resource dynamics

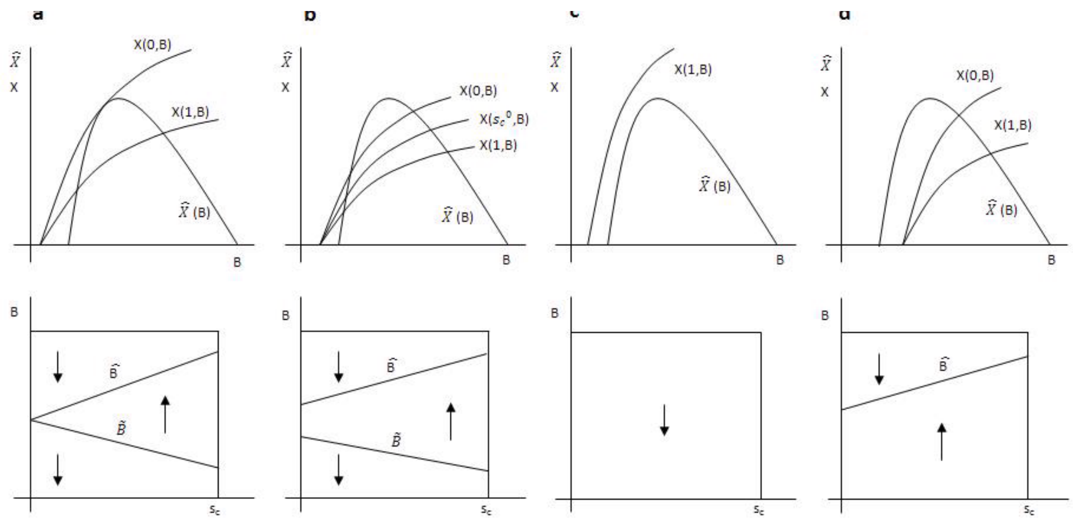

Fig 2. Other natural resource dynamics

2.3 Farmers Behavior

We present a model of agricultural management, where a set of N producers belongs to a farming community whose agricultural land, L_Z hectares, has been included in some resource preservation program. We assume that each farmer owns an hectare. Therefore, the extension of area L_z and the number of farmers N are given and fixed.[22] We assume that the environmental agency has established a convention about the appropriated farming practices. Non-environmentally friendly farming practices such as, the improper use of fertilizers, pesticides and phytosanitary products or the high frequency of irrigation, can damage natural resources, and in particular, the habitat of steppe birds. Establishing appropriated farming practices usually imply to set limits on the maximum levels of non-environmentally friendly inputs that can be used per unit of farmland, we represent this limit by $\overline{x}$.[23] Once the envi-

[22] We assume that the land area owned by each farmer are fixed and equal for all them.

[23] Under the Birds Directive each Member States has the duty to safeguard the habitats of threatened birds on their national territory. The types of limitations imposed in each protected area are specific, however,

ronmental agency has established a convention about the appropriate farming practices, any farmer can be classified as conservationist or non-conservationist, depending on whether the amount of non-environmentally friendly inputs used is below or above the standard set by the environmental office, $\overline{x}$. The harvest function $H(x_i, B)$, is a twice-continuously differentiable function that depends on x_i, and on B. We assume that the harvest function is increasing and concave respect to x_i, $\frac{\partial H}{\partial x_i} > 0$, and $\frac{\partial^2 H}{\partial x_i^2} \leq 0$.[24] Each farmer $i \in N$ chooses its own level of non-environmentally friendly inputs used, we refer to agents choosing an amount $x_c \leq \overline{x}$ as conservationist and to agents that choose a level $x_{nc} > \overline{x}$ as non-conservationist. We assume that the production function is the same for both types of farmers and that the only difference is the degree of non-environmentally friendly inputs used. Therefore agent choose between two input levels $\{x_c, x_{nc}\}$ where $x_c < x_{nc}$.

Moreover, we consider that the harvest function is a decreasing function of the bird population B, $\frac{\partial H}{\partial B} < 0$. We further assume that the use of x_i can, to some extent, counterbalance the reduction on the harvest caused by the population of birds B.[25] Farmers benefit from a local effect of the use of non-environmentally friendly inputs, birds are less comfortable in the areas with a higher use of pesticides or less fallow surface. Accordingly, for a given stock B the larger the amount of x_i used by farmer i, the larger the harvest, and therefore $H(x_{nc}, B) > H(x_c, B)$.

in general they require to limit the farmers exploitation level, for exemple through limitations in the use of irrigation and/or limitations in the use of some chemical treatments in fallow areas or on margins, such as has happened in Segarra-Garrigues Natura 2000 areas. We assume that, each member state, through its corresponding environmental office, determines the farming practices that can be carried out in each area, and determines the maximum exploitation level authorized.

[24] Several types of non-environmentally friendly inputs could be used during the production process, some more damaging than the others. We do not distinguish among different types of non-environmentally friendly inputs and we summarize their effects in one variable. A part from that, it could be argued that these inputs could be substituted by environmentally friendly inputs, but we assume that the optimal combination of both types of intputs have been already determined during the maximization process and that at this point there are no apropriate substitutes left for these non-environmentally friendly inputs represented by x_i.

[25] We follow a production function similar to Noailly, 2008 and we assume that B is a negative externality that afects farmers' crops.

Also, the larger the amount of pesticides and chemical products used by farmer i, the smaller (in absolute value) the reduction in the harvest caused by an increase in B in its parcel of land, $\left|\frac{\partial H(x_{nc},B)}{\partial B}\right| < \left|\frac{\partial H(x_c,B)}{\partial B}\right|$.[26] When B increases, non-environmentally friendly inputs, x_i, become more valuable. The marginal product of the non-environmentally friendly inputs $\frac{\partial H}{\partial x_i}$ increases with increases in B. Thus it is reasonable to assume that both $x_c(B)$ and $x_{nc}(B)$ are increasing functions of B and that $\frac{\partial(x_{nc}-x_c)}{\partial B} > 0$. Given these assumptions $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} > 0$.[27] Additionally, the use of x_i by farmer i causes a long run effect when reducing the population of birds, this effect on B is captured by the wipe out function.

Moreover, we assume that the population of birds is evenly distributed over the whole area and that they can migrate from one parcel to another, therefore we consider that the aggregated population of birds, B, affect all farmers in the same way. In our case B is, from farmers point of view, a bad that is non-rival. We model B as a non-rival negative externality because the benefits associated with reduction on the stock of B is enjoyed by all farmers.[28]

[26] For a given level of B the larger is x_i the larger the harvest $H(x_i,B)$, the smaller the reduction on $H(x_i,B)$ due to the increase in B, and also then as x_i increases the reduction on $H(x_i,B)$ due to the increase in B decreases in absolute value, $\frac{\partial^2 H}{\partial x_i \partial B} \geq 0$. As an example Lapiedra *et al.,* 2011 highlights the crops as a source of food for protected species.

[27] If we analyze the expression: $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} = \left[p\left(\frac{\partial H(x_{nc},B)}{\partial x_{nc}}\frac{\partial x_{nc}}{\partial B} + \frac{\partial H(x_{nc},B)}{\partial B}\right) - c\frac{\partial x_{nc}}{\partial B}\right] - \left[p\left(\frac{\partial H(x_c,B)}{\partial x_c}\frac{\partial x_c}{\partial B} + \frac{\partial H(x_c,B)}{\partial B}\right) - c\frac{\partial x_c}{\partial B}\right] = \left(\left(p\frac{\partial H(x_{nc},B)}{\partial x_{nc}} - c\right)\frac{\partial x_{nc}}{\partial B}\right) - \left(\left(p\frac{\partial H(x_n,B)}{\partial x_c} - c\right)\frac{\partial x_c}{\partial B}\right) + p\left(\frac{\partial H(x_{nc},B)}{\partial B} - \frac{\partial H(x_c,B)}{\partial B}\right)$.

We have assumed that $\left|\frac{\partial H(x_{nc},B)}{\partial B}\right| < \left|\frac{\partial H(x_c,B)}{\partial B}\right|$, the reduction of $H(x_i,B)$ due to an increase in B is smaller the larger the amount of pesticides and chemical products used, and therefore $p\left(\frac{\partial H(x_{nc},B)}{\partial B} - \frac{\partial H(x_c,B)}{\partial B}\right) > 0$. Additionally, we have assumed that farmers are profit maximizing agents, and therefore for non-conservationist farmers $p\frac{\partial H(x_{nc},B)}{\partial x_{nc}} - c = 0$. Conservationist farmers are also profit maximizers, however they face a constrain, $x_{nc} \leq \overline{x}$ therefore either $p\frac{\partial H(x_c,B)}{\partial x_c} - c = 0$ or they are in a corner solution, $x_c = \overline{x}$ and then $\frac{\partial x_c}{\partial B} = \frac{\partial \overline{x}}{\partial B} = 0$.Then $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} > 0$.

[28] Most papers in this tradition such as Oses-Eraso and Viladrich-Grau, 2007 and Blanco *et al.,* 2009 consider the natural resource as a common resource pool.

Other papers have represented a positive relationship between nature and private goods,[29] but we choose to represent a negative externality, some studies have highlighted the negative externalities that can cause some protected species to crops when they are recovered.[30]

Furthermore, and as we have said before farmers are subject to the pressures of global markets. Most agricultural products are traded in highly competitive markets therefore farmers will be taking the output price as given. This is true for most agricultural product from cereals to vegetables and from legumes to fruit.[31] Therefore, we are going to assume that both, conservationist and non-conservationist farmers produce the same output, and that the crop market is competitive and therefore price is taken as given by both types of farmers.

Each farmer $i \in N$ selects a set of harvesting practices x_i that maximizes individual profits, $\pi_i(x_i, B) = pH(x_i, B) - cx_i$ where x_i represents the quantity of non-environmentally friendly inputs used by farmer i, c represents the opportunity cost of these inputs, and p the harvest market price. Non-conservationist agents will choose the strategy that yields higher returns then non-conservationist farmers will choose the static Nash solution, $x_{nc} = x_N$.[32] Also, in our model, conservationist are also adaptive agents, who follow the strategy that yields the maximum level of profits without violating the extraction standards $\overline{x}$, this level is strictly smaller than x_{nc}, and therefore of x_N.[33] As $\pi_i(x_i, B)$ increase with x_i conservationist will choose the static solution, $x_c = \overline{x}$.Then the profit of non-conservationist farmers will be at

[29] Other papers have considered that the protection of a natural resource generates a positive externality to the agents, see Blanco *et al.*, 2009.

[30] Rollins and Briggs, 1996 analize compensation for crop damages from geese in Wisconsin (USA). They take the natural resource as a public good. Also Deinet *et al.,* 2013 report the negative externalities that can cause to crops some protected species when they are recoverd.

[31] The only remarcable excepction are products with some type of distintive label, ecolabel or local label. In such cases product price could be under the control of the farmers of the single out area.

[32] If the set of initial strategies includes the static Nash solution, x_N.

[33] The results of our model would work with any two effort levels, as long as, $x_c < x_{nc} \leq x_N$ and harvest rents are positive.

least equal to the profits of conservationist farmers $\pi_{nc} > \pi_c$.

Furthermore, note that there could be a level of stock above which farm production is not worthwhile, $B_{\max}$. For $B \geq B_{\max}$ the stock of birds is so large that farm production is not profitable, $\pi_i \leq 0$, for any x_i. For $B \geq B_{\max}$ there are no farming practices that can counterbalance the effect of B and allow for a positive profit. For $B \geq B_{\max}$ farmer profits are negative and therefore $x_c = x_{nc} = 0$.[34] We do not consider this case. We assume that $B < B_{\max}$ and farmers can obtain positive profits for positive levels of non-environmentall friendly inputs. Moreover, we assume for each B such that $B < B_{\max}$ there exist a minimum amount of non-environmentally friendly input, $x_{\min}(B)$, that allows for a positive profit.[35] We assume that the agreed upon standard, $\overline{x}$, allows for positive profits. Conservationist farmer will choose to apply a level of inputs that complies with the agreed conservation standard $x_{\min} \leq x_c \leq \overline{x}$, and non-conservationist farmers will choose a level $x_{nc} \leq x_N$, where x_N is the static Nash equilibrium level of input use. The individual level of input used will satisfy that $x_{\min} \leq x_c \leq \overline{x} \leq x_{nc} \leq x_N$.

Given a farming community with N farmers, the use of non-environmentally friendly inputs is $X(s_c, B) \equiv n\left[s_c x_c(B) + (1 - s_c)x_{nc}(B)\right]$, where s_c is the proportion of conservationists farmers. The total level of non-environmentally friendly inputs is a positive, continuous and decreasing function of s_c.[36] The level of non-environmentally friendly inputs used by the N farmers in area L_z is also a increasing function of bird stock level B for any $B < B_{\max}$.

[34] This would be an extrem case, where a population of birds have become a plague.

[35] This minimum amount could be zero.

[36] If the amount of non-environmentally friendly inputs used are positive, then $\frac{\partial X}{\partial s_c} = n\,(x_c - x_{nc}) < 0$. Also, as n is finite, s_c can take discrete values in some cases; we abstract from this and assume that s_c is non-negative and continuous.

2.4 The Replicator Dynamic

We assume that farmers select a level of inputs x_i and respond to differences in payoff by modifying their choices. In order to prevent sudden changes in behavior patterns, we will adopt the assumption that the composition of the population shifts gradually towards the group whose payoff is above the average. We incorporate these ideas by assuming the evolution of the composition of the population is described by the replicator dynamics: $\dot{s}_c = s_c\,(u_c - \bar{u})$. Because the average payoff is $\bar{u} = s_c u_c + (1 - s_c)\,u_{nc}$, this differential equation can be rewritten as:

$$\dot{s}_c = s_c\,(1 - s_c)\,(u_c - u_{nc}) = -s_c\,(1 - s_c)\,(u_{nc} - u_c) \tag{2}$$

The replicator dynamic represents the behavior of adaptive farmers. Farmers alter their strategies to imitate their more successful fellow-farmers. In this dynamic system the change in the proportion of conservationist is a gradual process. Moreover, as $0 < s_c < 1$ we can see that the change in behavior depends on the difference between the payoff obtained by a conservationist and that obtained by a non-conservationist. If $u_c > u_{nc}$ the proportion of conservationists will increase, and if $u_c < u_{nc}$ it will decrease. The frequency of a strategy increases when it has above average payoff. The payoff differential among farmers exerts pressure on the composition of the population: the greater the difference in payoff, the more likely the agent is to perceive it and then to change strategy. We will attain an equilibrium in the farmers dynamic when the proportion of conservationist farmers remains constant over time, that is $\dot{s}_c = 0$. From equation 2 we can see that there are three cases where $\dot{s}_c = 0$: i) when everybody is conservationist, $s_c = 1$; ii) when everybody is non conservationist, $s_c = 0$;

and iii) when the payoff level of conservationists equals that of non-conservationists, that is $(u_{nc} - u_c) = 0$.

This type of specification allows us to analyze the out-of-equilibrium dynamics, identifying some equilibria that turn out to be irrelevant once the evolutionary process is taken into account, and vice-versa some out-of-equilibria situation that are very relevant for the sustainability of the natural resource. Even thought the replicator dynamics does not force a Nash equilibrium in every time period. It can be shown, however, that, given an evolutionary game that satisfies the replicator dynamics, an asymptotically stable equilibrium of the replicator dynamics is a Nash equilibrium of the game.[37]

Therefore, we are interested in the steady states of the dynamic system given by equations 1 and 2. An equilibrium of the systems is a pair (s_c^*, B^*) such that $\dot{B} = 0$ and $\dot{s_c} = 0$.

3 The equilibrium conditions of farmer's behavior

Now we move on to analyze the evolution of the farmers behavior. Farmers face a cost in taking actions intended to protect biodiversity, therefore to encourage conservationist behavior, environmental agencies have introduced incentive schemes. EU has introduced a range of schemes that focus mainly on rewarding those farmers that contribute to the public good rather than punishing those that behave as non-conservationist. Introducing some type of incentive is necessary. To see this, recall that we have assumed that non-conservationist farmers will choose to use the volume of non-environmentally friendly inputs, x_{nc}, that maximize profits and that conservationist will follow the strategy that yields the maximum level of profits

[37]See p. 201 of Gintis (2000).

without violating the standards settled by the environmental agency, $x_{nc} \leq \overline{x}$. Then, for any given B, the profit of a non-conservationist farmer will be larger (or at least equal) to the profits of a conservationist farmer. That is $pH(x_{nc}, B) - cx_{nc} \geq pH(x_c, B) - cx_c$ and hence $u_{nc} \geq u_c$ for all B.[38] Note that the profit function is an independent function of s_c and therefore this inequality held for any $s_c \in (0, 1)$. All farmers will end up being non-conservationists $(s_c, B) = (0, B)$ and the sustainable management of natural resources will be compromised. This equilibrium would be stable, because by the replicator dynamics, as $u_{nc} \geq u_c$ for all $s_c \in (0, 1)$, any conservationist farmer will alter his strategies to imitate the more successful farmers, and all farmers will end up being non-conservationist. On the other side, an allocation where all farmers behave as a conservationists $(s_c, B) = (1, B)$ would be an equilibrium but unstable. Furthermore, an heterogeneous equilibrium could never exist, except in the trivial case that $x_{nc} = x_c$.

Claim: If the payoff function for any agent i is $u_i = \pi_i = pH(x_i, B) - cx_i$ then the only stable equilibrium is the full non-conservationists equilibrium $(s_c, B) = (0, B)$. A full conservationists equilibrium could exist but will not be stable $(s_c, B) = (1, B)$. An heterogeneous equilibrium could never exist except in the case that $x_{nc} = x_c$.

In the next subsections we are going to incorporate the above mentioned economic incentives to the profit function and we are going to analyze the stability conditions of the farmer dynamics.

[38] Only in the case of $x_{nc} = x_c$ can be that $u_{nc} = u_c$. But we have assumed that always $x_{nc} > x_c$.

3.1 Farmer behavior under payment schemes

We model the payoff function of a representative farmer as:

$$u_i(x_i, B) = \pi_i(x_i, B) + \phi_i(s_c) = pH(x_i, B) - cx_i + \phi_i(s_c) \tag{3}$$

where farmers receive a per hectare payment of $\phi_c(s_c)$ if they participate in the conservation program. We further assume that the agency faces a binding budget constrain. In such a case the agency will only allocate a finite amount of money to each conservation project. We analyze two different types of payment schemes. First, a uniform subsidy per hectare, ϕ_i, where any farmer who meets the biodiversity conservation requirements set by the regulator receives a constant payment per hectare, *i.e.* $\frac{\partial \phi_i(,s_c)}{\partial s_c} = 0$. And second, a fixed subsidy for project where the amount assigned to a conservation project will be fixed and then the individual subsidy received by each farmer decrease as the number of conservationist farmers increases, thus, $\frac{\partial \phi_i(s_c)}{\partial s_c} < 0$. The amount of the subsidy depends on the proportion of conservationist among farmers, in this case the subsidy that a farmer receives depends on what fellow farmers do. The larger s_c the smaller the individual subsidy received by each conservationist farmer $\phi_c(s_c)$, and therefore the smaller u_c.[39]

Often the growth of natural resource depends on the number of farmers that participate in a conservation program, the larger the number of participating farmers, the larger the chances that the preservation goals are fulfilled. Furthermore, in most cases a minimum level of farmers' participation is needed to assure the success of the conservation program.[40]

[39] We could have assumed that non-conservationist farmers could also received a payment ϕ_{nc} such that $\phi_c > \phi_{nc}$ but we assume, from now on, without loss of generality that $\phi_{nc} = 0$.

[40] See Le Cloent *et al.,* 2015

Note that the individual subsidy could have increased, decreased or remained constant with the proportion of conservationists, $\frac{\partial \phi_i(s_c)}{\partial s_c} \lesseqgtr 0$. Even though the increasing assumption is appealing because introduces an incentive for farmers to enrol in conservationist practices, it is not realistic in the sense that it could be difficult to implement by agencies that faces budgetary constrains. On the other side, if the agency had an unbound budget a large enough individual subsidy could be paid to convince all non-conservationist farmers to behave as conservationist. We do not consider this case in this paper.[41] Problems arise when agencies face binding budget constraints.

Recall that if there were no subsidies it would be always the case that $\pi_{nc}(x_c, B) > \pi_c(x_c, B)$. Let us define $B_{far}(s_c^Q)$ as the level of resource stock B such that given a proportion of conservationists farmers s_c^Q, s.t. $1 > s_c^Q > 0$ satisfies $(\pi_{nc} - \pi_c)(B) = \phi_c(s_c^Q)$. If $B = B_{far}(s_c^Q)$, then $(\pi_{nc} - \pi_c)(B_{far}(s_c^Q)) - \phi_c(s_c^Q) = 0$ and $(B_{far}(s_c^Q), s_c^Q)$ defines an heterogeneous equilibrium point of the farmers dynamics.

Lemma 3: If for a given $s_c^* \in (0,1)$ there is B^* such that $B^* = B_{far}(s_c^*)$, then (B^*, s_c^*) is an asymptotically locally stable equilibrium point of the farmers dynamics if $\frac{\partial \phi_c(s_c^*)}{\partial s_c} < 0$. Furthermore, if $\frac{\partial \phi_c(s_c)}{\partial s_c} = 0$ and there is a B^* such that the equilibrium condition $(\pi_{nc} - \pi_c)(B^*) = \phi_c(s_c)$ holds, then it holds for all s_c and (B^*, s_c) defines a continuum of equilibrium points (B^*, s_c) where B^* is constant and does not depend on s_c, that is $\frac{dB_{far}}{ds_c} = 0$. Then the farmers dynamics does not have an isolated equilibrium point but a continuum of equilibrium points.[42]

[41] We worked out the equilibrium condition under this hypotesys $\frac{\partial \phi_i(s_c)}{\partial s_c} > 0$. See in Lemma 3 the results obtained. Summaring, if there is no budget contrain large enough subsidies will let all farmers to behave as conservationist.

[42] Note that if for a given $s_c^* \in (0,1)$ there were B^* such that $B^* = B_{far}(s_c^*)$, then (B^*, s_c^*) is an asymptotically locally unstable equilibrium point of the farmers dynamics if $\frac{\partial \phi_c(s_c^*)}{\partial s_c} > 0$. As we said above we do not consider this case in this paper. It is not realistic in the sense could be difficult to implement by an agency that faces a fixed budget. In any case we present the proof of the corresponding equilibria if the agency could have an unbound budget such that ia allowed $\frac{\partial \phi_c(s_c^*)}{\partial s_c} > 0$. As it can be seen from our proofs in this case the full

For the two types of subsidies schemes to have the same total budget, P, it has to hold that $\phi(s_c)s_c = \phi s_c = P$ for $s_c = 1$.[43] That is for any change on s_c then $\phi(s_c)s_c \leq P$. For this to be true it is necessary that $\frac{\partial \phi_c}{\partial s_c}\frac{s_c}{\phi_c} \leq -1$.[44] Further, note that if it is the case where $\phi(s_c)s_c = P$ for all s_c then the proportion of conservationists elasticity of ϕ_c must be unitary, that is $\left|\varepsilon_{\phi_c}\right| = 1$.

The relation between the resource stock and the proportion of conservationist farmers in equilibrium is described in Lemma 4.

Lemma 4 The set of stable equilibrium points $\widehat{B}_{far}(s_c)$ of the farmers dynamics is a decreasing function of s_c. Whenever $\frac{\partial \phi_c(s_c)}{\partial s_c} = 0$ the continuum of equilibrium points (B^*, s_c) is a constant function of s_c.

We represent by $\widehat{B}_{far}(s_c)$ as the set of stable equilibria $(B_{far}(s_c^*), s_c^*)$ of the farmers dynamics, it is depicted in the phase diagrams of Figure 3. Moreover, for an easier summary of our results , we represent the farmers' dynamic continuum of equilibria (B^*, s_c) also as $\widehat{B}_{far}(s_c)$.

Recall that at any B, $\frac{\partial(\pi_{nc}-\pi_c)(B)}{\partial B} > 0$ and $\frac{\partial \phi_i(s_c)}{\partial B} = 0$. Then at an equilibrium $(B_{far}(s_c^*), s_c^*)$, the difference in profits $(\pi_{nc}-\pi_c)$ is more responsive to changes in B than the payment scheme ϕ_c, that is $\frac{\partial(\pi_{nc}-\pi_c)(B)}{\partial B} > \frac{\partial \phi_i(s_c)}{\partial B}$ then an increase on B will make the non-conservationists strategy more attractive to farmers and $\widehat{B}_{far}(s_c)$ will be a decreasing function of s_c.[45] If additionally $\frac{\partial \phi_i(s_c)}{\partial s_c} = 0$ then $\widehat{B}_{far}(s_c)$ is a constant function of s_c.[46]

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conservationist equilibria is an stable equilibria of the farmers dynamics.

[43] A situation where all farmers receives the individual constant subsidy defines a situation where the total budget is full allocated.

[44] Note that $\frac{\partial \phi(s_c)}{\partial s_c} = \frac{\partial \phi_c}{\partial s_c}s_c + \phi = \frac{\partial \phi_c}{\partial s_c}\frac{s_c}{\phi_c} + 1 \leq 0$. That is $\frac{\partial \phi_c}{s_c}\frac{s_c}{\phi_c} \leq -1$.

[45] Decreasing $\widehat{B}_{far}(s_c)$ examples are represented in the pair of Figures (3a and 3b). Increasing $\widetilde{B}_{far}(s_c)$ examples are represented in the pair of Figures (3e and 3f).

[46] These cases are represented in the pair (3c and 3d)

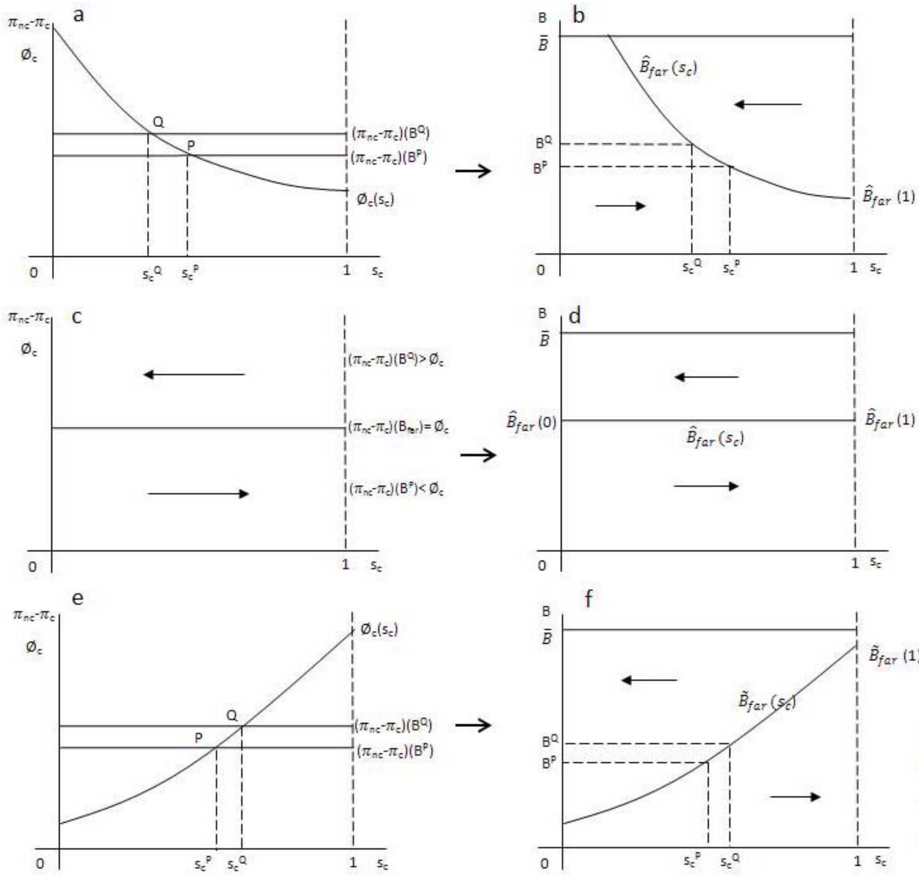

Fig 3. Farmers dynamics
*Q and P= Equilibrium points of the farmers dynamics, that is when $(\pi_{nc}-\pi_c)$=Ø$_c$
*$\hat{B}_{far}$ (s_c)= Stable equilibrium points of the farmers dynamics
*$\tilde{B}_{far}$ (s_c)= Unstable equilibrium points of the farmers dynamics

4 Are natural resources sustainable?: The full system

The sustainability of a natural resource requires that a given resource stock would remain constant in the long run, that is, it requires that the system sets in a stable equilibrium point of the resource dynamics. The stable equilibrium point of the resource dynamics depends, on our motivation example on farmers behavior, the sustainability of steppe bird depends on the farmers' agricultural practices. The long run equilibrium of the population of birds will require an appropriated proportion of farmers to follow conservationist practices. In the next propositions and corollaries, we identify the characteristics of the long run invariant combinations of (B, s_c) or equilibrium points of the combined system.

Proposition 1. Whenever $\widehat{B}_{far}(s_c)$ intersects $\widehat{B}(s_c)$ or $\widetilde{B}(s_c)$ for a positive proportion of conservationist farmers s_c^*, $0 < s_c^* < 1$ there exist an heterogeneous equilibrium of the combined system $(B^*(s_c^*), s_c^*)$. This heterogenous equilibrium point is an asymptotically locally stable equilibrium of the combined system if it is an asymptotically stable equilibrium of the birds dynamics $\widehat{B}(s_c)$.

We have represented this asymptotically stable equilibrium of the joint dynamics as M in the phase diagrams depicted in Figure 4 which results from superposing the phase diagrams of the resource dynamics depicted in Figure 1d and of the farmers dynamics depicted in Figures, 3b and 3d.

Corollary P1.1 Contrary, if $(B^*(s_c^*), s_c^*)$ for s_c^*, $0 < s_c^* < 1$ is an unstable equilibrium of the resource dynamics, then it can be either an unstable or an undetermined heterogeneous equilibrium point of the combined system. See point m in the phase diagrams depicted in Appendix 2.[47]

Proposition 2. An all-conservationists equilibrium $(\widehat{B}(1), 1)$ is asymptotically locally stable (unstable) whether $\widehat{B}(1) < B_{far}(1)$ $\left(\widehat{B}(1) > B_{far}(1)\right)$.[48] In addition, an all-conservationist equilibrium $(\widetilde{B}(1), 1)$ is always unstable.

Further, if the resource stock reaches a point B such that $B < \widetilde{B}(1)$ for a given s_c the resource will be always let to exhaustion. See areas I in Figure 4. Therefore, a sufficient condition for resource exhaustion is that $B < \widetilde{B}(1)$.

[47]The phase diagrams on Appendix 2 results from superposing the phase diagrams of the resource dynamics depicted in Figure 1d and of the farmers dynamics depicted in Figure 3f.

[48]If $\frac{\partial \phi_i(s_c)}{\partial s_c} > 0$ an heterogeneous equilibrium point such as M does not exist, and point C is the unique stable equilibrium point assuring the conservation of the natural resource. See in Appendix 2 Figure 1b and 1c.

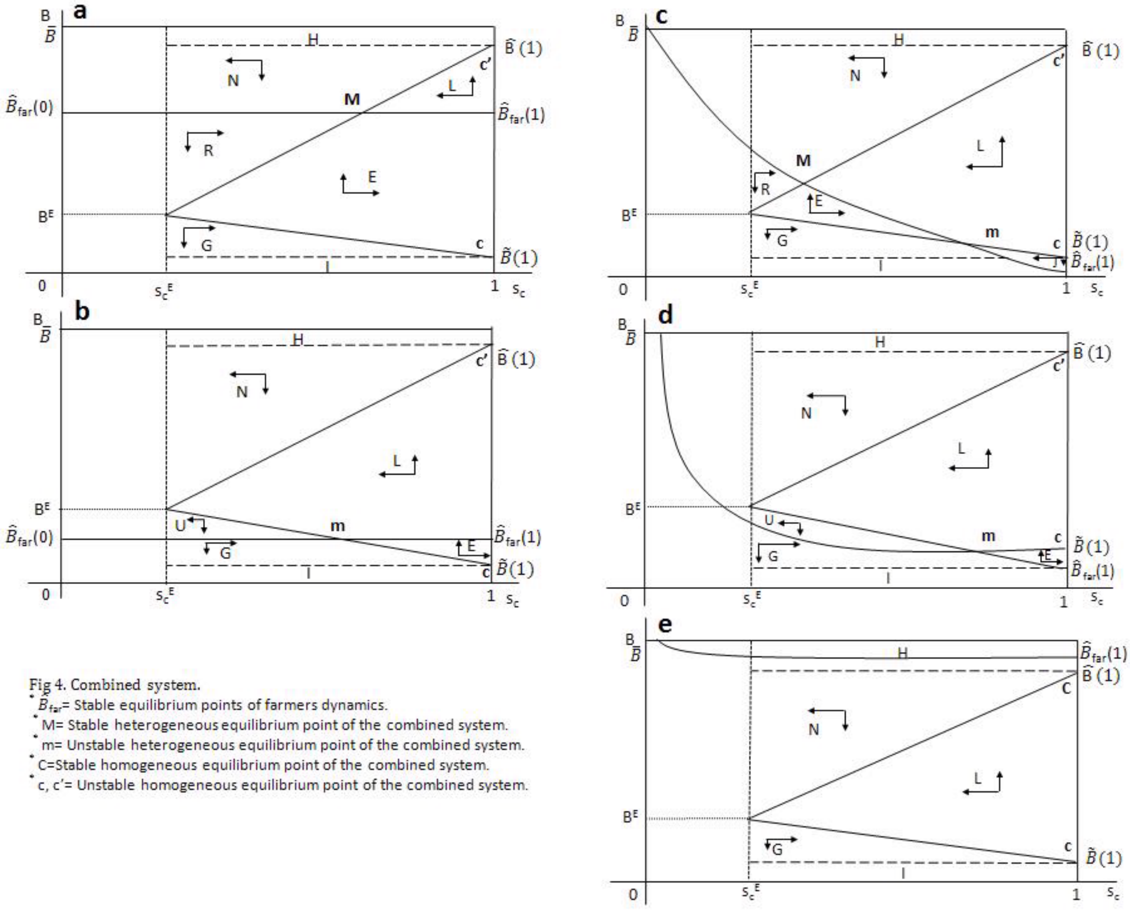

Fig 4. Combined system.
* $\hat{B}_{far}$= Stable equilibrium points of farmers dynamics.
* M= Stable heterogeneous equilibrium point of the combined system.
* m= Unstable heterogeneous equilibrium point of the combined system.
* C=Stable homogeneous equilibrium point of the combined system.
* c, c'= Unstable homogeneous equilibrium point of the combined system.

4.1 Characteristic of the equilibriums

In Figures 4a and 4b we represent the combined system of birds stock and farmers behavior dynamics when ϕ_c is a constant subsidy per hectare. In Figure 4a point M represents a stable heterogeneous equilibrium point of the combined system. By proposition 1, there is only a level of s_c that enables the stock of birds $\widehat{B}(s_c)$ to remain stable at the level $\widehat{B}(s_c) = \widehat{B}_{far}(s_c)$. If this proportion of conservationist is s_c^* the stock of birds $\widehat{B}(s_c^*)$ would remain stable at the level $\widehat{B}(s_c^*) = \widehat{B}_{far}(s_c^*)$. Thus the resource level that allows the rate of extraction to equate the rate of renewal. This equality will define a point (B^*, s_c^*) such that $\widehat{B}_{far}(s_c^*) = \widehat{B}(s_c^*) = B^*$.

Also to attain the stable heterogeneous equilibrium of the combined dynamics represented by point M it is at least required that the equilibrium stock level of the farmers dynamics $B_{far}(s_c)$ is such that $B_{far}(s_c) > B^E$. The individual subsidy has to be large enough to guarantee that the resource stock $B_{far}(s_c) > B^E$. On the other side, point m in Figure 4b, is an unstable equilibrium of the combined system. The subsidy is not large enough to assure $B_{far}(s_c) > B^E$ and then $\hat{B}_{far}(s_c)$ intersect $\tilde{B}(s_c)$ but not $\widehat{B}(s_c)$.[49]

In addition, in Figures 4c, 4d and 4e we represent the combined system of birds stock and farmers behavior dynamics where $\phi_c(s_c)$ is a decreasing function of s_c, that is $\frac{\partial \phi_i(s_c)}{\partial s_c} < 0$. By Lemma 4 $\hat{B}_{far}$, the set of stable equilibria of the farmers dynamics, is a decreasing function of s_c. In Figure 4c we show the phase diagram of this combined system where a stable heterogeneous equilibrium point such as (B^*, s_c^*) where $\widehat{B}_{far}(s_c^*) = \widehat{B}(s_c^*) = B^*$ is represented by point M. Note graphically that, as it happen with fixed subsidies, if $B < B^E$ the natural resource will be probably driven to extinction (areas G, J, U and I) except if areas E or L are reached, in these areas the combined system can lead to the point M. The higher the individual incentive the higher the likelihood to reach areas where the resource could be recovered, because is much more profitable for farmers to behave as conservationists.

In addition, if for a given $\widehat{B}_{far}$ there is a level of s_c that enables $\widetilde{B}(s_c) = \widehat{B}_{far}(s_c)$ this point is an unstable equilibrium point of the combined system.[50] In Figure 4c and 4d these unstable heterogeneous equilibrium point are represented by point m. Moreover, in Figure 4d all farmers behaving as non-conservationists is the unique stable equilibrium point of the combined system, as happens with a fixed subsidy in Figure 4b. Note that,the likelihood

[49] See claim 3 in appendix 1

[50] Claim 2 in appendix 1

to reach an heterogeneous equilibrium of the joint system increase with the agency budget. Ceteris paribus, $\widehat{B}_{far}(s_c)$ moves upward with A and therefore it is more likely that $\widehat{B}_{far}(s_c)$ intersects $\widehat{B}(s_c)$ instead of $\widetilde{B}(s_c)$. Therefore, the higher is A the higher is the equilibrium point s_c^* and B^*.[51] Finally, in figure 4e the budget is high enough to assure always an stable all-conservationists equilibrium.

The heterogeneous equilibria M can have different characteristics depending on the characteristic of the species to protect. Let us start with the parameters of the natural growth function, $F(B)$, a modification in the natural resource growth rate leads to changes in s_c^E and $\widehat{B}(s_c)$. The higher the intrinsic rate of growth and/or the higher the carrying capacity, the higher the natural resource growth rate, ceteris paribus, the higher is the wipe out rate that would keep the resource population constant over time. Therefore, $\widehat{B}(s_c)$ moves upwards and s_c^E decrease.[52] Then the new equilibrium point has a lower s_c^* and a larger B^* (only when a partnership subsidy scheme is applied, if not B^* is constant). This is represented in Fig. 5 when point M_1 shifts to M_2 and s_{c1}^Eshifts to s_{c2}^E.

The most resilient species, with larger regeneration capacity are those with higher $F(B)$ and then larger $\widehat{B}(s_c)$. It is broadly true that generalist species that adapt easily to habitat changes, are more resilient. On the other side, the most vulnerable species, for example specialists species that have more ecological requirements on their habitat, tend to be less resilient to changes in farming practices (Andres and Seiler, 1997; Smith and Smith, 2001). Note that the higher is s_c^E the stronger would be the needed of the agency to promote the conservationists behavior in initial stages. Therefore with those most vulnerable species could

[51] See Figure 5 when point M_3 shifts to M_2

[52] If the population dynamic, $\widehat{B}_{far}(s_c)$ remains constant.

be more of interest for the agency to give a partnership subsidy than a constant one.

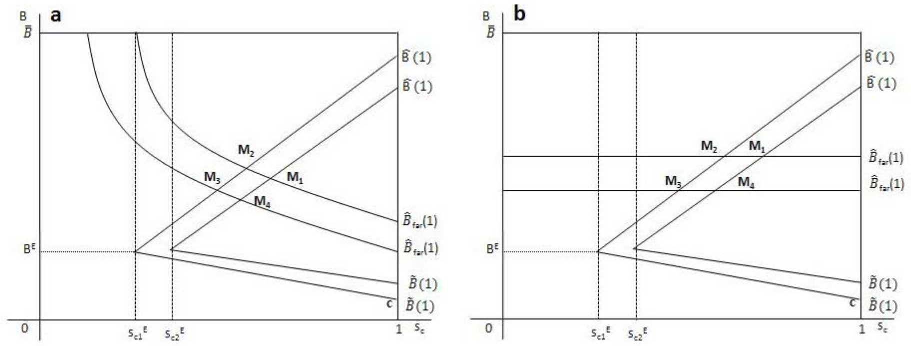

Fig 5. Shifts in the combined system.

5 Simulation example

In this section we analyze the performance of these agri-environmental schemes in an evolutionary framework using explicit functions and providing specific information and data to the model. The specifications used in our example, functional forms and parameter values, are based on the characteristic of a specific Natura 2000 area in the Plain of Lleida in Catalonia affected by the hydrologic investment project, the Segarra-Garrigues channel. The channel allows the irrigation of large areas with a long dryland agricultural tradition. This has generated many conflicts between farmers and the environmental agency due to the transformation of dryland in to irrigation, threatening the survival of a large number of steppe birds (Reguant and Lletjós, 2014). Our motivational example focus on the populations of Little Bustard (*Tetrax tetrax*) into this protected area. This is an steppe and omnivorous specie that lives in fallow areas and dry cereal crops, mainly barley (Bota *et al.* 2004). Little Bustard has been cataloged as endangered in Catalonia (Herrando and Anton, 2013) and its population have been reduced in the last decades due to the process of agriculture intensification (De Juana *et* *al.,* 1993; Brotons *et al.,* 2003).[53][54]

Our aim is to compare the performance of the two types of agri-environmental schemes presented above in a realistic scenario. First, we compare a partnership subsidy (Fig 6a) with an individual subsidy (Fig. 6d) where the budget allocated in the equilibrium is the same in both cases. To compare the performance of these two schemes we have represented the basins of attraction of the heterogeneous equilibrium point M_1 (cloud of points in Figures 6a and 6d). A partnership subsidy presents larger basins of attractions than an individual subsidy.[55]

Observation 1: For the same equilibrium a partnership subsidy presents larger basins of attraction than a constant individual subsidy.

Also note that the main differences between those basins of attraction appear for low values of s_c and B. This observation takes a special relevance in the case of an endangered specie. By definition endangered resource are characterized by initial conditions with low B. In this sense enjoying larger basins of attraction for a given budget in these first stages could be and interesting point for the regulatory agency.

Observation 2: For low levels of natural resource stock B and given the same budget a partnership subsidy scheme is able to protect an endangered natural resource against extinction more effectively than a constant individual scheme.

Furthermore, we have used a parameter ω to adjust the speed at which farmers imitate each other. In this dynamic system behavioral changes are a gradual process, increasing the value ω increases the speed at which adaptive farmers change behavior towards the strategy

[53] The simulations and the graphical representations has been done with Excel v.14.0.7208.5000 and Maxima v.17.10.0 respectivelly.

[54] See Appendix 3 to see the explicit functions and the parameters specification.

[55] See the same differences comparing also point M_1 in Fig 6b and Fig 6e .

that provides a higher reward. If the conservationist strategy offers a higher reward, the larger the value ω the faster the proportion of conservationist will grow. Comparing Figures 6a and 6b (and Figures 6d and 6e) we can note that the larger the speed of adjustment ω, the larger the size of the basins of attractions.

Observation 3: The larger the speed of the farmers adjustment process the larger the size of the basin of attraction.

Additionally, in Figure 6f we represent a direct payment per hectare independent of agent behavior where the total budget allocated to this uniform subsidy is equal to the equilibrium budget of Figures 6a, 6b,6d and 6e. However, in Figure 6f there is no stable heterogeneous equilibrium (neither there is a full-compliers equilibrium). In this case a uniform subsidy is assigned to all farmers despite of their behavior, on the contrary in Figures 6a, 6b,6d and 6e, agents only receive a subsidy if the behave as a conservationist. For a given budget, uniform subsidies that are independent of agents behavior are less useful in protecting natural resources than subsidies that are conditional on agents behavior.

Observation 4: Given the same budget, subsidies that are conditional on agents behavior are more useful protecting natural resources than subsidies that are independent of agent behavior.

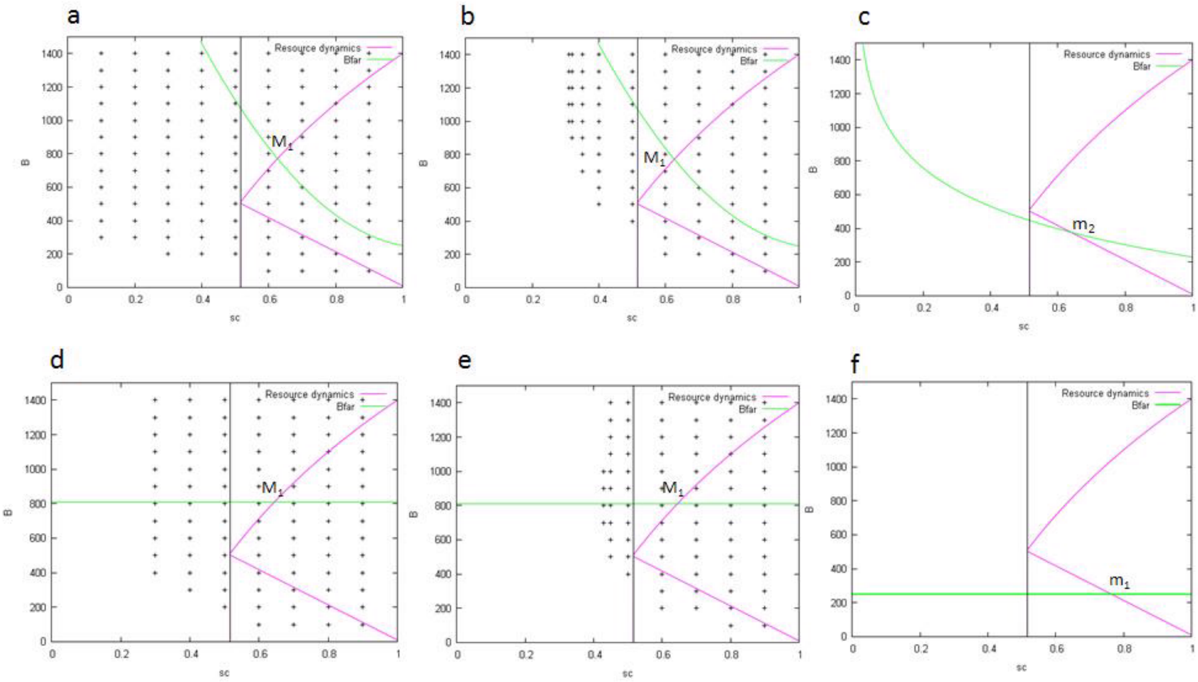

Fig 6a. Partnership mechanism. Stable equilibrium in M_1 ($w=1\cdot10^{-4}$).
Fig 6b. Partnership mechanism . Stable equilibrium in M_1 ($w=1,2\cdot10^{-5}$).
Fig 6c. Partnership mechanism. Unstable equilibrium in m_2 ($w=1\cdot10^{-4}/1,2\cdot10^{-5}$).
Fig 6d. Individual mechanism. Stable equilibrium in M_1 ($w=1\cdot10^{-4}$).
Fig 6e. Individual mechanism. Stable equilibrium in M_1 ($w=1,2\cdot10^{-5}$).
Fig 6f. Individual mechanism. Unstable equilibrium in m_1 ($w=1\cdot10^{-4}/1,2\cdot10^{-5}$).

6 Conclusions: Individual or partnership subsidy schemes?

We have analyzed the performance of two different subsidy schemes, the partnership and the individual constant subsidies. Now we are going to compare them and comment on their similarities and on their differences. It is clear that a budget that allows farmers to receive the same individual subsidy under both schemes allow for reaching the same stable heterogeneous equilibria M in both cases. In equilibria, the proportion of conservationist farmers s_c^* and the stock of natural resources will coincide and B^* will be the same under both schemes. In addition, the amount of subsidy that an individual farmer should receive to attain an stable equilibrium point such M is the same regardless of the sign of $\frac{\partial \phi_i(s_c)}{\partial s_c}$. That is, the same budget, P, will be spent by the environmental agency in both cases. Therefore, there are no differences in equilibria, the main differences between these two types of subsidy schemes appear out of equilibria where the dynamics and the basins of attraction of the two types of stable equilibria differ.

The EU policy instruments are aimed to the recovery of endangered species. It is highly likely that the initial resource stock level B is low or close to extinction when the policy is introduced, therefore not all the basins of attraction of stable equilibria are of equal interest but the ones that correspond to low levels of resource stock are more relevant for an endangered specie recovery. In fact, the more endangered a specie is, the lower is the actual stock B and the farther away is from a sustainable stock level. That is, the dynamic out of equilibria for low levels of resource stock should be taken into account when choosing a policy instrument. To assure that farmers are attracted to conservationist behavior at early stages is necessary large enough subsidies at early stages of the policy implementation. Accordingly, and as our observation 1 suggest it is of interest for the regulatory agency to design a subsidy that depends inversally on the proportion of farmers that act as conservationists, s_c.

In the case of a constant individual subsidy ϕ_c if the initial allocation (B, s_c) is in area N (Fig 4) where for example, the difference in profits is larger than the constant subsidy rate, $(\pi_{nc} - \pi_c) > \phi$ the proportion of non-conservationist farmers, $(1 - s_c)$, will rise. The reduction on the proportion of conservationist farmers s_c can be accompanied of a reduction on B. After several stages the dynamics can enter the basin of attraction of the heterogeneous stable equilibria M and converge again towards it, but however, it could also let to the extinction of the resource. In the case of partnership subsidy schemes the possibility of extinction is much lower. Note that the initial dynamics in area N are the same, however in this case, as the proportion of conservationist farmers decreases the individual subsidy rate increases closing the gap and equating the difference in profit to the larger subsidy rate. In such circumstances the proportion of conservationist farmers will cease to decrease and the stock level B will start recovering, the trajectory towards extinction will have been stopped. Stopping the trajectory towards extinction of a natrual resource could determine which type of subsidy should be applyed, and given a fixed budget, a decreassing subsidy on s_c allows to allocate more efforts in initial fases where B and s_c are lower (see observation 2), and this could assure better the conservation of the natural resource when with a fixed subsidy is not.

Nevertheless, a subsidy that increases as the proportion of conservationist, s_c, decreases could be also useful even if resource stock B is highly recovered. In such a case, the difference between the profits of conservationist and non-conservationist farmers can be very large as the difference between profits increases with B. If this difference increases, the number of non-conservationists will increase, the popularity of the non-conservationist strategy would increase and the resource can be endangered again. To compensate for this rise in the difference of profits it would be necessary to increase the individual subsidy. An individual subsidy that increases as the number of conservationist decreases could solve the problem and be most appropriated In most scenarios, budget constraints are a fact, and the authorities responsible for aids management must fit on to the budget. The results show that when there is an adjusted budget the best incentives are those related negatively to the proportion of conservationists (a decreasing function of s_c). Then if the number of conservationists is low, the subsidy received by each farmer increases and there is a chance to stop the extinction of the resource.

7 Appendix 1: Proofs of Lemmas and Propositions

Proof of Lemma 1

Let (B^*, sc^*) be an isolated equilibrium point of the resource stock dynamic. Following Takayama (1994) this point is asymptotically locally stable if $\frac{\partial \dot{B}}{\partial B} < 0$ (unstable if $\frac{\partial \dot{B}}{\partial B} > 0$). From the resource stock dynamic we obtain:

$$\frac{\partial \dot{B}}{\partial B} = \frac{dF}{dB} - \frac{\partial W}{\partial B} - \frac{\partial W}{\partial X}\frac{\partial X}{\partial B}$$

The$\frac{\partial F}{\partial B}$ is positive until B^M and then become negative. We assume that $\frac{\partial W}{\partial B}$ and $\frac{\partial W}{\partial X}$ are both positive. A sufficient condition to $\frac{\partial \dot{B}}{\partial B} < 0$ is that $\frac{\partial X}{\partial B} > \frac{(\frac{\partial F}{\partial B} - \frac{\partial W}{\partial B})}{\frac{\partial W}{\partial X}}$. Note that the right hand side expression is equal to $\frac{\partial \widehat{X}}{\partial B}$, because by definition of $\widehat{X}$, $F(B) - W(B, \widehat{X}) = 0$ and applying the implicit function theorem we obtain that $\frac{\partial \widehat{X}}{\partial B} = \frac{(\frac{\partial F}{\partial B} - \frac{\partial W}{\partial B})}{\frac{\partial W}{\partial X}}$. Therefore a sufficient condition for $\frac{\partial \dot{B}}{\partial B} < 0$ is that $\frac{\partial X}{\partial B} > \frac{\partial \widehat{X}}{\partial B}$. Therefore, the resource stock dynamic is asymptotically local stable (unstable) if$\frac{\partial X}{\partial B} > \frac{\partial \widehat{X}}{\partial B}$ ($\frac{\partial X}{\partial B} < \frac{\partial \widehat{X}}{\partial B}$).

Proof of Lemma 2

By applying the implicit theorem function to the equilibrium equation of the resource stock dynamic we obtain:

$$\frac{\partial B}{\partial s_c} = \frac{\frac{\partial W}{\partial X}\frac{\partial X}{\partial s_c}}{\frac{dF}{dB} - \frac{\partial W}{\partial B} - \frac{\partial W}{\partial X}\frac{\partial X}{\partial B}}$$

The numerator is negative as $\frac{\partial W}{\partial X} > 0$ and $\frac{\partial X}{\partial s_c} < 0$. From Lemma 1 we know that for a stable equilibrium is true that $\frac{dF}{dB} - \frac{\partial W}{\partial B} - \frac{\partial W}{\partial X}\frac{\partial X}{\partial B} < 0$ and the denominator will be also negative. As a consequence the stability condition for the resource stock dynamic implies that $\frac{\partial \widehat{B}}{\partial sc} > 0$. A similar reasoning can be applied for the unstable equilibrium, in this case $\frac{dF}{dB} - \frac{\partial W}{\partial B} - \frac{\partial W}{\partial X}\frac{\partial X}{\partial B} > 0$ and the denominator will be positive. and therefore $\frac{\partial \widetilde{B}}{\partial sc} < 0$.

Proof of Lemma 3

Recall that the utility function is: $u_i(x_i, B) = \pi_i(x_i, B) + \phi_i(s_c) = pH(x_i, B) - cx_i + \phi_i(s_c)$. Given a proportion of individuals s_c^* of conservationist farmers, we define a set $\psi = \{(B, s_c^*)|0 < B < \bar{B}\}$. Then we assume that there is a pair $(B_{far}(s_c^*), s_c^*) \in \psi$ such that $(\pi_{nc} - \pi_c)(B_{far}(s_c^*)) = \phi_c(s_c^*)$ then (B^*, s_c^*) where $B^* = B_{far}(s_c^*)$ is an equilibrium point of the population dynamics. Following Takayama this point is an asymptotically stable equilibrium if $\frac{\partial \dot{s}_c}{\partial s_c} < 0$, where $\frac{\partial \dot{s}_c}{\partial s_c} = -s_c(1 - s_c)\left(\frac{\partial(u_{nc} - u_c)}{\partial s_c}\right) = -s_c(1 - s_c)\left(\frac{\partial(\pi_{nc} - \pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right)$. Note that $\frac{\partial[\pi_{nc} - \pi_c]}{\partial s_c} = 0$, then the sign of $\frac{\partial(u_{nc} - u_c)}{\partial s_c}$ depends on the sign of $\frac{\partial \phi_c(s_c)}{\partial s_c}$. Then (B^*, s_c^*) is an asymptotically locally stable (unstable) equilibrium point of the farmers dynamics if $\frac{\partial \phi_c(s_c^*)}{\partial s_c} < 0 \left(\frac{\partial \phi_c(s_c^*)}{\partial s_c} > 0\right)$. This is only a sufficient condition but not a necessary condition.

Case L3.1. Note that with a constant subsidy, ϕ_c is is always de case where $\frac{\partial \phi_c(s_c)}{\partial s_c} = 0$, then $\frac{\partial \dot{s}_c}{\partial s_c} = -s_c(1 - s_c)\left(\frac{\partial(\pi_{nc} - \pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right) = 0$.

Proof of Lemma 4

Applying the implicit function theorem to the equilibrium condition $(u_n - u_c)(B_{far}(s_c^*), s_c^*) = 0$, we obtain: $dB_{far}\left[\frac{\partial(u_{nc} - u_c)}{\partial B}\right] + ds_c\left[\frac{\partial(u_{nc} - u_c)}{\partial sc}\right] = 0$ that is:

$$\frac{dB_{far}}{ds_c} = -\frac{\frac{\partial(u_{nc} - u_c)}{\partial sc}}{\frac{\partial(u_{nc} - u_c)}{\partial B}} = -\frac{-\frac{\partial \phi_c(s_c)}{\partial s_c}}{\frac{\partial(u_{nc} - u_c)}{\partial B}}$$

The utility function is $u_i(x_i, B) = \pi_i(x_i, B) + \phi_i(s_c) = pH(x_i, B) - cx_i + \phi_i(s_c)$. Moreover, note that $(u_{nc} - u_c) = \pi_{nc} + \phi_{nc}(s_c) - [\pi_c + \phi_c(s_c)] = pH(x_{nc}, B) - cx_{nc} + \phi_{nc}(s_c) - [pH(x_c, B) - cx_c + \phi_c(s_c)]$. Recall that $\phi_i \in \{\phi_c, \phi_{nc}\}$, $\phi_c > 0$ and $\phi_{nc} = 0$. Then $(u_{nc} - u_c) =$

$\pi_{nc} - [\pi_c + \phi_c(s_c)] = pH(x_{nc}, B) - cx_{nc} - [pH(x_c, B) - cx_c + \phi_c(s_c)]$ and

$$\begin{aligned}\frac{\partial(u_{nc} - u_c)}{\partial B} &= \left[p\left(\frac{\partial H(x_{nc}, B)}{\partial x_{nc}}\frac{\partial x_{nc}}{\partial B} + \frac{\partial H(x_{nc}, B)}{\partial B}\right) - c\frac{\partial x_{nc}}{\partial B}\right] \\ &\quad - \left[p\left(\left(\frac{\partial H(x_c, B)}{\partial x_c}\frac{\partial x_c}{\partial B} + \frac{\partial H(x_c, B)}{\partial B}\right) - c\frac{\partial x_c}{\partial B}\right) + \frac{\partial \phi_c(s_c)}{\partial B}\right]\end{aligned}$$

As we have assumed that in equilibrium $x_c = \overline{x}$ and $\overline{x}$ is exogenously given by the environmental agency, that is in equilibrium $\frac{\partial \overline{x}_c}{\partial B} = 0$.Also note that by the profit maximizing condition the behavior of non-conservationists farmers in equilibrium implies $p\frac{\partial H(x_{nc},B)}{\partial x_{nc}} - c = 0$. Applying these assumptions in the previous equation we have:

$$\begin{aligned}\frac{\partial(u_{nc} - u_c)}{\partial B} &= \left[p\left(\frac{\partial H(x_{nc}, B)}{\partial x_{nc}}\frac{\partial x_{nc}}{\partial B} + \frac{\partial H(x_{nc}, B)}{\partial B}\right) - c\frac{\partial x_{nc}}{\partial B}\right] - \left[p\frac{\partial H(x_c, B)}{\partial B} + \frac{\partial \phi_c(s_c)}{\partial B}\right] \\ &= \left(p\frac{\partial H(x_{nc}, B)}{\partial x_{nc}} - c\right)\frac{\partial x_{nc}}{\partial B} + p\left(\frac{\partial H(x_{nc}, B)}{\partial B} - \frac{\partial H(x_c, B)}{\partial B}\right) - \frac{\partial \phi_c(s_c)}{\partial B} \\ &= p\left(\frac{\partial H(x_{nc}, B)}{\partial B} - \frac{\partial H(x_c, B)}{\partial B}\right) - \frac{\partial \phi_c(s_c)}{\partial B}\end{aligned}$$

Recall that $\frac{\partial H(x_i,B)}{\partial B} < 0$, and by assumption $\left|\frac{\partial H(x_{nc},B)}{\partial B}\right| < \left|\frac{\partial H(x_c,B)}{\partial B}\right|$ then $p\left(\frac{\partial H(x_{nc},B)}{\partial B} - \frac{\partial H(x_c,B)}{\partial B}\right) > 0$. Moreover, $\frac{\partial \phi_c(s_c)}{\partial B} = 0$. Consequently, the sign of $\frac{\partial(u_{nc}-u_c)}{\partial B}$ depends on the sing of $p\left(\frac{\partial H(x_{nc},B)}{\partial B} - \frac{\partial H(x_c,B)}{\partial B}\right)$. and then $\frac{\partial(u_{nc}-u_c)}{\partial B} > 0$. On the other side the sign of the numerator will be positive because by lemma 3 for an stable equilibrium point of the farmers dynamic $\frac{\partial \phi_c(s_c)}{\partial s_c} < 0$ and $\frac{\partial(u_{nc}-u_c)}{\partial sc} > 0$ then $\frac{d\widehat{B}_{far}}{ds_c} < 0$. Consequently, $\widehat{B}_{far}(s_c)$ is a decreasing function of s_c.

Case L4.1. Let us analyze de cases where $\frac{\partial \phi_i(s_c)}{\partial s_c} = 0$. In this case if $\frac{\partial \phi_c(s_c)}{\partial s_c} = 0$ and $\frac{\partial(u_{nc}-u_c)}{\partial s_c} = 0$ then the numerator is zero and independently of the sign of the denominator

$\frac{dB_{far}}{ds_c} = 0.$

Proof of corollary L4.1. When by lemma 3 the farmers dynamics is unstable, that is $\frac{\partial \phi_c(B,s_c)}{\partial s_c} > 0$, then whether $\frac{\partial (u_{nc}-u_c)}{\partial sc} > 0$ then $\frac{d\widetilde{B}_{far}}{ds_c} < 0$.Consequently, in this case $\widetilde{B}_{far}(s_c)$ is a decreasing function of s_c. Contrary, if $\frac{\partial (u_{nc}-u_c)}{\partial sc} < 0$ then $\frac{d\widetilde{B}_{far}}{ds_c} > 0$.Consequently, in this case $\widetilde{B}_{far}(s_c)$ is an increasing function of s_c.

Proof of Proposition 1

The Jacobian of the two dimensional system given by equation 1 and equation 2 is:

$$J_{(B,s_c)} = \begin{pmatrix} \frac{dF}{dB} - \frac{\partial H}{\partial B} - \frac{\partial W}{\partial X}\frac{\partial X}{\partial B} & -\frac{\partial W}{\partial X}\frac{\partial X}{\partial s_c} \\ -s_c(1-s_c)\left[\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} - \frac{\partial \phi_c(s_c)}{\partial B}\right] & \begin{matrix} -(1-2s_c)\left(\pi_{nc}-\pi_c-\phi_c(s_c)\right) - s_c(1-s_c) \\ \left[\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right] \end{matrix} \end{pmatrix}$$

The Jacobian evaluated at an interior equilibrium point (B^*, s_c^*) is given by:

$$J_{(B,s_c)} = \begin{pmatrix} \frac{dF}{dB} - \frac{\partial W}{\partial B} - \frac{\partial W}{\partial X}\frac{\partial X}{\partial B} & -\frac{\partial W}{\partial X}\frac{\partial X}{\partial s_c} \\ -s_c^*(1-s_c^*)\left[\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} - \frac{\partial \phi_c(s_c)}{\partial B}\right] & -s_c^*(1-s_c^*)\left[\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right] \end{pmatrix}$$

Any isolated equilibrium point of the system, say (s_c^*, B^*), would be asymptotically locally stable if the Jacobian has a negative trace and a positive determinant. According to Lemma 2 and 4 the trace of $J_{(B,s_c)}$ can be written as:

$$trJ_{(B,s_c)} = \left[\frac{\partial \dot{B}}{\partial B}\right] + \left[-s_c^*(1-s_c^*)\left(\frac{\partial\left(\pi_{nc}-\pi_c\right)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right)\right]$$

and the determinant of $J_{(B,s_c)}$ can be written as:

$$
\begin{aligned}
\left|J_{(B,s_c)}\right| &= -s_c^*\left(1-s_c^*\right)\left[\frac{\partial(u_{nc}-u_c)}{\partial s_c}\right]\left[\frac{\partial \dot{B}}{\partial B}\right] - \left[-s_c^*(1-s_c^*)\left[\frac{\partial(u_{nc}-u_c)}{\partial B}\right]\right]\left[-\frac{\partial W}{\partial X}\frac{\partial X}{\partial s_c}\right] \\
&= -s_c^*\left(1-s_c^*\right)\left[\frac{\partial(u_{nc}-u_c)}{\partial s_c}\right]\left[\frac{\partial \dot{B}}{\partial B}\right] - \left[s_c^*(1-s_c^*)\left[\frac{\partial(u_{nc}-u_c)}{\partial B}\right]\right]\left[\frac{\partial W}{\partial X}\frac{\partial X}{\partial s_c}\right] \\
&= \left[\frac{-\left[\frac{\partial(u_{nc}-u_c)}{\partial sc}\right]}{\left[\frac{\partial(u_{nc}-u_c)}{\partial B}\right]}\left[\frac{\partial \dot{B}}{\partial B}\right] - \left[\frac{\partial W}{\partial X}\frac{\partial X}{\partial s_c}\right]\right] s_c^*(1-s_c^*)\left[\frac{\partial(u_{nc}-u_c)}{\partial B}\right] \\
&= \left[\frac{dB_{far}}{ds_c}\left[\frac{\partial \dot{B}}{\partial B}\right] - \left[\frac{\partial W}{\partial X}\frac{\partial X}{\partial s_c}\right]\right] s_c^*(1-s_c^*)\left[\frac{\partial(u_{nc}-u_c)}{\partial B}\right] \\
&= \left[\frac{dB_{far}}{ds_c}\frac{\frac{\partial \dot{B}}{\partial B}}{\frac{\partial \dot{B}}{\partial B}} - \frac{\left[\frac{\partial W}{\partial X}\frac{\partial X}{\partial sc}\right]}{\frac{\partial \dot{B}}{\partial B}}\right] s_c^*(1-s_c^*)\left[\frac{\partial(u_{nc}-u_c)}{\partial B}\right]\left[\frac{\partial \dot{B}}{\partial B}\right] \\
&= \left[\frac{dB_{far}}{ds_c} - \frac{dB}{ds_c}\right] s_c^*(1-s_c^*)\left[\frac{\partial(u_{nc}-u_c)}{\partial B}\right]\left[\frac{\partial \dot{B}}{\partial B}\right] \\
&= s_c^*\left(1-s_c^*\right)\left[\frac{\partial \dot{B}}{\partial B}\right]\left[\frac{dB_{far}}{ds_c} - \frac{dB}{ds_c}\right]\left[\frac{\partial(u_{nc}-u_c)}{\partial B}\right] \\
&= s_c^*\left(1-s_c^*\right)\left[\frac{\partial \dot{B}}{\partial B}\right]\left[\frac{dB_{far}}{ds_c} - \frac{dB}{ds_c}\right]\left[\frac{\partial\left(\pi_{nc}-\pi_c\right)}{\partial B} - \frac{\partial \phi_c(s_c)}{\partial B}\right]
\end{aligned}
$$

Let us examine the trace first for a stable equilibrium point of both the resource and the farmers dynamics. Whenever (B^*, s_c^*) is a stable equilibrium point of the resource stock then by Lemma 1 $\frac{\partial \dot{B}}{\partial B} < 0$. Further by lemma 3 a stable equilibrium point of the farmers dynamics requires $\frac{\partial \phi_c(s_c)}{\partial s_c} < 0$ and $\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right) > 0$ as $\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} = 0$, the trace is always negative.

Let's now look at the Jacobian for a stable equilibrium point of the resource and farmers dynamics. Note that $s_c^*(1-s_c^*) > 0$ for all s_c and by lemma 1 $\frac{\partial \dot{B}}{\partial B} < 0$. Also by Lemma 2 $\frac{dB}{ds_c} = \frac{\left[\frac{\partial W}{\partial X}\frac{\partial X}{\partial sc}\right]}{\frac{\partial \dot{B}}{\partial B}}$ and the stability condition of the resource stock dynamics implies that $\frac{\partial \widehat{B}}{\partial sc} > 0$. By Lemma 3 $\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right) > 0$ or what it is the same $\frac{\partial(u_{nc}-u_c)}{\partial s_c} > 0$. Therefore, the sign of the Jacobian depends on the difference $\left(\frac{d\widehat{B}_{far}}{ds_c} - \frac{\partial \widehat{B}}{\partial sc}\right)$. Moreover, by Lemma 4 $\frac{d\widehat{B}_{far}}{ds_c} = \frac{-\left[\frac{\partial(u_{nc}-u_c)}{\partial sc}\right]}{\left[\frac{\partial(u_{nc}-u_c)}{\partial B}\right]} < 0$. Then Jacobian would be always positive, that is $(B^*, s_c^*,)$ would be an asymptotically locally stable equilibrium point of the joint dynamic system.

Case P1.1 Let us analyze the constant subsidy case where $\frac{\partial \phi_i(s_c)}{\partial s_c} = 0$. Recall that by lemma 3 case L3.1$\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right) = 0$ then the trace would be always negative $trJ_E = \left[\frac{\partial \dot{B}}{\partial B}\right] < 0$. Analyzing the Jacobian note that $\frac{dB_{far}}{ds_c} = 0$ and $\frac{\partial \phi_c(s_c)}{\partial B} = 0$ then $\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} - \frac{\partial \phi_c(s_c)}{\partial B}\right) > 0$.Consequently, the Jacobian would be always positive, that is $(B^*, s_c^*,)$ would be an asymptotically locally stable equilibrium point of the combined system.

Proof of corollary P1.1. We consider other four different situations.

Claim 1. Whenever (B^*, s_c^*) is a stable equilibrium of the resource stock dynamics but an unstable equilibrium point of the farmers dynamics. Then by lemma 1 $\frac{\partial \dot{B}}{\partial B} < 0$ and by lemma 2 $\frac{\partial \widehat{B}}{\partial sc} > 0$. Also by lemma 3 $\frac{\partial \phi_c(s_c^*)}{\partial s_c} > 0$ then $\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right) \gtrless 0$ and as $\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} - \frac{\partial \phi_c(s_c)}{\partial B}\right) > 0$ then by lemma 4 $\frac{d\widetilde{B}_{far}}{ds_c} \lesseqgtr 0$.Therefore the sign of the determinant depends on the sign of $\left[\frac{d\widetilde{B}_{far}}{ds_c} - \frac{\partial \widehat{B}}{\partial sc}\right]$.Three cases are possible:

Whenever $\frac{d\widetilde{B}_{far}}{ds_c} > 0$ and $\frac{d\widetilde{B}_{far}}{ds_c} > \frac{\partial \widehat{B}}{\partial sc}$ then $\left|J_{(B,s_c)}\right| < 0$.Consequently, (B^*, s_c^*) is an unstable equilibrium point.

Whether, $\frac{d\widetilde{B}_{far}}{ds_c} < \frac{\partial \widehat{B}}{\partial sc}$ [56] then $\left|J_{(B,s_c)}\right| > 0$. However, the trace could be negative only if and only if $\left|\frac{\partial \dot{B}}{\partial B}\right| > \left|s_c^*(1-s_c^*)\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right)\right|$. Then the trace is inclusive and the equilibrium point is undetermined.

Finally, it could be the case that $\frac{d\widetilde{B}_{far}}{ds_c} = \frac{\partial \widehat{B}}{\partial sc}$ then $\left|J_{(B,s_c)}\right| = 0$.However, the trace is inclusive and the equilibrium point is undetermined.

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[56] Including $\frac{d\widetilde{B}_{far}}{ds_c} < 0$

Claim 2. Whenever (B^{*}, s_c^{*}) is an unstable equilibrium of the resource stock dynamics but a stable equilibrium point of the farmers dynamics. Then by lemma 1 $\frac{\partial \dot{B}}{\partial B} > 0$ and by lemma 2 $\frac{\partial \widetilde{B}}{\partial sc} < 0$. Also by lemma 3 $\frac{\partial \phi_c(s_c^{*})}{\partial s_c} < 0$ then $\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c} > 0$ and by lemma 4 $\frac{dB_{far}}{ds_c} < 0$. Therefore the sign of the determinant depends on the sign of $\frac{d\widehat{B}_{far}}{ds_c} - \frac{\partial \widetilde{B}}{\partial sc}$. Three cases are possible:

Whenever $\left|\frac{d\widehat{B}_{far}}{ds_c}\right| > \frac{\partial \widetilde{B}}{\partial sc}$ then $\left[\frac{d\widehat{B}_{far}}{ds_c} - \frac{\partial \widetilde{B}}{\partial sc}\right] < 0$ and $\left|J_{(B,s_c)}\right| < 0$.Consequently, (B^{*}, s_c^{*}) is an unstable equilibrium point.

Whether,$\left|\frac{d\widehat{B}_{far}}{ds_c}\right| < \frac{\partial \widetilde{B}}{\partial sc}$ then $\left[\frac{d\widehat{B}_{far}}{ds_c} - \frac{\partial \widetilde{B}}{\partial sc}\right] > 0$ and $\left|J_{(B,s_c)}\right| > 0$. However, the trace could be negative only if and only if $\left|\frac{\partial \dot{B}}{\partial B}\right| < \left|s_c^{*}(1-s_c^{*})\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right)\right|$. Then the trace is inclusive and the equilibrium point is undetermined.

Finally, it could be the case that $\frac{d\widehat{B}_{far}}{ds_c} = \frac{\partial \widetilde{B}}{\partial sc}$ then $\left|J_{(B,s_c)}\right| = 0$.However, the trace is inclusive and the equilibrium point is undetermined

Claim 3. Whenever (B^{*}, s_c^{*}) is an unstable equilibrium of the resource stock dynamics and a semi-stable equilibrium point of the farmers dynamics (i.e.,$\frac{dB_{far}}{ds_c} = 0$). Then by lemma 1 $\frac{\partial \dot{B}}{\partial B} > 0$ and by lemma 2 $\frac{\partial \widetilde{B}}{\partial sc} < 0$. Also by lemma 3 $\frac{\partial \phi_c(s_c^{*})}{\partial s_c} = 0$ then $\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right) = 0$. Therefore, $trJ_{(B,s_c)} > 0$ the equilibrium point is unstable.

Claim 4. Whenever (B^{*}, s_c^{*}) is an unstable equilibrium of the resource stock dynamics and an unstable equilibrium point of the farmers dynamics. Then by lemma 1 $\frac{\partial \dot{B}}{\partial B} > 0$ and by lemma 2 $\frac{\partial \widetilde{B}}{\partial sc} < 0$. Also by lemma 3 $\frac{\partial \phi_c(s_c^{*})}{\partial s_c} > 0$ then $\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right) \gtreqless 0$.and as $\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} - \frac{\partial \phi_c(s_c)}{\partial B}\right) > 0$ then by lemma 4 $\frac{d\widetilde{B}_{far}}{ds_c} \lesseqgtr 0$.Therefore the sign of the determinant depends on the sign of $\left[\frac{d\widetilde{B}_{far}}{ds_c} - \frac{\partial \widehat{B}}{\partial sc}\right]$.Three cases are possible:

Whenever $\frac{d\widetilde{B}_{far}}{ds_c} > 0$ and $\frac{d\widetilde{B}_{far}}{ds_c} > \left|\frac{\partial \widehat{B}}{\partial sc}\right|$ then $\left|J_{(B,s_c)}\right| > 0$.However, the trace could be negative only if and only if $\left|\frac{\partial \dot{B}}{\partial B}\right| < \left|s_c^{*}(1-s_c^{*})\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right)\right|$. Then the trace is inconclusive and the equilibrium point is undetermined.

Whether and $\frac{d\widetilde{B}_{far}}{ds_c} < \left|\frac{\partial \widehat{B}}{\partial sc}\right|$ [57] then $\left|J_{(B,s_c)}\right| < 0$.Consequently, (B^*, s_c^*) is an unstable equilibrium point.

Finally, it could be the case that $\frac{d\widetilde{B}_{far}}{ds_c} > 0$ and $\frac{d\widetilde{B}_{far}}{ds_c} = \frac{\partial \widehat{B}}{\partial sc}$ then $\left|J_{(B,s_c)}\right| = 0$.However, the trace is inconclusive and the equilibrium point is undetermined.

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Proof of Proposition 2. The Jacobian of two-dimensional system at an all-conservationists equilibrium is:

$$J_{(B,1)} = \begin{pmatrix} \frac{dF}{dB} - \frac{\partial W}{\partial B} - \frac{\partial W}{\partial X}\frac{\partial X}{\partial B} & -\frac{\partial W}{\partial X}\frac{\partial X}{\partial s_c} \\ 0 & (\pi_{nc} - \pi_c) - \phi_c(s_c) \end{pmatrix}$$

At $(\widehat{B}(1), 1)$ $J_{11} < 0$, as it is a stable equilibrium point of the resource stock dynamics. Note that $J_{22} = (\pi_{nc} - \pi_c) - \phi_c(1) = 0$ if $\widehat{B}(1) = B_{far}(1)$.Furthermore, if $\widehat{B}(1) < B_{far}(1)$ then by definition $(\pi_{nc} - \pi_c)(B) - \phi_c(1) < 0$. In such case the trace is negative and the determinant is positive and $(\widehat{B}(1), 1)$ is an asymptotically locally stable (unstable) point of the combined system if $\widehat{B}(1) < B_{far}(1)$ $(\widehat{B}(1) > B_{far}(1))$. On the other side at $(\widetilde{B}(1), 1)$ $J_{11} > 0$ and the conditions for stability are not satisfied.

[57] Including $\frac{d\widetilde{B}_{far}}{ds_c} < 0$

8 Appendix 2: Phase diagrams of the combined system (Unstable cases of the farmers dynamics)

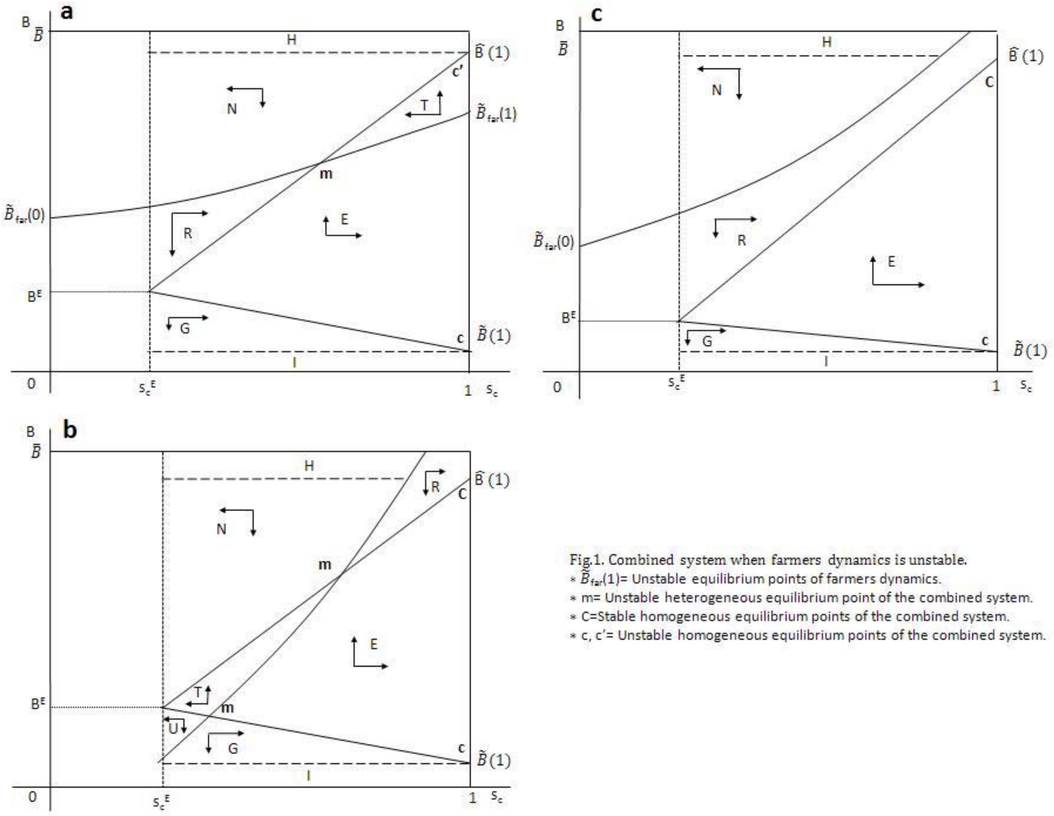

Fig.1. Combined system when farmers dynamics is unstable.
* $\tilde{B}_{far}(1)$= Unstable equilibrium points of farmers dynamics.
* m= Unstable heterogeneous equilibrium point of the combined system.
* C=Stable homogeneous equilibrium points of the combined system.
* c, c'= Unstable homogeneous equilibrium points of the combined system.

9 Appendix 3: Simulation

9.1 The explicit functions

We represent the natural evolution of the birds population, $F(B)$, with a logistic growth function (Verhulst, 1838) where the dynamics of the resource stock depends on its natural rate of growth, which is function of the resource stock level, B. Then we represent the rate of replenishment with the following expression:

$$F(B) = rB(1 - \frac{B}{\overline{B}}) \tag{4}$$

where r is the natural rate of growth, and it is such that $r > 0$, and B is the stock of birds, and $\overline{B}$ is the maximum stock of birds that the environment is able to support.

Further, we take irrigation water is an appropriated variable to summarize the agricultural intensification effect on both, Little bustard population and farm productivity. To represent the irrigation effect on Little bustard population we define $W(B, X)$ as the wipe out function, that measures the vulnerability of the specie due to the use of irrigation water in the protected area, X, and due to the natural resource stock level, B. We represent $W(B, X)$ by the following specification:

$$W(B, X) = qX^{\alpha}B^{\beta} \tag{5}$$

where, $0 < \alpha, \beta < 1$ and $q > 0$. In addition, α is the effect of irrigation water on bird population and β is the effect of the resource stock size on the intrinsic capacity of regeneration of the specie. Note that α and β are both constants. In addition, parameter q is the so called total factor productivity in the traditional Cobb-douglas and is related to the available technology. Finally, given these functional forms, the Little bustard stock dynamics can be represented by the following expression:

$$\dot{B} = rB(1 - \frac{B}{\overline{B}}) - qX^{\alpha}B^{\beta} \tag{6}$$

We model the harvest function as:

$$H(B, x_i) = Ax_i^{\gamma}(1 - \frac{B^{\varphi_i}}{x_i}) \tag{7}$$

where $0 < \gamma, \varphi_i < 1$, $\gamma > \varphi_i$, $A > 0$. We define $i \in (nc, c)$.and we use nc to refer to a non-conservationist farmer an c to refer to a conservationist farmer. We define x_i as the individual total amount of water used by an agent i and the total amount of water used in the zone is $X = \sum x_i$. Moreover, note that $\frac{\partial H(B,x_i)}{\partial x_i} > 0$, $\frac{\partial H^2(B,x_i)}{\partial x_i^2} < 0$ and $\frac{\partial H^2(B,x_i)}{\partial x_i \partial B} \geq 0$.[58] Therefore, the responsiveness of output to a change in levels of input x_i depends on γ. Similarly φ_i helps to determine the responsiveness of output to a changes in levels of B. Parameters A, γ and φ_i are determined by available technology. We assume $\varphi_{nc} < \varphi_c$ Further, we define p as the price of the resource stock and c as the opportunity cost of the non-environmental friendly inputs; the profit function that farmer gets from the harvest is then:

$$\pi_i = p\left[Ax_i^{\gamma}(1 - \frac{B^{\varphi_i}}{x_i})\right] - cx_i \tag{8}$$

Moreover, we modulate the economic incentives given to farmers with a payment per hectare

[58] Note that we can writen $H(B, x_i)$ as $H(B, x_i) = Ax_i^{\gamma} - \frac{Ax_i^{\gamma}B^{\varphi_i}}{x_i}$ and then $\frac{\partial H(B,x_i)}{\partial x_i} = A\gamma x_i^{\gamma-1} - \left(\frac{A\gamma x_i^{\gamma-1}B^{\varphi_i}x_i - Ax_i^{\gamma}B^{\varphi_i}}{x_i^2}\right) = A\gamma x_i^{\gamma-1} - \left(A\gamma x_i^{\gamma-2}B^{\varphi_i} - Ax_i^{\gamma-2}B^{\varphi_i}\right) = A(\gamma x_i^{\gamma-1} + x_i^{\gamma-2}B^{\varphi_i}(-\gamma+1))$. Note that if $(-\gamma+1) > 0$, then $\frac{\partial H(B,x_i)}{\partial x_i} > 0$. Further note that,
$\frac{\partial H^2(B,x_i)}{\partial x_i^2} = A(\gamma(\gamma-1)x_i^{\gamma-2} + (\gamma-2)x_i^{\gamma-3}B^{\varphi_i}(-\gamma+1))$, and as $(\gamma-1) < 0, (\gamma-2) < 0$ then $\frac{\partial H^2(B,x_i)}{\partial x_i^2} \leq 0$.
Also, $\frac{\partial H(B,x_i)}{\partial B} = Ax_i^{\gamma}(-\frac{\varphi_i B^{\varphi_i-1}x_i}{x_i^2}) = -Ax_i^{\gamma-1}\varphi_i B^{\varphi_i-1} < 0$, then, $\frac{\partial H^2(B,x_i)}{\partial x_i \partial B} = Ax_i^{\gamma-2}\varphi_i B^{\varphi_i-1}(-\gamma+1) \geq 0$.

function that we represent by:

$$\phi_i(s_c) = S s_c^{\sigma} \tag{9}$$

Note that if $\sigma = 0$ the payment per hectare received by farmers is fixed per hectare Therefore, the utility function of farmer i is equal to:

$$u_i = p \left[A x_i^{\gamma} (1 - \frac{B^{\varphi_i}}{x_i}) \right] - c x_i + S s_c^{\sigma} \tag{10}$$

Finally, assuming without loss of generality that $\phi_{nc}(s_c) = 0$ the farmers dynamics can be represented by the replicator dynamics as:

$$\dot{s}_c = w \left[sc(1 - sc) \left(pA \left[\left[x_{nc}^{\gamma} (1 - \frac{B^{\varphi_i}}{x_{nc}}) \right] - \left[\left[x_c^{\gamma} (1 - \frac{B^{\varphi_i}}{x_c}) \right] + \phi_c(s_c) \right] \right] - c\,(x_{nc} + x_c) \right) \right] \tag{11}$$

where w is an adjustment of the speed at which farmers imitate each other.

9.2 Parameters on the natural resource stock dynamics

We parametrize the functions describing Little bustard stock dynamics using real data about the specie in S-G irrigation area. First, we define L as the current surface occupied by the Little bustard. The protected zone covers an area of $37,325ha$. Nevertheless, Little bustard is a dry crop cereal specialized specie (Bota *et al.*, 2004) and not all the protected area is dedicated to cereal cropping. Therefore, seams reasonable to focus only on these surface dedicated to cereal cropping, that are 23.594 ha into the protected area.[59] We take this value as the total habitat

[59] We determine this last surface by the percentages obtained by the MPSP in the Lleida Plains, 2010.

available for the specie, and then we assume $L = 23.594$ ha. Moreover, the compulsory Environmental Impact Assessment (DIA) carried on the S-G area in 2010 determines that the number of individuals of the specie into the protected area of the irrigation project is $B = 905, 79$.[60] Further, we take N as the total number of farmers farming in the protected area. We take $N_1 = 236$ where each farmer owns 100 hectares of farmland.

First, we specify parameters on $F(B)$. Following the results obtained by Morales *et al.* (2005a) and the DIA (2010) we define the carrying capacity of this site, represented by $\overline{B}$.[61] Morales *et al.* 2004 calculates the carrying capacity as $\overline{B} = 1.5B$. Moreover, between 2002 and 2009 was estimated a decrease of 17% of males and 34% of no-males of the Little bustard population in the Lleida Plains due to the increase of the inadequate land use for the specie (DIA, 2010). We think that the carrying capacity of the specie could be similar than the population existing in the zone before .the increase of those inadequate practices from 2002 Using this information we take a carrying capacity range between $\overline{B} = [1.1B - 2B]$. Finally, we take the natural rate of growth between $r \in [0.7, 1]$.[62]

In addition, we specify parameters on $W(B, X)$. By definition, the vulnerability of the specie is related by α and β. For a specialized specie with strict habitat requirements α take values near 1. Note that the larger is α the lower is $\hat{X}(B)$. On the contrary, if the specie does not have strict habitat requirements this value would be close to 0. Summarizing, the larger

[60] The DIA (2010) determines that the 89% of the total population afected by the project is into the protected areas. Then into these areas are located the majority of the Little bustard population. Moreover, the 60% of the Catalan population is located on three of these areas (Plans de Sió, Bellmunt-Almenara and Belianes-Preixana, that are 20.591ha). Becoming the most important zones for birds conservation. (See also AGS, 2010).

[61] Morales *et al.* 2005a and Inchausti and Bretagnolle, 2005 for a similar aproximation with the same specie in France.

[62] We take this values as the population growth rate calculed for the same specie by Inchausti and Bretagnolle (2005) in southwest France.

the α the more specialized is a specie and the more vulnerable is to changes in its habitat.[63] Little Bustard is a dry crop cereal specialized specie that can move to irrigation alfalfa zones particularly in winter (Bota *et al.*, 2004), given these characteristics it seems reasonable to choose α such that $\alpha \in [0.6, 0.9]$.[64] On the other side, β represents the percent increase in the wipe out rate as the size of the resource stock increases. The larger the population of Little bustards in a given area the easiest is to kill them and therefore the larger the number of birds kill per unit of time. By assumption the effect of the total amount of water used is larger than the population effect, β, so $\alpha > \beta$.[65] For a first parameterization we take $\beta \in [0.1, 0.8]$.[66]

Finally, we need to fix parameter q. In the S-G project are allowed three irrigation schemes. The dotation of $3,500m^3$ used to reduce productive uncertainty in cereal crops. The dotation of $1,500m^3$ allowed for dry woody crops, such as almond, olive or vineyard. And the $6,500m^3$ dotation used in high intensified crops, such as fruit. Whether all the area could become irrigated with a dotation of $6,500m^3$ then the birds population will be extinct (it won't be habitat for the birds survival because Little bustard needs non-intensified agricultural systems to survive). Then the maximum total volume of water the specie can tolerate needs to be below the level reached when all the area is full-irrigated. This level is reached for an specific

[63] See Andrén and Seiler, 1997 for a more precise explanation.

[64] It is possible to provide the model with $\alpha \geq 1$.Nevertheles, in this case the specie is so vulnerable that the only possible situation where the Little bustard could be recovery is a situation where all farmers behave as a conservationists. This could be one interpretation of the current situation on the zone.

[65] By definition $\hat{X}(B)$ have a bell-shape (Fig 1a). Nevertheles if $\beta > 1$, then $\hat{X}(B)$ becomes a deacreasing function of B. The fact that $\hat{X}$ becomes a deacreasing function of B means that when the population decrease the wipe out increase.and contrary when the population increase the wipe out decrease. This case could be related with species with a high intrinsic competence, where if the population increase then the population mortality increase too due to the intrinsic competence of the specie for the habitat, or if we interpret the wipe out function as a hunting effort function where the hunter needs to find the prey, and the presure carried out to the prey when there are less population increae because is more difficult for the hunter to find the prey. Nevertheless, this is not our case. Moreover, recall that we are talking about an endangered specie. Then, seans reasonable to assume that the Little bustard is more vulnerable the lower is his population Therefore, it is necessary to avoid using water to protect the specie specially when B is low.

[66] Note that as by assumption $\alpha > \beta$. Therefore, β can not be equal or greater than 0.9.

B, that is B^E . The agency has already fixed this total volume allowing $39,673,460m^3$ of water per year in the whole area.[67] Moreover, we suppose that the agency has fixed this maximum total amount of water according to the habitat requirements of the steppe birds existing in the zone and therefore according to *Little bustard* requirements. Then we further assume that the maximum total level of irrigation water that the *Little bustard* can tolerate, that is $\hat{X}(B)$ when $B = B_{\max}$ is the one fixed by the agency, that is $39,673,460m^3$ per year.[68] We can adjust $\hat{X}(B)$ to $\hat{X}(B) = 39,673,460m^3$ by adjusting $W(B, X)$ through the parameter q. We have fixed parameter q according to average values of the specie intrinsic characteristics and of the wipe out function that we have taken , where $r = 0.85$, $\overline{B} = 1404$, $\alpha = 0.75$ and $\beta = 0.45$. To reach this desired level we have take $q = 3,35 \cdot 10^{-5}$.

Note that the agency determines the total amount of water allowed in the zone, and that we have take this amount as the maximum amount of water that the specie can tolerate without a decrease on their population when $B = B^E$. However, this is only an assumption. The unique way to know exactly the maximum amount of water that the specie can tolerate is knowing exactly the values of parameters q, α and β.[69] Moreover, due to we are fixing the maximum level of water by modulating parameter q and according to the maximum level allowed by the agency, we could be underestimating or overestimating other parameters, such as α and β, in the wipe out function, which also have an important weight in determining $\hat{X}(B)$.

[67] The dotation of $3,500m^3$ in $4,597ha$ and the dotation of $6,500m^3$ in $3,628ha$. The dotation of $1,500m^3$ is not applied in this area. (See AGS, 2010)

[68] The dotation of $6,500m^3$ per hectarea allows a transformation on more productive crop. Note that in this case the harvest parametres and the price would not be the same for conservationists and non-conservatinoists farmers.This case should be further analized. For a first simulation we assume the there is no a crop transfomation in any case.

[69] It is possible to determine the values of α, β and q by linearizing the cobb douglas function, assuming $\alpha + \beta = 1$ trough historical data about W, X and B. Unfortunately, we do not have enough data to determine this parameters.

9.3 Parameters on the farmers dynamics

To modulate the farmers population dynamics functions we first assume that the only water available for the conservationist farmers is rainwater. Rainwater does not have any cost for farmers. Moreover, both conservationist an non-conservationist farmers can use it due to is not an excludable good. This natural dotation of water allows farmers to crop dry cereal, such as barley with a cost of water equal to 0.[70] We fix the rainwater disponibility in $4,000m^3$ per hectare and year.[71] Dry barley have and average yield per year of $H(B, x_i) \in (2,000 - 3,000)\, kg/ha$ in this area.[72] Recalling that $\frac{\partial H(x_i,B)}{\partial B} < 0$. We take the calculated profits obtained by conservationists when $B = 1$ as a baseline for non-conservationists farmers profits.[73]

That means that the profit function of non-conservationists farmers is equal to the profit function of the conservationists farmers when $B = 1$, more the increase on profits due to the increase on productivity for the use of an extra irrigation. Further, we have assumed that non-conservationists will irrigate with a provision of $3,500m^3$ per hectare.[74] [75] This larger water allocation allows for an increase in productivity. and the yield obtained by non-conservationists farmers is $H(B, x_i) \in (5,000 - 6,000)\, kg/ha$.[76] Note also that in our motivational example c represent the opportunity cost of irrigation water and we represent this opportunity cost

[70] We take barley as it is the most produced crop in the zone.

[71] See MPSP in the Lleida Plains, 2010.

[72] See Memòria socioeconòmica del regadiu Segarra-Garrigues, 2010.

[73] that according our exemple is $H = 2940kg/ha$

[74] Note that this dotation is agregated to the natural rainwater of $4,000m^3$ per hectarea and year. Then the profits obteined by non-conservationist farmers are equal to the profits obteined by using $4,000m^3$ with an opportunity cost of 0 and the obteined by $3,500m^3$ with an opportunity cost different to 0.

[75] As we have assumed that there is not a crop transformation (only allowed with the dotation of $6,500m^3$ per hectarea) but an increase on crop productivity we supose that farmers only use the $3,500m^3$ dotation.

[76] See Memòria socioeconòmica del regadiu Segarra-Garrigues, 2010.

with the price of irrigation water, that in this area is around $0.13€/m^3$.[77] Finally we fix the price of barley in $p = 0.163€/kg$.[78][79] Moreover, the harvest function depends on other several parameters. Parameters A, γ and φ_{nc} are related with the technology available for cropping. we consider $\varphi_{nc} = 0.5$ and $\varphi_c \in [0.6, 0.9]$.[80]. Due to we have specific data about crop yield we adjust parameters A and γ in order to reach the desired yield. Then we take $A = 1.79$ and $\gamma = 0.912$.[81].

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[79] We checked other source of data such as, Resultados técnico-económicos de explotaciones agricolas de aragon, 2006 and Avance Anuario Estadistico, 2015, to compare prices and yields.

[80] Where $\varphi_i \leq \gamma$ and $\varphi_{nc} < \varphi_c$.

[81] Note that A, γ and φ_i are important factors in determining the harvest function (the yield crop). Nevertheless, we already have real data about yields in the zone. Therefore, we do not need to attend so much importance to this factors. What it is important in determining the profits is the reached yield, the opportunity cost and product prices. We have real data about all this parameters.

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