Universitat de Lleida

Protecting biodiversity on farmland: Which type of agri-environmental measure does it better?

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DOCTORAL THESIS

Protecting biodiversity on farmland: Which type of agri-environmental measure does it better?

Esther Estruch Bosch

This dissertation is submitted for the degree of Doctor of the University of Lleida
Programme of Law and Business Administration

Supervised by:
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Dedicated to

My parents

Francesc and Carme

My siblings

Xavier and Cristina

My partner and his daughter

Aleix and Paula

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Summary

General intensification in agriculture has led to biodiversity losses and also biodiversity protection reduces farm productivity. This Thesis, first, aims at, applying an evolutionary game theoretical framework, identifying which are the policy instruments better suited for promoting farmers participation in nature conservation programmes. Three policy instruments are considered, a constant subsidy, a collective subsidy and market mechanism. It is shown that any of these schemes allows for stable equilibria where natural resources sustainability and farm productivity are both possible. Second, a simulation model is parameterized using data that captures the characteristics of an endangered species of steppe bird, in an irrigation area in Catalonia. In this case, collective subsidies are better at protecting natural resources than constant subsidies and further that price differentiation scheme could better assures the natural resource conservation depending on the output price elasticity. Third, we use three experimental games to identify the farmers characteristics that are relevant in determining farmers participation in natural resources conservation programmes. We show that when farmers payoff depends on other agents' investment decisions, there is a high percentage of participation on natural resource protection.

Resum

Per una banda la intensificació general de l'agricultura condueix a la pèrdua de biodiversitat, i per l'altra, la protecció de la biodiversitat redueix la productivitat de les explotacions agrícoles. Aquesta Tesi té com a objectiu identificar quins són els instruments de política ambiental que millor promouen la participació dels agricultors en programes de conservació dels recursos naturals. Considerem tres instruments de política; un subsidi constant, un subsidi col.lectiu i un mecanisme de mercat. Mostrem que qualsevol d'aquests esquemes permet arribar a equilibris estables on la sostenibilitat dels recursos naturals i la productivitat de les explotacions agrícoles és possible. També hem parametritzat un model de simulació utilitzant dades d'una espècie d'au estèpica en perill d'extinció en una zona de regadiu a Catalunya. En aquest cas particular, els subsidis col.lectius funcionen millor que els constants a l'hora d'assegurar la protecció dels recursos naturals. A més, l'esquema de diferenciació de preus pot ser millor protegint els recursos naturals que els subsidis en funció de l'elasticitat preu del bé produit. Finalment, utilitzem tres jocs experimentals per identificar les caracterstiques dels agricultors que determinen la seva participació en programes de conservació dels recursos naturals. Mostrem que quan els beneficis dels agricultors depenen de les decisions d'inversió dels altres agricultors, hi ha un percentatge més elevat de participació en aquests programes.

Resumen

Por un lado, la intensificación general de la agricultura conduce a la pérdida de biodiversidad, y por el otro, la protección de la biodiversidad reduce la productividad de les explotaciones agrícolas. Esta Tesis tiene como objetivo identificar cuáles son los instrumentos de política ambiental que mejor promueven la participación de los agricultores en programas de conservación de los recursos naturales. Primero, consideramos tres instrumentos de política; un subsidio constante, un subsidio colectivo y un mecanismo de mercado. Mostramos que cualquiera de estos esquemas permite llegar a equilibrios estables donde la sostenibilidad de los recursos naturales y la productividad de las explotaciones agrícolas es posible. También hemos parametrizado un modelo de simulación utilizando datos de una especie de ave esteparia en peligro de extinción en una zona de regadío de Cataluna. En este caso particular, los subsidios colectivos funcionan mejor que los constantes a la hora de asegurar la protección de los recursos naturales. Además, el esquema de diferenciación de precios puede ser mejor protegiendo los recursos naturales en función de la elasticidad precio del bien producido. Finalmente, utilizamos tres juegos experimentales para identificar las caractersticas de los agricultores que determinen su participación en programas de conservación de los recursos naturales. Mostramos que cuando los beneficios de los agricultores dependen de las decisiones de inversión de otros agricultores, hay un porcentaje mayor de participación

en estos programas.

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Introduction

The loss of biodiversity is one of the main environmental challenges facing the planet. Even though the extinction of species has always occurred, the UN Environment Programme affirms that the Earth is now in the midst of a mass extinction. Scientists estimate that nearly 200 species of plant, insect, bird and mammal become extinct every 24 hours. To halt this loss of biodiversity, it is necessary to curb the set of activities that damage the environment. Farming was a major guarantor of the sustainability of biodiversity, since often farming traditions resulted in the development and preservation of habitats able to sustain a large range of species (Bignal and McCracken, 1996; Farina, 1997; Blanco *et al.,* 1998). However, nowadays, the trend towards monocultures, the intensive use of water, fertilizers, pesticides and phytosanitary products have jeopardized the preservation of natural environments. There is often a trade-off between farm productivity and sustainability of natural resources. General intensification in agriculture has led to biodiversity losses (Buckwell and Armstrong-Brown, 2004 and Young *et al.,* 2005) and biodiversity protection reduces farm productivity. However, biodiversity is crucial to guarantee the provision of a broad range of ecosystem services and public goods that benefit not only the natural and agricultural systems but also human health. Biodiversity is essential in assuring a soil rich in fungi and microorganisms that guarantee the existence of the necessary nutrients for plants; it is also essential in the preservation of pollinator communities, and in the production of healthy foods because it allows the dependence on chemical fertilizers and pesticides to be reduced. The conservation and recovery of biodiversity has been deemed a priority in most developed countries, and in particular in the European Union (EU), where initiatives such as the Natura 2000 network have been developed.

In this sense, the EU has enacted two major Directives to help reduce the rate of species extinction, the Habitats and the Birds Directive.[1] These two Directives provide mechanisms for the conservation of natural habitats and wild fauna and flora. Natura 2000 is a biodiversity preservation sites network created by the European Union to protect and ensure the conservation of protected species and of habitats of community interest protected under these two directives. It comprises all EU member state and every member state has to appoint its Natura 2000 sites according to the European Habitats and Birds Directive, and has to maintain such sites in a favourable state of conservation. The preservation of Natura 2000 areas results in the provision of environmental public goods, such as biodiversity protection, habitat conservation and landscape. Farmland is crucially important as 38% of the total area included in the Natura 2000 network is agricultural land.[2] However, making the preservation of natural resources compatible with intensive agriculture requires convincing farmers to follow a strict set of steps that often results in a reduction in farm profitability. Protecting a natural resource on private farmland usually implies applying some restrictions to the harvesting process, which increases production costs and/or reduces farmers' profits. In such cases, farmers often resist the incorporation of their land into the network or, once it has been included, they refuse to comply with the conservation plans designed

[1] Directive (EU) 92/43/EEC of the Council, of 21 May 1992, on the conservation of natural habitats and of wild fauna and flora and Directive (EU) 2009/147/EC of the Council, of 30 November 2009, on the conservation of wild birds.

[2] See European Commission (2014).

by the regulatory authorities.[3]

The aim of this thesis is to provide policy insights, analyzing different agri-environmental schemes focused on promoting farmers' participation in conservation programmes and to determine the performance of each one on protecting biodiversity on farmland. We are also interested in identifying farmers' characteristics and factors affecting farmers' willingness to collaborate with natural resource preservation programmes. The thesis is divided into 4 chapters.

In the first chapter, we capture the challenge faced by farmers through a co-evolutionary model where the evolution of a natural resource is affected by farmers' harvesting practices. In particular, we focus on the evolution of an endangered bird species and we assume that this bird population needs a minimum stock level to reach the protection goal.[4] We assume that farmers' goal is to maximize profits and they can follow two strategies: to be conservationists or non-conservationists. We use the evolutionary game theory based on the replicator dynamics (Taylor and Jonker, 1978) to evaluate changes in the composition in farmers' population between conservationists and non-conservationists. We demonstrate that the sustainability of natural resources and biodiversity on farmland requires the implementation of some kind of agri-environmental scheme promoting farmers' participation in natural resources conservation programmes.

In chapter 2, we analyze, also from a theoretical perspective, the performance of three different agri-environmental schemes on promoting natural resources conservation

[3]For example, the controversy generated by the Natura 2000 areas located in the Segarra-Garrigues channel project (Reguant and Lletjós, 2014) or the non-participatory implementation of Natura 2000 in Lower Austria (Geitzenauer *et al.,* 2016)

[4]We have taken a bird population because low intensity arable systems such as dry cereal steppe lands are often designated as Natura 2000 sites because they support rare and highly threatened species, such as for example some globally threatened birds, including the Great Bustard (*Otis tarda*) or Little Bustard (*Tetrax tetrax*), among others. See European Commission (2014).

on farmland. In this sense, to make habitats and species preservation compatible with economically sustainable agricultural practices, the EU has issued a set of measures aimed at supporting farmers' activity in protected areas through agri-environmental schemes. After reviewing the literature, it is clear that most of these schemes are carried out through direct payments per hectare.[5] Therefore, we first consider a constant subsidy per hectare subject to conditionality, that is only those farmers complying with the conservation programme harvesting measures receive an economic incentive. Second, we also introduce a collective subsidy scheme that represents a fixed payment per project or goal. It is inspired by the EU Leader and LIFE projects that aim to support partnership among different agents to protect a specific natural resource. In LIFE programs the EU designate a specific budget to a partnership group for the development of a specific conservation plan. Both LIFE projects and Leader introduce a partnership philosophy for natural resource conservation. Our collective subsidy scheme maintains this partnership philosophy and allows for a changing number of partners during the policy implementation process. Any policy design that had been assigned a fixed budget and had embraced a partnerships philosophy that allowed for a changing number of partners would result in an individual retribution that will depends on the number of participants. This is the reason why we decided to study a collective subsidy where the individual retribution depends on the number of participants. Finally, we introduce a price differentiation scheme. Countries have also developed market instruments based on tag systems aimed at supporting farmers' activity and natural resource protection, such as the organic certification in Europe.[6] We demonstrate that with any of these three agri-environmental schemes stable equilibria where natural resource and farm

[5]The most important source of funding of direct payments is the European Agricultural Fund for Rural Development (EAFRD). Regulation (EC) 1305/2013 of the Council, of 17 December 2013, on support for rural development by the European Agricultural Fund for Rural Development (EAFRD).

[6]Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91.

productivity are both sustained are possible and we further analyze differences among them.

Nevertheless, the compatibility of natural resource protection and farm productivity can become more complex when we turn towards the field evidence. In chapter 3, we analyze the performance of our co-evolutionary model using explicit functions and providing it with specific information and data. We use as an example a specific Natura 2000 area in the Plains of Lleida in Catalonia, where an endangered bird species, called Little bustard (*Tetrax tetrax*), is affected by the hydrologic investment project, the Segarra-Garrigues channel (Brotons *et al.,* 2004 and Reguant and Lletjós, 2014). We parameterize our theoretical model to analyze the performance of each agri-environmental scheme on protecting the bird population species.

Finally, in chapter 4 we analyze factors influencing human behaviour when people are asked to contribute to natural resource conservation. We develop three controlled experiments where we analyze the main factors affecting agents' contribution to natural resources conservation. In our theoretical model we assume that agents' behaviour is only conditioned by differences in payoffs; however, this does not need to be the case. In this sense, altruism, natural resource characteristics or risk aversion, among other factors, can also determine agents' behaviour (Olson, 1965; Eckel and Grossman, 1996; Herr, *et al.,* 1997; Fischer *et al.,* 2004; Ariely *et al.,* 2009). In order to highlight some of these factors we design three economic incentive experiments where a minimum number of farmers complying with the conservationist requirements is needed to assure the natural resource conservation. In the first setting, we design a basic game where farmers' investment decision process is undertaken without economic incentives. In this setting, the best strategy is always to make the investment decision associated with non-conservationist behaviour. Second, we introduce a threshold experiment where conservationists receiving a subsidy only depend on their own behaviour but not on other farmers' investments decisions. This threshold assures the natural resource recovery. Finally, we introduce another threshold incentive where whether or not a farmer receives the incentive depends not only on their own investment decisions, but also on fellow farmers' investment decisions. Our experiments' results show that when payoff depends on other agents' investment decisions, there is a higher percentage of natural resource protection success.

Chapter 1

Natural resource dynamics and farmers' behaviour co-evolutionary model

1.1 Introduction

Farmland is crucially important in natural resources conservation. In the EU, a large number of species and habitats protected under the Habitats or the Birds Directive depend on agricultural land. 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.[1] 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 certain modernization projects, such as the

[1]See Keenleyside *et al.* (2014*a*).

development of irrigation projects or the introduction of intensive farming practices.[2] In such cases, farmers often resist the incorporation of their land into the network or, once it has been included, they refuse to comply with the conservation plans designed by the regulatory authorities. Protecting these Natura 2000 sites usually leads to developing conservation plans oriented toward the protection of the natural environment, which usually results in setting limits to agricultural practices. These restrictions usually increase production costs and/or reduce farmers' profits, making it more difficult for farmers to comply with them. It is necessary to design farm production strategies and policy mechanisms that allow both farm profitability and biodiversity sustainability.

Furthermore, and quite often, farmers who harvest on Nature 2000 sites work under difficult economic conditions. Usually they are small owners that have to manage their harvests under increasingly difficult competitive conditions. Often these farmers are highly vulnerable and face global economic pressures that can lead to the abandonment of low-intensity farming practices or to the abandonment of the agricultural activity altogether (IEEP and Veenecology, 2005 and 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 incentives to modify agricultural practices and enable their economic sustainability, while also enabling the sustainability of habitats and biodiversity.

Our goal in this chapter is to demonstrate that the joint sustainability of natural resources and agricultural systems requires the introduction of agricultural schemes promoting environmentally friendly agricultural practices. We try to explain, from a theoretical perspective, the challenge faced by these farmers farming in these protected

[2]For example, the controversy generated by the Natura 2000 areas located in the Segarra-Garrigues channel project (Reguant and Lletjós, 2014) or the non-participatory implementation of Natura 2000 in Lower Austria (Geitzenauer *et al.,* 2016)

areas, and we present a bird population dynamics and farmers' behaviour co-evolution model in an evolutionary framework. We assume that individuals select a set of management actions, such as the level of fertilizer, pesticide and phytosanitary inputs used, and respond to differences in payoff by modifying their choices. We adopt the assumption that the weight of the population shifts gradually towards the group whose payoff is above average, that is, we assume that the evolution of the composition of the population is described by the replicator dynamics. This evolutionary approach differs from standard non-cooperative game theory, as it is not a game where agents use best-replies; our agents are myopic. 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 (Sethi and Somanathan, 1996; Noailly, 2003; Oses-Eraso and Viladrich-Grau, 2007*a*; De silva *et al.,* 2010; Sigmund *et al.,* 2011). Instead, we consider a situation where each agent exploits their own farmland in a resource preservation area such as Natura 2000. In our case, each farmer selects the level of inputs used during their production process, where both inputs and land are privately owned.[3] Farmers' goals is to maximize individual profits and choose the level of non-environmentally friendly inputs used during their farming activity. The use of these non-environmentally friendly inputs results in damages to the population of an endangered species, for example an endangered bird species. We assume that the natural resource is a non-excludable and non-rival good;

[3]See Blanco *et al.* (2009) for a similar application of replicator dynamics on private properties.

it also results in a negative externality for farmers.

Further, it is known that the recovery of a natural resource often requires reaching a minimum stock level or threshold (see Palfrey and Rosenthal 1984; Croson and Marks 2000; Suleiman *et al.,* 2001; Cartwright and Stepanova, 2017). It could be the case that, even if there is a proportion of farmers using environmentally friendly inputs, the natural resource is not recovered. That is, those farmers' efforts do not offset the damage caused by other farmers using non-environmentally friendly inputs. In these situations, the growth of natural resources depends on the number of farmers that participate in a conservation programme: the higher the number of participating farmers, the greater the chances that the preservation goals will be fulfilled. Furthermore, in most cases a minimum level of farmers' participation is needed to assure the success of the conservation programme. That is, the natural resource is only preserved if a certain conservationists' threshold is reached. In this sense, we introduce in the natural resource dynamics a minimum level effort required to reach a level of B where the natural resource could be sustained.[4]

This chapter is organized as follows. In the first section we describe the dynamics of the natural resource stock and its possible equilibria. In the second section we analyze the farmers' behaviour and its equilibria. Finally, we present our conclusions and we show that, without any type of agri-environmental scheme, the only possible equilibrium is an equilibrium where no one uses environmentally friendly inputs and the endangered species is driven to extinction.

[4]We use a similar natural resource dynamics to Osés-Eraso and Viladrich-Grau (2007*a*); nevertheless, we have introduced a participation threshold below which the natural resource could not be recovered.

1.2 Resource Stock Dynamics

We consider a model where a farming land area of L_Z hectares provides habitat for an endangered species of birds, B. We represent the natural evolution of the bird population with the classic growth model, where the rate of replenishment depends on the resource stock level, B, and is represented by a differentiable function $F(B)$. We assume that this function satisfies the usual assumptions describing the dynamics of renewable resources. 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 $B > \bar{B}$ $F(B) = 0$.[5] This function is depicted in Figure 1.1.

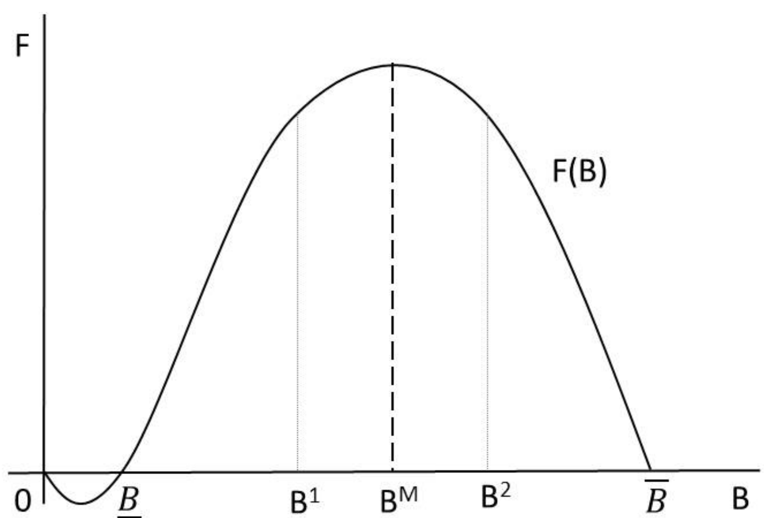


Figure 1.1: $F(B)$ function.

[5]A similar resource dynamics can be found in Osés-Eraso and Viladrich-Grau (2007*a*).

Farming activities, that include the use of non-environmentally friendly inputs, can damage the bird habitat and therefore can threaten the conservation of the bird population. We represent this situation with a so-called wipe out or extinction function, $W(B, X)$. Each farmer determines the individual amount of non-environmentally friendly inputs used x_i (such as pesticides and phytosanitary products or excess irrigation) during the harvesting process and $X = \sum_{i=1}^{N} x_i$ is the total volume of non-environmentally friendly inputs used by the N farmers that own agricultural land in L_Z. $W(B, X)$ determines the amount of resources wiped out due to the use by the community of a level of non-environmentally friendly inputs equal to X, and given a stock level equal to B. It is a twice-continuously differentiable function, $\frac{\partial W}{\partial X} \geq 0$, $\frac{\partial^2 W}{\partial X^2} \leq 0$, $\frac{\partial W}{\partial B} \geq 0$, $\frac{\partial^2 W}{\partial B^2} \leq 0$, $\frac{\partial^2 W}{\partial B \partial X} \geq 0$, and $\frac{\partial (W/X)}{\partial B} \geq 0$,[6] and also $W(0, X) = W(B, 0) = 0$. The evolution of the resource stock depends on this function and, therefore, the resource stock changes at a rate equal to the difference between the renewal and the wipe out or extinction rate:

$$\dot{B} = F(B) - W(B, X) \tag{1.1}$$

A natural resource is in equilibrium when its stock remains constant over time, that is, when the rate of renewal is equal to the extinction rate, $\dot{B} = 0$. We assume that, for any stock of birds, $\underline{B} \leq B \leq \bar{B}$, there is a non-environmentally friendly amount of inputs, X, such that the wipe out rate, $W(B, X)$, coincides with the rate of renewal, $F(B)$, that is, $\dot{B} = 0$; we represent this amount by $\widehat{X}(B)$.[7] Further, note that the total amount of non-environmentally friendly input used by the community X does not necessarily coincide with the $\widehat{X}(B)$. The amount of non-environmentally friendly input

[6]These are standard assumptions to characterize an extraction function. For a more detailed description see, for example, Dasgupta and Heal (1979).

[7]If this were not the case, the resource would be inexhaustible. For a full description of this function $\widehat{X}(B)$, see Appendix 1.5.1.

used by the community X is determined by farmers' individual behaviour.

We consider that a set of $N = \{1, \ldots, n\}, n \geq 2$ farmers cultivate in an area L_Z. We assume that the environmental agency establishes a convention on the appropriate farming practices, setting limits for the maximum levels of non-environmentally friendly inputs used per unit of farmland; we represent this limit by $\overline{x}$.[8] A 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, $\overline{x}$. Each farmer $i \in N$ chooses their own level of non-environmentally friendly inputs used per unit of farmland, x_i. 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, agents choose between two input levels $\{x_c, x_{nc}\}$ where $x_c < x_{nc}$.

1.2.1 The equilibrium conditions of natural resource dynamics

We assume that the bird population is evenly distributed over the whole area and that they can migrate from one plot to another; therefore, we consider that the aggregated population of birds, B, can affect all farmers. In our case B is a non-rival negative externality such that the benefits associated with the reduction of B are enjoyed by all farmers.[9] Furthermore, note that there could be a level of stock B above which

[8] The types of limitations imposed for the organic certification in the EU are limitations to the use of irrigation and/or limitations to the use of some chemical treatments.

[9] Examples of this case can be found in Rollins and Briggs (1996) who analyze 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 be caused to crops by some protected

farm production is not worthwhile, $B_{\max}$. For $B > B_{\max}$ the stock of birds is so large that farm production is not profitable, $u_i < 0$, for any x_i. For $B > B_{\max}$ there are no farming practices that can counterbalance the effect of B and allow a positive profit. For $B > B_{\max}$ farmer profits are negative and there is no harvesting effort. This would be an extreme case, where a population of birds has become a plague. We do not consider this case in our paper. We assume that $B < B_{\max}$ and farmers can obtain positive profits. Moreover, we assume for each B such that $B < B_{\max}$ that there is a minimum amount of non-environmentally friendly input, $x_{\min}(B)$, that allows a positive profit.[10] We assume that the agreed upon standard, $\overline{x}$, allows positive profits. Conservationist farmers 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 $x_{\min} \leq x_c \leq \overline{x} \leq x_{nc} \leq x_N$.

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 conservationist farmers.[11] The total level of non-environmentally friendly inputs is a positive, continuous and decreasing function of s_c.[12] The level of non-environmentally friendly inputs used by the N farmers in area L_z is also an increasing function of bird stock level B for any $B < B_{\max}$. 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 $s_c^E \in (0, 1)$ is such that $X(s_c^E, B^E) = \widehat{X}(B^E)$, see Fig.1.2a where

species when they are recovered.

[10] This minimum amount could be zero.

[11] We assume 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 $X(B)$ was a decreasing or constant function of B.

[12] If the amount of non-environmentally friendly inputs used is positive, then $\frac{\partial X}{\partial s_c} = n\left(x_c - x_{nc}\right) < 0$. 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.

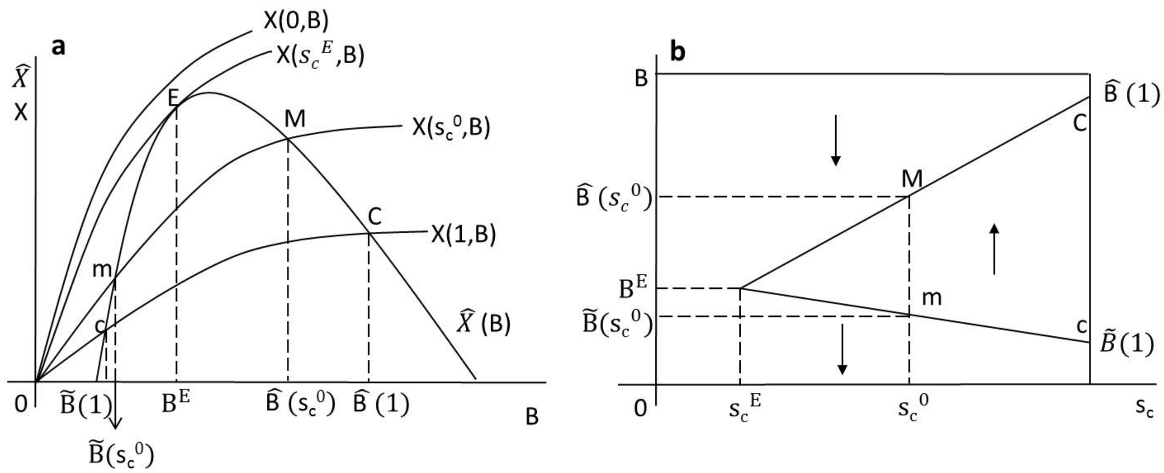


Figure 1.2: Natural resource equilibria.

point E is a semi-stable equilibrium point of the resource dynamics. Therefore, we have introduced a threshold below which the existence of a sustainable natural resource equilibrium is not possible.[13] 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 be 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 1.2a, respectively.[14] Not all intersection points determine stable equilibria, 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 $B = 0$.*

[13]Oses- Eraso and Viladrich-Grau, 2007a did not introduce this s_c threshold.

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

Points C, and M in Fig. 1.2a represent stable equilibria, while the unstable equilibria are represented by 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. 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 $B < \widetilde{B}(s_c^0)$.[15] We also represent these equilibria in the phase diagram of Fig 1.2b, 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.

1.3 Farmers' Behaviour

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 programme. We assume that each farmer owns one hectare and that the extension of area L_z and the number of farmers N are given and fixed. Non-environmentally friendly farming practices, such as the improper use of fertilizers, pesticides and phytosanitary products or a high frequency of irrigation, can damage natural resources, and in particular, the habitat of steppe birds. We assume that

[15] Other equilibrium cases are possible; for all these cases the conditions for stable equilibrium stated in Lemma 1 would continue to hold. Figure 1.4 in Appendix 1.5.1 illustrates some possible resource dynamics.

the environmental agency has established a convention about the appropriate farming practices. Establishing appropriate farming practices usually implies setting limits to the maximum levels of non-environmentally friendly inputs that can be used per unit of farmland; we represent this limit by $\overline{x}$.[16] A 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 $\frac{\partial^2 h}{\partial x_i^2} \leq 0$. [17] Moreover, we consider that the harvest function is a decreasing function of the bird population B, $\frac{\partial h}{\partial B} < 0$.[18] We assume that B is a negative externality that affects all farmers' crops in area L_Z. We further assume that the use of x_i can, to some extent, counterbalance the reduction in the individual harvest caused by the population of birds B, $\frac{\partial^2 h}{\partial x_i \partial B} \geq 0$.[19] Farmers benefit from a local effect from the use of non-environmentally friendly inputs; birds are less comfortable in fields where a large volume of pesticides is used or where irrigated crops are grown. Accordingly, for a given stock B, the larger the amount of x_i used by farmer i, the larger

[16]Under the Birds Directive each Member State has the duty to safeguard the habitats of threatened birds in their national territory. The types of limitations imposed in each protected area are specific; however, in general they require limiting the farmers' exploitation level, for example through limitations to the use of irrigation and/or limitations to the use of some chemical treatments in fallow areas or on margins, 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.

[17]Several types of non-environmentally friendly inputs could be used during the production process, some more damaging than others. We do not distinguish among different types of non-environmentally friendly inputs and we summarize their effects in one variable. Apart 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 inputs has already been determined during the maximization process and that at this point there are no appropriate substitutes left for these non-environmentally friendly inputs represented by x_i.

[18]It could be the case where $\frac{\partial h}{\partial B} = 0$. We demonstrate later that this case does not change our conclusions.

[19]We follow a production function similar to Noailly (2008).

the harvest, and therefore $h(x_{nc}, B) > h(x_c, B)$. 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 their plot of land, $\left|\frac{\partial h(x_{nc},B)}{\partial B}\right| < \left|\frac{\partial h(x_c,B)}{\partial B}\right|$.[20] 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 $\frac{\partial(x_{nc}-x_c)}{\partial B} > 0$. 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. Further, we assume that this non-environmental friendly input is costly. We represent by c the cost per unit of input, we assume c is constant and only includes the private cost of the input. Farmers do not consider the social cost of the inputs used.[21]

Further, we assume that individuals select a level of inputs x_i and respond to differences in payoff by modifying their choices. We model the payoff function of a representative farmers as $u_i(x_i, B) = ph(x_i, B) - cx_i$, where p is the output price assumed constant. In order to prevent sudden changes in behaviour patterns, we adopt the assumption that the weight of the population shifts gradually towards the group whose payoff is above average. We incorporate this by assuming that the evolution of the composition of the population is described by the replicator dynamics: $\dot{s}_c = \omega s_c \left(u_c - \overline{u}\right)$. Because the average payoff is $\overline{u} = s_c u_c + \left(1 - s_c\right) u_{nc}$, this differential equation can be

[20]Also, the larger the x_i the smaller the reduction in $h(x_i, B)$ caused by B, that is, $\frac{\partial^2 h}{\partial x_i \partial B} \geq 0$. The reduction $\frac{\partial h_i}{\partial B} < 0$ decreases in absolute value.

[21]We could have assumed that conservationist farmers paid the full or social cost of the inputs used, as for example ascertains the Water Framework Directive of the EU (2000/60/EC), in such a case the unitary cost of the input for conservationist farmers should have been lower than for non-conservationist, $c_n < c_{ns}$. However, in the area of study, the Segarra-Garrigues irrigation area, environmental cost are not considered in the price of inputs, and in particular the price of irrigation water is the same for all types of farmers. We thank Renan Goetz for suggesting this interesting interpretation of our model. We plan on approaching this modification in future research.

rewritten as:

$$\dot{s}_c = \omega s_c (1 - s_c)(u_c - u_{nc}) = -\omega s_c (1 - s_c)(u_{nc} - u_c) \tag{1.2}$$

where ω represents the rate at which farmers imitate each other. The replicator dynamics represents the behaviour of adaptive farmers. Farmers alter their strategies to imitate their more successful fellow farmers. In this dynamic system, the change in the proportion of conservationists is a gradual process. Moreover, as $0 < s_c < 1$, we can see that the change in behaviour depends on the differences 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 to change strategy. We are interested in the steady states of the dynamic system given by equations 1.1 and 1.2. An equilibrium of the systems is a pair (s_c^*, B^*) such that $\dot{B} = 0$ and $\dot{s_c} = 0$.

We will attain an equilibrium in the farmers' dynamics when the proportion of conservationist farmers remains constant over time, that is $\dot{s}_c = 0$. From equation 1.2 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 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 situations that are very relevant for the sustainability of the natural resource. However, the replicator dynamics does not force a Nash equilibrium in every time period. It can be shown, though, 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.[22] Therefore, we are interested in the steady states of the dynamic system given by equations 1.1 and 1.2. An equilibrium of the systems is a pair (s_c^*, B^*) such that $\dot{B} = 0$ and $\dot{s_c} = 0$.

1.3.1 The equilibrium conditions of farmers' behaviour

Now we move on to analyze the evolution of the farmers' behaviour. Farmers face a cost on taking actions to protect biodiversity; therefore, to encourage conservationist behaviour, environmental agencies have introduced agri-environmental schemes. For example, the EU has introduced a range of schemes that focus mainly on rewarding those farmers that contribute to the natural resource rather than punishing those that behave as non-conservationists. The EU has also created other types of mechanisms such as market instruments.[23] Therefore, it is necessary to introduce some type of mechanism to promote conservationist behaviour. To see this, recall that non-conservationist farmers choose x_{nc}, which maximizes payoff, and that conservationists follow the strategy that yields the maximum level of profits without violating the standards set by the environmental agency, $x_{nc} \leq \overline{x}$. Whether any agri-environmental scheme is applied we define the payoff function as $u_i = \pi_i = ph(x_i, B) - cx_i$. Then, for any given B, the payoff of a non-conservationist farmer will be larger than (or at least equal to) the payoff of a conservationist farmer, that is, $u_{nc} \geq u_c$ for all B.[24] Note that the payoff function

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

[23]We analyze this mechanism in greater depth in chapter 2.

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

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 due to the replicator dynamics, as $u_{nc} \geq u_c$ for all $s_c \in (0,1)$, any conservationist farmer will alter their strategies to imitate the more successful farmers, and all farmers will end up being non-conservationist. On the other hand, an allocation where all farmers behave as conservationists $(s_c, B) = (1, B)$ would be an equilibrium but unstable. Furthermore, a heterogeneous equilibrium could never exist, except in the trivial case that $x_{nc} = x_c$.

Claim 1.1 *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-conservationist equilibrium $(s_c, B) = (0, B)$. A full conservationist equilibrium could exist but will not be stable $(s_c, B) = (1, B)$. A heterogeneous equilibrium could never exist except in the case that $x_{nc} = x_c$.*

Recall that the natural resource needs a minimum level of sc, that is sc^E to allow the existence of a stable equilibrium, and we are interested in an equilibrium of the systems (s_c^*, B^*) such that $\dot{B} = 0$ and $\dot{s_c} = 0$. Therefore, if the unique farmers' equilibrium is a full non-conservationist equilibrium, the natural resource will always be driven to extinction and the joint sustainability of natural resources and agricultural systems is not possible.

1.4 Conclusions

In this first chapter we introduced the theoretical co-evolutionary model and we demonstrated that, without any mechanism promoting conservationist behaviour, the only stable equilibrium is an all non-conservationists equilibrium; therefore, in this situation the natural resource is driven to extinction. Further, note that the existence of a threshold means that below this level the unique natural resource equilibria is $B = 0$. In the next chapters we have better analyzed the threshold effect. Finally, it is clear that farmers farming on protected areas face a harvesting challenge; therefore, it is necessary to introduce some kind of agricultural scheme promoting conservationist behaviour.

1.5 Appendix

1.5.1 Natural resource dynamics complementary material

We represent the natural resource equilibrium level by the function $\widehat{X}(B)$, as seen in Figure 1.3. 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.[25] On the other hand, however, when stocks are lower than B^M the non-environmentally friendly input level, $\widehat{X}(B)$, may be either an increasing or a decreasing function of B,[26] see Fig. 1.3. 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 the stock to be maintained must be the same in both situations. How-

[25] 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 $B > B^M$.

[26] 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 $\frac{dF}{dB} < \frac{\partial W}{\partial B}$.

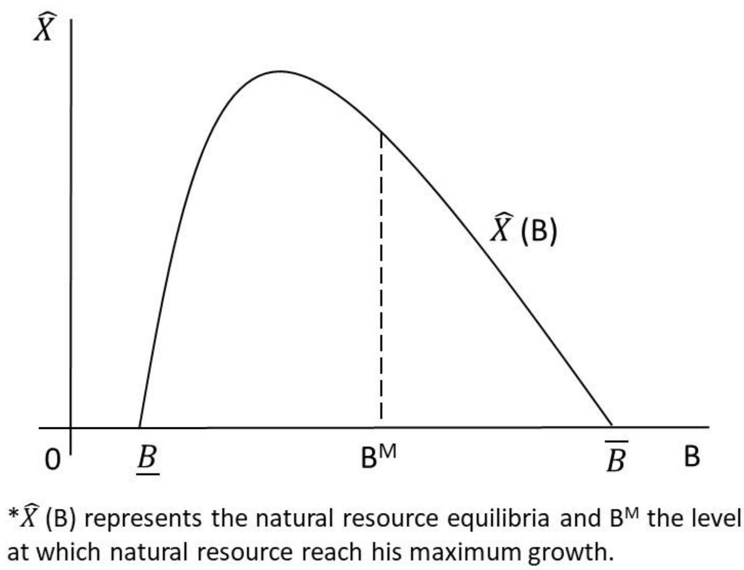


Figure 1.3: Natural resource equilibria, $\widehat{X}(B)$, function.

ever, B_2 is larger than B_1; the larger the number of units of a resource the easier it will be to hunt for a given amount, and therefore less effort will be necessary to hunt for the same number of units. It is easier to hunt for a given number of resources 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 1.3. 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. Other possible natural resource equilibria are represented in Figure 1.4.

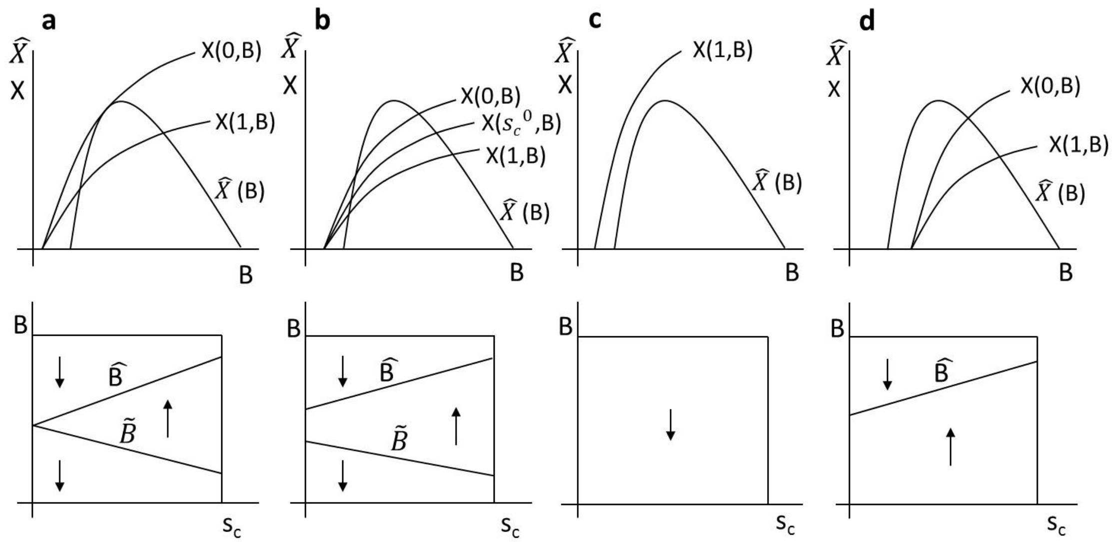


Figure 1.4: Other natural resource dynamics.

1.5.2 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 becomes 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 on 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 locally 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 it 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 also be negative. Consequently, 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 $\frac{\partial \widetilde{B}}{\partial sc} < 0$.

Chapter 2

Agri-environmental scheme models: Subsidies and market instruments

2.1 Introduction

To make habitat preservation compatible with economically sustainable agricultural practices, most countries have issued a set of measures aimed at supporting farmers' activity in protected areas through agri-environmental schemes.[1] In the EU, 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. The most important source of funding in agricultural areas is the European Agricultural Fund for Rural Development (EAFRD) that funds a large part of the Common

[1]For example, the U.S. provides incentive-based conservation programmes on which farmers can enrol voluntarily, such as the Environmental Quality Incentives Program, 2009.

Agricultural Policy (CAP), particularly Pillar II, aimed at rural development.[2] The EAFRD also includes the Leader funds that aim to capitalize natural resource conservation through the creation of partnership groups with a common identity. Leader finances Local Action Groups (LAGs) and promotes sustainable development projects on a small scale. Thus, Leader funds promote cooperation among farmers to carry out projects that combine resource conservation and land use (See European Commission, 2014). Moreover, Pillar I of the CAP is financed by the European Agricultural Guidance and Guarantee Fund (EAGGF), which is a major source of direct payments per hectare subject to conditionalities. Pillar I can, especially, give support to the economic viability of farms with low-intensity systems, as occurs, in some cases, on agricultural land within Natura 2000. There are other instruments which can be used to finance Natura 2000, such as the LIFE Programme, created by the EU to support environmental projects, nature conservation and climate actions. Over half of the budget destined to the environment sub-programme is spent on actions to support nature and biodiversity, with particular attention to Natura 2000.[3] After reviewing these programmes, it is clear that most of these agri-environmental schemes are carried out through direct payments per hectare and are subject to conditionality. That is, only farmers that comply with the regulations receive a per hectare subsidy.[4]

Nevertheless, subsidies are not necessarily the only mechanism able to protect natural resources on farmland. In this respect, in recent decades a growing interest in environmentally friendly agricultural products has appeared. Many studies have shown

[2]According to Regulation (EC) 1305/2013 of the Council, of 17 December 2013, on support for rural development by the European Agricultural Fund for Rural Development (EAFRD). See also IEEP and Veenecology (2005).

[3]See other sources of funding in Farmer (2012) and European Commission (2014).

[4]Farmers who are located in Natura 2000 sites generate environmental services such as biodiversity or landscape conservation and, therefore, it could be argued that they should be rewarded through result-based agri-environment schemes, such as payments for environmental services (PES), as some authors have proposed (Swinton et al.. 2007; Keenleyside *et al.*, 2014*b*; Smith and Sullivan, 2014).

an increase in consumers' willingness to pay for these products (Loureiro *et al.,* 2002; Chen, 2007; Zhou *et al.,* 2016). Ecological and environmentally friendly products are highly related to the healthy perception of food. People have become more conscious about their health and a growing market for ecological and environmentally friendly agricultural products has arisen (Vega-Zamora *et al.,* 2013). These products are attractive to a particular segment of the market, which is usually willing to pay a higher price for them than for conventional products. Farming ecological or environmentally friendly food could have some market advantages compared to conventional crops if they could be distinguished from these. Conventional farmers rarely have any market power; agricultural products such as cereals, fruits and vegetables are commodities that are bought and sold purely on price. Therefore, farmers usually sell their products in competitive and global markets taking the prices as given. On the contrary, environmentally friendly products have some market power when this type of food can be distinguished from conventional production. Examples abound because governments and associations have developed tag systems and certifications to single out ecological and environmentally friendly agricultural production, such as the organic certification in Europe[5] or the United States Department of Agriculture (USDA) organic label.[6][7] Often, the main goal of tag systems is to provide information to the consumer about the farming process rather than to protect the environment. Nevertheless, protecting these special areas also helps to protect the habitat and biodiversity. Some examples are the PDO of "Delta del Ebre" rice. That is a rice produced in the natural park of "Delta de l'Ebre" in Catalonia. And the PGI of Pyrenean beef that assures an extensive livestock

[5]Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91.

[6]National Organic Program (2019).

[7]There are other market instruments different from tag systems. For example, the Bush Tender in Australia (Department of Sustainability and Environment of Australia, 2006), where the state rewarded farmers for the generation of environmental services through payment schemes based on the market.

system throughout the Pyrenean zone (Spain and France).[8] Many authors have studied the market power of environmentally friendly products (Amacher *et al.,* 2004; Conrad 2005; Ferraro *et al.,* 2005; Grolleau and Ibanez, 2008; Blanco *et al.,* 2009 and Lozano *et al.,* 2010 among others).

In this chapter, we analyze and compare the performance of three types of agri-environmental schemes on protecting natural resources. We provide our model with three different types of schemes and we analyze their capability on protecting an endangered bird species. First, we consider a fixed payment per hectare subject to conditionality. This type of payment is the most widespread. Second, we introduce payment schemes that represent a fixed payment by project or goal.[9] This payment is also subject to conditionality, only conservationist farmers receive a payment. The individual payment per conservationist farmer depends on the number of conservationist farmers participating in the project. Finally, we introduce a price differentiation scheme to analyze whether label systems could be used to improve the sustainability of a natural resource, given that labels allow product differentiation that could then enjoy higher prices and less competition.

Our goal is to analyze, from a theoretical perspective, the performance of these different types of agri-environmental schemes with the goal of ensuring the sustainability of natural resources in agricultural systems. We compare the performance of these three types of measures, and we contribute to the joint analysis of their economic viability and their capability to protect an endangered bird species. This chapter is organized as

[8] In the EU there are the protected designations of origin (PDO), protected geographical indications (PGI) and traditional specialities guaranteed (TSG) for agricultural products and foodstuffs. Regulation (EU) No 1151/2012 of the Council, of 21 November 2012, on quality schemes for agricultural products and foodstuffs.

[9] We do not aim to exactly reproduce Leader or LIFE programmes because these aids also include the participation of other types of agents different from farmers; however, we incorporate their cooperation philosophy.

follows. In the first section, we analyze the farmers' behaviour under payment and price differentiation schemes. Next, in section 2, we analyze the policy measures that can provide, in equilibrium, both sustainable management of the natural resource and an economically sustainable agricultural activity. In section 3, we present our conclusions.

2.2 The farmers' dynamics under agri-environmental schemes

2.2.1 Farmers' behaviour under payment schemes

We model the payoff function of a representative farmer as:

$$u_i(x_i, B) = \pi_i(x_i, B) + \phi_i(s_c) = ph(x_i, B) - cx_i + \phi_i(s_c) \tag{2.1}$$

where farmers receive a per hectare payment of $\phi_c(s_c)$ if they participate in the conservation programme.[10] 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.* $\frac{\partial \phi_i(,s_c)}{\partial s_c} = 0$.

Second, a payment scheme assigned to reach a given goal. A fixed subsidy per project where the total budget assigned to the conservation project will be fixed and then the individual subsidy received by each conservationist farmer will decrease as the

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

number of conservationist farmers increases, thus, $\frac{\partial \phi_i(s_c)}{\partial s_c} < 0$. Other things being equal, if the total budget for a conservation project is given and the number of conservationist farmers involved in the conservation project increases then the individual subsidy will have to decrease. That is, the individual subsidy depends on the proportion of conservationists 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. We focus on this type of payment scheme because most nature preservation programs are associated to a fixed budget for the development of a conservation plan such as LIFE in the EU and the Conservation Reserve Program in the US (see Stubbs, 2014).[11] Furthermore, the environmental benefits, such as biodiversity or habitat conservation, provided by conservationist farmers will increase with the percentage of conservationist, however it is reasonable to assume that these benefits increase at a decreasing rate. That is, it seems that it is reasonable to expect that as the number of conservationist rises the marginal benefit generated by an additional conservationist decrease. Therefore, if those benefits would have to be rewarded with a policy scheme, such as a subsidy for natural resources conservation, the scheme that will better mimic the marginal benefit function will be an individual payment scheme that is a decreasing function of the number of conservationist farmers.

Finally, we do not consider a subsidy where the individual amount received by each agent increases as the number of conservationist farmers increases, $\frac{\partial \phi_i(s_c)}{\partial s_c} > 0$. Even though it is appealing because it 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 constraints. On the other hand, if the agency had

[11]Even though in these cases the number of agents that participate in these programs it does not evolves with the payments received.

an unlimited budget, a large enough individual subsidy could be paid to convince all non-conservationist farmers to behave as conservationists. We further assume that the application of these policy instruments is managed by a unique regulatory agency. We abstract from analyzing the complex decision process and conflicts that can emerge when several governmental agencies are involved.[12] We acknowledge that these differences can let to political and legal conflict and make even more difficult the application of the environmental regulation but we do not address this topic in this Thesis. We do not consider either the existence of monitoring and enforcement problems.

Recall that if there were not subsidies it would always be the case that $u_{nc}(x_c, B) > u_c(x_c, B)$. Let us define $B_{far}(s_c^Q)$ as the level of resource stock B such that given a proportion of conservationist farmers s_c^Q, s.t. $1 > s_c^Q > 0$ satisfies $(u_{nc} - u_c)(B) = 0$, or in other words $(\pi_{nc} - \pi_c)(B) = \phi_c(s_c^Q)$. 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 a heterogeneous equilibrium point of the farmers' dynamics.

Lemma 3A *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 rather a continuum of equilibrium points.*[13]

[12] As it was the case for example, in the Segarra-Garrigues channel where the "Departament de Medi Ambient I Habitatge" and the "Departament d'Agricultura Ramaderia i Pesca" of the Catalan government had opposite views about the application and enforcement of the Birds Directive on the Plain of Lleida. The conflict between these two governmental departments was a reflection of the opposite interest of the two stakeholdes, farmers and conservationist groups in these area.

[13] 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

We are assuming that the agency faces a binding budget constraint. In such a case the agency will only allocate a finite amount of money to each conservation project. For the constant and the decreasing subsidy schemes to have the same allowance A it has to hold that $\phi(s_c)s_c = \phi s_c = A$ for $s_c = 1$. That is, for any change in s_c then $\phi(s_c)s_c \leq A$, that is $\frac{\partial \phi(s_c)}{s_c} \leq 0$. For this to be true, it is necessary that $\frac{\partial \phi_c}{\partial s_c}\frac{s_c}{\phi_c} \leq -1$.[14] Further, note that if $\phi(s_c)s_c = A$ for all s_c then the elasticity of ϕ_c with respect to s_c must be unitary, that is $|\epsilon_{\phi_c}| = 1$. The relation between the resource stock and the proportion of conservationist farmers in equilibrium is described in Lemma 4.

Lemma 4A *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.*

For an easier summary of our results, we represent the farmers' dynamic continuum of stable equilibria (B^*, s_c) as $\widehat{B}_{far}(s_c)$. We represent $\widehat{B}_{far}(s_c)$ in the phase diagrams of Figure 2.1. In Figure 2.1a, we represent two functions, the payoff differences $(\pi_{nc} - \pi_c)$ and the subsidy $\phi(s_c)$; our independent variable is B. Recall that $\frac{\partial[\pi_{nc}-\pi_c](B)}{\partial B} > 0$ and $\frac{\partial \phi_i(s_c)}{\partial B} = 0$. The intersection of these two functions determines an equilibrium $(\widehat{B}_{far}(s_c^*), s_c^*)$, where $(\pi_{nc} - \pi_c) = \phi_c(s_c)$.

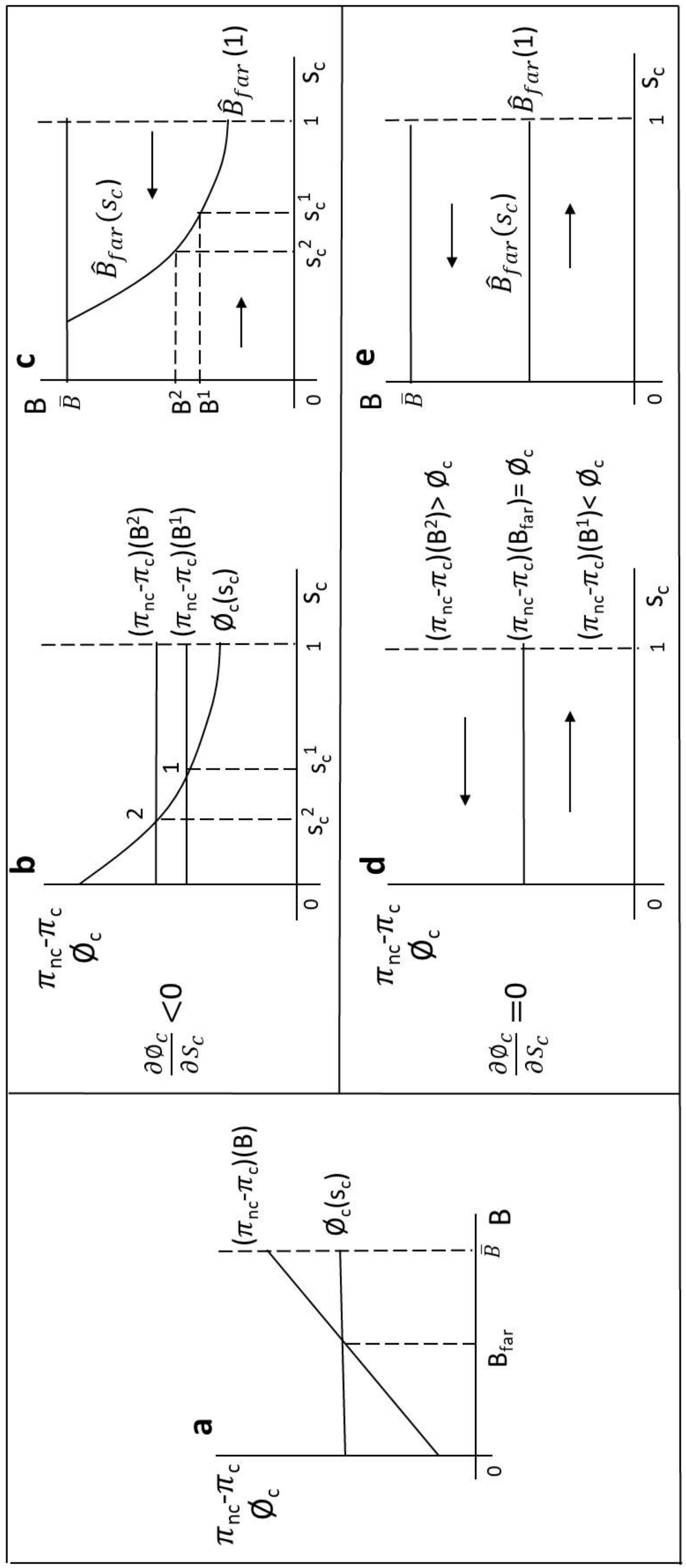
Further, in Figures 2.1b and 2.1d we represent the payoff differences $(\pi_{nc} - \pi_c)$ and the subsidy $\phi(s_c)$; now our independent variable is s_c. Recall that $\frac{\partial[\pi_{nc}-\pi_c](s_c)}{\partial s_c} = 0$ and $\frac{\partial \phi_i(s_c)}{\partial s_c} \leq 0$. In Figure 2.1b, we represent the case where the subsidy is a decreasing function of s_c, that is $\frac{\partial \phi_i(s_c)}{\partial s_c} < 0$ and, in Figure 2.1d, we represent a fixed subsidy,

above, we do not consider this case in this paper. It is not realistic in the sense that it could be difficult to be implemented 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 it allowed $\frac{\partial \phi_c(s_c^*)}{\partial s_c} > 0$. As can be seen from our proofs, in this case the full conservationist equilibria are stable equilibria of the farmers' dynamics. For a graphical representation see Figures 2.5 and 2.6 in Appendix 2.6.2.

[14] 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, $\frac{\partial \phi_c}{s_c}\frac{s_c}{\phi_c} \leq -1$.

that is $\frac{\partial \phi_i(s_c)}{\partial s_c} = 0$. In points 1 and 2 of Figure 2.1b, $(\pi_{nc} - \pi_c)(B) = \phi_c(s_c)$ are heterogeneous equilibrium points of the farmers' dynamics. Note that $B^1 < B^2$ and then $(\pi_{nc} - \pi_c)(B^1) < (\pi_{nc} - \pi_c)(B^2)$; therefore, a larger B results in a larger $(\pi_{nc} - \pi_c)(B)$. The subsidy $\phi_c(s_c)$ that equates the difference in profits in B^2 would have to be larger than in B^1. As $\phi_c(s_c)$ is a decreasing function of s_c then $s_c^2 < s_c^1$. And $\widehat{B}_{far}(s_c)$ would be a decreasing function of s_c. Decreasing $\widehat{B}_{far}(s_c)$ examples are represented in 2.1c. However, if $\frac{\partial \phi_i(s_c)}{\partial s_c} = 0$, as in Figure 2.1d, there would only be a B such that $(\pi_{nc} - \pi_c)(B) = \phi_c$ then $\widehat{B}_{far}(s_c)$ is a constant function of s_c. This case is represented in 2.1e.[15]

[15] We represent the set of unstable equilibria $(B_{far}(s_c^*), s_c^*)$ as $\tilde{B}_{far}(s_c)$. Increasing $\widetilde{B}_{far}(s_c)$ examples are represented in Figure 2.5 of Appendix 2.6.2.



* In all panels we assume $B^1 < B^2$. In equilibria the corresponding proportion of conservationists, s_c, adjust to reach the corresponding equilibria. Allocation 1 represents the equilibrium point (B^1, s_c^1). A similar interpretation could be done for point 2. Finally, $\hat{B}_{far}(s_c)$ represents the set of stable equilibrium points (B, s_c) of the farmers' dynamics.

Figure 2.1: Farmers' dynamics under subsidies schemes.

2.2.2 Farmers' behaviour under a price differentiation scheme

We assume now that conservationist farmers can identify their output with a label that singles them out as environmentally friendly producers and differentiates their output from that produced by non-conservationist farmers. Most agricultural products, from cereals to vegetables and from legumes to fruit, are traded in highly competitive markets; therefore, we assume that non-conservationist farmers sell their products in competitive markets and take output prices as given. However, irrespective of whether conservationist farmers, due to their sustainable farming conditions, are authorized to label their output, they are in fact being allowed to differentiate their output. Consequently, there could be a difference between the price of the output produced by conservationist farmers and the price of the output produced by non-conservationist farmers. Usually, the supply of these sustainable farming products is limited, as they are associated with specific farming conditions or geographical areas. This limitation translates into market power for conservationist producers. An example could be products associated under protected designation of origin. In such cases, it is highly likely that conservationist farmers can charge a higher price for their crop than non-conservationist farmers.

Each conservationist farmer produces output $h(x_c, B)$, and Q_c is the total amount produced by all conservationist farmers, that is $Q_c = \Sigma_{i=1}^{N} h(x_c, B)$. If we assume that all conservationist farmers are equal, then we can rewrite $Q_c = n_c h(x_c, B)$. Multiplying and dividing by the total number of farmers N in area L_z, we can write $Q_c = \frac{n_c h(x_c,B)N}{N} = s_c h(x_c, B)N = Q_c(s_c, h, N)$. We now assume that conservationist farmers produce under a label that limits the use of input x_i up to x_c. Only the farmers that follow this restriction in the area can sell under this label. That is, conservationist farmers have some monopolistic power, and therefore we assume that they do not take price as given but that equilibrium market price p_c presents a negative relationship with the quantity produced by conservationist farmers Q_c, $\frac{\partial p_c}{\partial Qc} \leq 0$. When the quantity produced by conservationist farmers Q_c increases, the market price of the labelled crop, *Ceteris paribus*, will decrease. Therefore, $p_c(Q_c(s_c, h, N))$ and $\frac{\partial p_c}{\partial s_c} = \frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial s_c}$ where $\frac{\partial Q_c}{\partial s_c} > 0$ and $\frac{\partial p_c}{\partial Qc} \leq 0$ by assumption; under these assumptions $\frac{\partial p_c}{\partial s_c} = \frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial s_c} \leq 0$.[16] Summarizing, in our model we assume that conservationist farmers have market power $\frac{\partial p_c(s_c)}{\partial Q_c} < 0$; however, non-conservationist farmers have to compete in the global markets and then $\frac{\partial p_{nc}}{\partial Q_{nc}} = 0$, showing the absence of any market power. We represent market price in the case of conservationist farmers as $p_c(s_c)$ and in the non-conservationist as p_{nc}.

The individual payoff is equal to:

$$u_i(x_i, B) = \pi_i(x_i, B) = p_i\,(s_c)\,h(x_i, B) - cx_i \tag{2.2}$$

where p_i is the harvest market price for $i \in (c, nc)$, x_i represents the quantity of non-environmentally friendly inputs used by farmer i, and c represents the opportunity cost of these inputs.

Let us analyze the stability conditions of the farmers' dynamics. If the prices were $p_c(s_c) \leq p_{nc}$, then it will always be the case that $(\pi_{nc} - \pi_c) > 0$, as we have assumed that $x_{nc} \geqslant x_c$ for all cases, and a full non-conservationist farmers' equilibrium $s_c = 0$ would be stable. However, note that if prices $p_c(s_c) > p_{nc}$ even if it were the case that $x_{nc} > x_c$, other types of equilibria can exist. A heterogeneous equilibrium would exist if

[16]If $\frac{\partial p_c}{\partial s_c} = \frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial s_c} = 0$ then it is the same case where p_c is constant and $p_c > p_{nc}$ in Appendix 2.6.3. In this case similar results can be obtained as with the constant subsidy. From now on we will assume that $\frac{\partial p_c}{\partial s_c} = \frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial s_c} < 0$.

$p_{nc}h(x_{nc}, B) - cx_{nc} = p_c(s_c)h(x_c, B) - cx_c$, or what is the same if $(\pi_{nc} - \pi_c)(s_c, B) = 0$. In this equilibrium the effects of $x_{nc} > x_c$ and $p_c(s_c) > p_{nc}$ would counterbalance each other, allowing for $\pi_{nc} = \pi_c$. Also, a full conservationists' equilibrium $s_c = 1$ would be possible.

Let us define $B_{far}(s_c^*)$ as the level of resource stock B such that given a proportion of conservationists s_c^*, s.t. $1 > s_c^* > 0$ satisfies $(\pi_{nc} - \pi_c)(s_c^*, B^*) = 0$. If $B^* = B_{far}(s_c^*)$, then the point $(s_c^*, B_{far}(s_c^*))$ is a heterogeneous equilibrium point of the farmers' dynamics. Note that $\pi_{nc} - \pi_c = p_{nc}h(x_{nc}, B) + cx_{nc} - p_c(s_c)h(x_c, B) - cx_c$ and $\frac{\partial[\pi_{nc}-\pi_c]}{\partial s_c} = -\frac{\partial p_c}{\partial s_c}h(x_c, B)$. Recall that $\frac{\partial p_c}{\partial sc} = \frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial sc}$, where $Q_c = s_c hN$, and therefore $\frac{\partial Q_c}{\partial s_c} = Nh_c > 0$. By assumption $\frac{\partial p_c}{\partial Q_c} < 0$, then $\frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial sc}h(x_c, B,) < 0$ for any s_c. Therefore $\frac{\partial[\pi_{nc}-\pi_c]}{\partial sc} = -\frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial sc}h(B, x_c) > 0$ and $\frac{\partial \dot{s}c}{\partial sc} < 0$. Consequently and following Takayama (1994), (s_c^*, B^*) is an asymptotically stable equilibrium point of the farmers' dynamics.

Note that, for any value $s_c > s_c^*$ then $(\pi_{nc} - \pi_c)(s_c, B) > 0$ or what it is the same $p_{nc}h(x_{nc}, B) - cx_{nc} > p_c(s_c)h(x_c, B) - cx_c$, and for any value of $s_c < s_c^*$ then $(\pi_{nc} - \pi_c)(s_c, B) < 0$ or what it is the same $p_{nc}h(x_{nc}, B) - cx_{nc} < p_c(s_c)h(x_c, B) - cx_c$.

Lemma 3B *If for a given $s_c^* \in (0, 1)$ there is B^* such that $B^* = B_{far}(s_c^*)$, then (s_c^*, B^*) is an asymptotically stable heterogeneous equilibrium point of the farmers' dynamics.*

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

Lemma 4B *The set of stable equilibrium points $B_{far}(s_c)$ could be both a decreas-*

ing and an increasing function of s_c. *First,* $B_{far}(s_c)$ *would be a decreasing function,* $\frac{dB_{far}}{ds_c} < 0$, *if* $\left|p_{nc}\frac{\partial h(x_{nc},B)}{\partial B}\right| < \left|p_c(s_c)\frac{\partial h(x_c,B)}{\partial B}\left(1+\frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}\right)\right|$. *Similarly,* $B_{far}(s_c)$ *would be an increasing function of* s_c, $\frac{dB_{far}}{ds_c} > 0$, *if* $\left|p_{nc}\frac{\partial h(x_{nc},B)}{\partial B}\right| > \left|p_c(s_c)\frac{\partial h(x_c,B)}{\partial B}\left(1+\frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}\right)\right|$ *or if* $p_c(s_c)\frac{\partial h(x_c,B)}{\partial B}\left(1+\frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}\right) > 0$.

For an easier summary of our results, as in the subsidy case, we represent the set of stable equilibria $(B_{far}(s_c^*), s_c^*)$ of the farmers' dynamics by $\widehat{B}_{far}(s_c)$. We represent $\widehat{B}_{far}(s_c)$ in the phase diagrams of Figure 2.2. In Figures 2.2a, 2.2d and 2.2f we represent π_c and π_{nc} as a function of B. Additionally, in Figures 2.2b, 2.2e and 2.2g we represent π_c and π_{nc} as a function of s_c. Recall that it is always the case where $\frac{\partial \pi_{nc}}{\partial s_c} = 0$ and $\frac{\partial \pi_c}{\partial s_c} < 0$.

We have assumed that the larger the amount of a non-environmental friendly input, such as a pesticide, used by farmer i the smaller (in absolute value) the reduction in the harvest caused by an increase in B. Also, we have assumed that $x_{nc} > x_c$ then $\left|\frac{\partial h(x_{nc},B)}{\partial B}\right| < \left|\frac{\partial h(x_c,B)}{\partial B}\right|$. Therefore, in the subsidy case, an increase in B results in an increase in the difference between profits, that is, $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} > 0$ and then $\frac{d\widehat{B}_{far}}{ds_c} < 0$. $\widehat{B}_{far}(s_c)$ would be a decreasing function of s_c.

Now, an increase from B^1 to B^2 will reduce the amount of output produced by both, conservationist and non-conservationist farmers, however, the change in conservationist farmers' profits has a non clear sign, that is, $\frac{\partial \pi_c}{\partial B} \gtrless 0$. An increase in B would reduced the amount produced $h_c(x_c, B)$ and this would have a negative effect on the profit level π_c, but simultaneously, this reduction would lead to a reduction in the total output produced by conservationist farmers, $Q_c = \Sigma_{i=1}^N h_c(x_c, B)$, and in the new equilibrium, if the output produced by conservationist farmers were highly demanded, its price could have increased. The final effect on conservationist profits could be positive or negative and in the first case conservationist profit would increase.[17]

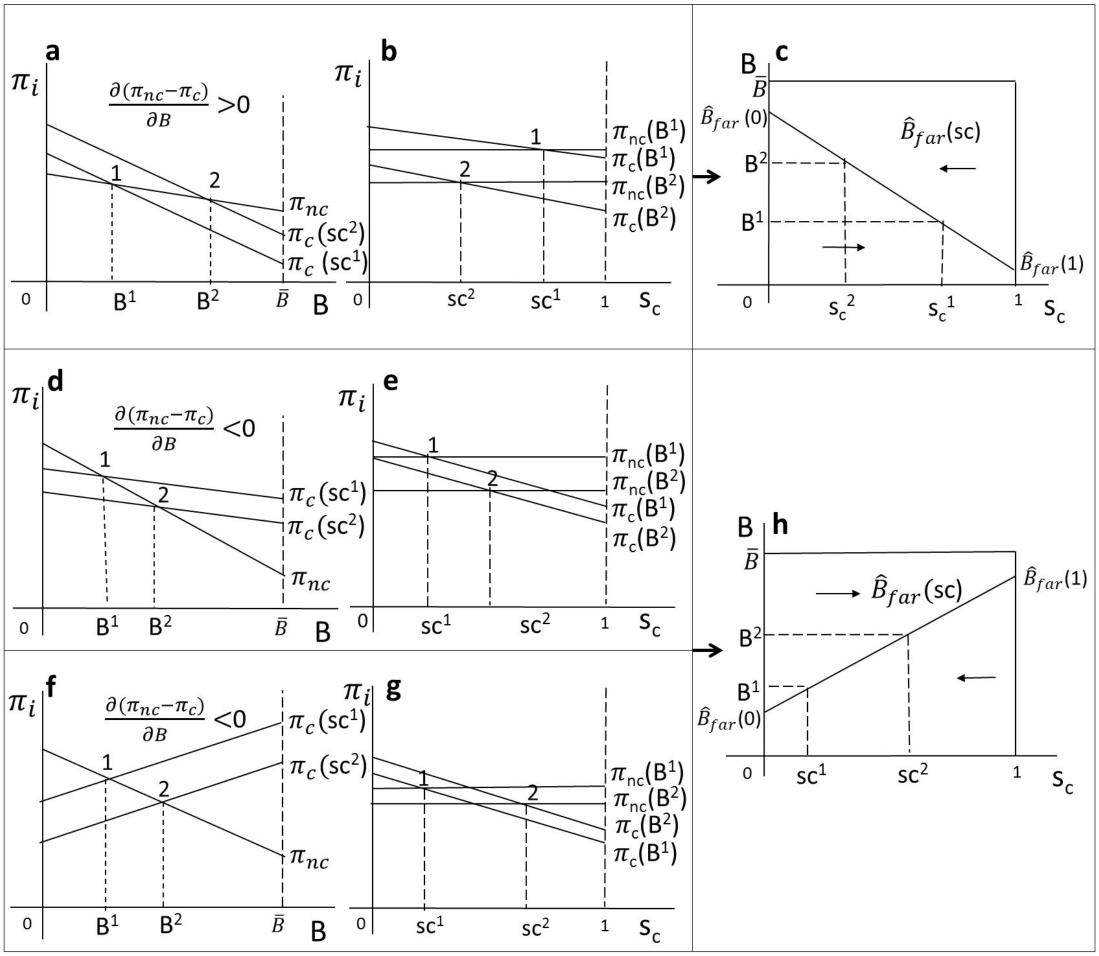
Now $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B}$ could be either positive or negative.[18] Summarizing, if given an increase in B the reduction in the non-conservationist farmers' profits is smaller than the reduction in the conservationist farmers' profits, this increase in B results in an increase in the difference between profits $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} > 0$ and then $\frac{d\widehat{B}_{far}}{ds_c} < 0$. $\widehat{B}_{far}(s_c)$ would be a decreasing function of s_c (phase diagram of Figures 2.2a, 2.2b and 2.2c).

Similarly, if given an increase in B the reduction in the non-conservationist farmers' profits is larger than the reduction in the conservationist farmers' profits (Figure 2.2d), or if the conservationist profit increases (Figure 2.2f), then this increase in B results in a reduction in the difference between profits $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} < 0$ then $\frac{d\widehat{B}_{far}}{ds_c} > 0$, then $\widehat{B}_{far}(s_c)$ would be an increasing function of s_c (Figure 2.2h). An increase in B would have to result in a reduction in the volumes of output produced by conservationist farmers that would have to result in an increase of the new equilibrium price able to offset the loss of profits associated with the reduction in production.

Summarizing, $\frac{d\widehat{B}_{far}}{ds_c} < 0$ represents a case where the non-conservationist farmers' profits decrease less than the conservationist farmers' profits given an increase in B, because the increase in p_c does not offset the decrease caused by bird population. Similarly, $\frac{d\widehat{B}_{far}}{ds_c} > 0$ represents a case where the non-conservationist farmers' profits decrease more than the conservationist farmers' profits when B increases; this happens because the increase in p_c offsets the decrease caused by the bird population (that can even lead to an increase in the conservationist farmers' profits).

[17] Recall that $\pi_c = p_c(Q_c)h(x_c, B) - cx_c$, then $\frac{\partial \pi_c}{\partial B} = \frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial B}h(x_c, B) + p_c(s_c)\frac{\partial h(x_c,B)}{\partial B}$. At the new equilibrium it could be the case that $\frac{\partial \pi_c}{\partial B} > 0$ in such a case $\left|\frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial B}h(x_c, B)\right| > \left|p_c(s_c)\frac{\partial h(x_c,B)}{\partial B}\right|$. And then $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} < 0$. Also, even if $\frac{\partial \pi_c}{\partial B} < 0$ as long as $\left|\frac{\partial \pi_{nc}}{\partial B}\right| > \left|\frac{\partial \pi_c}{\partial B}\right|$ then $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} < 0$. Furthermore, it could be the case that $\frac{\partial h}{\partial B} = 0$. This case does not change our conclusions. See Appendix 2.6.4.

[18] See proof of Lemma 4B in Appendix 2.6.1.



* In all panels we assume $B^1 < B^2$. In equilibria the corresponding proportion of conservationists, s_c, adjust to reach the corresponding equilibria. Allocation 1 represents the equilibrium point (B^1, s_c^1). A similar interpretation could be done for point 2. Finally, $\hat{B}_{far}(s_c)$ represents the set of stable equilibrium points (B, s_c) of the farmers' dynamics.

Figure 2.2: Farmers' dynamics under price differentiation scheme.

2.3 The full system

The sustainability of a natural resource requires that the resource stock remains at least constant in the long run; that is, it requires the system to set in a stable equilibrium point of the resource dynamics. The sustainability of the natural resource depends on the farmers' agricultural practices. The long run equilibrium of the natural resource will require an appropriate proportion of farmers to follow conservationist practices. According to Lemma 1, this proportion should be larger than s_c^E, so that if $s_c < s_c^E$ then the asymptotically stable equilibrium of the resource dynamics is $B = 0$, and the resource will be driven to extinction. In the following propositions and corollaries, we identify the characteristics of the long-run invariant combinations of (B, s_c) and determine when these equilibria allow a long-run sustainable resource stock.

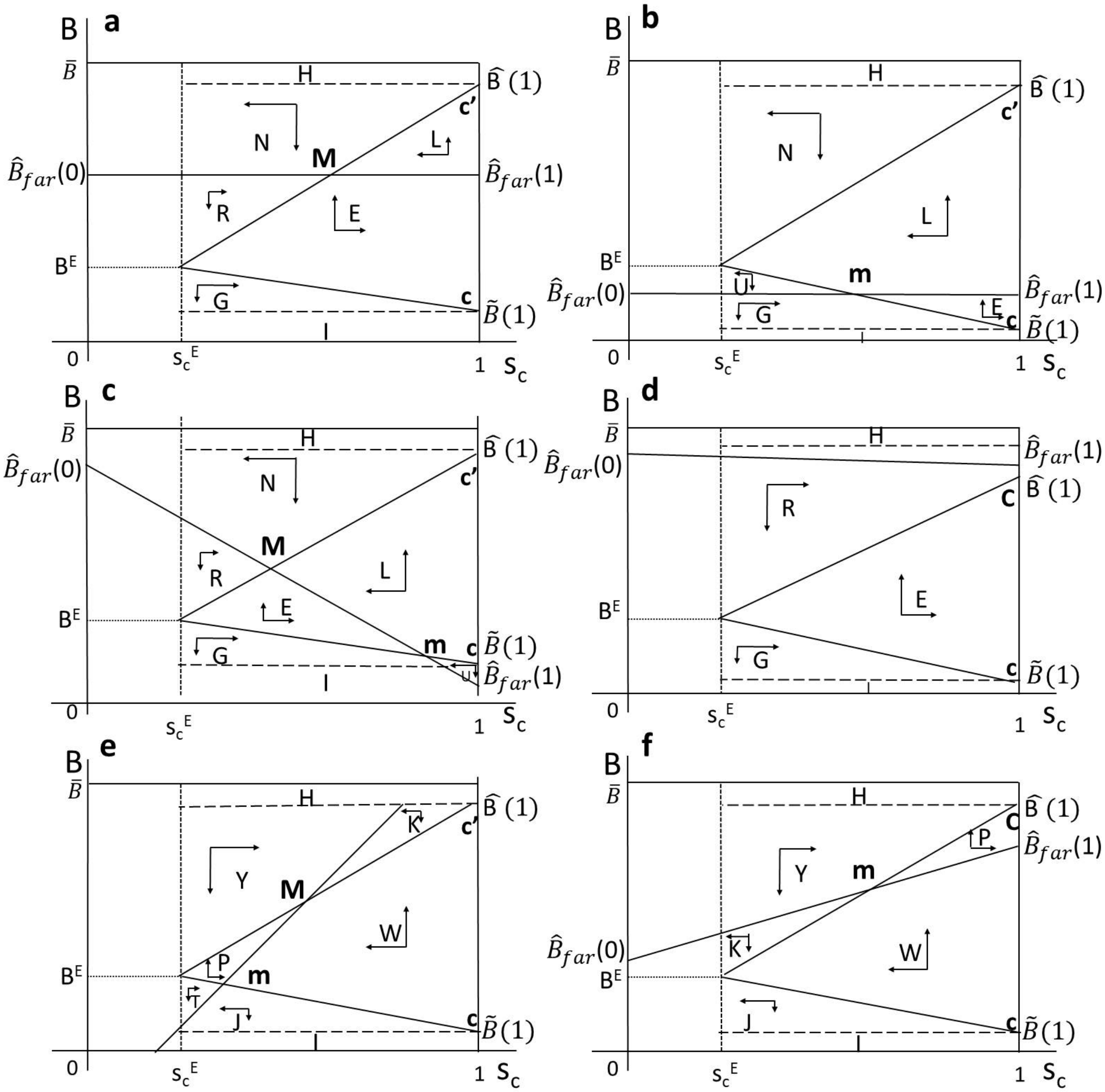
Proposition 1 *Whenever* $\widehat{B}_{far}(s_c)$ *intersects* $\widehat{B}(s_c)$ *for a positive proportion of conservationist farmers* s_c^**,* $0 < s_c^* < 1$ *there is a heterogeneous equilibrium point of the combined system* $(B^*(s_c^*), s_c^*)$ *.This point* $(B^*(s_c^*), s_c^*)$ *is an asymptotically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

Corollary P1 *Contrarily, 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. In this equilibrium, the resource will not be sustainable at the stock* $B^*(s_c^*)$*.*

Proposition 2 *An all-conservationists equilibrium* $(\widehat{B}(1), 1)$ *is asymptotically locally stable (unstable) if* $\widehat{B}(1) < B_{far}(1)$ $\left(\widehat{B}(1) > B_{far}(1)\right)$*. Further, an all-conservationist equilibrium* $(\widetilde{B}(1), 1)$ *is always unstable.*

Further, if the resource stock reaches a point $B(s_c)$ such that $B(s_c) < \widetilde{B}(1)$ for a given s_c the resource will be led to exhaustion. A sufficient condition for resource exhaustion is that $B < \widetilde{B}(1)$.

We have represented the asymptotically stable equilibria of the joint dynamics as M and the unstable equilibria as m in the phase diagrams depicted in Figure 2.3, which results from superposing the phase diagrams of the resource dynamics depicted in Figure 1.2b in chapter 1 and of the farmers' dynamics depicted in Figures 2.1 and 2.2. Point M in these figures illustrates the asymptotically stable equilibria of the joint dynamics stated in proposition 1. On the other side, point m illustrates the unstable equilibria of the joint dynamics stated in Corollary P1.



* In all panels, $\hat{B}_{far}(s_c)$ represents the set of stable equilibrium points (B, s_c) of the farmers' dynamics, M is a stable heterogeneous equilibrium point of the combined system, m is an unstable heterogeneous equilibrium point of the combined system, C is a stable homogeneous equilibrium point of the combined system and c and c' are unstable homogeneous equilibrium points of the combined system.

Figure 2.3: Combined system.

2.3.1 The full system under subsidy schemes

In Figures 2.3a and 2.3b, we represent the combined system of bird stock and farmers' behaviour dynamics when ϕ_c is a constant subsidy per hectare. According to proposition 1, there is only a level of s_c^* that enables the bird population to be sustainable at the stock $\widehat{B}(s_c^*) = \widehat{B}_{far}(s_c^*) = B^*$. At this resource stock, the rate of resource extraction is equal to the rate of resource renewal. Also note that 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 $\widehat{B}_{far}(s_c)$ is such that $\widehat{B}_{far}(s_c) > B^E$. The individual subsidy has to be large enough to guarantee that the resource stock $\widehat{B}_{far}(s_c) > B^E$. If the subsidy is not large enough to assure $\widehat{B}_{far}(s_c) > B^E$ and then $\widehat{B}_{far}(s_c)$ intersects $\widetilde{B}(s_c)$ then the equilibrium is unstable.[19] In such a case, even if the resource has reached a stock level such as $\widehat{B}_{far}(s_c)$ in Figure 2.3b, it will not be sustainable. If $\widehat{B}_{far}(s_c) < B^E$ the natural resource will probably be driven to extinction in areas G, and I. However, also for allocations $(B(s_c), s_c)$ in areas E, L or N, the joint dynamics could lead to equilibria where the resource stock is non-sustainable or zero.

In addition, in Figure 2.3c we represent the combined system of natural resource stock and farmers' behaviour dynamics when a collective subsidy is applied and, therefore, $\phi_c(s_c)$ is a decreasing function of s_c, that is $\frac{\partial \phi_i(s_c)}{\partial s_c} < 0$. According to Lemma 4 $\widehat{B}_{far}$, the set of stable equilibria of the farmers' dynamics is a decreasing function of s_c. In Figure 2.3c, we show the phase diagram of this combined system where a stable heterogeneous equilibrium point such as (B^*, s_c^*) where $B^* = \widehat{B}_{far}(s_c^*) = \widehat{B}(s_c^*)$ is represented by point M. If areas N, R, E or L are reached, the dynamics of the combined system will lead to allocation M and the population of birds would be sustainable at this stock level B^*. Note graphically that, as occurs with constant subsidies, if $B < B^E$

[19] See Claim 2.3 in Appendix 2.6.1.

the natural resource will probably be driven to extinction in areas J, and I of Figure 2.3c.

Further, if for a given $\widehat{B}_{far}$ there is a level of s_c that enables $\widehat{B}_{far}(s_c) = \widetilde{B}(s_c)$, this point is an unstable equilibrium point of the combined system and the population of birds would not be sustainable at this stock level.[20] These equilibria are represented by point m in Figure 2.3c. Note that also these equilibria could be represented by point m in Figure similar to in 2.3b. Now $\frac{\partial \phi_i(s_c)}{\partial s_c} < 0$ and $\widehat{B}_{far}(s_c)$ will be a decreasing function of s_c but the dynamics of the combined system will be similar to the dynamics of Figure 2.3b. In Figure 2.3b there is no stable equilibrium where the resource is sustainable. In fact, in Figure 2.3b the all non-conservationists is the unique stable equilibrium point of the combined system and, in such cases, the resource is not sustainable.[21]

Finally, note that we can reach an asymptotically locally stable equilibrium of the combined system where $\widehat{B}_{far}(s_c^*) = \widehat{B}(s_c^*)$ in both cases, when $\frac{\partial \phi_c(s_c)}{\partial s_c} = 0$ and when $\frac{\partial \phi_c(s_c)}{\partial s_c} < 0$. This asymptotically locally stable equilibrium $(B^*(s_c^*), s_c^*)$ will be the same for both cases if the characteristics of the resource dynamics are equal. For a proportion s_c of agents to behave as conservationists, if all the characteristics of the resource are the same, will require the same individual subsidy. Therefore, the same $(B^*(s_c^*), s_c^*)$ would be a stable equilibrium of the combined system and we will need, in equilibrium, the same budget to attain this allocation. In addition, the higher the individual incentive the higher the likelihood of reaching areas where the resource could be recovered, because it is much more profitable for farmers to behave as conservationists.

[20] See Claim 2.2 in Appendix 2.6.1.

[21] See Appendix 2.6.2 for the combined system when farmers' dynamics is unstable, that is when $\frac{\partial \phi_c(s_c)}{\partial s_c} > 0$.

2.3.2 The full system under price differentiation schemes

Recall that with price differentiation it could be the case that $\frac{d\widehat{B}_{far}}{ds_c} < 0$ and the case that $\frac{d\widehat{B}_{far}}{ds_c} > 0$. The first case, $\frac{d\widehat{B}_{far}}{ds_c} < 0$, is represented by Figure 2.3c. Note that it presents the same dynamics as the decreasing subsidy, $\frac{\partial\phi_i(s_c)}{\partial s_c} < 0$. In Figure 2.3c, if areas N, R, E or L are reached, the dynamics of the combined system will lead to allocation M and the population of birds would be sustainable at stock level B^*. Further, if for a given $\widehat{B}_{far}$ there is a level of s_c that enables $\widehat{B}_{far}(s_c) = \widetilde{B}(s_c)$, this point is an unstable or an undetermined equilibrium point of the combined system and the population of birds would not be sustainable.[22] These equilibria are represented in Figures 2.3c and 2.3b by point m.

Let us analyze the case where $\frac{d\widehat{B}_{far}}{ds_c} > 0$ in Figures 2.3e and 2.3f. Whenever $\frac{d\widehat{B}_{far}}{ds_c} > \frac{d\widehat{B}}{ds_c}$ the dynamics converge towards stable equilibrium point M (See Figure 2.3e). Further, if it is the case that $\frac{d\widehat{B}_{far}}{ds_c} < \frac{d\widehat{B}}{ds_c}$ the heterogeneous equilibrium is unstable; see point m in Figure 2.3f. In this case, both a full non-conservationists' and a full conservationists' equilibrium are possible. The full conservationists' equilibrium is represented by point C. For example, in area W of Figures 2.3e and 2.3f $(\pi_{nc} - \pi_c) > 0$ and the proportion of conservationist decreases, simultaneously the resource stock B increases. As B increases and as $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} < 0$ the difference $(\pi_{nc} - \pi_c)$ narrows but as long as it is still positive the proportion of conservationist farmers keeps decreasing. In Figure 2.3e the dynamic will let to point M. On the contrary, heterogeneous equilibrium point is unstable in Figure 2.3f, both an homogeneous equilibrium point where all farmers are conservationists and the resource is preserved and another where the resource is brought to extinction are possible. The dynamics can bring the system to area K or to area P. In the first case, if the conservationists' price is not high

[22] See Claim 2 in Appendix 2.6.1.

enough to offset the productivity losses the dynamics brings the system to the full non-conservationist equilibrium and the natural resource will be extinct and all farmers will behave as non-conservationists. In this situation, the product differentiation is not effective, and another mechanism different from that should be introduced, such as for example subsidies. In the second case when the dynamics brings the system to area P the combined system will lead to a stable homogeneous equilibrium point where all farmers behave as conservationists.

Finally, note graphically that, as was happening with subsidies if $B < B^E$, the natural resource will probably be driven to extinction (see areas G, I and U of Figures 2.3c and areas J and I in Figures 2.3e and 2.3f). Except in area T of Figure 2.3e where the dynamics could both lead the natural resource to extinction and reach the stable heterogeneous equilibrium point M.

2.4 Comparative statics

We analyze here the effect of changes in the parameters values on farmers' dynamics and on natural resource dynamics or what is the same on stable equilibrium points (B^*, s_c^*). We describe here the case when $\widehat{B}_{far}$ is a decreasing function of s_c, the case depicted in Figure 2.4.[23] A summary of these results is presented in Table 2.1.

[23]See Appendix 2.6.5 to see the comparative static results that correspond to the cases where $\widehat{B}_{far}$ is a constant and a increasing function of s_c.

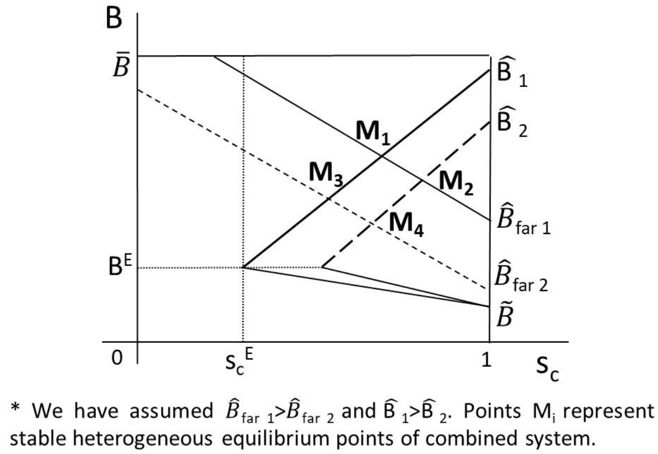


Figure 2.4: Stable equilibrium point $(B,\, s_c)$ changes depending on $\widehat{B}_{far}$ and $\widehat{B}$.

In this sense, let us suppose that an innovation results on the non-environmentally friendly input, X, becoming less damaging for the natural resource while keeping the farms productivity constant. That is, the damage caused to the natural resource by a given level of non-environmentally friendly input becomes lower. Farmers have to use a larger volume of X to do the same damage.[24] This innovation would move locus $\widehat{X}(B)$ upwards. The new technology increases the level of non-environmentally friendly input needed for the wipe out rate, $W(X, B)$, to equate the resource growth rate, $F(B)$ and therefore $\widehat{B}$ moves upwards. Moreover, as the new technology does not affect farmers productivity $\widehat{B}_{far}$ remains constant and the new equilibrium moves from M_4 to M_3 as shown in Figure 2.4. At the new equilibrium a lower proportion of conservationist will be able to preserve a large stock of natural resource.

[24]Recall that $\widehat{X}(B)$ is the level of non-environmentally friendly inputs used that keeps the natural resource constant at the stock level, B.

Parameters	$\widehat{B}$	$\widehat{B}_{far}$	The stable equilibrium point (B, s_c) ends having:	Shifts on the equilibrium point
Less damaging technology	Upwards	No change	Higher B Smaller s_c	From M_4 to M_3
More productive harvesting technology	No change	Downwards	Smaller B Smaller s_c	From M_1 to M_3
Higher $F(B)$	Upwards	No change	Higher Smaller s_c	From M_4 to M_3
Higher birds damage on $h(x_i, B)$	No change	Downwards	Smaller B Smaller s_c	From M_1 to M_3
Opportunity cost, c.	No change	Upwards	Higher B Higher s_c	From M_3 to M_1
Subsidy schemes				
ϕ_c	No change	Upwards	Higher B Higher s_c	From M_3 to M_1
p	No change	Downwards	Smaller B Smaller s_c	From M_1 to M_3
Price differentiation scheme				
p_c	No change	?	B? s_c?	?
p_{nc}	No change	?	B? s_c?	?

* ? depends of own price elasticity and cross elasticity.

Table 2.1: Effect of changes in different parameters values on the equilibrium point (B, s_c).

In contrast, we suppose now that the harvesting technology becomes more productive while keeping the damage caused to the natural resource constant. Now, with the same level of non-environmentally friendly input higher harvests are possible. We assume that with this innovation the increase on the harvest per unit of non-environmental friendly input is the same for both non-conservationist and conservationists farmers. Moreover, an increase on the harvest increase the farmers payoff, and as by assumption the level of non-environmental friendly inputs used by non-conservationists is higher than the level used by conservationists, the increase on the non-conservationists payoff is larger than the increase in the conservationist payoff, that is the difference $(\pi_{nc} - \pi_c)$ increases and $\widehat{B}_{far}$ moves downwards.[25] A part from that, the level of non-environmentally friendly inputs needed to equal the wipe out function with the rate of growth of birds do not change and therefore $\widehat{B}$ is kept constant. The new equilibrium moves from M_1 to M_3 as shown in Figure 2.4 and both the proportion of conservationist and the resource stock level are smaller in the new equilibrium. This will be a stable equilibrium but with a lower level of resource stock and a lower proportion of conservationist.

Furthermore, if we analyze the effect of changes on the natural resource growth rate, $F(B)$, we observe that a variation on $F(B)$ leads to a variation on locus $\widehat{B}$. The higher the rate of growth of the natural resource, $F(B)$, the higher the wipe out rate needed to keeps the resource population constant over time. Or what is the same, the higher the level of non-environmental friendly inputs needed to reach and equilibrium, that is $\widehat{X}(B)$ is higher and $\widehat{B}$ moves upwards. Nevertheless, $\widehat{B}_{far}$ remains constant. The equilibrium moves from M_4 to M_3 in Figure 2.4.

[25]To see this look, for example, at Figure 2.1a. An exogenous increase in the difference of profits shift upwards $(\pi_{nc}-\pi_c)$, then for a given level of s_c the stock level $\widehat{B}_{far}$ at which the difference between conservationist and non-conservationist equate the subsidy rate, $\phi_c(s_c)$ will be lower.

In a similar fashion, we can also explore how changes on the damages caused by birds on the harvest function alter the model. Whether damages caused by birds on the harvest function increases then $h(B, X)$ decrease and the payoff function of both types of farmers decreases. By assumption birds' damages are higher in the conservationists harvest function than in the non-conservationists harvest function, therefore the decreases on the payoff will be larger for the conservationist than for the non-conservationist, that is $(\pi_{nc} - \pi_c)$ increases. Consequently, $\widehat{B}_{far}$ moves downwards and $\widehat{B}$ remains constant. The new equilibrium moves from M_1 to M_3 as shown in Figure 2.4. The new equilibrium presents a smaller proportion of conservationists, s_c, and a smaller resource stock level, B.

We also analyze the effects of changes in the opportunity cost of inputs, c. An increase in c cause a decrease in both π_{nc} and π_c, additionally, as non-conservationist use a larger volume of non-environmentally friendly input x_i than conservationist the difference $(\pi_{nc} - \pi_c)$ decreases too. Consequently, $\widehat{B}_{far}$ moves upwards while $\widehat{B}$ remains constant. The equilibrium point moves from M_3 to M_1, the new equilibrium presents a higher proportion of conservationists, s_c, and a higher resource stock level, B.

Furthermore, in the subsidy schemes case where $u_c(x_c, B) = \pi_c(x_c, B) + \phi_c(s_c)$ an increase in ϕ_c while others parameters remain constants causes an increase in u_c that reduces the difference $(u_{nc} - u_c)$ and makes $\widehat{B}_{far}$ moves upwards. In contrast, a change in ϕ_c has no effect on the natural resource stock, then $\widehat{B}$ remains constant. The new equilibrium point moves from M_3 to M_1 and present higher proportion of conservationist and a higher resource stock level. As well, an increase in output price, p, causes an increase in the difference $(u_{nc} - u_c)$ and $\widehat{B}_{far}$ moves downwards. The new equilibrium point moves from M_1 to M_3 and present lower proportion of conservationist farmers and a lower resource stock level.

On the other side, in the price differentiation scheme case an exogenous, *Ceteris paribus*, increase in conservationists price, p_c, due for example to a change in consumer tastes, can cause an increase or a decrease on π_c depending on the own price elasticity. If the demand for conservationist products is inelastic π_c increases, on the contrary, if it is elastic π_c decreases. Further, as we have assumed that the output produced by conservationist and by non-conservationist farmers are substitute the sign of the change of the difference $(\pi_{nc} - \pi_c)$ depends also on the cross elasticity between these two products. If we assume that the non-conservationist product, as most agricultural products, is traded in global and competitive markets, we can also assume that neither changes in the price of a conservationist product nor in its quantity would have a significant effect on the demand of non-conservationist output. Under this assumption if the demand for conservationist products is inelastic an increase in p_c will result in a decrease in the difference $(\pi_{nc} - \pi_c)$, and $\widehat{B}_{far}(s_c)$ moves upwards. That is, the equilibrium point moves from M_3 to M_1. The proportion of conservationist farmers increases and also it does the resource stock. On the contrary, if the demand for conservationist products were elastic an increase in p_c will result in a decrease in π_c and the difference $(\pi_{nc} - \pi_c)$ would increase and $\widehat{B}_{far}(s_c)$ would move downwards. The equilibrium point moves from M_1 to M_3. The proportion of conservationist farmers decreases and also it does the resource stock.

Finally, we believe that it is highly likely that changes in the price of non-conservationist output have a relevant effect on the demand for conservationist output. It is important to analyze this effect on $\widehat{B}_{far}$. Recall that by definition of substitute goods, the quantity demanded of the good produced by conservationist farmers depends on the price of the good produced by non-conservationist farmers p_{nc}. By definition of substitute products, an increase in p_{nc} causes an upward shift on the conservationist product demand curve.

Therefore, in the new market equilibrium, the quantity demanded of conservationist output will be larger, *Ceteris paribus*. For increases in p_{nc}, the more substitute are the outputs the larger will be the increases in the quantity demanded of conservationist output and the larger will expect the increase on conservationist profits to be.[26] Note also that changes in p_{nc} also affect non-conservationists profits π_{nc}. Non-conservationist payoff can increase or decrease depending on its own product price elasticity. Let us assume, for example, that non-conservationists product is inelastic, then increases in p_{nc} results on increases in π_{nc}. The difference $(\pi_{nc} - \pi_c)$ depends in both, the non-conservationist output own price elasticity of demand and the cross elasticity of the conservationist output demand. This difference will increase if the effect of the own elasticity of p_{nc} in π_{nc} is larger than the effect of the cross elasticity in π_c. Whether, the difference $(\pi_{nc} - \pi_c)$ increases $\widehat{B}_{far}$ moves downwards. Moreover, $\widehat{B}$ remains constant. Therefore, if the difference $(\pi_{nc} - \pi_c)$ increases the equilibrium point will shift from M_1 to M_3 and presents a lower proportion of conservationist farmer and a lower resource stock level. Contrary, whether, the difference $(\pi_{nc} - \pi_c)$ decreases $\widehat{B}_{far}$ moves upwards and the equilibrium point will shift from M_3 to M_1.

2.5 Conclusions

We have analyzed the performance of three different schemes, the constant subsidy, the collective subsidy and the price differentiation scheme. It is clear that with the three types of schemes it is possible to reach stable equilibria where the natural resource is protected.

[26] Contrary, decreases in p_{nc} cause decreases in the quantity demanded of conservationists products. Therefore, for decreases in p_{nc} the more substitute are the goods the higher will be the the losses on conservationists profits.

Let us first analyze the constant and collective subsidies. In most scenarios, budget constraints are a fact, and the authorities responsible for aid management must comply with the budget. Recall that we have assumed that with collective subsidies the total allowance A is always fully allocated. Therefore, at point M the allowance A is used. The same stable heterogeneous equilibrium point M can be reached with a constant subsidy scheme. At M farmers would receive the same individual subsidy. However, with a constant subsidy and out of equilibrium the agency will need a total allowance larger than A to assure that all farmers receive the constant incentive in the case that a proportion of farmers larger than in equilibrium behave as conservationists. Nevertheless, note that at the stable heterogeneous equilibrium, M, farmers receive the same individual subsidy under both subsidy schemes. In equilibrium, the proportion of conservationist farmers s_c^* and the stock of natural resource B^* will coincide and the subsidy needed to offset conservationists' profit losses caused by B^* will be the same under both schemes. Therefore, the amount of subsidy that an individual farmer should receive to attain a stable equilibrium point such as M is the same. That is, the same budget will be spent by the environmental agency in both cases once an equilibrium is reached. Therefore, there are no differences in equilibrium; the main differences between these two types of subsidy schemes appear out of equilibrium where the dynamics and the basins of attraction of the two stable equilibria differ.

The EU policy instruments are aimed at 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 initial points and paths towards a stable equilibirum are of equal interest, but the ones that correspond to low levels of resource stock are more relevant for an endangered species recovery. In fact, the more endangered a species is, the lower is the actual stock B and the farther away it 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 behaviour at early stages, it could be interesting to be able to provide large enough subsidies at early stages of policy implementation. Accordingly, it could be of interest for the regulatory agency to design a subsidy that depends inversely on the proportion of farmers that act as conservationists, s_c. In this sense, in the case of a constant subsidy if the initial allocation (B, s_c) is in area N (Fig 2.3a), for example, where 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 in the proportion of conservationist farmers s_c is accompanied by a reduction in B. After several stages, the dynamics can enter the basin of attraction of the heterogeneous stable equilibrium M and converge again towards it but, however, it could also lead to the extinction of the resource. In the case of a collective subsidy scheme the possibility of extinction can be much lower. Note that the dynamics in area N is the same; however, in this case, as the proportion of conservationist farmers decreases the individual subsidy rate increases equating the difference in profit to this larger subsidy rate (Fig 2.3c) and closing the gap between conservationist and non-conservationist income. In such circumstances, the trajectory towards extinction will also have a larger likelihood of being diverted. The capability of diverting the trajectory towards extinction of a natural resource could determine which type of subsidy should be applied. A decreasing subsidy in s_c can better guarantee that in the initial phases extinction is avoided and better assure the conservation of the natural resource when it is not assured with a constant subsidy.

Let us focus now on the price differentiation scheme. It is clear that price differentiation allows similar heterogeneous equilibria to the collective subsidy (Fig 2.3c);

however, it differs in that it allows a stable farmers' dynamics equilibria when $\widehat{B}_{far}$ is an increasing function of s_c (Fig 2.3e). Increases in B can cause decreases in the quantity produce of conservationist output that could result in increases in p_c. Note that if $\frac{\partial \widehat{B}_{far}}{\partial s_c} > 0$, it means that we are in a case that the increases in p_c are large enough to compensate for conservationists' profit losses caused by increases in B. In this case, $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} < 0$. This would mean that the output produced by conservationists farmers it is so highly demanded and has no close substitute goods that when the quantity supplied decreases due to an increase in B the increases in the p_c is large enough for profits to increase. That is, the increase in p_c can compensate for the decrease in the quantity produce due to B.

In addition, when $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} < 0$ and the heterogeneous equilibrium point is unstable (Figure 2.3f), both a homogeneous equilibrium point where all farmers are conservationist and one where all farmers are non-conservationist are possible depending on $(\pi_{nc} - \pi_c)$. Recall that, with subsidies, this point C was possible only under the assumption of unbound budget. See Appendix 2.6.2. Nevertheless, in a price differentiation scheme, as the market regulates the prices, to reach point C is possible whenever the conservationists' price is large enough. If this is the case, there will not be a conflict between farms' productivity and natural resource preservation, because being conservationists will always be the best strategy.

2.6 Appendix

2.6.1 Proofs of Lemmas and Propositions

Proof of Lemma 3

Given a proportion of individuals s_c^* of conservationist farmers, we define a set $\psi = \left\{(B, s_c^*)|0 < B < \bar{B}\right\}$. 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 (1994), a sufficient but not necessary condition for a point s_c^* to be an asymptotically stable equilibrium of $B_{far}(s_c)$ is that $\frac{\partial \dot{s}_c}{\partial s_c}|_{s_c^*} < 0$.

Lemma 3A

Recall that the utility function is: $u_i(x_i, B) = \pi_i(x_i, B) + \phi_i(s_c) = ph(x_i, B) - cx_i + \phi_i(s_c)$. Then $\frac{\partial \dot{s}_c}{\partial s_c} = -s_c(1 - s_c)\left(\frac{\partial[\pi_{nc} - \pi_c]}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}\right)$. Further, note that $\frac{\partial[\pi_{nc} - \pi_c]}{\partial s_c} = 0$ for all s_c, 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 $\frac{\partial \phi_c(s_c^*)}{\partial s_c} < 0 \left(\frac{\partial \phi_c(s_c^*)}{\partial s_c} > 0\right)$. Further, with a constant subsidy $\frac{\partial \phi_c(s_c)}{\partial s_c} = 0$, then $\frac{\partial \dot{s}_c}{\partial s_c} = 0$ and the equilibrium is indeterminate.

Lemma 3B

Recall that the utility function is: $u_i(x_i, B) = \pi_i(x_i, B) = p_i(s_c)h(x_i, B) - cx_i$. Note that $\frac{\partial \dot{s}_c}{\partial s_c} = -s_c(1 - s_c)\left(\frac{\partial(u_{nc} - u_c)}{\partial s_c}\right) = -s_c(1 - s_c)\left(\frac{\partial[\pi_{nc} - \pi_c]}{\partial s_c}\right)$. Note that $\frac{\partial[\pi_{nc} - \pi_c]}{\partial s_c} = -\frac{\partial p_c}{\partial s_c}h(x_c, B)$, and that $\frac{\partial p_c}{\partial sc} = \frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial sc}$. Recall, that $Q_c = s_c hN$, and therefore $\frac{\partial Q_c}{\partial s_c} = Nh_c > 0$. As per assumption $\frac{\partial p_c}{\partial Q_c} < 0$, then $\frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial sc}h(x_c, B,) < 0$ for any s_c. Therefore,

$\frac{\partial(u_{nc}-u_c)}{\partial sc} = \frac{\partial[\pi_{nc}-\pi_c]}{\partial s_c} = -\frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial sc}h\left(B,x_c\right) > 0$ and $\frac{\partial \dot{s}c}{\partial sc} < 0$. Consequently, (s_c^*, B^*) is always asymptotically stable. Finally, if $\frac{\partial(u_{nc}-u_c)}{\partial sc} = 0$, then $\frac{\partial \dot{s}_c}{\partial s_c} = 0$ and the equilibrium is indeterminate. This is the case of a constant differentiation price scheme (See Appendix 2.5.3).

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:

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

Lemma 4A

Note that $\frac{\partial(u_{nc}-u_c)}{\partial sc} = -\frac{\partial\phi_c(s_c)}{\partial s_c}$. Therefore, in the subsidy schemes cases we can write:

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

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

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

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, due to the profit maximizing condition, the behaviour of non-conservationist 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 the denominator, $\frac{\partial(u_{nc}-u_c)}{\partial B} > 0$.

On the other side the sign of the numerator depends on the sign of $\frac{\partial \phi_c(s_c)}{\partial s_c}$. We will have three cases: 1) If $\frac{\partial \phi_c(s_c^*)}{\partial s_c} < 0$ by lemma 3 $(B_{far}(s_c^*), s_c^*)$ is a stable equilibrium point of the farmers' dynamics and $\frac{\partial(u_{nc}-u_c)}{\partial s_c} > 0$ then $\frac{dB_{far}}{ds_c} < 0$. Consequently, $\widehat{B}_{far}(s_c)$ is a decreasing function of s_c. 2). If $\frac{\partial \phi_c(s_c^*)}{\partial s_c} > 0$ by lemma 3 $(B_{far}(s_c^*), s_c^*)$ is an unstable equilibrium point of the farmers' dynamics and $\frac{\partial(u_{nc}-u_c)}{\partial s_c} < 0$ then $\frac{dB_{far}}{ds_c} > 0$. Consequently, $\tilde{B}_{far}(s_c)$ is an increasing function of s_c. And 3) if $\frac{\partial \phi_i(s_c)}{\partial s_c} = 0$ then $\frac{\partial(u_{nc}-u_c)}{\partial s_c} = 0$ then the numerator is zero and $\frac{dB_{far}}{ds_c} = 0$ independently of the sign of the denominator, and the equilibrium point is indeterminate.

Lemma 4B

Recall that in price differentiation schemes $u_i = \pi_i$, that is:

$$\frac{dB_{far}}{ds_c} = -\frac{\frac{\partial[\pi_{nc}-\pi_c]}{\partial sc}}{\frac{\partial[\pi_{nc}-\pi_c]}{\partial B}}$$

First, and as we have just seen, the numerator is positive $\frac{\partial[\pi_{nc}-\pi_c]}{\partial s_c} = -\frac{\partial p_c}{\partial s_c}h(x_c, B) > 0$. On the other side, $\pi_{nc} - \pi_c = (p_{nc}h_{nc}(x_{nc}, B) - cx_{nc}) - (p_c(Q_c)h_c(x_c, B) - cx_c)$ and

$$\begin{aligned}\frac{\partial\left[\pi_{nc}-\pi_c\right]}{\partial B} &= \left[p_{nc}\left(\frac{\partial h(x_{nc}, B)}{\partial x_{nc}}\frac{\partial x_{nc}}{\partial B} + \frac{\partial h(x_{nc}, B)}{\partial B}\right) - c\frac{\partial x_{nc}}{\partial B}\right] \\ &\quad - \left[p_c\left(\frac{\partial h(x_c, B)}{\partial x_c}\frac{\partial x_c}{\partial B} + \frac{\partial h(x_c, B)}{\partial B}\right) + \frac{\partial p_c}{\partial B}h(x_c, B) - c\frac{\partial x_c}{\partial B}\right]\end{aligned}$$

Note that $\frac{\partial p_c}{\partial B} = \frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial B} = \frac{\partial p_c}{\partial Q_c}s_cN\left(\frac{\partial h_c}{\partial x_c}\frac{\partial x_c}{\partial B} + \frac{\partial h_c}{\partial B}\right)$, as we have assumed that x_c is exogenously given by the environmental agency, that is $\frac{\partial x_c}{\partial B} = 0$; consequently $\frac{\partial p_c}{\partial B} = \frac{\partial p_c}{\partial Q_c}s_cN\left(\frac{\partial h(x_{nc},B)}{\partial B}\right)$. Also note that by the profit maximizing condition $p_{nc}\frac{\partial h(x_{nc},B)}{\partial x_{nc}} - c = 0$. Applying these assumptions in the previous equation we have:

$$\begin{aligned}\frac{\partial\left[\pi_{nc}-\pi_c\right]}{\partial B} &= \left[\left(p_{nc}\frac{\partial h(x_{nc}, B)}{\partial x_{nc}} - c\right)\frac{\partial x_{nc}}{\partial B} + p_{nc}\frac{\partial h(x_{nc}, B)}{\partial B}\right] \\ &\quad - \left[p_c\frac{\partial h(x_c, B)}{\partial B} + \frac{\partial p_c}{\partial Q_c}s_cN\left(\frac{\partial h(x_c, B)}{\partial B}\right)h(x_c, B)\right] \\ &= p_{nc}\frac{\partial h(x_{nc}, B)}{\partial B} - p_c\frac{\partial h(x_c, B)}{\partial B}\left(1 + \frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}\right)\end{aligned}$$

Recall that $\frac{\partial h(x_i,B)}{\partial B} < 0$ and by assumption $p_c(s_c) > p_{nc}$ and $\left|\frac{\partial h(x_{nc},B)}{\partial B}\right| < \left|\frac{\partial h(x_c,B)}{\partial B}\right|$. Note that the sign of $\frac{\partial[\pi_{nc}-\pi_c]}{\partial B}$ depends on the difference $p_{nc}\frac{\partial h(x_{nc},B)}{\partial B} - p_c\frac{\partial h(x_c,B)}{\partial B}\left(1 + \frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}\right)$. Whenever, $p_c\frac{\partial h_c}{\partial B}\left(1 + \frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}\right) > 0$ then always $\frac{\partial[\pi_{nc}-\pi_c]}{\partial B} < 0$, and therefore $\frac{dB_{far}}{ds_c} > 0$

for a stable equilibrium point.

On the other hand, if $p_c \frac{\partial H_c}{\partial B}\left(1+\frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}\right)<0$ the sign of $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B}$ will depend on the difference $p_{nc}\frac{\partial h(x_{nc},B)}{\partial B}-p_c\frac{\partial h(x_c,B)}{\partial B}\left(1+\frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}\right)$. If $\left|p_{nc}\frac{\partial h(x_{nc},B)}{\partial B}\right|>\left|p_c\frac{\partial h(x_c,B)}{\partial B}\left(1+\frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}\right)\right|$ then, as before, $\frac{\partial[\pi_{nc}-\pi_c]}{\partial B}<0$ and $\frac{dB_{far}}{ds_c}>0$. Otherwise, if $\left|p_{nc}\frac{\partial h(x_{nc},B)}{\partial B}\right|<\left|p_c\frac{\partial h(x_c,B)}{\partial B}\left(1+\frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}\right)\right|$ then $\frac{\partial[\pi_{nc}-\pi_c]}{\partial B}>0$ and $\frac{dB_{far}}{ds_c}<0$ for a stable equilibrium point.

Proof of Proposition 1

The Jacobian of the two-dimensional system given by equation 1.1 and equation 1.2 of chapter 1 is:

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

The Jacobian evaluated at an interior equilibrium point (B^*, s_c^*) where $u_{nc}-u_c=0$ is given by:

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

Any isolated equilibrium point of the system, called (B^*, s_c^*), would be asymptotically locally stable if the Jacobian has a negative trace and a positive determinant. According to Lemma 1 in chapter 1, the trace of $J_{(B,s_c)}$ can be written as:

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

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

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

Whenever (B^*, s_c^*) is a stable equilibrium of the resource stock dynamics and a stable or indeterminate equilibrium point of the farmers' dynamics then by Lemma 1 $\frac{\partial\dot{B}}{\partial B} < 0$ and by lemma 3 $\frac{\partial(u_{nc}-u_c)}{\partial sc} \geq 0$. Therefore, the trace is always negative. Let us now look at the Jacobian. By lemma 2 in chapter 1 $\frac{\partial\widehat{B}}{\partial s_c} > 0$ and note that $s_c^*(1-s_c^*) > 0$ for all s_c, also by lemma 4 if $\frac{\partial(u_{nc}-u_c)}{\partial B} > 0$ then $\frac{dB_{far}}{ds_c} < 0$. Then the determinant is positive. Consequently, in those cases the (B^*, s_c^*) would be an asymptotically locally stable equilibrium point of the joint dynamic combined system.

In addition, in the price differentiation scheme of lemma 4B, if $\frac{\partial(u_{nc}-u_c)}{\partial B} < 0$ then $\frac{dB_{far}}{ds_c} > 0$.[27] The sign of the determinant will depend on the difference $\left[\frac{dB_{far}}{ds_c} - \frac{\partial\widehat{B}}{\partial s_c}\right]$.

[27] Note that in the payment schemes by lemma 3A and 4A, if $\frac{dB_{far}}{ds_c} > 0$ the farmers' dynamics is unstable. We analyze this case in claim 1.

Whenever $\frac{dB_{far}}{ds_c} > \frac{\partial \widehat{B}}{\partial s_c}$ the determinant is positive and (B^*, s_c^*) would be an asymptotically locally stable equilibrium point of the joint dynamic combined system.

Whenever $\frac{dB_{far}}{ds_c} < \frac{\partial \widehat{B}}{\partial s_c}$ the determinant is negative and (B^*, s_c^*) would be an asymptotically locally unstable equilibrium point of the joint dynamic combined system.

Whenever $\frac{dB_{far}}{ds_c} = \frac{\partial \widehat{B}}{\partial s_c}$ then $\left|J_{(B,s_c)}\right| = 0$. Note that this defines a continuum of stable equilibrium points where $B_{far} = \widehat{B}$ for any s_c.

Finally, if $\frac{\partial(u_{nc}-u_c)}{\partial sc} = 0$ then independently of the sign of $\frac{\partial(u_{nc}-u_c)}{\partial B}$ it is always the case that $\frac{dB_{far}}{ds_c} = 0$. In this case two situations are possible. First, if $\frac{\partial(u_{nc}-u_c)}{\partial B} > 0$ then the determinant is positive. Consequently, in those cases the (B^*, s_c^*) would be an asymptotically locally stable equilibrium point of the joint dynamic combined system. Note that this is always the case when a constant subsidy is applied. [28]

Proof of corollary P1 We consider four other situations.

Claim 2.1 Whenever (B^*, s_c^*) is a stable equilibrium of the resource stock dynamics but an unstable equilibrium point of the farmers' dynamics by Lemma 1 $\frac{\partial \dot{B}}{\partial B} < 0$ and by lemma 3 $\frac{\partial(u_{nc}-u_c)}{\partial sc} < 0$. By Lemma 2 $\frac{\partial \widehat{B}}{\partial sc} > 0$; consequently, the sign of the Jacobian depends on the sign of $\left[\frac{\partial(u_{nc}-u_c)}{\partial B}\right]$ and on the sign of $\left[\frac{\partial B_{far}}{\partial s_c} - \frac{\partial \hat{B}}{\partial s_c}\right]$.

First, if $\frac{\partial(u_{nc}-u_c)}{\partial B} < 0$ then by lemma 2 $\frac{\partial B_{far}}{\partial s_c} < 0$ and the determinant is negative and the equilibrium point is unstable.

Second, $\frac{\partial(u_{nc}-u_c)}{\partial B} > 0$ then $\frac{\partial B_{far}}{\partial s_c} > 0$ and three cases are possible. First, if $\frac{\partial B_{far}}{\partial s_c} > \frac{\partial \hat{B}}{\partial s_c}$ the Jacobian is negative and the equilibrium point is unstable. Second, if $\frac{\partial B_{far}}{\partial s_c} < \frac{\partial \hat{B}}{\partial s_c}$

[28]Nevertheless, if $\frac{\partial(u_{nc}-u_c)}{\partial B} < 0$, then the determinant is negative and (B^*, s_c^*) would be an asymptotically locally unstable equilibrium point of the joint dynamic combined system. We have not found such a case.

the Jacobian is positive. However, the trace is inconclusive and the equilibrium point is indeterminate. Finally, if $\frac{\partial B_{far}}{\partial s_c} = \frac{\partial \hat{B}}{\partial s_c}$ then $\left|J_{(B,s_c)}\right| = 0$. However, the trace is inconclusive and the equilibrium point is indeterminate.

Claim 2.2 Whenever (B^*, s_c^*) is an unstable equilibrium of the resource stock dynamics but a stable equilibrium point of the farmers' dynamics by Lemma 1 $\frac{\partial \dot{B}}{\partial B} > 0$ and by lemma 3 $\frac{\partial (u_{nc}-u_c)}{\partial sc} > 0$. By Lemma 2 $\frac{\partial \widetilde{B}}{\partial sc} < 0$; consequently, the sign of the Jacobian depends on the sign of $\left[\frac{\partial (u_{nc}-u_c)}{\partial B}\right]$ and on the sign of $\left[\frac{\partial B_{far}}{\partial s_c} - \frac{\partial \widetilde{B}}{\partial sc}\right]$.

First, if $\frac{\partial (u_{nc}-u_c)}{\partial B} < 0$ by lemma 2 then $\frac{\partial B_{far}}{\partial s_c} > 0$ the determinant is negative and the equilibrium point is unstable.

Second, if $\frac{\partial (u_{nc}-u_c)}{\partial B} > 0$ then $\frac{\partial B_{far}}{\partial s_c} < 0$ and three cases are possible. First, if $\left|\frac{dB_{far}}{ds_c}\right| > \left|\frac{\partial \widetilde{B}}{\partial sc}\right|$ the determinant is negative and the equilibrium point is unstable. Second, if $\left|\frac{dB_{far}}{ds_c}\right| < \left|\frac{\partial \widetilde{B}}{\partial sc}\right|$ the determinant is positive. However, the trace is inconclusive and the equilibrium point is indeterminate. Finally, if $\left|\frac{dB_{far}}{ds_c}\right| = \left|\frac{\partial \widetilde{B}}{\partial sc}\right|$ then $\left|J_{(B,s_c)}\right| = 0$. However, the trace is inconclusive and the equilibrium point is indeterminate. This point could be stable only if $\left|\frac{\partial \dot{B}}{\partial B}\right| < \left|s_c^*(1-s_c^*)\frac{\partial (u_{nc}-u_c)}{\partial s_c}\right|$.

Claim 2.3 Whenever (B^*, s_c^*) is an unstable equilibrium of the resource stock dynamics and an indeterminate equilibrium point of the farmers' dynamics (i.e.,$\frac{dB_{far}}{ds_c} = 0$). Then by lemma 1 $\frac{\partial \dot{B}}{\partial B} > 0$. Also by lemma 3 $\frac{\partial (u_{nc}-u_c)}{\partial s_c} = 0$. Therefore, $trJ_{(B,s_c)} > 0$ and the equilibrium point is unstable.

Claim 2.4 Whenever (B^*, s_c^*) is an unstable equilibrium of the resource stock dynamics and an unstable equilibrium point of the farmers' dynamics by Lemma 1 $\frac{\partial \dot{B}}{\partial B} > 0$ and by lemma 3 $\frac{\partial (u_{nc}-u_c)}{\partial sc} < 0$. Therefore, $trJ_{(B,s_c)} > 0$ and the equilibrium point is unstable.

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

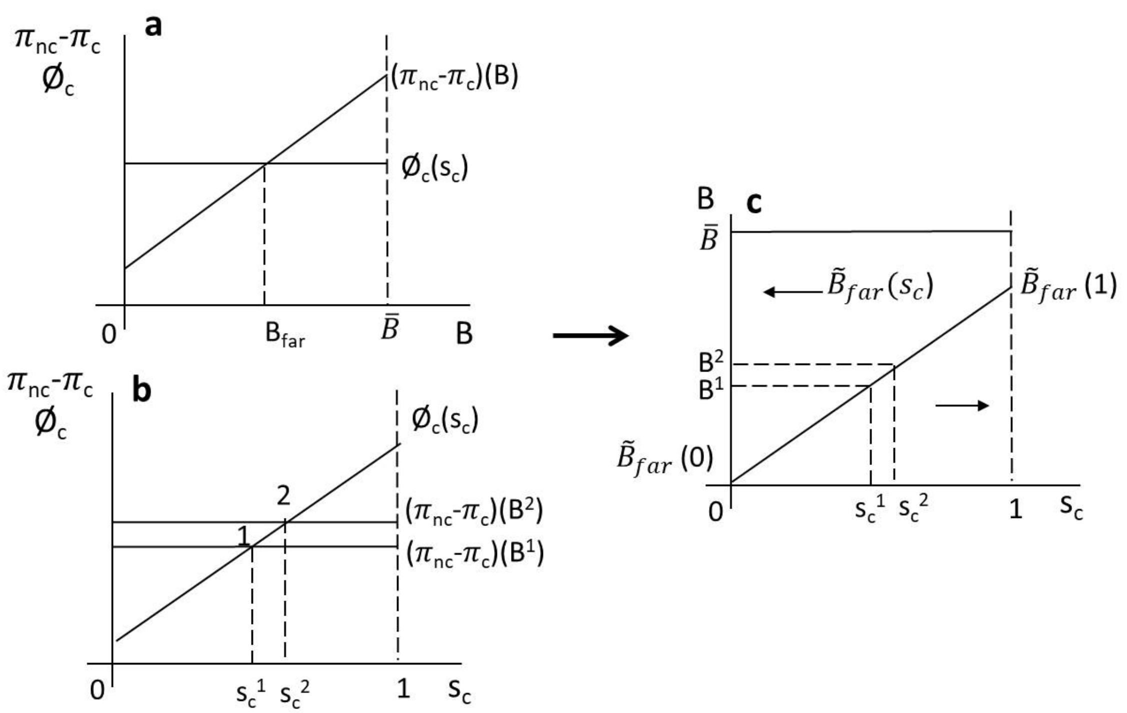
$$J_{(B,1)} = \begin{pmatrix} \frac{dF}{dB} - \frac{\partial W}{\partial B} - \frac{\partial W}{\partial X}\frac{\partial X}{\partial B} & -\frac{\partial W}{\partial X}\frac{\partial X}{\partial s_c} \\ 0 & (u_{nc} - u_c) \end{pmatrix}$$

At $(\widehat{B}(1), 1)$ $J_{11} < 0$, as it is a stable equilibrium point of the resource stock dynamics. Further, note that $J_{22} = (u_{nc} - u_c) = 0$ if $\widehat{B}(1) = B_{far}(1)$ the trace is negative and the determinant is $\left|J_{(B,1)}\right| = 0$. and $(\widehat{B}(1), 1)$ is stable. Moreover, if $\widehat{B}(1) < B_{far}(1)$ by definition $(u_{nc} - u_c)(B) < 0$. In such a case the trace is negative and the determinant is positive and $(\widehat{B}(1), 1)$ is an asymptotically locally stable point of the combined system. Finally, if $\widehat{B}(1) > B_{far}(1)$ then by definition $(u_{nc} - u_c)(B) > 0$, the determinant is negative and $(\widehat{B}(1), 1)$ is an asymptotically locally unstable point of the combined system. On the other side at $(\widetilde{B}(1), 1)$ $J_{11} > 0$ the trace is inconclusive.

2.6.2 The combined system of an increasing subsidy scheme

Additionally, whenever $\frac{\partial \phi_i(s_c)}{\partial s_c} > 0$ by lemma 3 the farmers' dynamics is unstable. We represent these unstable equilibria as $\widetilde{B}_{far}(s_c)$ in Figure 2.5.

In this situation a heterogeneous equilibrium point such as M does not exist, and point C is the unique stable equilibrium point assuring the sustainability of the natural resource. See the phase diagrams on Figure 2.6 that results from superposing the phase diagrams of the resource dynamics depicted in Figure 1.2b chapter 1 and of the farmers' dynamics depicted in Figure 2.5c. Note that to reach the homogeneous equilibrium point C, we need to increase the budget. If the agency has enough money to pay farmers such a point where $u_{nc} - u_c < 0$ when $s_c = 1$, then all agents will behave as conservationists; however, we have assumed a binding budget and therefore this is not a realistic situation. Further, in this case there is not a management problem, as the agency can pay an amount large enough to convince all farmers to behave as conservationists.



*In all panels we assume $B^1 < B^2$. Allocation 1 represents the equilibrium point (B^1, s_c^1) where $(\pi_{nc}-\pi_c)=\emptyset_c$. A similar interpretation could be done for point 2. Finally, $\tilde{B}_{far}$ (s_c) represents the set of unstable equilibrium points (B, s_c) of the farmers' dynamics.

Figure 2.5: Farmers' dynamics under a subsidy that increase with s_c.

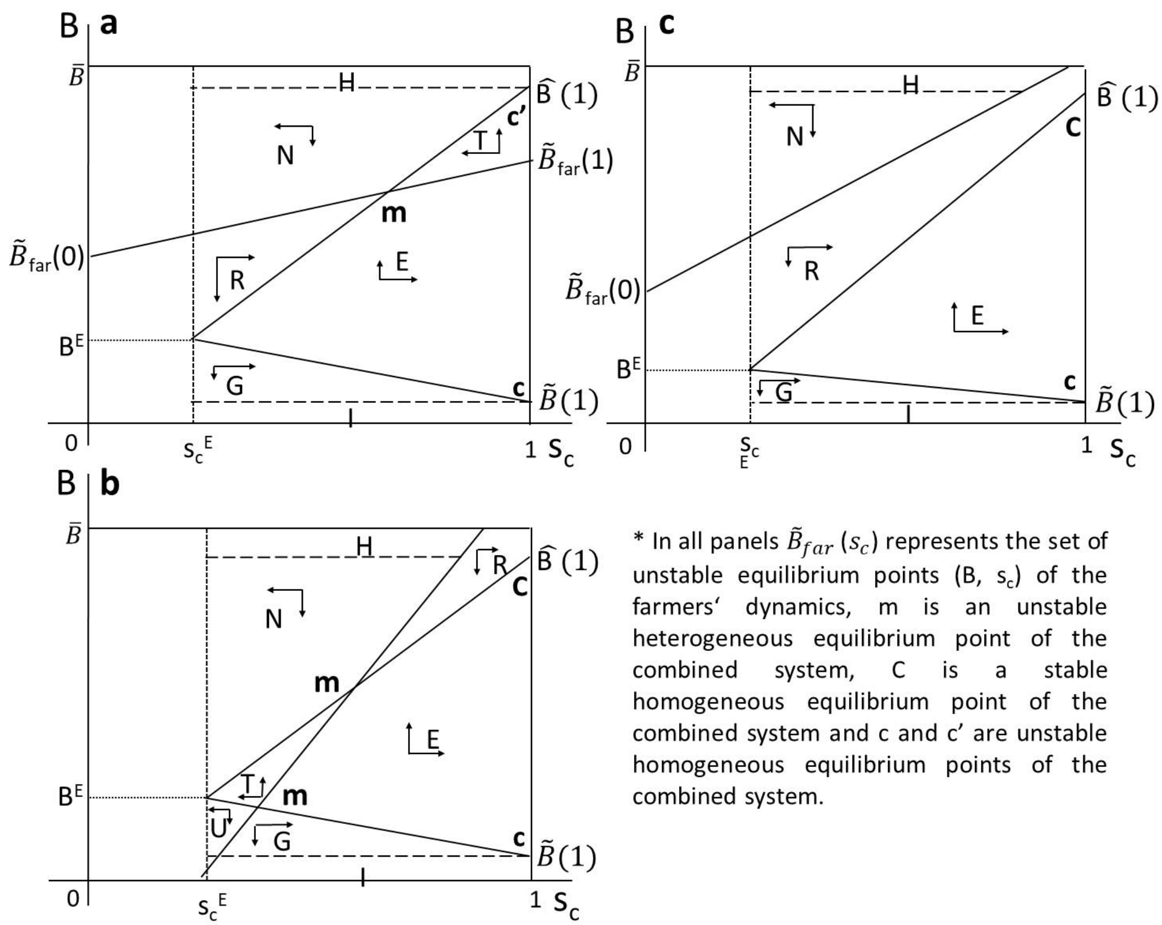


Figure 2.6: Combined system when the farmers' dynamics is unstable.

2.6.3 The constant price differentiation case

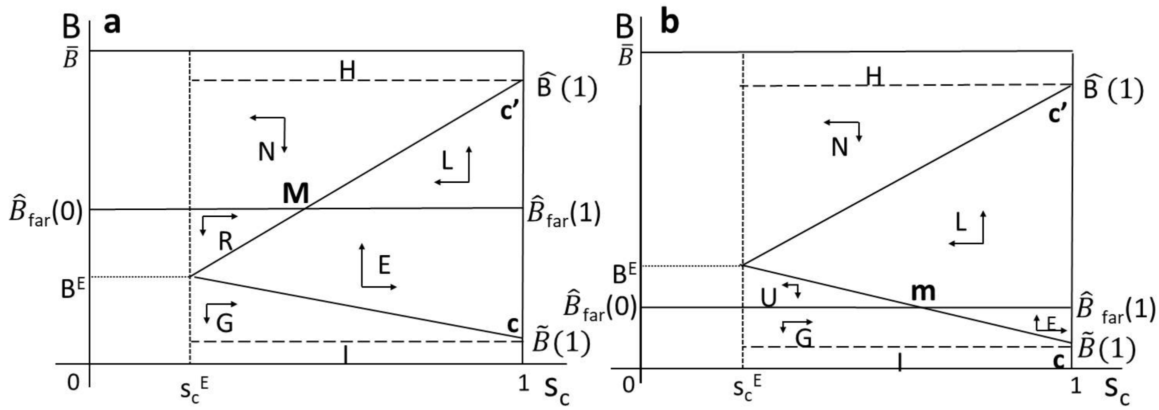
Note that in the case where p_c is a constant function of Q_c, and $p_c > p_{nc}$ we are assuming that there is product differentiation and that markets are competitive. If it was the case that $p_c > p_{nc}$ and both were constant, a heterogeneous equilibrium could exist if $(\pi_{nc} - \pi_c)(B) = 0$ or what is the same if $p_{nc}h(x_{nc}, B) - cx_{nc} = p_c h(x_c, B) - cx_c$. In this case, we are representing a situation where the proportion of conservationists does not affect farmers' profits; therefore, there could be a level B^* s.t. $\underline{B} < B^* < \bar{B}$ for any s_c that we define as B_{far} where $(\pi_{nc} - \pi_c)(B_{far}) = 0$. Then, whenever $B^* =$

B_{far} the location B_{far} will define a heterogeneous equilibrium point for any s_c, that is (s_c, B^*). Following Takayama, this point is an asymptotically stable equilibrium if $\frac{\partial \dot{s}_c}{\partial s_c} < 0$, where $\frac{\partial \dot{s}_c}{\partial s_c} = -s_c(1-s_c)\left(\frac{\partial(u_{nc}-u_c)}{\partial s_c}\right) = -s_c(1-s_c)\left(\frac{\partial(\pi_{nc}-\pi_c)}{\partial s_c}\right)$. Note that $\frac{\partial[\pi_{nc}-\pi_c]}{\partial s_c} = 0$; therefore, $\frac{\partial \dot{s}c}{\partial sc} = 0$. (s_c, B^*) is an indeterminate equilibrium point of the farmers' dynamics. Moreover, and as the benefits function does not depend on s_c, B_{far} will be unique for all s_c, $1 > s_c > 0$, that is $\frac{\partial B_{far}}{\partial sc} = 0$. Furthermore, for values of $B > B_{far}$ then $(\pi_{nc} - \pi_c)(B) > 0$ and for values of $B < B_{far}$ then $(\pi_{nc} - \pi_c)(B) < 0$ as $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} > 0$ for all B. [29]

Whenever $\widehat{B}(s_c)$ intersects B_{far} there is a heterogeneous equilibrium point of the joint dynamics system (s_c^*, B^*). This point by proposition 1 is a stable equilibrium point of the combined system. Contrarily, whenever $\widetilde{B}(s_c)$ intersects B_{far} there is a heterogeneous equilibrium point of the joint dynamics system (s_c^*, B^*). This point is an unstable equilibrium point. See the graphical representation of stable heterogenous equilibrium point, represented by point M in Figure 2.7a and the unstable heterogenous equilibrium point, represented by point m in Figure 2.7b.

[29]Recall that by lemma 4B $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} = p_{nc}\frac{\partial h(x_{nc},B)}{\partial B} - p_c\frac{\partial h(x_c,B)}{\partial B}\left(1 + \frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}\right)$

Now $\frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c} = 0$; therefore, the sign of $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B}$ depends on the difference $p_{nc}\frac{\partial h(x_{nc},B)}{\partial B} - p_c\frac{\partial h(x_c,B)}{\partial B}$ Recall that $\frac{\partial h(x_i,B)}{\partial B} < 0$, and by assumption $\left|\frac{\partial h(x_{nc},B)}{\partial B}\right| < \left|\frac{\partial h(x_c,B)}{\partial B}\right|$ moreover $p_c > p_{nc}$ therefore $\frac{\partial(\pi_{nc}-\pi_c)}{\partial B} = p_{nc}\frac{\partial h(x_{nc},B)}{\partial B} - p_c\frac{\partial h(x_c,B)}{\partial B} > 0$.



* B_{far} represents the set of stable equilibrium points (B, s_c) of the farmers' dynamics, M is a stable heterogeneous equilibrium point of the combined system, m is an unstable heterogeneous equilibrium point of the combined system and c and c' are unstable homogeneous equilibrium point of the combined system.

Figure 2.7: Combined system under a constant price differentiation.

2.6.4 A case where bird population does not damage farmers' harvest function

A case where $\frac{\partial(u_{nc}-u_c)}{\partial B} = 0$ occurs when $\frac{\partial h(x_c,B)}{\partial B} = 0$ or when $p_{nc}\frac{\partial h(x_{nc},B)}{\partial B} - p_c\frac{\partial h(x_c,B)}{\partial B}$ $\left(1 + \frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}\right) = 0$.[30] In this case, we are representing a situation where the bird population does not affect farmers' profits and therefore farmers' dynamics does not depend on bird population.[31] That is, there could be a level sc^* s.t. $0 < sc^* < 1$ for any B where $(\pi_{nc} - \pi_c)(sc^*) = 0$. Then, sc^* will define a heterogeneous equilibrium point for any B, that is (s_c^*, B) called B_{far} (See Figure 2.8). As the benefits function does not depend on B, B_{far} will be unique for all B, $\underline{B} < B < \bar{B}$, that is $\frac{\partial B_{far}}{\partial sc} = \infty$.[32]

[30] We assume that $\left|\frac{\partial h(x_c,B)}{\partial B}\right| > \left|\frac{\partial h(x_{nc},B)}{\partial B}\right|$; therefore, if $\frac{\partial h(x_c,B)}{\partial B} = 0$ then $\frac{\partial h(x_{nc},B)}{\partial B} = 0$.

[31] Note that assuming $\frac{\partial h(x_c,B)}{\partial B} = 0$ means that the bird population does not generate a negative externality on farmers. This could be the case where the natural resource is not affecting farmers' profits negatively; however, when a regulation is introduced, farmers are forced to comply with some harvesting constraints; therefore, there is a negative externality in this sense.

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

Furthermore, if we assume that the farmers' dynamics is stable, that is $\frac{\partial(u_{nc}-u_c)}{\partial sc} > 0$, for values of $sc^* > B_{far}$ then $(u_{nc} - u_c)(B) > 0$ and for values of $sc^* < B_{far}$ then $(u_{nc} - u_c)(B) < 0$ as for all B. Given any level of natural resource stock B as long as $\underline{B} < B < \bar{B}$, we assume that there is a location sc^* between $0 < sc^* < 1$ where $(u_{nc} - u_c)(s_c^*, B) = 0$. Then we assume that there is a pair (s_c^*, B) called $B_{far}(s_c^*)$ that is an equilibrium point of the population dynamics. Following Lemma 3, this point is an asymptotically stable equilibrium if $\frac{\partial(u_{nc}-u_c)}{\partial s_c} > 0$ and then $\frac{\partial \dot{s}_c}{\partial s_c} < 0$. Consequently, (s_c^*, B) can be asymptotically stable.

Whenever $B_{far}(s_c)$ intersects $B(s_c)$ for a positive proportion of conservationist farmers s_c^*, $0 < s_c^* < 1$ there is a heterogeneous equilibrium of the combined system $(B^*(s_c^*), s_c^*)$. Further, the Jacobian evaluated at this interior equilibrium point (B^*, s_c^*) is given by

$$J_{(B,s_c)} = \begin{pmatrix} \frac{dF}{dB} - \frac{\partial H}{\partial B} - \frac{\partial W}{\partial X}\frac{\partial X}{\partial B} & -\frac{\partial W}{\partial X}\frac{\partial X}{\partial s_c} \\ 0 & -s_c(1-s_c)\left[\frac{\partial(u_{nc}-u_c)}{\partial s_c}\right] \end{pmatrix}$$

The trace and the determinant of J_X can be written as:

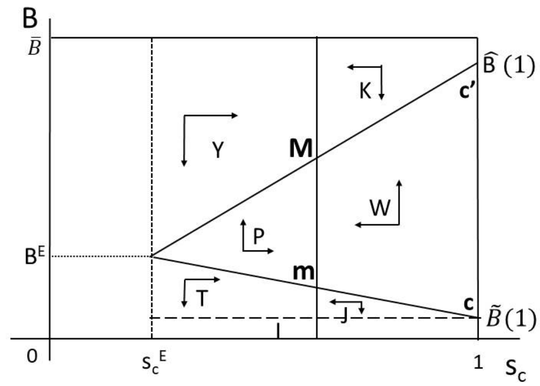
$$trJ_E = \left[\frac{\partial \dot{B}}{\partial B}\right] + \left[-sc^*(1-sc^*)\left(\frac{\partial(u_{nc}-\pi_c)}{\partial sc}\right)\right]$$

$$|J_E| = -s_c^*(1-s_c^*)\left[\frac{\partial(u_{nc}-u_c)}{\partial s_c}\right]\left[\frac{\partial \dot{B}}{\partial B}\right]$$

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

Assuming $\frac{\partial(u_{nc}-u_c)}{\partial B} = 0$, then $\frac{\partial B_{far}}{\partial s_c} = \infty$

Note that in the collective subsidy case if we assume $\frac{\partial(u_{nc}-u_c)}{\partial B} = 0$ then we are also in the case where $\frac{\partial B_{far}}{\partial s_c} = \infty$ and the results are the same as the ones obtained with price differentiation. Nevertheless, with a constant subsidy we obtain the indetermination $\frac{\partial B_{far}}{\partial s_c} = -\frac{0}{0}$. In such a case B_{far} could be any combination of (B, s_c).

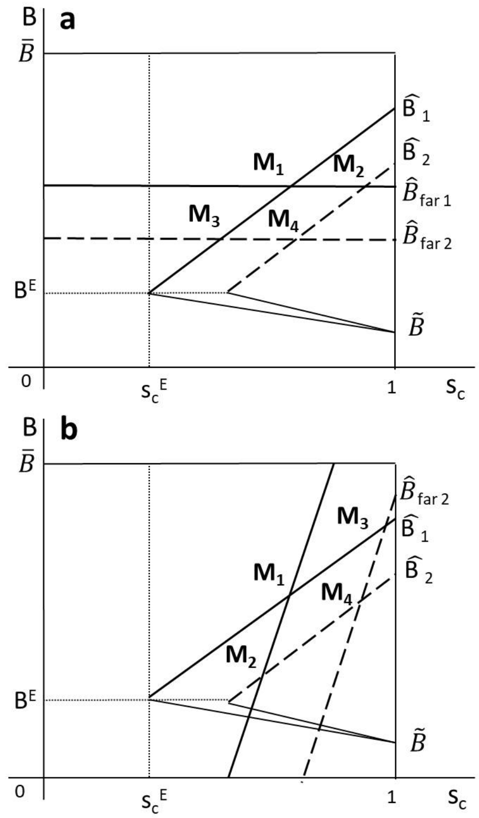


* $\hat{B}_{far}$ (s_c) represents the set of stable equilibrium points (B, s_c) of the farmers' dynamics, M is a stable heterogeneous equilibrium point of the combined system, m is an unstable heterogeneous equilibrium point of the combined system, C is a stable homogeneous equilibrium point of the combined system and c and c' are unstable homogeneous equilibrium points of the combined system.

Figure 2.8: Combined system when bird population does not affect farmers' harvest function

Whenever (B^*, s_c^*) is a stable equilibrium of the resource stock, then by Lemma 1 $\frac{\partial \dot{B}}{\partial B} < 0$. If it is also a stable equilibrium of the farmers' dynamics by Lemma 3, $\frac{\partial(u_{nc}-u_c)}{\partial sc} > 0$. Consequently, the trace is always negative. Further, the determinant is always positive $|J_E| > 0$ and (B^*, s_c^*) is a stable heterogeneous equilibrium point of the combined system. Contrarily, whenever (B^*, s_c^*) is an unstable equilibrium of the resource stock dynamics but a stable equilibrium point of the farmers' dynamics by Lemma 1 $\frac{\partial \dot{B}}{\partial B} > 0$ and by Lemma 3 $\frac{\partial(u_{nc}-u_c)}{\partial sc} > 0$. The determinant is always negative and (B^*, s_c^*) is an unstable heterogeneous equilibrium point of the combined system. Finally, if (B^*, s_c^*) is an unstable equilibrium of the resource stock dynamics and an unstable equilibrium point of the farmers' dynamics by Lemma 1 $\frac{\partial \dot{B}}{\partial B} > 0$ and by Lemma 3 $\frac{\partial(u_{nc}-u_c)}{\partial sc} < 0$. The trace is always positive and (B^*, s_c^*) is an unstable heterogeneous equilibrium point of the combined system. See the graphical representation of stable (unstable) heterogenous equilibrium point, represented by point M (m) in Figure 2.8.

2.6.5 Other comparative statics



* In panel (a) there is the graphical representation of the $\widehat{B}_{far}$ constant function of s_c case and in panel (b) the $\widehat{B}_{far}$ increasing function of s_c. We have assumed $\widehat{B}_{far\,1} > \widehat{B}_{far\,2}$ and $\widehat{B}_1 > \widehat{B}_2$. Points M_i represent stable heterogeneous equilibrium points of combined system.

Figure 2.9: Other stable equilibrium point $(B,\, s_c)$ changes depending on $\widehat{B}_{far}$ and $\hat{B}$

Parameters	$\widehat{B}$	$\widehat{B}_{far}$	Whether $\widehat{B}_{far}$ is a constant function of s_c the stable equilibrium point (B, s_c) ends having:	Shifts on the equilibrium point
Less birds damaging technology	Upwards	No change	Constant B Smaller s_c	From M_4 to M_3
More productive harvesting technology	No change	Downwards	Smaller B Smaller s_c	From M_1 to M_3
Higher $F(B)$.	Upwards	No change	Constant B Smaller s_c	From M_4 to M_3
Higher birds damage on $H(X, B)$	No change	Downwards	Smaller B Smaller s_c	From M_1 to M_3
Opportunity cost , c.	No change	Upwards	Higher B Higher s_c	From M_3 to M_1
Subsidy schemes				
ϕ_c	No change	Upwards	Higher B Higher s_c	From M_3 to M_1
p	No change	Downwards	Smaller B Smaller s_c	From M_1 to M_3

Table 2.2: Effect of changes in different parameters values on the equilibrium point (B, s_c) when $\hat{B}_{far}$ is a constant function of s_c.

Parameters	$\widehat{B}$	$\widehat{B}_{far}$	Whether $\widehat{B}_{far}$ is an increasing function of s_c the stable equilibrium point (B, s_c) ends having:	Shifts on the equilibrium point
Less birds damaging technology	Upwards	No change	Higher B Higher s_c	From M_2 to M_1
More productive harvesting technology	No change	Downwards	Higher B Higher s_c	From M_1 to M_3
Higher $F(B)$.	Upwards	No change	Higher B Higher s_c	From M_2 to M_1
Higher birds damage on $H(X, B)$	No change	Downwards	Higher B Higher s_c	From M_1 to M_3
Opportunity cost , c.	No change	Upwards	Smaller B Smaller s_c	From M_3 to M_1
Price differentiation scheme				
p_c	No change	?	B? s_c?	?
p_{nc}	No change	?	B? s_c?	?

* ? depends of own price elasticity and cross elasticity.

Table 2.3: Effect of changes in different parameters values on the equilibrium point (B, s_c) when $\hat{B}_{far}$ is an increasing function of s_c.

2.6.6 Definition summary of the variables and parameters of the model

Resource stock dynamics parameters	Definition
L_z	Protected surface area in ha.
N	Number of agents farming in the protected area L_z.
B	Resource stock level.
$F(B)$	Natural rate of replenishment of the resource stock.
X	Level of non-environmentally friendly inputs used by the community of farmers as a whole (N).
$W(B,X)$	Wipe out function or amount of natural resource removed due to the use of non-environmentally friendly inputs.
$\dot{B}$	Rate of change of the natural resource stock, it represents the resource stock changes, where $\dot{B} = F(B) - W(B,X)$.
$\hat{X}(B)$	Level of non-environmentally friendly inputs that equates $F(B)$ and $W(B,X)$ for an specific level of B. These points define equilibrium points of the resource dynamics where $\dot{B} = 0$.
x_i	Individual level of non-environmentally friendly inputs used by each farmer i ($i \in N$).Note that $X = \sum x_i$.
s_c	Proportion of conservationists farmers.
$\widehat{B}(s_c)$	Resource stock level that corresponds to a stable equilibrium point of the resource dynamics when the proportion of conservationist farmers is s_c ($\dot{B} = 0$).
$\widetilde{B}(s_c)$	Resource stock level that corresponds to an unstable equilibrium point of the resource dynamics when the proportion of conservationist farmers is s_c ($\dot{B} = 0$).
Farmers behavior dynamics parameters	**Definition**
$h(x_i, B)$	Farmers' harvest function.
p_i	Output price.
c	Opportunity cost of the non-environmental friendly inputs used.
$\phi_i(s_c)$	Individual subsidy received by each farmer i. It can be constant subsidy rate ϕ_i or a decreasing function of s_c.
u_i	Farmers payoff function. In the subsidy schemes $u_i = \pi_i + \phi_i$ and in the price differentiation scheme $u_i = \pi_i$.Where $\pi_i = ph_i(x_i, B) - cx_i$.
$\dot{s}_c$	Rate of change of the proportion of conservationists farmers, such that $\dot{s}_c = \omega(1 - s_c)(u_{nc} - u_c)$.
$\widehat{B}_{far}$	Farmers dynamics continuum of stable equilibrium points. The farmers dynamics is in equilibrium when $\dot{s}_c = 0$.
$\widetilde{B}_{far}$	Farmers dynamics continuum of unstable equilibrium points.
Q_c	Total amount of output produced by conservationists farmers. $Q_c = \sum_{i=1}^{N} h(x_c, B)$.In the price differentiation scheme $p_c(Q)$.

Table 2.4: Definition summary of the variables and parameters of the model.

Chapter 3

A simulation example: The Little bustard case

3.1 Introduction

Our motivational example focuses on the populations of Little bustard (*Tetrax tetrax*) in the Segarra-Garrigues protected area. This is a steppe and omnivorous species that lives in fallow and dry cereal areas such as barley (Ponjoan *et al.,* 2004). The population of Little bustard has gone down in the last few decades due to the process of agricultural intensification (Lapiedra *et al.,* 2011), and it has been catalogued as an endangered species in Catalonia (Herrando and Anton, 2013, status revised in 2012). In this chapter, we are going to parametrize our theoretical model taking into account the characteristics of the Segarra-Garrigues irrigation area and of the Little bustard (*Tetrax tetrax*). The canal has favoured agricultural intensification, allowing irrigation to reach large areas with a long dryland agricultural tradition. This has generated many conflicts between farmers and the environmental agency due to the transformation of dry into irrigation land and threatening the survival of a large number of steppe birds (Reguant and Lletjós, 2014).[1]

The functional forms and parameter values used in our simulations are based on the characteristics of this species in the Segarra-Garrigues area (See Figure 3.1). The investment project affects $70,150ha$ of agricultural land in six Catalan counties,[2] of which $34,183ha$ are protected under the Natura 2000 network (Reguant and Lletjós, 2014). Using the available information from the protected zone and the protected species, we established our model and created a scenario able to represent the situation of the Little bustard in the Segarra-Garrigues area. We analyzed farmers' population dynamics under the three agri-environmental schemes presented before, the constant subsidy per hectare, the collective subsidy, and the price differentiation scheme.

Our aim is to evaluate and compare the capacity of these three different schemes to protect the Little bustard in the Segarra-Garrigues irrigation area. As we have already shown in this thesis, these three schemes enable the regulatory agency to reach stable equilibrium allocation where the resource is sustainable. Nevertheless, knowing whether one of these mechanisms performs better than another under the same conditions is crucial for designing and applying regulatory policies. We aimed to determine and compare the characteristics of the equilibrium points and the basin of attraction that can be attained under each regulatory scheme to ascertain which scheme is the most appropriate under different sets of circumstances. Recall that the aim is to recover an endangered species and, accordingly, we expect that the environmental agency probably

[1]The simulations and the graphical representations were performed with Excel v.14.0.7208.5000 and wxMaxima 17.10.0

[2]Called Segarra, Garrigues, Noguera, Urgell, Pla d'Urgell and Segrià. (see the Segarra-Garrigues compulsory environmental impact assessment, Resolució, MAH/3644/2010, 2010).

faces a set of initial conditions with low levels of both B and of s_c. Therefore, we pay special attention to these sets of initial conditions and we focus on identifying the regulatory mechanism that more easily facilitates the recovery of the endangered species under demanding circumstances.

This chapter is organized as follows. In the first section, we present the functions and the parameters that we use to describe the bird population dynamics. We also present a parameter sensitivity analysis. In section 2, we describe the functions and parameters describing farmers' behaviour and we introduce the agri-environmental schemes' explicit functions. In section 3, we present the combined system and the simulation results for each proposed agri-environmental scheme and we compare them. Finally, in section 4 we present the conclusions.

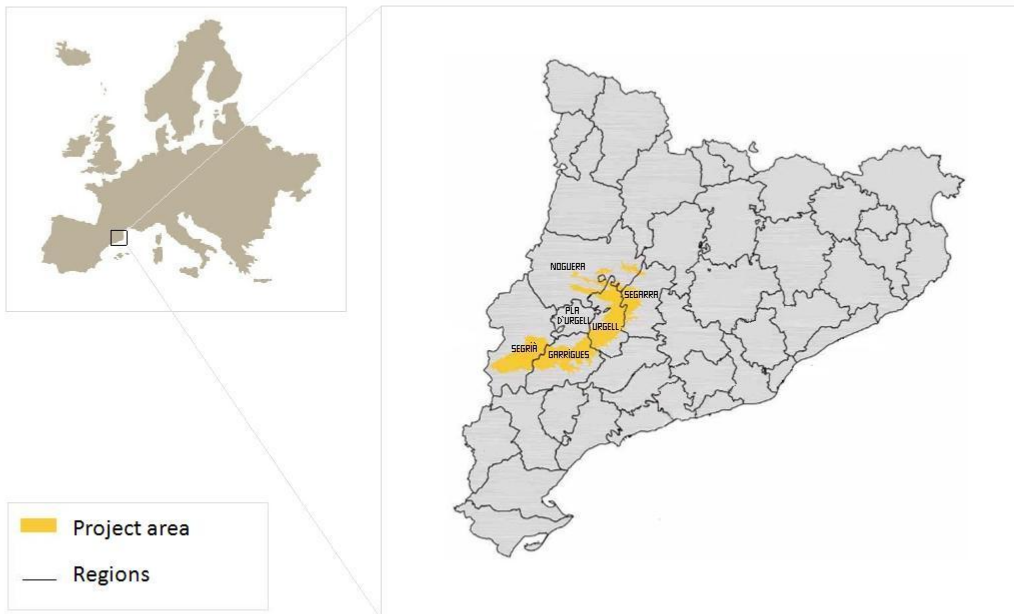


Figure 3.1: Location of the Segarra-Garrigues irrigation project.

3.2 Bird population parametrization

We first aim to describe the Little bustard's habitat and characteristics. The Little bustard is a dry crop cereal specialized bird and, therefore, we have considered that the habitat available for the species coincides with this extension of dryland. However, this area could be over-irrigated due to non-environmentally friendly harvesting practices. Out of the $34,183$ha protected area included in the Natura 2000 network (Reguant and Lletjós, 2014), the total surface area dedicated to cereal cropping in dryland is $23,600$ha.[3] Furthermore, we assume that there are $N = 236$ farmers in the protected area and that each one of them owns 100 hectares of farmland.

[3]We obtain this information from the use of soil percentages described in the Management and Special Environmental and Landscape Protection Plan of the Protected Natural Areas in the Plains of Lleida (MSPP) carried out in 2010 (Departament de Medi Ambient i Habitatge, 2010).

We represent the natural evolution of the bird population, $F(B)$, with a logistic growth function:

$$F(B) = rB(1 - \frac{B}{\overline{B}}) \tag{3.1}$$

where $r > 0$ is the natural rate of growth, and $\overline{B}$ is the maximum stock of birds that the area is able to support. A compulsory environmental impact assessment (EIA) was carried out by the Catalan Government in 2010 and determined that the population of Little bustard in this protected area consisted of $B = 905$ individuals.[4] Moreover, according to the EIA, between 2002 and 2009 the population of males decreased by 17% and that of non-males by 34% in this protected zone. That is, in 2002 the Little bustard population was supposed to be around $1,800$ individuals. This decrease was due to the inadequate land use carried out during those years (see the EIA). Further, Morales *et al.* (2005) calculated that the carrying capacity of Little bustard in the south of France was equal to $\overline{B} = 1.5B$. After considering this information we assume that the carrying capacity for Little bustard in the Segarra-Garrigues area is equal to $\overline{B} = [1.1B - 2B]$, where $B = 905$; this range includes the population stock level that existed before 2002 and the carrying capacity estimated by Morales *et al.* in 2005. Finally, Inchausti and Bretagnolle (2005) determined that the natural rate of growth for the same species in the Southwest of France was $r \in [0.7, 1]$ and we took this parameter as our natural growth rate range.

We define $W(B, X)$ as the wipe out function, which measures the Little bustard's vulnerability to agricultural intensification; we represent agricultural intensification with the excessive use of irrigation water, X. In our example, the excessive use of irrigation water conveys the effect of agricultural intensification on the Little bustard population.[5] $W(B, X)$ tells us the reduction in the Little bustard population (in num-

[4]Resolució, MAH/3644/2010, 2010. We refer to this as EIA from now on.

[5]The Segarra-Garrigues irrigation project, according to the EIA, has to comply with several types

ber of individuals) due the use of irrigation water. Note that this function also depends on the natural resource stock level, B; thus, we assume that the resource vulnerability rate also changes with stock size. In particular, we represent $W(B, X)$ with the following function:

$$W(B, X) = qX^{\alpha}B^{\beta} \tag{3.2}$$

where, α represents the elasticity of the wipe out function with respect to irrigation water use, β represents the elasticity of the wipe out function in relation to stock size and q is an adjustment factor. Further, we assume that $0 < \alpha$, $0 < \beta < 1$ and $q > 0$. For a specialized species with strict habitat requirements, α takes values near 1. On the contrary, if the species does not have strict habitat requirements, α would be close to 0. Recall that we defined $\hat{X}(B)$ as the volume of irrigation water at which the rate of extraction of the resource stock B is equal to its rate of renewal. Note that the larger α the lower $\hat{X}(B)$ is. Summarizing, the larger the α the more specialized a species is, the more vulnerable it is to changes in its habitat and, in particular, to changes in the volume of irrigation water used.[6] The Little bustard is a dry crop cereal specialized species and it seems reasonable to choose α such that $\alpha \in [0.6, 0.9]$.[7] On the other side, β represents the increase in the wipe out rate as the resource stock B increases. The larger the population of Little bustards in a given area, the easier it is to kill one of them and therefore the larger the number of birds exterminated per unit of time. By assumption, the wiping out effect of irrigation water is larger than the bird population

of regulations, such as restrictions about the minimum extension of fallow areas, bans on phytosanitary products and limitations on the use of irrigation water, among others. Nevertheless, what generates the most controversy among farmers is the irrigation water restrictions, because the volume of irrigation is what actually determines farm productivity.

[6] See Andrén and Seiler (1997) for a more precise explanation.

[7] It is possible to provide the model with $\alpha \geq 1$. Nevertheless, in this case the species is so vulnerable that the only possible situation where the Little bustard could be recovered is a situation where all farmers behave as conservationists.

effect, and thus we assume $\alpha > \beta$,[8] and we assume $\beta \in [0.1, 0.8]$.[9] See Table 3.1 for a parameter and variables definition summary.

Given these functional forms, the Little bustard stock dynamics can be represented by the following expression:

$$\dot{B} = rB(1 - \frac{B}{\overline{\overline{B}}}) - qX^{\alpha}B^{\beta} \tag{3.3}$$

Finally, note that the larger $W(X, B)$ is, the larger its effect on the bird population dynamics, $\dot{B}$. That is, depending on $W(X, B)$, the natural resource can evolve very quickly. Imagine a situation where the vulnerability of the species to a non-environmentally friendly input is high enough to extinguish the species immediately after the input has been applied as, for example, happens when farmers apply insecticides to deal with a pest. In a situation like this, there would not be a chance to introduce an agri-environmental scheme to stop its extinction, because the species will be quickly extinguished. In our model, we assume that the natural resource dynamics shifts gradually and can be affected by the farmers' behaviour and the population dynamics, $\dot{s}_c$.

[8] We have assumed that $\hat{X}(B)$ is bell-shaped if $\beta > 1$, then $\hat{X}(B)$ would become a decreasing function of B. That would mean that when the resource stock decreases the wipe out rate increases. This case is appropriate for species with a high intrinsic competence, where the vulnerability rate increases fast when the population is large due to the intrinsic competence of the species for the habitat. Nevertheless, this is not our case; recall that we are talking about an endangered species. Then, it is reasonable to assume that the Little bustard is more vulnerable the lower its population, and irrigation should be avoided especially when B is low.

[9] As by assumption $\alpha > \beta$, then β cannot be equal to or greater than 0.9.

		Minimun	Average	Maximum
Parameters of the natural resource dynamics				
$\overline{B}$	Bird population carrying capacity	996	1404	1812
r	Bird population natural rate of growth	0.7	0.85	1
α	Elasticity of the wipe out function to irrigation water use	0.6	0.75	0.9
β	Elasticity of the wipe out function to stock size	0.1	0.45	0.8
q	Wipe out adjustment parameter	–	$6 \cdot 10^{-5}$	–
Parameters of the farmers' behaviour dynamics				
φ	Damage caused by birds to the conservationists' harvest function related to the damage caused to the non-conservationists' harvest function	2	–	9
σ	Elasticity of the subsidy to changes in the proportion of conservationists. For the constant subsidy, $\sigma = 0$ and for the collective $\sigma = 1$	0	–	1
ρ	Price elasticity of the conservationists' output, Q_c	0.5	–	10
ω	Speed at which farmers adjust their behaviour	10^{-6}	–	1

Table 3.1: Natural resource dynamics parameters and variables definition

3.2.1 Bird population equilibria

Our theoretical model shows that, at the natural resource stock equilibrium, $\dot{B} = 0$, the volume of water used by farmers for irrigation is such that the birds' rate of extinction, $W(X, B)$, is equal to its rate of renewal, $F(B)$, for bird stock B. In Figure 3.2a, we represent an equilibrium point B^E where the proportion of farmers $s_c^E \in (0, 1)$ is such that the volume of water used for irrigation $X(s_c^E, B)$ coincides and is tangent to $\hat{X}(B^E)$ at B^E. At B^E there is a stable equilibrium of the resource stock and $\hat{X}(B^E)$ is the volume of water that farmers can use for irrigation purposes that allows a stable (and sustainable) equilibrium of the endangered species at B^E.

Furthermore, $\hat{X}(B^E)$ is the maximum amount of water that farmers can use for irrigation purposes that allows a sustainable resource equilibrium. Note that the volume of water used for irrigation $X(s_c^E, B)$ is tangent to $\hat{X}(B^E)$ at B^E and therefore, if a larger volume of water were used, then the natural resource would not be sustainable. We assume that the agency had determined this maximum amount of water taking into consideration the sustainability of the Little bustard. In our simulation example, this means that farmers can use a water irrigation allocation of at most $2,014m^3/ha$, in this protected area.[10] Therefore, in our simulations we assume $\hat{X}(B^E) = 2,014m^3/ha$ as the maximum total level of irrigation water that the Little bustard can tolerate per year.[11]

For our simulation example, we choose to use as baseline parameters for the population dynamics the average values discussed in the previous section (see Table 3.1). Our baseline carrying capacity is $\bar{B} = [1.1B - 2B] = 1,404$ where $B = 905$; the intrinsic rate of growth is $r = 0.85$, the Little bustard vulnerability elasticity to irrigation water is $\alpha = 0.75$ and the vulnerability elasticity of the stock is $\beta = 0.45$. We also take $q = 6 \cdot 10^{-5}$ to adjust $W(B, X)$, such that the maximum water allowance per hectare in the protected area $\hat{X}(B^E) = 2,014m^3/ha$ coincides with the water allocation that corresponds to equilibrium B^E.

Under this parametrization, the set of equilibria of the bird population dynamics is represented in Figure 3.2b. Further, we use point $\left(s_c^E, B^E\right) = (0.52, 959)$ as the reference point for the bird population dynamics (See Point E in Figure 3.2). That is, the minimum proportion of conservationist farmers required to reach a stable equilibrium is $s_c^E = 0.52$, the bird stock is 959 individuals and the water used by farmers is $2,014m^3/ha$ which is the maximum volume of irrigation water that allows the species

[10] In this protected area the irrigation water allowance is $3,500m^3/ha$ in 13.579 ha. However, there are 23,600ha. in this area devoted to cereals crops. (Reguant and Lletjós, 2014). We assume that the total water allowance in the whole cereal crop protected area is $47,526,500$ m^3 per year.

[11] This is only an approximation. The only way to know exactly the maximum amount of water the species can tolerate is by linearizing the $W(X, B)$ function through historical data about W, X and B to know exactly the values of its parameters and be able, later, to better define $\hat{X}(B^E)$.

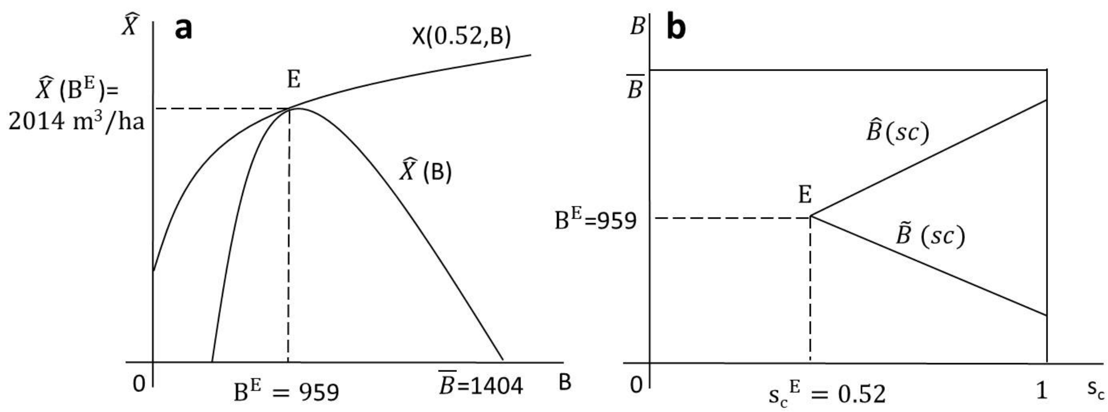


Figure 3.2: Natural resource dynamics.

to grow sustainably.

3.2.2 Bird population parameters sensitivity analysis

We now present the sensitivity analysis of the bird population dynamics, see Figure 3.2. In the third column of panels 3.2a and 3.2b we show the equilibrium pairs $\left(s_c^E, B^E\right)$ that correspond to the values of α and β posted in the first and second columns of panels 3.2a and 3.2b. In panel a the maximum carrying capacity is $\overline{B} = 1,812$ and the natural rate of growth is $r = 1$. In panel b these values are, $\overline{B} = 996$ and $r = 0.7$, respectively.

We have run several simulation examples and we have evaluated the parameters of the bird population dynamics at their minimum, maximum and average values, see Table 3.2.[12] We do not present the results of evaluating the parameters of the bird population dynamics at their average value because the resulting equilibrium pairs

[12]Except for $\overline{B}$ and r where we only take the maximum and the minimum. The results of choosing the maximum for $\overline{B}$ and r are presented in Table 3.2a and the minimum (Table 3.2b) values that these parameters can take.

$\left(s_c^E, B^E\right)$ are already included in the results obtained in Table 3.2. Here we only present the extreme cases. The set of parameters that we have chosen allows $\left(s_c^E, B^E\right)$ to be such that $(0, 1225) < \left(s_c^E, B^E\right) < (1, 643)$.

On analyzing Table 3.2, we see that when the vulnerability of the species increases - that is larger values for α and β - the proportion of conservationists needed to reach a stable resource equilibrium, s_c^E is also larger. See for example the case in Table 3.2a where $\alpha = 0.9$ and $\beta = 0.1$, then the species would need the proportion of conservationist farmers to be equal to 0.04 and if β increases to 0.8, the proportion of conservationists required is 1. Note that when $\alpha = 0.9$ and $\beta = 0.8$, in Table 3.2a the proportion of conservationists required to reach a natural resource sustainable equilibrium is $s_c^E = 1$. Therefore, in these circumstances the bird population is sustainable only in an all-conservationists equilibrium.

(a) Assuming $\overline{B} = 1812$ and $r = 1$

α	β	(s_c^E, B^E)	$\hat{X}\left(B^E\right)$
0.6	0.1	$(0, 1225)$	29170735
	0.5	$(0, 1144)$	258346
0.75	0.45	$(0, 1185)$	4566
0.9	0.1	$(0.04, 1263)$	3303
	0.8	$(1, 1101)$	13

(b) Assuming $\overline{B} = 996$ and $r = 0.7$

α	β	(s_c^E, B^E)	$\hat{X}\left(B^E\right)$
0.6	0.1	$(0, 704)$	1661139
	0.5	$(0, 674)$	21261
0.75	0.45	$(0.83, 674)$	597
0.9	0.1	$(0.86, 704)$	449
	0.8	$(1, 643)$	3

* Rounding decimals.
* Recall that r and $\overline{B}$ are positively related with $\hat{X}\ (B^E)$.
* And α and β are negatively related with $\hat{X}\ (B^E)$.

Table 3.2: Parameter sensitivity analysis and implications for $\hat{X}(B^E)$ and $\left(s_c^E, B^E\right)$.

In contrast, if the species is more generalist - that is small values of α and β - then a stable equilibria could exist for any s_c^E. In these cases, the damage caused by water to birds is almost null, and then a high quantity of irrigation water is tolerated by the species. Water use restrictions would not be necessary in these cases. See, for example in Table 3.2b, that when $\alpha = 0.6$ and $\beta = 0.1$, according to the model the proportion of conservationists required is 0. Here, we have presented extreme cases to demonstrate that our range of parameter values covers all situations: situations where all farmers need to behave as conservationists to protect the natural resource and situations where irrigation water does not damage the bird population and all farmers can behave as non-conservationists. In our simulations, we use the baseline values that are more realistic and fall between these two extremes.

Next, we analyze how changes in our parameter values affect the maximum level of water that farmers can use while keeping the resource sustainable. In particular, in Table 3.3 we show how a variation of ($\pm 10\%$) in the value of the parameters posted in the second column - $\overline{B}$, r, q, α, and β - affects the volume of water that farmers can use for irrigation while keeping the bird population sustainable, $\hat{X}(B^E)$.[13] For example, in Table 3.3 we show that an increase of 10% in parameter $\overline{B}$ from $\overline{B} = 1,404$ to $\overline{B} = 1,544$ results in an increase of 27% in the maximum volume of irrigation water that farmers can use while keeping the bird population sustainable.

From our results, we observe that changes in α and β have a large effect on $\hat{X}(B^E)$. A variation of 10% in parameter α can cause a variation in $\hat{X}(B^E)$ larger than 600%. This parameter, jointly with β, has a huge effect on bird population dynamics. These results highlight the importance of determining α, β and q in the wipe out function.

[13]When we analyze one parameter, others are kept constant at their average values.

	Parameter	Parameter value	Variation of ±10% in parameter value	Associated variation caused on $\hat{X}$ (B^E) in %
Bird population growth function, $F(B)$	$\overline{B}$	1404	1544 1263	+27% −23.9%
	r	0.85	0.935 0.765	+13% −13
Wipe out function, $W(X, B)$	q	$6 \cdot 10^{-5}$	$6.6 \cdot 10^{-5}$ $5.4 \cdot 10^{-5}$	−12% +15%
	α	0.75	0.825 0.675	−79% +610%
	β	0.45	0.495 0.405	−33% +50%

*Rounding decimals.
* Recall that r and $\overline{B}$ are positively related with $\hat{X}$ (B^E) and α and β are negatively related with $\hat{X}$ (B^E).
* % variations are not symmetric because functions are not linear.

Table 3.3: Parameter variation effect on $\hat{X}(B^E)$.

3.3 Farmers' behaviour parametrization

We model the harvest function as:

$$h(x_i, B) = Ax_i^{\gamma}(1 - \frac{B^{\varphi_i}}{x_i}) \tag{3.4}$$

where x_i represents the amount of water used by farmer i. 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 changes in B or what is the same the damage caused by birds to the harvest function, where $\varphi_i \epsilon\, (\varphi_{nc}, \varphi_c)$. Finally, A is an adjustment parameter. We assume that $0 < \gamma < 1$, $0 < \varphi_i < 1$, and $A > 0$. In addition, it seems reasonable to assume that the level of water used, x_i, has a larger effect on the harvest function than bird population, B, that is $\gamma > \varphi_i$. Also, we assume that the population of birds damages the conservationist farmer harvest function more than the non-conservationist one, that is $\varphi_{nc} < \varphi_c$. Finally, this function satisfies the properties of our theoretical model $\frac{\partial h(B,x_i)}{\partial x_i} > 0$, $\frac{\partial h(x_i,B)}{\partial B} < 0$, $\frac{\partial h^2(B,x_i)}{\partial x_i^2} < 0$ and $\frac{\partial h^2(B,x_i)}{\partial x_i \partial B} \geq 0$. [14]

Further, we define p_i as the market output price, where $i \, \epsilon \, [nc, c]$, and c as the opportunity cost of the use of water. Therefore, the farmers' profit function is:

$$\pi_i = p_i \left[A x_i^{\gamma} (1 - \frac{B^{\varphi_i}}{x_i}) \right] - c x_i \tag{3.5}$$

where c represents the opportunity cost of irrigation water which is the price of irrigation water which in this area is $0.13€/m^3$.[15] In our simulation example we take as a reference price the private cost of water. We do not consider the environmental cost or other cost associated with the social cost of water (See Expósito, 2018).[16] However, we believe that our model could be reinterpreted to take into account the social cost of water.[17] The market price of barley in 2014 was $p = 0.163€/kg$.[18]

Rainwater would be the only water available to farmers if no irrigation system was

[14]Note that we can write $h(B, x_i)$ as $h(B, x_i) = A x_i^{\gamma} - \frac{A x_i^{\gamma} B^{\varphi_i}}{x_i}$ and then $\frac{\partial h(B,x_i)}{\partial x_i} = A\gamma x_i^{\gamma-1} - \left(\frac{A\gamma x_i^{\gamma-1} B^{\varphi_i} x_i - A x_i^{\gamma} B^{\varphi_i}}{x_i^2} \right) = A\gamma x_i^{\gamma-1} - \left(A\gamma x_i^{\gamma-2} B^{\varphi_i} - A x_i^{\gamma-2} B^{\varphi_i} \right) = A(\gamma x_i^{\gamma-1} + x_i^{\gamma-2} B^{\varphi_i} (-\gamma+1))$. 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, $\frac{\partial h(B,x_i)}{\partial B} = A x_i^{\gamma} (-\frac{\varphi_i B^{\varphi_i - 1} x_i}{x_i^2}) = -A x_i^{\gamma-1} \varphi_i B^{\varphi_i - 1} < 0$, then $\frac{\partial h^2(B,x_i)}{\partial x_i \partial B} = A x_i^{\gamma-2} \varphi_i B^{\varphi_i - 1} (-\gamma + 1) \geq 0$.

[15]This is the 2016 tariff. Checked on http://www.aiguessegarragarrigues.cat website (10/11/2016 at 11:04)

[16]Note that the EU Water Framework Directive (Directive 2000/60/EC) foresees full-cost recovery.

[17]The social cost associated to non-conservationist farmers' behavior will be larger than the social cost associated to conservationist farmers' behavior. Therefore, if the social cost of water were considered in our model the difference in social cost would have to be taken into account by the policy scheme. In the case of our subsidy, and if we assume that non-conservationist farmers pay for the full social cost of water, the conservationist farmers would have to be subsidized. The amount of this subsidy would have to be equal to the difference between the social cost faced by non-conservationist and conservationist farmers. We believe that the reinterpretation of our model under this light would let quite similar results to our current model. We plan on developing further this point in the near future.

[18]See Ministerio de Agricultura, Alimentación y Medio Ambiente, (2016).

operative. The cost of rainwater is zero and both conservationist and non-conservationist farmers can use it as a non-excludable good. We assume that conservationist farmers use only rainwater and non-conservationists use rainwater and irrigation water. The MSPP (2010) report determines that the rainwater availability in the area is $4,000m^3$ per hectare and year. Rainwater enables farmers to crop dry cereals, such as barley.[19] The average yield of barley per hectare ranges between 2,000 and 3,000 kg per year in this area. Therefore, we assume conservationist farmers' yield is $h(B, x_c) \in (2,000 - 3,000)$kg/ha.[20] Furthermore, recall that we assume that non-conservationist farmers irrigate with an additional provision of 3,500m^3 per hectare.[21] This additional water allows an increase in crop productivity. The yield associated with this water allocation ranges between 5,000 and 6,000 kg/ha, that is, we assume that the average yield per hectare of a non-conservationist farmer is $h(B, x_{nc}) \in (5,000 - 6,000)\, kg/ha$.[22]

Note that parameters A, γ and φ_{nc} determine the harvest function; however, as we have real information about yields in this area, we have adjusted these parameters to represent a realistic yield. We take $A = 1.79$ and $\gamma = 0.912$. Further, we consider $\varphi_{nc} = 0.1$ and $\varphi_c \in [0.2, 0.9]$. In the next subsection, we define farmers' utility functions depending on which type of scheme is applied and we present the corresponding replicator dynamics resulting function.

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

[20]See Departament d'Agricultura, Alimentació i Acció Rural, (2010).

[21]Note that this allowance is added to the natural rainwater of $4,000m^3$ per hectare and year. Then, the profits obtained by non-conservationist farmers are equal to the profits obtained by using $4,000m^3$ with an opportunity cost of 0 and those obtained by using $3,500m^3$ with a positive opportunity cost.

[22]See Departament d'Agricultura, Alimentació i Acció Rural, (2010). We checked other sources of data, such as Subsecretaria de Agricultura, Pesca y Alimentación, (2006).

3.3.1 Subsidy parametrization

We assume that there is no product differentiation; therefore, p is the market price that we take as given and equal for both conservationist and non-conservationist farmers: we choose $p = 0.163€/kg$.[23] Moreover, we model the per hectare economic incentive scheme with function:

$$\phi_c(s_c) = Ss_c^{\sigma} \tag{3.6}$$

where S is a positive constant and σ represents the elasticity of subsidy $\phi_c(s_c)$ to changes in the proportion of conservationist farmers. Note that if $\sigma = 0$ the payment per hectare received by farmer i would be independent of s_c and constant. Further, to compare the different types of subsidies we assume that the environmental agency has assigned the same budget A to each of them. Recall that in the collective subsidy scheme we assume $\phi(s_c)s_c = A$ for all s_c then the elasticity of ϕ_c with respect to s_c must be unitary to keep the budget constant as s_c increases, that is $\sigma = -1$. The utility function of a representative farmer i would be equal to:

$$u_i = p\left[Ax_i^{\gamma}(1 - \frac{B^{\varphi_i}}{x_i})\right] - cx_i + Ss_c^{\sigma} \tag{3.7}$$

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

$$\dot{s}_c = \omega s_c(1 - s_c)pA\left[\left[x_{nc}^{\gamma}(1 - \frac{B^{\varphi_{nc}}}{x_{nc}})\right] - \left[\left[x_c^{\gamma}(1 - \frac{B^{\varphi_c}}{x_c})\right] + Ss_c^{\sigma}\right]\right] - c\left(x_{nc} + x_c\right) \tag{3.8}$$

Last, note that we have used a parameter ω to adjust the speed at which farmers

[23]See Ministerio de Agricultura, Alimentación y Medio Ambiente, (2016).

imitate the most profitable strategy. In this dynamic system, behavioural changes are a gradual process, and increasing the value ω increases the speed at which adaptive farmers change their behaviour towards the strategy that provides a higher reward.[24] We have chosen $\omega \in [10^{-6}, 1]$.

3.3.2 Price parametrization

In the case of the price differentiation model, we take $p = 0.163€/kg$ as the market price p_{nc}. To modulate the conservationists' price, p_c, we have used the function:

$$p_c = \Omega Q_c^{\rho} \tag{3.9}$$

where $Q_c = n_c h(x_c, B)$ is the quantity sold by conservationist farmers and Ω is a positive constant. In our model, we assumed that conservationist farmers can identify their output with a label that singles it out as an environmentally friendly product and differentiates it from that produced by non-conservationist farmers. We have assumed that conservationist agents have market power; in fact, we assume that they behave as a monopolist. They face their product demand curve and therefore, when they choose the quantity to produce, they know what the market price would be. That is, we assume that the relationship between the quantity produced and the market price is negative. Then, by assumption, $\frac{\partial p_c}{\partial Q_c} < 0$ and $\rho < 0$. Note that $\frac{1}{\rho}$ could be interpreted as the price elasticity of conservationist farmers' output Q_c.[25] The farmers' dynamics can be

[24] ω could depend, for example, on crop type. It is easier to switch behaviour in the case of a cereal crop than in fruit orchard tree cultivation. It also could depend on farmers' social network. That is, if farmers are closely related, imitating each other, behaviour change should be easier and faster. For a detailed study of the social network effect on the replicator dynamics see Marco-Renau, (2018). However, he does not model this effect through ω.

[25] Note that $\frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c} = \Omega\rho Q_c^{1-\rho}\frac{Q_c}{p_c} = \rho$ then $\frac{1}{\frac{\partial p_c}{\partial Q_c}\frac{Q_c}{p_c}} = \frac{\partial Q_c}{\partial p_c}\frac{p_c}{Q_c} = \frac{1}{\rho}$

represented by the replicator dynamics as:

$$\dot{s}_c = \omega s_c(1 - s_c)A\left[p_{nc}\left[x_{nc}^{\gamma}(1 - \frac{B^{\varphi_{nc}}}{x_{nc}})\right] - p_c\left[x_c^{\gamma}(1 - \frac{B^{\varphi_c}}{x_c})\right]\right] - c\,(x_{nc} + x_c) \quad (3.10)$$

We have also chosen the $\omega \in [10^{-6}, 1]$.

3.4 Simulation results

Our aim is to guarantee the sustainability of Little bustard populations in the Segarra-Garrigues irrigation area. We have presented three policy instruments - a constant subsidy, a collective subsidy and a price differentiation scheme. Each of these regulatory schemes aims to change agents' behaviour in line with the enacted environmental policy. We capture the evolution of farmers' behaviour under each of these regulatory schemes with the replicator dynamics where $\dot{s}_c = \omega s_c(1 - s_c)\,(u_{nc} - u_c)$ shows the evolution of the proportion of conservationist agents in a farmers' community. All three policy instruments allow farmers to reach heterogeneous stable equilibria with their corresponding basins of attraction.[26] Now we are going to evaluate and compare the performance of these three instruments in fulfilling our goal.

We are going to compare the performance of these three regulatory schemes from two different vantage points of view. First, to compare the performance of these three regulatory policies, we compare their basins of attraction at a common stable equilib-

[26]For example, point M_1 can be reached using any of the three policy instruments. In our simulation example, point M_1 is the pair $B^* = 1116$ and $s_c^* = 0.6$.

rium, M_1. In our theoretical model, we have shown that any of the three regulatory schemes is able to reach stable equilibrium points where the resource stock is sustainable. Note that each of the three regulatory schemes allows the equilibrium M_1 to be reached, but even though the equilibrium point is the same this does not necessarily imply that the three basins of attraction coincide.[27] The size of the basin of attraction is an indicator of the capability of an equilibrium point to guarantee the sustainability of a natural resource. The larger the basin of attraction the larger the set of initial resource allocations that can be brought to a sustainable path. That is, we will compare these policy measures' capability.

Second, we will compare these regulatory schemes taking into account their resilience, that is, we will consider the capability of these regulatory schemes to maintain the resource on a stable equilibrium path when the relevant parameters of the model change. We are not going to focus on a particular equilibrium point but on the capacity of the scheme to reach stable equilibrium where the resource is sustainable. We will only require the equilibrium to be stable and therefore sustainable.

Next we analyze the parameters that can have an effect on the dynamics of the combined system.

3.4.1 Parameters that influence the equilibrium point and its basin of attraction

The determination of the stable equilibrium point and of its basin of attraction depends on both farmers' behaviour represented by $\dot{s}_c$ and resource stock evolution $\dot{B}$.

[27] The basin of attraction of equilibrium point M_1 is the set of initial points from which the path dynamics leads in the long run to M_1.

The basin of attraction of an equilibirum point (s_c, B) depends on the rate of change of the population dynamics $\dot{s}_c$ with respect to the rate of change of the natural resource dynamics $\dot{B}$. Most regulatory schemes aim to influence farmers' behaviour in order to introduce changes that alter the evolutionary pattern of the stock of the endangered species, pushing it towards a sustainable path. We now address the factors that influence the evolution of farmers' behaviour under each policy regime.

The evolution of farmers' behaviour, $\dot{s}_c$, depends on ω and on the difference between the utility functions of non-conservationist and conservationist agents, $[u_{nc} - u_c]$. We are not going to analyze the effect of changes in ω either on equilibrium point M_1 or on its basin of attraction because ω has no economic meaning in our model; it has been used as a constant of adjustment. This difference $[u_{nc} - u_c]$ depends on B, the volume of bird stock and on the damage caused by birds to the farmers' harvest function. This damage is represented by parameter φ_i. This parameter takes value φ_c when the farmer behaves as a conservationist and φ_{nc} when the farmer behaves as a non-conservationist.[28] By assumption, $\varphi_{nc} < \varphi_c$ and $[u_{nc} - u_c]$ depends on the relative value of φ_c with respect to φ_{nc}. We represent this relationship between the damage caused by the bird population to the harvest by ratio $\frac{\varphi_c}{\varphi_{nc}}$ as φ. The larger φ the larger the damage caused by birds to the conservationists' harvest with respect to the damage caused to the non-conservationist one.[29]

Additionally, this difference depends on s_c and also relies upon parameter σ in the subsidy models and upon parameter ρ in the price differentiation models.[30]

[28] In the subsidies case $\frac{\partial[u_{nc}-u_c]}{\partial B} = p\left(\frac{\partial h(x_{nc},B)}{\partial B} - \frac{\partial h(x_c,B)}{\partial B}\right) - \frac{\partial \phi_c(s_c)}{\partial B}$ as $\frac{\partial \phi_c(s_c)}{\partial B} = 0$ then $\frac{\partial[u_{nc}-u_c]}{\partial B}$ depends only on $\frac{\partial h(x_i,B)}{\partial B}$. Note that $\frac{\partial h(x_i,B)}{\partial B} = \varphi_i A x_i^{\gamma-1} B^{\varphi_i - 1}$.

[29] Recall that we have assumed that $\varphi_{nc} = 0.1$ and $0.1 < \varphi_c < 0.9$ and we use these value in our simulations.

[30] For the subsidies case $\frac{\partial[u_{nc}-u_c]}{\partial s_c} = \frac{\partial[\pi_{nc}-\pi_c]}{\partial s_c} - \frac{\partial \phi_c(s_c)}{\partial s_c}$ as $\frac{\partial[\pi_{nc}-\pi_c]}{\partial s_c} = 0$ then $\frac{\partial[u_{nc}-u_c]}{\partial sc} = \frac{\partial \phi_c(s_c)}{\partial s_c} = \sigma S s_c^{\sigma-1}$.

Recall that σ is constant and its value depends on the type of subsidy. For the constant susbidy $\sigma = 0$ and for the collective one $\sigma = -1$. Therefore, φ and ρ can influence farmers' payoff differences, $[u_{nc} - u_c]$ and that, together with ω, determines the speed at which adaptive farmers change their behaviour towards the strategy that provides higher rewards. *Ceteris paribus*, the larger ω, φ and ρ the faster the changes in the composition of the population, $\dot{s}_c$.

In our constant subsidy scheme $\sigma = 0$ and therefore $\frac{\partial [u_{nc} - u_c]}{\partial sc} = 0$, then $\widehat{B}_{far}(s_c)$ is constant and independent of s_c, its slope does not depend on φ or on σ. On the other side, in the collective subsidy scheme, $\sigma = -1$ and the slope of $\bar{B}_{far}(s_c)$ depends on φ. Finally, in the price differentiation scheme the slope of $\widehat{B}_{far}(s_c)$ is jointly determined by ρ and φ.

The equilibrium of the combined system is determined by the intersection of the resource dynamics set of stable equilibria, $\widehat{B}_{far}(s_c)$, and by the farmers' dynamic set of stable equilibria, $\widehat{B}(s_c)$. All three schemes allow farmers to reach a stable equilibrium M_1. Each of these schemes affects farmers' behaviour and we compare the performance of these three schemes, comparing their respective basin of attraction at equilibrium point M_1. As $\widehat{B}_{far}(s_c)$ represents agents' behaviour and changing agents' behaviour is the aim of the environmental policy, we focus on analyzing how the changes in $\widehat{B}_{far}(s_c)$ affect the basin of attraction of point M_1. In our comparisons, without loss of generality, we keep $\widehat{B}(s_c)$ constant.

For the price differentiation case:
$\frac{\partial(u_{nc}-u_c)}{\partial s_c} = \frac{\partial[\pi_{nc}-\pi_c]}{\partial s_c} = -\frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial s_c} h(B, x_c) = \frac{1}{\rho}\Omega Q^{\frac{1}{\rho}-1} N h(x_c, B)$.

3.4.2 The relevance of damage caused by birds on the harvest function

The subsidies case

Now we focus on analyzing the effects of φ (the damage caused by birds to the harvest function), first on the basin of attraction of a given stable equilibrium point such as M_1. In this case we allow the equilibrium budget to change for the system to remain in M_1. And second, we analyze the effect of φ on the stable equilibria keeping the equilibrium budget constant. In this second case, we allow the stable equilibrium to change. A change in φ leads to changes in $[u_{nc} - u_c]$ and therefore in $\widehat{B}_{far}$ and in the stable equilibrium point. We have assumed that $\omega = 10^{-4}$.

We consider several damage levels, from $\varphi = 2$ to $\varphi = 9$. A $\varphi = 2$ means that the damage caused by birds to the harvest of a conservationist farmer is twice as large as the damage caused by birds to the harvest of a non-conservationist farmer, and similarly for the rest of φ values. If the relative damage caused by birds to the harvest of a conservationist farmer increases with respect to the damage caused to the harvest of a non-conservationist farmer, or what is the same if φ increases, the difference between the utility functions of non-conservationist and conservationist farmers, $[u_{nc} - u_c]$ increases. To maintain the equilibrium point at M_1, that is, to keep the same proportion of conservationist agents, the environmental agency would be required to provide a larger individual subsidy to conservationist farmers. And, therefore, the budget allowance required to maintain the equilibrium point at M_1 would have to increase. To compare the basins of attraction of the two subsidy schemes we keep the same equilibrium budget for each damage level. Comparing these basins of attraction we can see that, for each damage level and given the same pairwise budget, the basins of attraction for the collective subsidy scheme are larger than the basins of attraction for the constant subsidy scheme. The graphical representation of point M_1 and its basins of attraction is presented in Figure 3.3 for three different levels of φ.

Observation 1 *The basin of attraction of the collective subsidy scheme is larger than the the basin of attraction of the constant subsidy scheme for different levels of damage, given the same pairwise budget.*

We first analyze the allowance needed to reach M_1 in the constant subsidy scheme. If the damage increases from $\varphi = 2$ to $\varphi = 6$, the agency would have to increase the total budget allocated from $1,018,340$€ to $1,254,340$€ to maintain the equilibrium point at M_1. Similarly, the individual subsidy for conservationist farmers would have to rise from 43.15€/ha to 53.15€/ha. In our specification, the individual subsidy received by each conservationist farmer at point M_1 starts at $43.15€/ha$ when $\varphi = 2$ and ends at $120.44€/ha$ when $\varphi = 9$. Note that the larger the damage φ the larger the individual subsidy that conservationists have to receive to reach equilibrium point M_1. In Table 3.4, we present the total and the equilibrium budget allowance and individual subsides required to keep the stable equilibrium at M_1. Note that we differentiate between total budget allowance and the equilibrium budget allowance. By total allowance we mean the result of multiplying the individual subsidy per hectare, i.e. $43.15€/ha$, by the total number of farmers.[31]. By equilibrium allowance we mean the result of multiplying the individual subsidy by the number of farmers that comply in equilibrium.[32]

[31] By assumption, there are 236 farmers in the protected area farming $100ha$ each. We assume that policymakers need to provide a budget that guarantees that each conservationist farmer would be able to receive a constant individual subsidy per hectare if they carry on the prescribed conservationist practices. That minimum total allowance would be $43.15€/ha * 236$ farmers$*$100 ha= $1,018,340$€ .

[32] In the case that $s_c^* = 0.6$, that is 142 farmers would behave as conservationists in the Segarra-Garrigues irrigation area, then the equilibrium allowance must be $43.15€/ha * 142$ farmers$*$100ha= $612,730$ €.

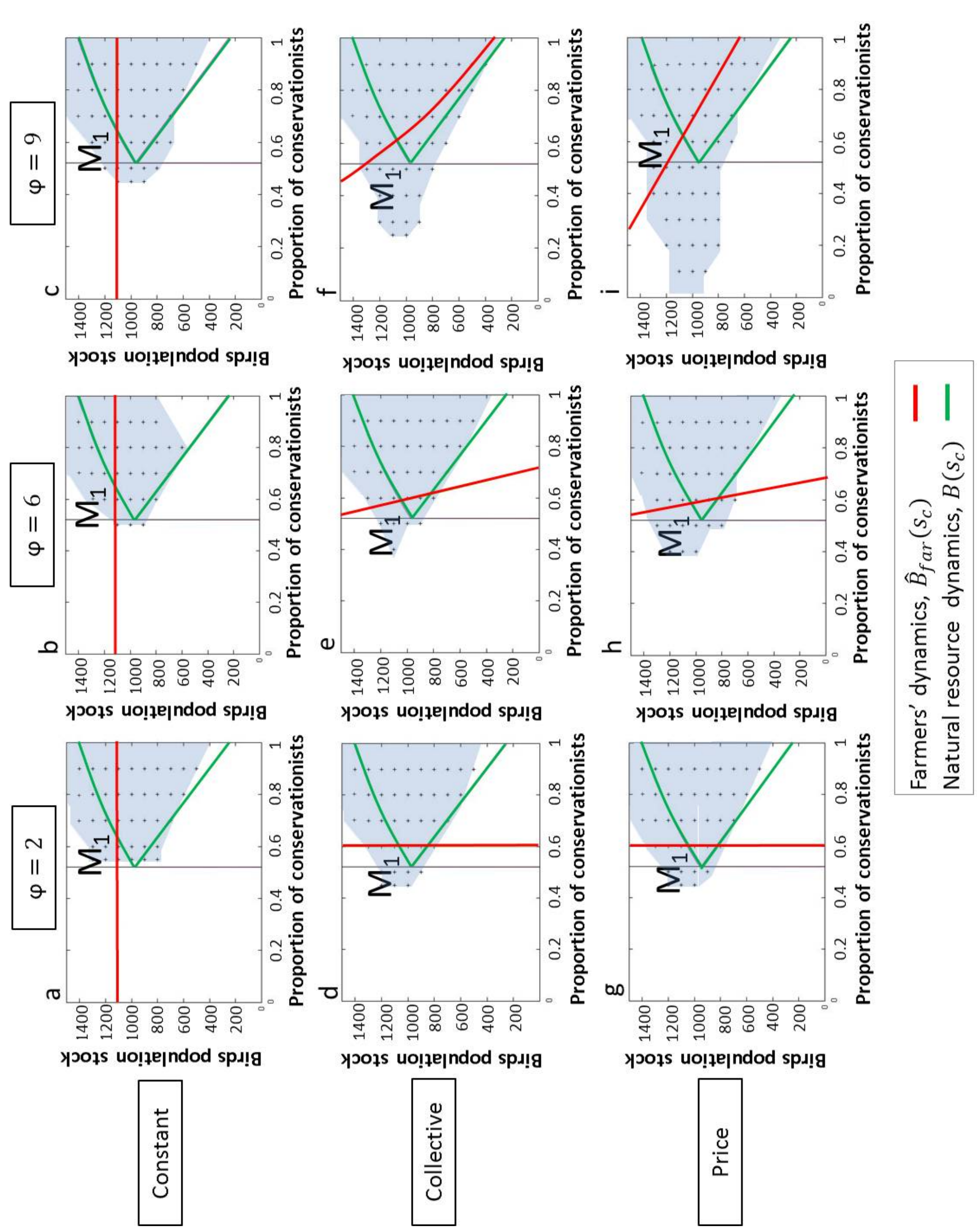


Figure 3.3: Stable point M_1 and its basin of attraction (shadowed areas) when a constant subsidy is applied (a,b and c), when a collective subsidy is applied (d, e and f) and when a price differentiation scheme $|\rho| = 0.1$ is applied (g,h and i), keeping $\omega = 10^{-4}$ and for different levels of φ.

φ	Individual subsidy (€/ha)	Allowance at the equilibrium (€)	Constant Total Allowance (€)	Collective Total Allowance (€)
2	43.15	$612,730$	$1,018,340$	$612,730$
6	53.15	$754,730$	$1,254,340$	$754,730$
9	120.44	$1,710,248$	$2,842,384$	$1,710,248$

Table 3.4: Individual subsidy and total allowance needed to reach point M_1 (Figure 3.3) depending on φ.

	Constant (Total Allowance of $1,018,340$€)		Collective (Total Allowance of $612,730$€)	
φ	Equilibrium point (s_c, B)	Individual subsidy (€/ha)	Equilibrium point (s_c, B)	Individual subsidy (€/ha)
2	$M_1 = (0.6, 1116)$	43.15	$M_1 = (0.6, 1116.4)$	43.15
3	-	-	$M_2 = (0.6, 1117)$	43.73
4	-	-	$M_3 = (0.58, 1089)$	44.88
5	-	-	$M_4 = (0.55, 1051)$	47.15
6	-	-	-	-

Table 3.5: Individual subsidy and allowance at the heterogeneous equilibrium points.

Second, if the damage caused by birds were to increases from $\varphi = 2$ to $\varphi = 6$ and the agency were to keep the budget allowance constant, it would not be able to reach a stable equilibrium point with a sustainable stock of natural resources. In Table 3.5, we show that as φ increases from 2 to 6, if the equilibrium allowance remains constant at $612,730$€ (or the individual subsidy remains at 43.15€/ha), no stable heterogenous equilibrium point with a sustainable bird population can be reached. The representation of these situation can be seen in the first row of Figure 3.4. In panel a with damage level $\varphi = 2$, a stable equilibrium is reached at allocation $(0.6, 1116)$, but no other sustainable stable equilibrium point can be reached as the relative damage by birds to conservationist farmers' harvest increases. In such a case, the initial budget allowance is not enough to compensate conservationist farmers for the damage suffered from birds. As the damage increases, the difference between conservationist and non-conservationist profits increases and the budget allowance does not permit the granting of any subsidy large enough to equate the benefits of conservationists and non-conservationists, and the only stable equilibrium will be an all non-conservationist farmers' equilibrium.

Observation 2 *In the constant subsidy case, if the relative damage caused by birds to the harvest of conservationist farmers increases, the agency would have to increase the equilibrium budget allowance for subsidies to maintain the same stable equilibrium point. Or, what is the same, the agency would have to increase the individual subsidy for conservationist farmers to keep the same stable equilibrium.*

Let us now study what happens when a collective subsidy is being implemented. Now, as before, when φ increases, the difference between the utility functions of non-conservationist and conservationist agents increases. To maintain the equilibrium point at M_1 the environmental agency would be required to provide a larger individual subsidy to conservationist farmers and, as in the constant subsidy case, the equilibrium budget allowance would be required to increase. In both cases, if the damage increases from $\varphi = 2$ to $\varphi = 6$ the agency, to maintain the equilibrium point at M_1, would have to increase the equilibrium budget allowance from $612,730$€ to $754,730$€, as can be seen in Table 3.4. Also, the individual subsidy of conservationist farmers would have to rise from 43.15€/ha to 53.15€/ha. That is, in equilibrium the allowance required in both the constant and the collective subsidy is the same. Further recall that, in the collective subsidy scheme, we have imposed the restriction that the equilibrium budget allowance remains constant even if the number of conservationist farmers increases. Therefore, we will now study whether new heterogeneous stable equilibria can be reached keeping the equilibrium budget constant when the relative damage caused by birds to the harvest function increases.

We show that, when the damage increases, a collective subsidy scheme allows other stable equilibria (with a positive sustainable stock of natural resources) to be reached even keeping the equilibrium allowance constant. Recall that this is not the case in the constant subsidy scheme. An example can be seen in the second row of Figure 3.4. In panel g with damage level $\varphi = 3$, a stable equilibrium is reached at allocation $M_2 = (0.6, 1117)$ with a collective subsidy scheme, but no such equilibrium can be reached with a constant subsidy scheme (panel b). In equilibrium $M_2 = (0.6, 1117)$ the individual subsidy is equal to 43.73€/ha. Further, if φ increases up to 5 another sustainable and stable equilibrium point $M_4 = (0.55, 1051)$ can be reached with the collective scheme but not with the constant subsidy scheme (see panel c). The total equilibrium budget will remain constant because at the new stable equilibrium M_4 the proportion of conservationist farmers would have decreased; it would be 0.55. And the value of the individual subsidy will have increased to 47.11€. Summarizing, the collective subsidy scheme allows the system to reach a new stable equilibrium that guarantees the sustainability of the Little bustard population, at a lower stock of 1050 birds instead of 1116 but with the same budget. In Table 3.5, we show that as φ increases from 2 to 5, even if the equilibrium allowance remains constant at $612,730$€ a stable equilibrium point with a sustainable bird population can be reached.

Observation 3 *In the collective subsidy case, as in the constant case, if the relative damage caused by birds to the harvest of conservationist farmers increases, the agency would have to increase the equilibrium budget allowance for subsidies to maintain the same stable equilibrium point, M_1. Or, what is the same, the agency would have to increase the individual subsidy for conservationist farmers to keep the same stable equilibrium.*

Observation 4 *In the collective subsidy case, but not in the constant case, if damage increases a new heterogeneous stable equilibrium can be reached, maintaining the same* *equilibrium budget allowance. This new equilibrium will take place at a higher individual subsidy, at a lower proportion of conservationist farmers and a lower resources stock. But the equilibrium will be stable and the resource sustainable.*

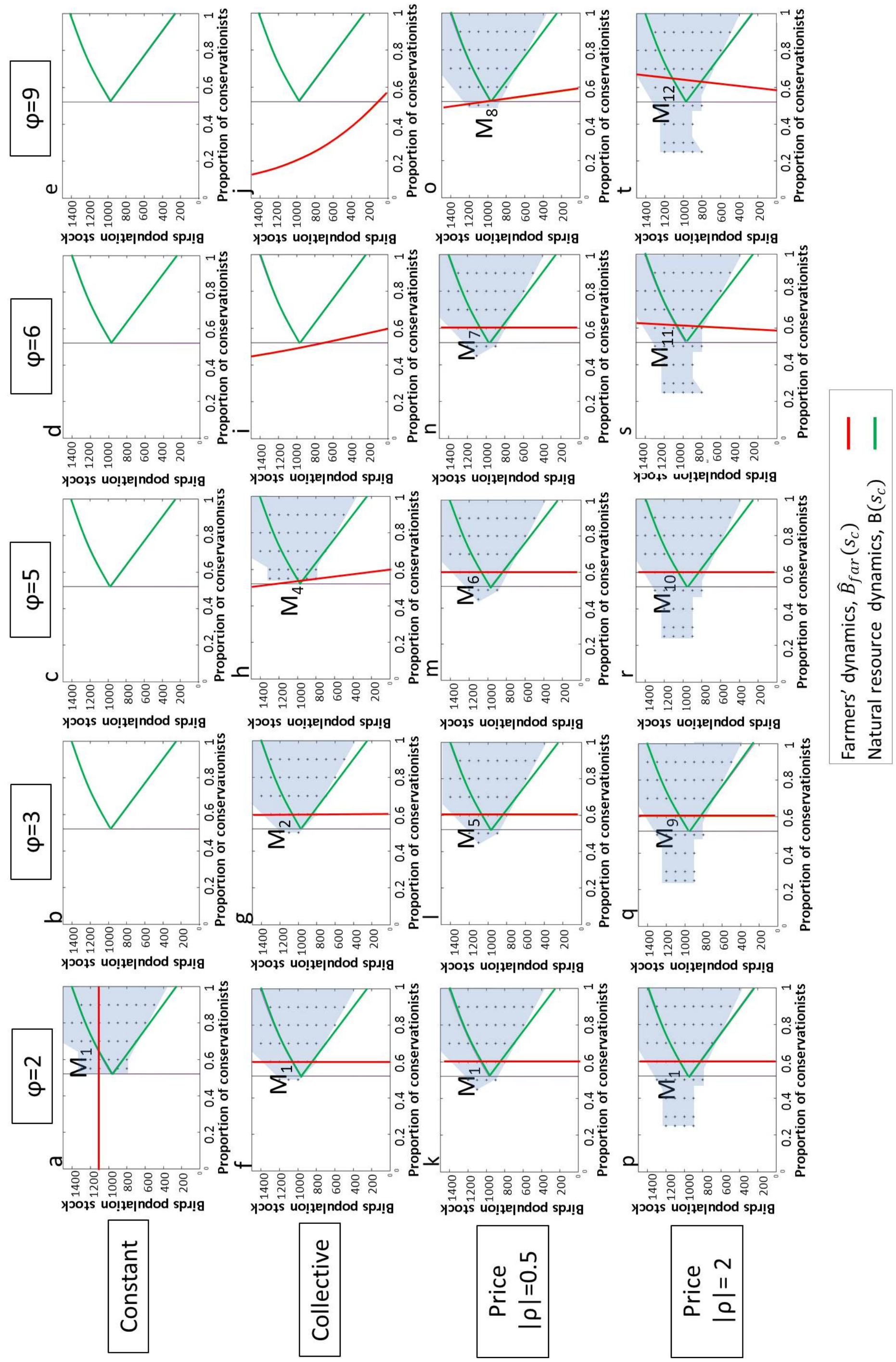


Figure 3.4: Equilibrium points depending on φ for a constant subsidy (a, b, c, d and e), a collective subsidy (f, g, h, i and j) and for a price differentiation scheme when $|\rho|$=0.5 (k, l, m, n and o) and when $|\rho|$ =2 (p, q, e, s and t), keeping the individual subsidy and the price function constant and $\omega = 10^{-5}$. See equilibrium points in Table 3.5.

The price differentiation case

The price differentiation scheme presents some differences with respect to subsidies. On the one hand, this price scheme does not depend on a budget allowance but rather on the structure of the output market. Recall that we consider it to be a competitive market for non-conservationist farmers' products where market price is taken as given and we consider it to be a monopolistic market for the produce of conservationist farmers, that is, we assume that conservationists have market power. Now changes to $\dot{s}_c$ depend on φ but also on ρ. We first comment on the effect of ρ (the inverse of the price elasticity for conservationist produce) on the basin of attraction of sustainable equilibrium point M_1 and then we analyze the effect of bird damage, φ, for diferent levels of ρ. Recall that $\rho < 0$.

Figure 3.5 shows the graphical representation of equilibrium point M_1 for different levels of $|\rho|$ and different levels of damage. The relative damage caused by birds to the conservationist harvest with respect to the non-conservationist is $\varphi = 2$ in the first row, $\varphi = 6$ in the second and $\varphi = 9$ in the third. Also, in the first column of Figure 3.5, $|\rho| = 0.1$, in the second it is $|\rho| = 0.5$, in the third it is $|\rho| = 1.5$ and in the fourth it is $|\rho| = 2$.

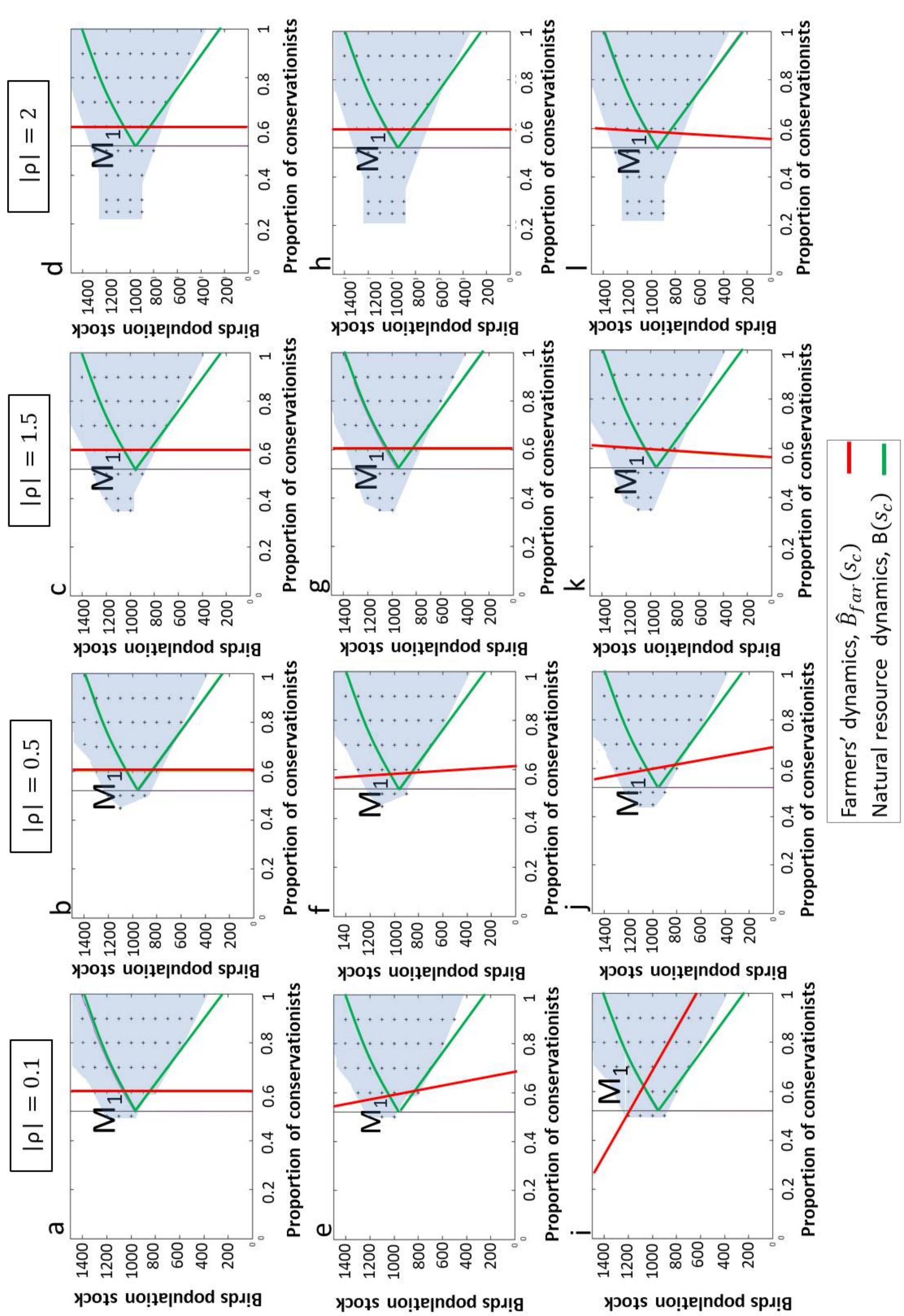


Figure 3.5: Stable point M_1 and its basin of attraction (shadowed areas) when a price differentiation scheme is applied for different levels of $|\rho|$ when $\omega = 10^{-5}$ and $\varphi = 2$ (a,b, c and d), $\varphi = 6$ (e, f, g and h) and $\varphi = 9$ (I, j, k and l).

We first observed that, for any given level of damage, the larger $|\rho|$ the larger the basin of attraction of equilibrium point M_1, especially for low values of s_c and B. The more responsive p_c is to changes in Q_c the larger the basin of attraction of equilibrium point M_1. A decrease in the proportion of conservationists s_c reduces the quantity produced by conservationists, Q_c, and will translate into an increase in the price p_c that will be more than proportional to the decrease in Q_c.[33] The revenues of conservationist farmers will increase, making conservationist farmers more resilient.[34]

The damage caused by birds to the conservationist harvest function plays a relevant role on determining the conservationists' price p_c needed to reach the equilibrium. In principle, the more damaging the natural resource the larger the price needs to be to compensate for conservationists farmers' losses. The larger φ the larger the p_c required at the equilibrium point for conservationist to equate to non-conservationist profits. In Table 3.6, we see how p_c has to increase for $u_{nc} = u_c$ to maintain the heterogeneous stable equilibrium at M_1. The more damaging birds are to conservationists farmers' harvest, the larger the price to compensate for the losses is required to be. Under our characterisation, the p_c that allows $u_{nc} = u_c$ at point M_1 is $p_c = 0.175$ when $\varphi = 2$; $p_c = 0.178$ when $\varphi = 6$, and $p_c = 0.203$ when $\varphi = 9$. That is an increase of 7.6%, 9.4% and 24.8% with respect to p_{nc}, respectively (See Table 3.6).

Observation 5 *The larger φ the larger the price premium needed to reach the heterogeneous equilibrium point M_1.*

[33] In this analysis we assume that the quantity provided by conservationist farmers is equal to the quantity sold in the market.

[34] However, this is not always the case, see Figure 3.9 in Appendix 3.6.1 where we have increased $\dot{s}_c$ raising the constant of adjustment until $\omega = 10^{-4}$. Observe how the basin of attraction of point M_1 changes with increases in $|\rho|$; it increases from panel a to b but it decreases from panel b to c. This is because the prices changes are so large that they allow large jumps in s_c making the replicator dynamics collapse.

φ	Conservationist price p_c	Ratio $\frac{p_c}{p_{nc}}$	Increase in % respect p_{nc}
2	0.175	1.076	7.6%
6	0.178	1.09	9.4%
9	0.203	1.24	24.8%

Table 3.6: Conservationists' prices at point M_1 depending on φ. Recall that $p_{nc} = 0.163$.

So far we have commented on how the conservationists' price has to be adjusted to reach M_1. Now we analyze, as we did in the case of the subsidy schemes, how the equilibrium point changes due to variations in the damage level if we do not keep the equilibrium at M_1.

The heterogeneous stable equilibrium points differ depending on the damage caused by birds to farmers, φ. In the third and fourth lines of Figure 3.4, we show the graphical representations of the effect of a variation on φ in the heterogeneous stable equilibrium point in a price differentiation scheme. In the third line of Figure 3.4, we have assumed that $|\rho| = 0.5$ and in the fourth $|\rho| = 2$. In all schemes we have allowed the price premium function to reach point M_1 when $\varphi = 2$ and we have analyzed the changes to the stable equilibrium point when Little bustard damage increases to $\varphi = 3$, $\varphi = 5$, $\varphi = 6$ and $\varphi = 9$.

An increase in the damage level leads to another equilibrium. We can see these changes in Table 3.7, where we show how the equilibrium point (s_c, B) evolves as the level of damage increases. When $|\rho| = 0.5$, as the damage increases, both, the proportion of conservationist farmers in the heterogeneous stable equilibrium decreases and the stock resource level decreases. See the third column of Table 3.7. When the damage increases from $\varphi = 2$ to $\varphi = 9$, the heterogeneous stable equilibrium goes from M_1 to M_8, the proportion of conservationists at the stable equilibrium drops from 0.606 to 0.530, and the resource stock from 1116.4 to 1005.

φ	$\lvert\rho\rvert$	Equilibrium point (s_c, B)	Conservationist price p_c	Ratio $\frac{p_c}{p_{nc}}$	Increase in % respect p_{nc}
2	$\lvert\rho\rvert = 0.5$ $\lvert\rho\rvert = 2$	$M_1 = (0.606, 1116.4)$	0.175	1.076	7.6%
3	$\lvert\rho\rvert = 0.5$ $\lvert\rho\rvert = 2$	$M_5 = (0.605, 1116.1)$ $M_9 = (0.607, 1116.8)$	0.176	1.077	7.7%
5	$\lvert\rho\rvert = 0.5$ $\lvert\rho\rvert = 2$	$M_6 = (0.602, 1112)$ $M_{10} = (0.608, 1119)$	0.177	1.08	8.5%
6	$\lvert\rho\rvert = 0.5$ $\lvert\rho\rvert = 2$	$M_7 = (0.597, 1106)$ $M_{11} = (0.611, 1121)$	0.178	1.09	9.4%
9	$\lvert\rho\rvert = 0.5$ $\lvert\rho\rvert = 2$	$M_8 = (0.530, 1005)$ $M_{12} = (0.654, 1158)$	0.200 0.205	1.23 1.25	23.7% 25.6%

Table 3.7: Prices at the heterogeneous equilibrium points. Recall that $p_{nc} = 0.163$.

Moreover, in the case that $|\rho| = 2$ represented in the fourth row of Figures 3.4 increases in φ can even increase the resource stock and the proportion of conservationists at the equilibrium point. Look again at the second column of Table 3.7. When the damage increases from $\varphi = 2$ to $\varphi = 9$, the heterogeneous stable equilibrium goes from M_1 to M_{12}, the proportion of conservationists at the stable equilibrium rises from 0.606 to 0.654, and the resource stock from 1116.4 to 1158.

That is, when $\widehat{B}_{far}$ is an increasing function of s_c then increases in φ cause losses in the harvest of conservationist farmers and, therefore, h_c and Q_c decrease; when $|\rho|$ is large a small decrease in the quantity produced results in a more than proportional increase in the price. The price effect is larger than the production losses, conservationist farmers more than offset this decrease in Q_c with larger prices, the revenues of conservationist farmers increase and s_c and B increase. These are cases where u_{nc} decreases in a larger proportion than u_c for an increase in B.[35]

[35]Given $u_c = p_c(s_c)h(x_c, B) - cx_c$ and recalling that $Q_c = n_c h(x_c, B)$ then $\frac{\partial \pi_c}{\partial B} = \frac{\partial p_c}{\partial Q_c}\frac{\partial Q_c}{\partial B}h(x_c, B) + p_c(s_c)\frac{\partial h(x_c,B)}{\partial B}. = p_c\frac{\partial h(x_c,B)}{\partial B}\left(1 + \frac{1}{\frac{\partial Q_c}{\partial p_c}\frac{p_c}{Q_c}}\right)$

Substituting $\frac{\partial Q_c}{\partial p_c}\frac{p_c}{Q_c} = \rho$ then

$\frac{\partial(u_{nc}-u_c)}{\partial B} = p_{nc}\frac{\partial h(x_{nc},B)}{\partial B} - p_c\frac{\partial h(x_c,B)}{\partial B}\left(1 + \frac{1}{\rho}\right).$

Whenever the demand is inelastic ($|\rho| < 1$) then $\frac{\partial(u_{nc}-u_c)}{\partial B} < 0$ and by Proposition 1 of Chapter 2

Observation 6 *Ceteri paribus, as the damage rate φ increases, both, the proportion of conservationist farmers and the resource stock level decrease at the heterogeneous stable equilibrium in a constant subsidy scheme, in a collective subsidy scheme and in a price differentiation scheme when $\widehat{B}_{far}$ is a decreasing function of s_c. However, when $\widehat{B}_{far}$ is an increasing function of s_c increases in φ result increase the in the proportion of conservationist farmers and the resource stock level at the heterogeneous stable equilibrium.*

We now compare the price differentiation with subsidy schemes. First, see in Figure 3.6 that, *Ceteri paribus*, the basin of attraction of point M_1 is larger in the price differentiation scheme than in the subsidy schemes. Moreover, the larger $|\rho|$ the larger the basin of attraction of point M_1 in the price differentiation scheme and therefore the larger the difference between the basin of attraction of in the subsidy scheme and the basin of the price differentiation scheme. Observe that in Figure 3.3 we can see that the basin of attraction of point M_1 is larger in the price differentiation scheme than in the subsidy schemes for each level of damage φ (in Figure 3.3 $|\rho|$ is kept constant).[36]

In addition, see in Figure 3.4, where the heterogeneous stable equilibrium point M_1 changes. In this case we keep the budget allowance and the stable equilibrium point changes due to variations in the damage level. *Ceteri paribus*, in the constant subsidy scheme an increase in φ drives the farmers' dynamics quickly towards situations where stable farmers' equilibria are not possible, that is, there is not a level of B such that $[u_{nc} - u_c] = 0$ or, what is the same, there is no $\widehat{B}_{far}$. See Figures 3.4a, 3.4b, 3.4c and

$\frac{\partial B_{far}}{\partial s_c} > 0$. And whenever the demand is elastic $\frac{\partial(u_{nc}-u_c)}{\partial B} \lesseqgtr 0$ and by Proposition 1 of Chapter 2 $\frac{\partial B_{far}}{\partial s_c} \gtrless 0$ depending on the difference $\left|p_{nc}\frac{\partial h(x_{nc},B)}{\partial B}\right| - \left|p_c\frac{\partial h(x_c,B)}{\partial B}\left(1+\frac{1}{\rho}\right)\right|$.

[36]Nevertheless, this does not hold for panels g and h of Figure 3.7 in Appendix 3.1.6. In this case the replicator dynamics collapses. Before collapsing there is always a previous decrease in the basin of attraction of the heterogeneous equilibrium point and that is what happens in panels g and h of Figure 3.7. In case we have raised to $\omega < 10^{-3}$.

3.4d and note how stable equilibria are only possible when $\varphi = 2$. In addition, for the collective subsidy scheme, when φ shifts from 2 (Figure 3.4i) to 5 (Figure 3.4j) $\widehat{B}_{far}$ moves downwards and the stable equilibrium point shifts from M_1 to M_2. Nevertheless, when the damage reaches $\varphi = 6$ or $\varphi = 9$, it is not possible to reach a heterogeneous equilibrium point of the combined system. However, for the price differentiation scheme, the heterogeneous equilibrium is always possible for any φ.

Observation 7 *The price differentiation scheme allows for the dynamics to reach a stable heterogeneous equilibrium point of the combined system with larger damage levels than the subsidy schemes, that is, with larger* φ.

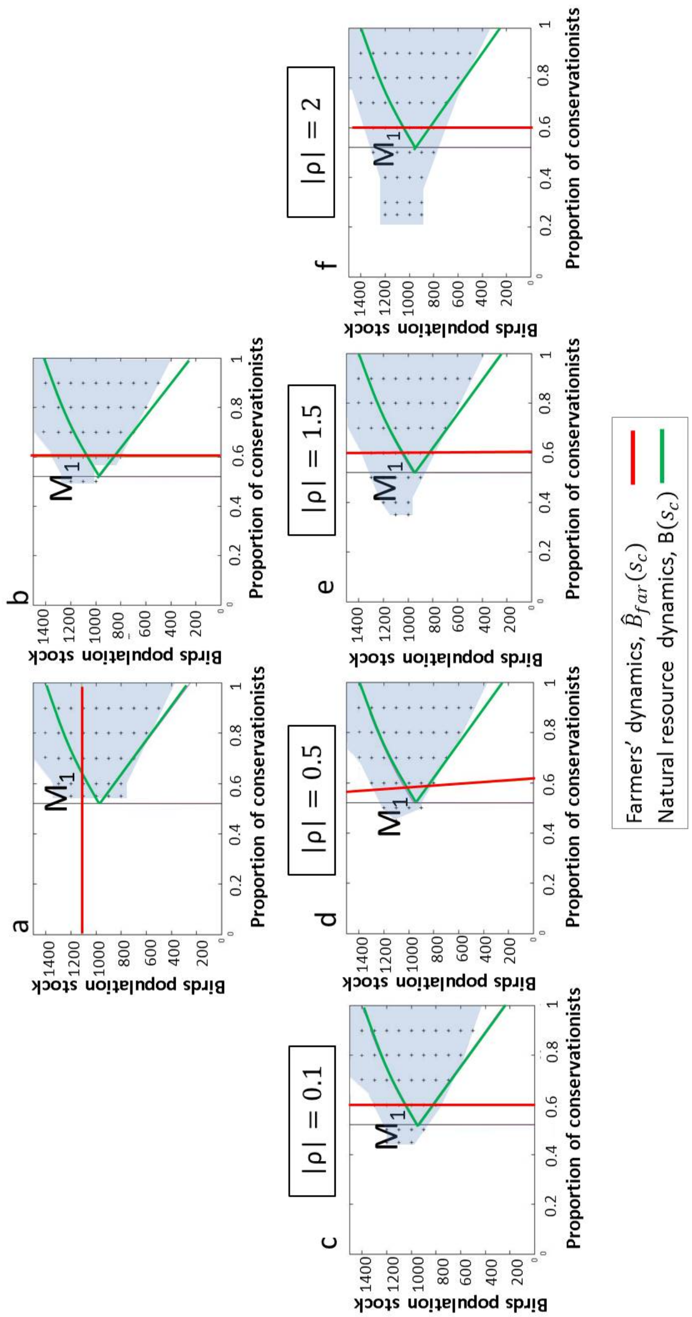


Figure 3.6: Point M_1 and its basin of attraction (shadowed areas) when a constant subsidy is applied (a), when a collective subsidy is applied (b) and when a price differentiation scheme for different levels of $|\rho|$ is applied (c, d, e and f) for $\varphi = 2$ and $\omega = 10^{-5}$.

3.5 Policy implications

From this simulation example, we have seen that the parameter that plays the most relevant role on determining the heterogeneous stable equilibrium and its basin of attraction is the damage caused by birds to the harvest function, φ. Further, in the price differentiation scheme, the inverse of the price elasticity of the conservationists' harvest, ρ, also plays a relevant role in determining the features of the heterogeneous stable equilibrium and its basin of attraction.[37] Now, we will analyze the suitability of each of these regulatory schemes to be implemented in the Segarra-Garrigues irrigation area.

First, in the plains of Lleida there are a total of $81,369.5ha$ protected and the budget allowance is around $6,500,000$€ per year, that is 79.8€$/ha$ (MPSP, 2010). If the damage caused by birds in the Segarra-Garrigues was large, then this budget allowance would probably not be enough to offset conservationists' productivity losses. Recall that, for example, when $\varphi = 9$ the individual subsidy needs to be 120.44€$/ha$ to reach point M_1. This highlights the importance of identifying bird damage to crops.

Second, we have shown that, given a fixed budget allowance, the collective subsidy allows a heterogeneous stable equilibrium point to be reached in cases where a constant subsidy does not. Therefore, if the environmental agency budget constraints are binding, the collective subsidy is a better subsidy scheme than the constant subsidy solution.

Moreover, the most widespread crops in the Segarra-Garrigues irrigation area are cereals. Additionally, from the Ecological Agricultural Production Price Report drafted

[37] Always keeping the natural resource parameters constant.

in 2009 by the Agriculture, Livestock, Fishing and Food Department of the Catalan Government, organic barley had a price that was 40% higher than the price of conventional barley. Therefore, price differentiation could allow conservationist farmers in the Segarra-Garrigues irrigation area to sell at a price high enough to compensate for the losses associated with the preservation of the Little bustard habitat.

Price differentiation schemes seem to be more reliable on protecting the Little bustard population, for low levels of conservationist farmers the larger the inverse of the price elasticity of the conservationists' harvest, $|\rho|$ see for example Figure 3.4. The larger $|\rho|$ the larger the basin of attraction of the price differentiation schemes and the more likely that they presents larger basins of attraction than subsidy schemes. Note that the larger $|\rho|$ the smaller the price elasticity of the conservationists' harvest, $\left|\frac{1}{\rho}\right|$. If $\left|\frac{1}{\rho}\right| < 1$ an increase in p_c would hardly decrease the quantity sold of conservationist products, and in such cases, the level of profits of conservationist farmers could even increase. The final effect on the heterogeneous equilibrium will depend on the difference between profits. If we assume that changes in p_c has a small effect on the price and the quantity produce by non-conservationist profits, then in those cases the difference between profits will tend to decrease and s_c could increase.

Although the price for organic cereals is much higher that the price for regular cereals and the demand for environmentally friendly cereals is increasing, plain cereals is still a close substitute for environmentally friendly cereals. Therefore, we do not expect that conservationist farmers have a large market power. If price of Segarra-Garrigues organic cereals would increase and plain cereals were a close substitute this increase in p_c could result in a decrease in the quantity demanded of organic cereals and in an increase in the quantity demanded of plain cereals. The profits of conservationist farmers will tend to decrease and the once of non-conservationist farmers will tend to increase and s_c would decrease. Nevertheless, the results suggest that as consumers demand for organic products become more widespread and less depending on price changes the protection of endangered species would be easier.

3.6 Appendix

3.6.1 Other simulation examples

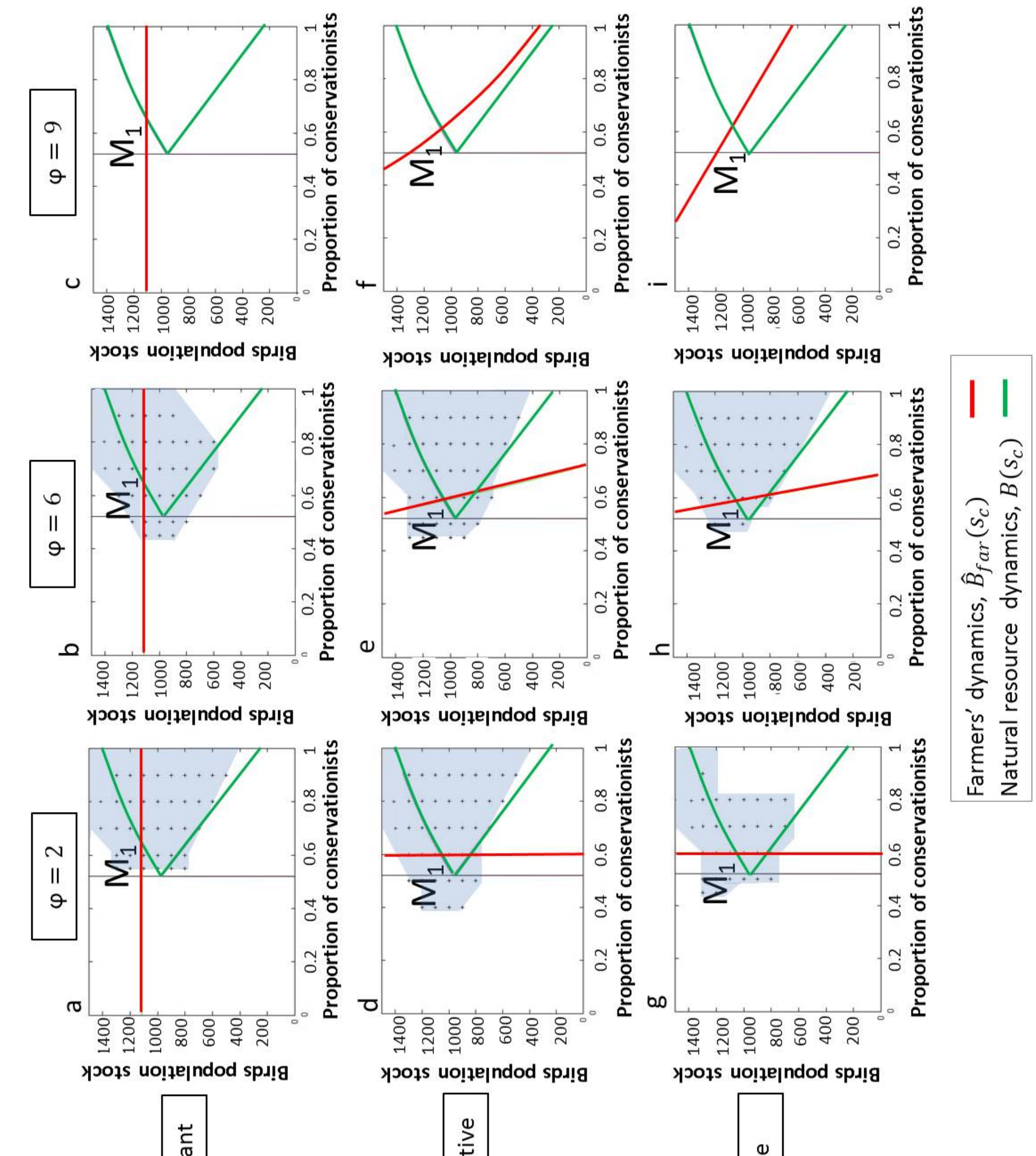


Figure 3.7: Point M_1 when a constant subsidy is applied (a, b and c), when a collective subsidy is applied (d, e and f) and when a price differentiation scheme $|\rho| = 0.1$ is applied (g, h and i), keeping $\omega = 10^{-3}$ and for different levels of φ.

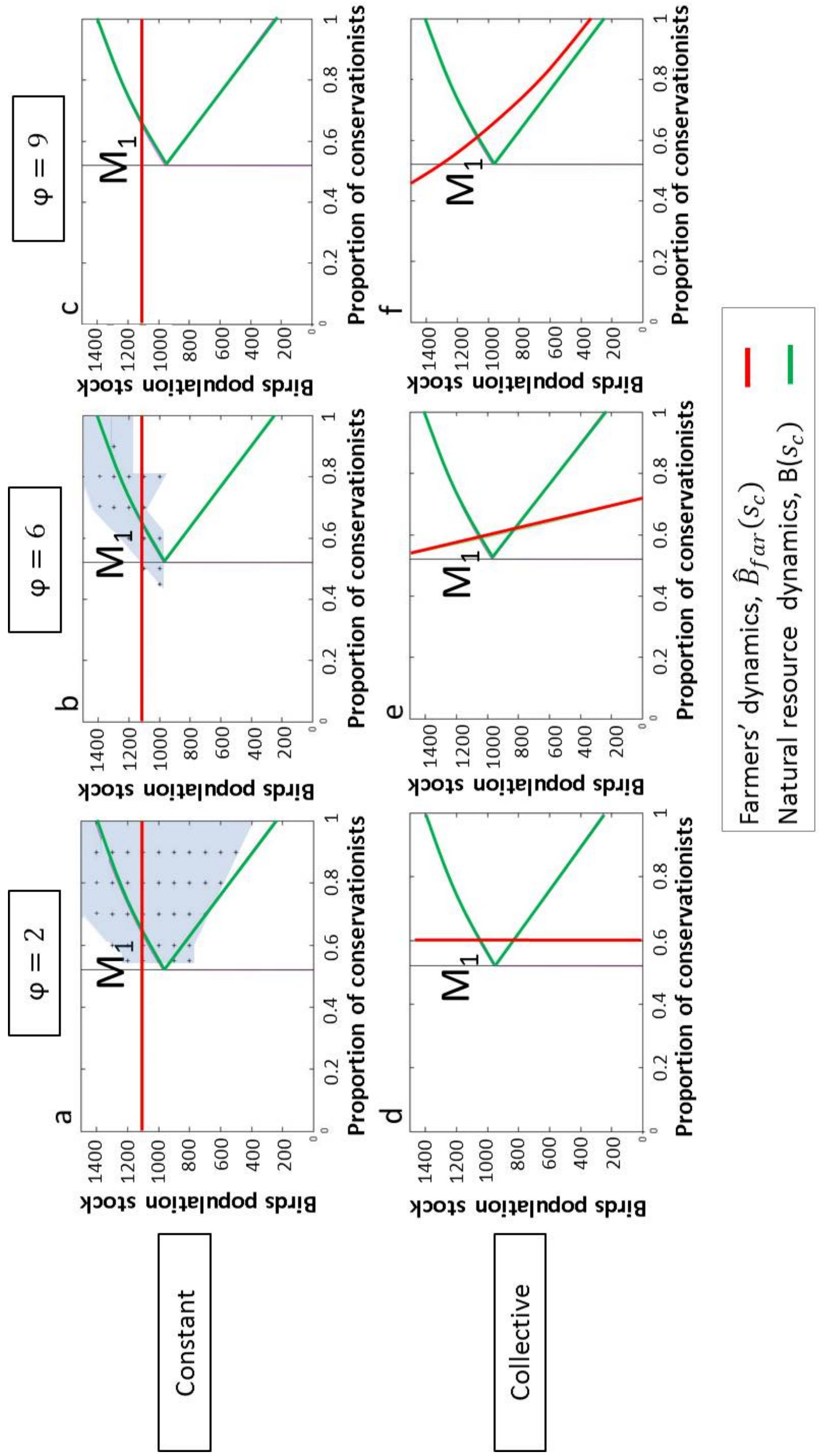


Figure 3.8: Point M_1 and its basins of attraction (shadowed areas) when a constant subsidy is applied (a, b and c) and a collective subsidy is applied (d, e and f) for different levels of φ and $\omega = 10^{-2}$

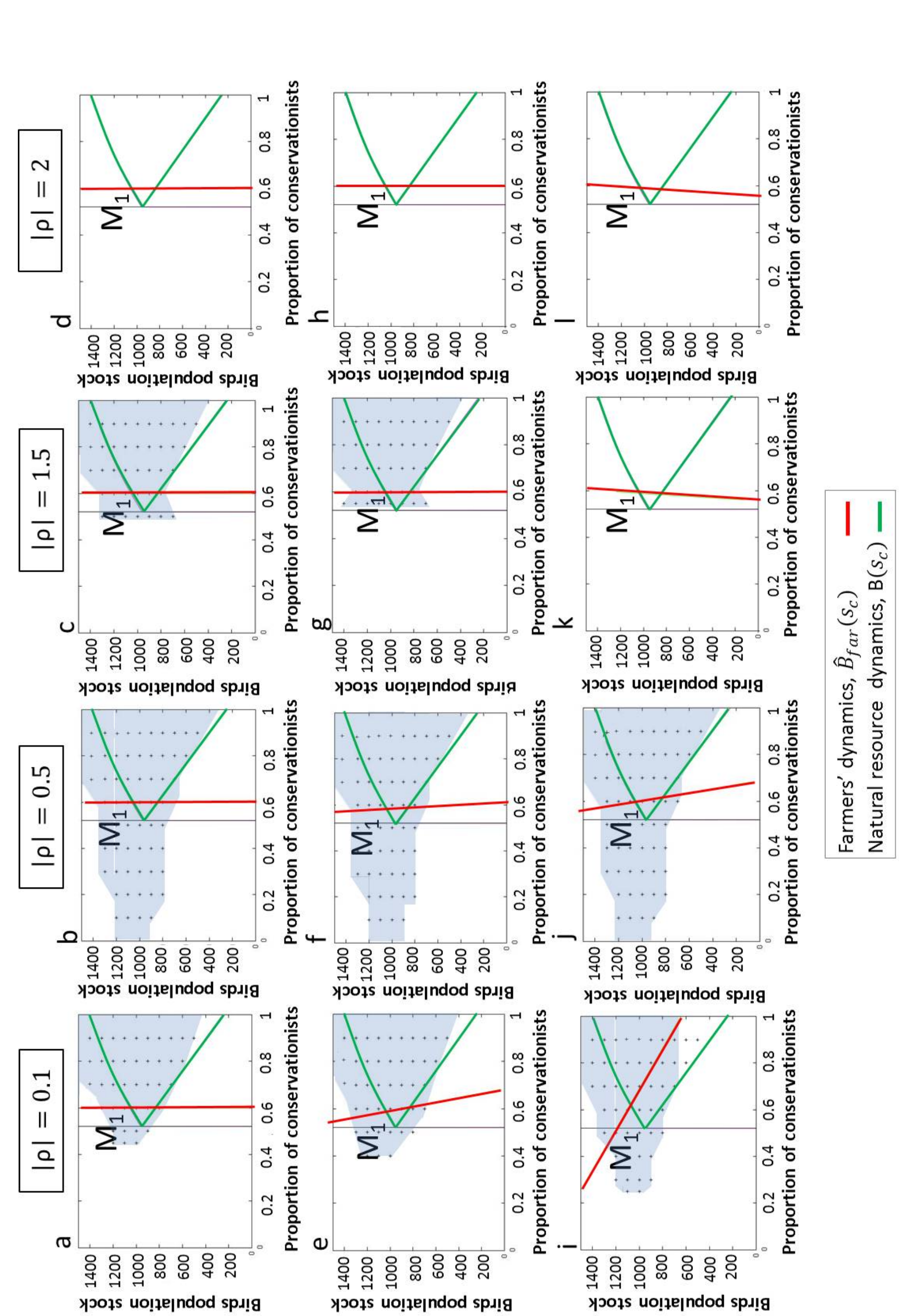


Figure 3.9: Point M_1 when a price differentiation scheme is applied for different levels of $|\rho|$ when $\omega = 10^{-4}$ and $\varphi = 2$ (a, b, c and d), $\varphi = 6$ (e, f, g and h) and $\varphi = 9$ (i, j, k and l).

3.6.2 Stable homogeneous equilibrium point

From the theoretical model we know that, whenever $\widehat{B}_{far}(1) < \widehat{B}\,(1)$, the heterogeneous equilibrium point reached is unstable because the stability conditions are not satisfied. However, a homogeneous equilibrium point, where all farmers behave as conservationists, is stable. At point C, the goal of natural resource protection is satisfied, and $B^* = \hat{B}(1)$. Nevertheless, under our parametrization, we do not reach this point in any case. To reach this point, we need to fit the model with $\varphi_c > 1$ and, in this situation, the assumption $\varphi_c < \gamma$ is not satisfied. Nevertheless, even if we do not satisfy this assumption and we analyze a case where point C could be reached (See Figure 3.19 where $\varphi_c = 1.16$), we see that there is a level of B that $B < \hat{B}(1)$, where the conservationists' harvest function becomes zero; that is, even if theoretically the existence of point C is possible, the damage caused by birds to the conservationists' harvest function is so large that it makes this function zero before reaching point C, and therefore $u_c = 0$. In all these situations, the unique stable equilibrium ends up being a homogeneous equilibrium point where all farmers are non-conservationists. [38]

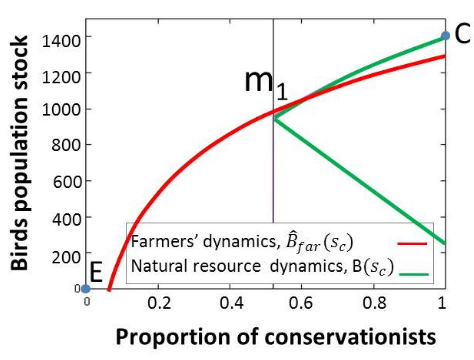


Figure 3.10: Stable homogeneous equilibrium point.

[38]To reach point C, the payoff differences need to be offset, even in the case $u_c = 0$. This is only possible with subsidies, because they do not depend on farmers' harvest. If the subsidy received by each farmer is high enough so that $u_c > u_{nc}$ for any B, then the homogeneous equilibrium C would be reached. We do not analyze this case because we are assuming budget constraint.

Chapter 4

Threshold games and sustainability of natural resources

4.1 Introduction

Agricultural practices have always played a significant role in natural resource conservation. As we have shown in previous chapters, introducing agri-environmental schemes is a necessary measure to stimulate the application of sustainable practices and compensate for the extra cost that these measures require. In this chapter, we analyze and compare the performance of three incentive mechanisms on promoting stakeholders' contributions to natural resource conservation.

A large number of socio-economic experiments have been designed to identify the main factors affecting stakeholders' willingness to contribute to natural resource preservation or any other public good (Olson, 1965; Eckel and Grossman, 1996; Herr, *et al.*, 1997; Fischer *et al.*, 2004; Ariely *et al.*, 2009). Moreover, in many cases, attaining a minimum level of contributions is a relevant factor to assure the maintenance of a public good or the sustainability of a resource (see Andreoni, 1998 for a classic example or Palfrey and Rosenthal, 1994, Croson and Marks, 2000, Suleiman *et al.,* 2001 and Cartwright and Stepanova, 2017). In these cases, despite some agents voluntarily contributing to the resource recovery, this is not preserved because it is necessary to reach a minimum resource stock level or threshold. The dynamics of voluntary donations and charity in public goods provision, such as natural resources, has been approached by many authors, such as Olson (1965); Andreoni, (1988 and 1990); Eckel and Gossman (1996); Ariely *et al.* (2009) and Blanco *et al.* (2012), among others.

In our case, we are going to assume that the recovery of a natural resource requires reaching a minimum resource stock level and, therefore, it is necessary to guarantee a minimum amount of contributions to ensure its sustainability. That is, we are going to focus on a threshold mechanism (or provision point). With our experiments we are trying to imitate, under laboratory conditions, the challenge faced by those farmers developing their activity in endangered species protected areas. In our model, agents can participate in a project and volunteer to implement environmentally sound practices for a payment that is only granted if a given threshold is reached. The use of monetary incentives is a way to give incentives to agents to carry out these sound environmental practices. In particular, we analyze and compare the performance of three incentive mechanisms on promoting contributions to natural resource conservation when the natural resource requires reaching a minimum stock level to ensure its sustainability. Two of the incentive mechanisms are threshold mechanisms where a specific minimum contribution level is needed both to earn the incentive and to ensure the sustainable growth of a natural resource. The third is a basic incentive mechanism where an agent receives an incentive if they cooperate with the preservation of the resource.

First, we introduce a collective threshold public good game where agents have to assure a minimum level of pro-social behaviour before the natural resource is recovered and a reward is granted to them.[1] Agents can behave pro-socially and contribute to preserving the stock of an endangered species, or they can behave selfishly, taking investment decisions that threaten the growth of that natural resource. In our game, the agency applies a collective provision point mechanism, that is a conditional subsidy that is granted to the farming community only if the sum of all agents' contributions allows the sustainability of the endangered species. The incentive is only granted if the resource is recovered. Our collective provision point mechanism presents some differentiated characteristics compared with other collective threshold games. Usually, in threshold public good experiments, the Nash equilibrium coincides with the threshold (see Croson and Marks, 2000), but this is not the case for our collective provision point mechanism. In our setting, the Nash equilibrium individual agent contribution is larger than the threshold individual agent contribution, which introduces a decision dilemma into the game. If players are risk averse then they may worry about contributing to a lost cause or about donating a redundant contribution. Therefore, our collective provision point mechanism introduces a coordination problem, as agents can identify multiple equilibria. Our claim is that this decision dilemma and the coordination problem, contrary to what is usually the case (for example, Suleiman and Rapoport, 1992 and Croson and Marks, 2000), can help to protect the natural resources. That is, far from being negative for the environment, this dilemma gives incentives to farmers to raise their individual contributions to pro-social behaviour.

[1]See Andreoni (1998) for a classic exemple of threshold public good provision or Palfrey and Rosenthal, (1994); Croson and Marks, (2000); Suleiman *et al.,* (2001) and Le Cloent *et al.,* 2014

Furthermore, we compared the collective with an individual provision point mechanism. In this case, a minimum level of personal investment in natural resource recovery has to be assured by each agent before the incentive is granted to them; however, to assure that the resource growth becomes sustainable, the investment level in resource preservation has to reach a minimum threshold. The main difference with the previous mechanism is that agents that show pro-social behaviour can receive the individual subsidy even if the resource is not recovered. With this individual provision point mechanism, we provide a focal point for agents where they can be sure of receiving the subsidy but not of recovering the resource. Furthermore, we compare the performance of these two mechanisms with a baseline experiment where agents can choose whether or not to voluntarily invest in a project to protect a specific natural resource. We further assume that those agents being pro-social have a reduced return on their investment decisions compared with selfish agents. Finally, as in the previous setting, the natural resource population is only sustained if a certain level of contributions is obtained.

Also, we compare the performance of our collective provision point mechanism with the permormance of an individual provision point mechanism that differs from the collective in that the individual payoff is not dependent on what other agents do; it only depends on individual behaviour. In the individual provision point mechanism, the extra payoff is given to an agent who reaches the threshold independently of what other agents do. Also, in the individual mechanism there is only one Nash equilibrium located exactly on the threshold and agents do not face a coordination problem. In addition, we use a basic game similar to the public good games where agents must take investment desicions.

Further, governments usually allocate a certain budget to promote private contributions to a specific environmental conservation programme. For example, to make habitat preservation compatible with economically sustainable agricultural practices, the EU has issued a set of measures aimed at supporting farmers' activity in Natura 2000 areas through agri-environmental schemes. As we have already said in this thesis, the most important source of funding for Natura 2000 is the European Agricultural Fund for Rural Development (EAFRD), which funds a large part of the Common Agricultural Policy (CAP), particularly Pillar II, aimed at rural development. Most of these payments must be distributed by hectare and year. Incentives are allocated individually to those farmers that undertake environmentally friendly farming practices. In this respect, and to make both the individual and the collective provision point mechanisms comparable, we have determined a fixed budget and we have kept the budget constraint constant in both settings. Finally, to make the experiment more realistic, if at the end of the experiment there is a natural resource stock level, a real economic donation to the SEO/Birdlife organization, dedicated to protecting endangered species of birds, is made.[2]

Finally, often experiments that focused on biodiversity or natural resource protection, have been designed in a common pool settings (see, for example, Herr, *et. al.,* 1997; Fischer *et. al.,* 2004 and Osés-Eraso and Viladrich-Grau, 2007*b*). However, our experiments are note design in a common pool setting but agents decision cause an externality to the natural resource stock. Our main goal is to determine which threshold mechanism best promotes conservationist behaviour and to highlight agents' main reasons to contribute to the preservation of the endangered bird species when they have to take investment decisions.

[2]Eckel and Grossman (1996) support the idea that altruistic behaviour increases the more deserving the donations' destination is.

Our goal is to identify the main factors affecting stakeholders' willingness to contribute to the sustainability of the natural resource and to analyze the Nash location effect on contribution level. This chapter is organized as follows. In the first section, we present the experimental design and procedure for the three games we have designed and the hypothesis to test. In section two, we present our results. In section three, we present a games comparison and a regression analysis and, finally, we set out our conclusions.

4.2 Experimental design and procedure

In this section, we present the three games; first, we present the basic game that we use as a benchmark, and then we present the two threshold mechanisms.

4.2.1 Basic Game

A group of n agents is involved in a productive activity that can bring a natural resource, B, to exhaustion. The environmental agency's goal is to assure that the resource is sustainable. We assume that agents can apply a productive effort to two different projects, projects C and D. Therefore, each agent receives an endowment of e points that they must invest either in project C or in project D. We define x_i as the number of points invested by agent i, $i = 1, ..., n$ in project C. Since the whole endowment must be invested, agent i invests $(e - x_i)$ in project D. Every point x_i placed in project C earns α points for the farmer i and increases the stock of natural resource by c points. As agents investing in project C are contributing to the protection of the natural resoruce, we also refer to investments in project C as "contributions". On the other hand, every point placed in project D earns ω points for the farmer and reduces the natural resource by d points. These investment decisions have a direct effect on the size of the natural resource that we represent by:

$$B_R = B_0 - d\sum_{i=1}^{n}(e - x_i) + c\sum_{i=1}^{n} x_i \tag{4.1}$$

where B_0 represents the initial resource stock size and B_R the remaining resource stock after all group agents have taken their investment decisions. We assume that B_0 is also the minimum stock level that allows sustainable resource growth. Therefore, if $B_R < B_0$ the resource will be led to exhaustion. Moreover, the payoff function of agent i can be represented by:

$$\pi_i = \omega\,(e - x_i) + \alpha x_i \tag{4.2}$$

where $\omega\,(e - x_i)$ represents the return obtained by agent i from project D and αx_i represents the return obtained by agent i from project C. By assumption, the individual net marginal benefit of investing in project D is $\omega > 0$ and in project C is $\alpha > 0$. Moreover, we assume that $\omega > \alpha$ and, under this assumption, the symmetric Nash equilibrium predicts that every agent will invest their entire endowment in project D, that is $x_i = 0$ is the best individual strategy. See the graphical representation of the individual payoff per point invested in x_i in Figure 4.1a, where point I/N represents the best individual strategy and also the Nash equilibrium. [3] Furthermore, we assume that the natural resource generates some social amenities; therefore, we represent the total social benefit (including amenities) of the investment decision as:

[3] As we have assumed that $\omega > \alpha$ the maximum payoff will be reached at a corner solution, $\frac{\partial \pi_i}{\partial x_i} = -\omega + \alpha \leq 0$. Consequently, the symmetric Nash equilibrium predicts full investment in project D, that is $x_i = 0$.

$$\sum_{i=1}^{n} SB_i = \sum_{i=1}^{n} \pi_i + B_R = (\omega - d)\sum_{i=1}^{n}(e - x_i) + (\alpha + c)\sum_{i=1}^{n} x_i + B_0 \tag{4.3}$$

The net social marginal benefits of investing in project D are $(\omega - d)$ and of investing in project C are $(\alpha + c)$. If we assume that $(\omega - d) < (\alpha + c)$, we have described the traditional social dilemma.[4] It is socially better to invest $x_i = e$ but the best individual strategy for each agent i is to invest $x_i = 0$. If n agents invest $x_i = 0$, the natural resource stock will be reduced to $B_R = B_0 - dne$.

Beside these individual strategies, there is a contribution level that is able to keep the resource stock constant; we call it the minimum strong-sustainable contribution and it is equal to $\sum_{i=1}^{n} x_i = \frac{dne}{(d+c)}$,[5] that is, where the sum of the n agents' contribution is such that the stock of the natural resource remains constant at B_0.[6] Intuitively, in such a case the stock reduction caused by some agents is counterbalanced by the investment decision of other agents. Finally, we also define the group optimum strategy as the point where agents maximize their benefits as a group without taking into account amenities associated with natural resource conservation. In this sense, as $\omega > \alpha$ the group optimum occurs when $\sum_{i=1}^{n} x_i = 0$, that is the group strategy.[7] The group optimum coincides with the individual optimum in this basic game.

[4]If the agency goal was to maximize social benefits, the best social strategy would be to invest all points in project C, that is $x_i = e \; \forall i$. Given the social benefits, and as $(\omega - d) < (\alpha + c)$, the maximum payoff will be reached at a corner solution, $\frac{\partial \pi_i}{\partial x_i} = -(\omega - d) + (\alpha + c) \geq 0$. Consequently, if we were to maximize social benefits, the aggregated efficiency would require $\sum_{i=1}^{n} x_i = ne$.

[5]See Dietz and Neumayer (2007) for an explanation of the strong sustainability concept.

[6]The natural resource is kept constant when $B_R = B_0$ or, what is the same, when $cne = (d + c)\sum_{i=1}^{n} x_i$. The minimum strong-sustainable strategy is $\sum_{i=1}^{n} x_i = \frac{dne}{(d+c)}$. The average minimum strong-sustainable strategy is $\frac{de}{(d+c)}$.

[7]The group benefits are defined by $\sum_{i=1}^{n} \pi_i = \omega \sum_{i=1}^{n}(e - x_i) + \alpha \sum_{i=1}^{n} x_i$. The maximum group payoff will be reached at a corner solution, $\frac{\partial \sum_{i=1}^{n} \pi_i}{\partial x_i} = -\omega + \alpha \leq 0$. Consequently, to maximize the group

4.2.2 The individual provision point mechanism

Now we assume that the agency introduces a conditional subsidy that is granted to agent i only if agent i invests at least $\bar{t}$ points in project C. We represent this conditional subsidy by κ and it is individually assigned and does not depend on the number of points placed in project C by third agents. It is a single payment and it does not increase with x_i. After each round, if agent i has invested $x_i \geq \bar{t}$ he will receive the subsidy κ. We assume that the individual threshold $\bar{t}$ is determined by the environmental agency such that $n\bar{t} = \overline{T}$, where $\overline{T}$ is the aggregated level of investment in project C that would allow the resource stock to be maintained at B_0, that is the minimum stock level that allows sustainable growth of the resource. This individual provision point mechanism does not assure that the budget is used efficiently; agents receive the incentive κ if their individual investment x_i is at least equal to $\bar{t}$; however, note that the natural resource is recovered only if $\sum_{i=1}^{n} x_i = \overline{T}$. Therefore, it could be the case that several agents (at most $n-1$) receive the subsidy but the resource is not recovered, that is, the minimum strong-sustainable investment in C level, B_0 , has not been reached but some agents receive the subsidy.[8] The individual payoff function would be equal to:

$$\pi_i = \left\{ \begin{array}{c} \omega\left(e - x_i\right) + \alpha x_i \text{ if } x_i < \bar{t} \\ \omega\left(e - x_i\right) + \alpha x_i + \kappa \text{ if } x_i \geq \bar{t} \end{array} \right\} \tag{4.4}$$

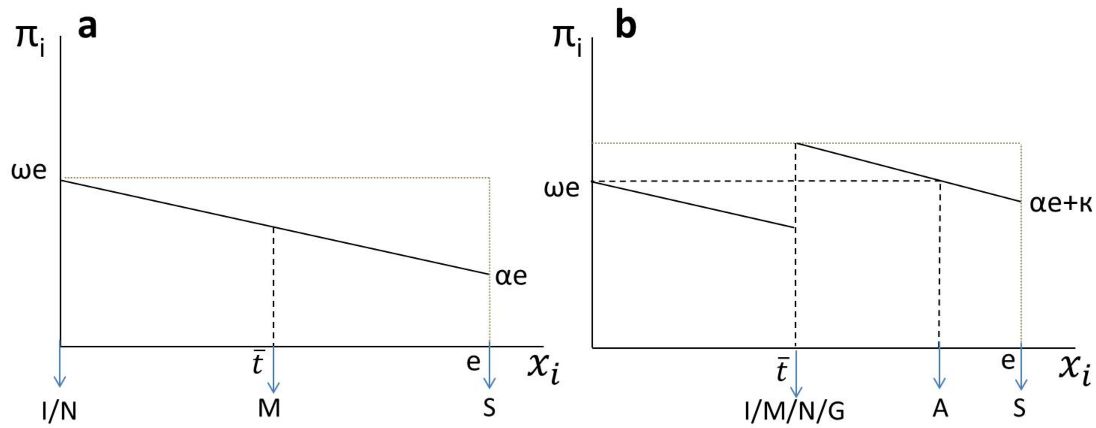
In this setting, agents have no incentives to invest more than $\bar{t}$ points in project C.

benefits would require $\sum_{i=1}^{n} x_i = 0$.

[8]The threshold $\overline{T}$ can be reached if the four agents invest $x_i = \bar{t}$ points in project C. It could also be the case that an agent invests $2\bar{t}$ in project C; then it will be possible to reach the minimum strong-sustainable with one agent investing zero in project C. However, if $(n-1)$ agents invest $x_i = \bar{t}$ points in project C and one agent invests zero in project C, the resource is not recovered. This is not the only possible combination; there is a wide range of combinations where agents contribute and the sustainability is not reached.

The maximum individual payoff when the threshold is reached is $\pi_i^{\bar{t}} = \omega(e-\bar{t})+\alpha\bar{t}+\kappa$. Each additional unit invested in project C will give a return α lower than the return ω that could be obtained if those units were invested in project D. Further, if the threshold $\bar{t}$ is not reached, the maximum individual payoff is $\pi_i^0 = \omega e$ when $x_i = 0$. Therefore, the best individual strategy depends on the difference between these two payoffs $\pi_i^{\bar{t}} - \pi_i^0 = \kappa - (\omega - \alpha)\bar{t}$. If we assume that $(\omega - \alpha)\,\bar{t} < \kappa$ the best individual strategy would be $x_i = \bar{t}\ \forall i$ (See point I Fig 4.1b).[9] In addition, the group optimum is $\sum x_i = \overline{T}$ (See point G in Fig 4.1b). Finally, as in the basic game, the best social strategy would be $\sum\limits_{i=1}^{n} x_i = ne$ (See point S in Figure 4.1b) and the minimum strong-sustainable strategy occurs when $\sum\limits_{i=1}^{n} x_i = \frac{dne}{(d+c)}$(See point M in Figure 4.1b).

[9]Two other cases are possible. First, if $(\omega - \alpha)\,\bar{t} = \kappa$ and second if $(\omega - \alpha)\bar{t} > \kappa$. See Figure 4.7 in Appendix 4.7.1.



*Where I is the Optimal Individual strategy, A the Average Payoff strategy, S the Optimal Social strategy, M the Optimal Minimum Strong-sustainable strategy. N the Nash equilibria and G the Optimal Group strategy.

Figure 4.1: Basic game (a) and individual provision point mechanism (b) total individual payoffs (π_i).

4.2.3 The collective provision point mechanism

In this third setting, we assume that the agency introduces a collective conditional subsidy; a budget S_G is granted to a community of n agents only if a minimum number of $\overline{T}$ points is invested in project C by community members, that is if $\sum_{i=1}^{n} x_i \geqq \overline{T}$. This threshold $\overline{T}$ is determined by the environmental agency such that $\overline{T}$ is the aggregated level of investment in project C that assures the recovery of the resource stock, that is, it guarantees that the resource stock reaches at least B_0. Further, if S_G is granted to the community, we assume that it is individually distributed among the 4 community members proportionally to the points placed by each agent i in project C, that is, each agent i will receive $\phi_i x_i = \frac{S_G}{\sum_{i=1}^{n} x_i} x_i$. Therefore, the higher the level of agents contributions the smaller the individual subsidy received by point invested in project C.[10] Recapitulating, if after a round, the total contribution of the community is at least

[10]Palm-Forster, *et al.,* 2018 have also introduced a decreasing subsidy in their experiments. They design a subsidy that is a decreasing function of the level of water contamination.

equal to $\overline{T}$, then S_G is granted to the group to be distributed, proportionally to their effort, among those group members that have contributed to project C.

Moreover, in our game we assume that $\overline{T}(\omega - \alpha) < S_G$. Note that the optimal group strategy depends on the difference between two payoffs, S_G, the collective subsidy granted by the environmental agency if a minimum level of investment in C is provided and $\overline{T}(\omega - \alpha)$, the opportunity cost of investing in project C, that is what the group would have earned if it had invested in D. If it were the case that $\overline{T}(\omega - \alpha) > S_G$, the environmental subsidy S_G would not be large enough to encourage agents to invest in project C. In this case, the optimal group strategy, and also the individual optimal and Nash equilibria would be $\sum_{i=1}^{n} x_i = 0$ and $x_i = 0$, respectively.[11]

The condition of attaining threshold $\overline{T}$ guarantees natural resource conservation and also assures that the budget is used efficiently, since agents receive the incentive only if the natural resource is recovered and not if the recovery is not assured, as could occur in the individual provision point mechanism. The individual payoff function is now equal to:

$$\pi_i = \left\{ \begin{array}{c} \omega(e - x_i) + \alpha x_i \text{ if } \sum_{i=1}^{n} x_i < \overline{T} \\ \omega(e - x_i) + \alpha x_i + \phi_i x_i \text{ if } \sum_{i=1}^{n} x_i \geq \overline{T} \end{array} \right\} \tag{4.5}$$

where $\phi_i x_i$ is the total extra amount received by agent i contributing x_i to project C, and it is a decreasing function of x_i.[12] Note that if the set of investment strategies in project C, $\left(x_1^* ... x_n^*\right)$ were such that $0 \leq x_i^* \leq e \ \forall i$, and $0 \leq \sum_{i=1}^{n} x_i^* < \sum_{i=1}^{n} x_i^m$ where $\sum_{i=1}^{n} x_i^m = \overline{T}$, the threshold would not be reached and in such a case the individual and

[11] See the case where $\overline{T}(\omega - \alpha) > S_G$ and other possible cases in Figure 4.7 of Appendix 4.7.1.

[12] $\frac{\partial[\phi(x_i)x_i]}{\partial x_i} = \frac{S_G}{\sum_{i=1}^{n} x_i} - \frac{S_G}{\left[\sum_{i=1}^{n} x_i\right]^2} x_i = \frac{S_G}{\sum_{i=1}^{n} x_i}\left(1 - \frac{x_i}{\sum_{i=1}^{n} x_i}\right) < 0$

the group optimum strategies would be equal to $x_i^* = 0$ and $\sum_{i=1}^{n} x_i^* = 0$, respectively (See I_1 and G_1 in Figure 4.2).[13] In this case, $\sum_{i=1}^{n} \pi_i = \omega ne$.

Let us now assume that there is a set of investment strategies $\left(x_1^* ... x_n^*\right)$ such that $0 \leq x_i^* \leq e \ \forall i$, and $\sum_{i=1}^{n} x_i^m \leq \sum_{i=1}^{n} x_i^* \leq ne$ where $\sum_{i=1}^{n} x_i^m = \overline{T}$, that is, the threshold is reached. In this case, the group reaches its maximum payoff when $\sum_{i=1}^{n} x_i^* = \sum_{i=1}^{n} x_i^m = \overline{T}$, that is $\sum_{i=1}^{n} \pi_i = \omega ne - (\omega - \alpha) \sum_{i=1}^{n} x_i^m + S_G$, note that for values of $\sum_{i=1}^{n} x_i^* > \overline{T}$ then $\sum_{i=1}^{n} \pi_i$ will decrease.[14]

Furthermore and considering the game to be symmetrical, the individual optimal strategy would be $x_i^* = \frac{\overline{T}}{n} \ \forall i$ because if $\omega ne - (\omega - \alpha)\overline{T} + S_G$ is the maximum group payoff, then $\frac{\omega ne - (\omega - \alpha)\overline{T} + S_G}{n}$ would be the maximum individual payoff. However, it is not a Nash equilibrium. At $\sum_{i=1}^{n} x_i^* = \sum_{i=1}^{n} x_i^m = \overline{T}$ it holds that $\omega < \alpha + \frac{S_G}{\sum_{i=1}^{n} x_i^m} \left(1 - \frac{x_i^m}{\sum_{i=1}^{n} x_i^m}\right)$, any agent investing x_i^* in project C will have incentives to increase their contributions to project C; therefore, $x_i^* = x_i^m$ is not a Nash equilibrium when $\sum_{i=1}^{n} x_i^* = \sum_{i=1}^{n} x_i^m = \overline{T}$.[15]

[13] If the threshold is not reached, the marginal individual benefits are $\pi_i = -\omega + \alpha$ and as $\omega > \alpha$, the best individual strategy is $x_i^* = 0$. The same happens at the group level.

[14] Note that when $\overline{T}\,(\omega - \alpha) < S_G$, if the group of agents were to place $\sum_{i=1}^{n} x_i^* > \sum_{i=1}^{n} x_i^m = \overline{T}$ points in project C, the environmental agency will grant them S_G, but the points invested in excess of $\sum_{i=1}^{n} x_i^m$ in project C $\left(\sum_{i=1}^{n} x_i^* - \sum_{i=1}^{n} x_i^m\right)$ will have a large opportunity cost. Each point invested in excess in project C could have been invested in project D and earned a ω, as by assumption $\omega > \alpha$. Then $\sum_{i=1}^{n} x_i^m$ is an optimal group allocation in the sense that it maximizes group benefits (point G_2 in Figure 4.2).

[15] Recall that the marginal benefits of investing in project D are ω and the marginal benefits of investing in project C are equal to:

$\alpha + \frac{S_G}{\sum_{i=1}^{n} x_i} \left(1 - \frac{x_i}{\sum_{i=1}^{n} x_i}\right)$; therefore, an agent will have incentives to increase their investments in C given that the investments of all other agents remain constant.

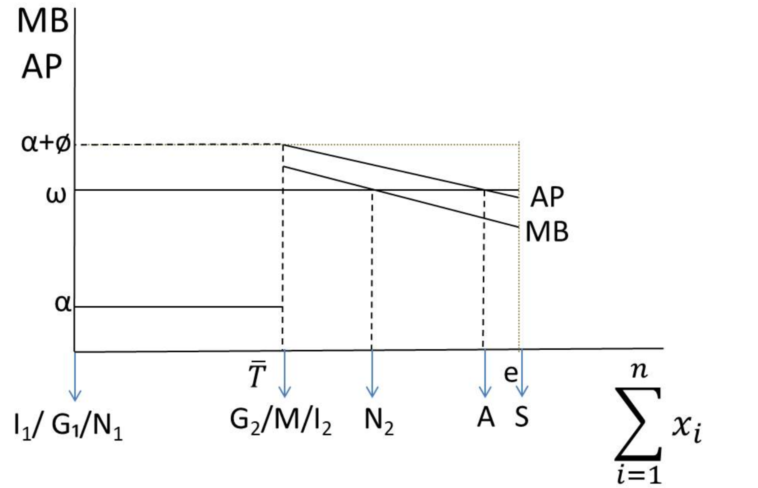
If we assume that this game is symmetric, then x_i^m will be the same for all i, and equal to $\frac{\overline{T}}{n}$ which will coincide with $\overline{t}$ of the individual provision point mechanism.

Further, if $\sum_{i=1}^{n} x_i^* > \sum_{i=1}^{n} x_i^m = \overline{T}$, and $\omega = \alpha + \frac{S_G}{\sum_{i=1}^{n} x_i^m}\left(1 - \frac{x_i^m}{\sum_{i=1}^{n} x_i^m}\right)$, this would be an individual Nash equilibrium (See point N_2 in Figure 4.2). At this point no agent will have incentives to increase their investment in C.[16]

In addition, as in the previous settings, the socially optimal strategy is $\sum_{i=1}^{n} x_i = ne$ and the minimum strong-sustainable strategy occurs when $\sum_{i=1}^{n} x_i = \frac{dne}{(d+c)}$ (See points S and M in Figure 4.2, respectively). Finally, note that there is a focal point when the average payoffs obtained by investing in project C and in project D are equal.[17] Note that, if the threshold is reached, the average payoff per unit invested in project C is $\alpha + \frac{S_G}{\sum_{i=1}^{n} x_i}$ and the average payoff per unit invested in project D is ω. If there is a set of actions $\left(x_1^* ... x_n^*\right)$ such that $0 \leq x_i^* \leq e \ \forall i$, the threshold is reached, $\sum_{i=1}^{n} x_i^* \geq \overline{T}$, and $\omega = \alpha + \frac{S_G}{\sum_{i=1}^{n} x_i^*}$ then to invest x_i^* points in project C and $(e - x_i^*)$ in project D for each i would be a focal point (See point A in Figure 4.2). At this point, the payoff obtained per unit of x_i by agent i would coincide with the payoff obtained if $x_i = 0$.

[16]See the Nash equilbrium point demostration assuming symmetry in Appendix 4.7.2.

[17]Note that once $\overline{T}$ is reached, the payoff per unit invested in project C is a decreasing function of x_i; that is the marginal payoff of investing in project C is above the average payoff (See Fig 4.2).



*Where I is the Optimal Individual strategy, A the Average Payoff strategy, S the Optimal Social strategy, M the Optimal Minimum Strong-sustainable strategy. N the Nash equilibria and G the Optimal Group strategy.

Figure 4.2: Collective provision point mechanism average payoff (AP) and marginal net benefits (MB).

4.2.4 Games parametrization

The experiments reported in this study were conducted using the z-tree program (Fischbacher, 2007) at Lineex (Laboratory for Research in Behavioural and Experimental Economics of the *Universitat de Valencia*) during the month of June 2018. We implemented the three different games presented above, the baseline game, the individual provision point mechanism and the collective provision point mechanism. 96 subjects, 60 females and 36 males, aged from 18 to 28 years, participated in the experiment. Each subject took part in only one treatment, that is, we implemented a between-subjects study. We ran one session per treatment, with 8 groups of 4 agents each; the 4 agents remained the same during the 10 rounds of the game. That is, we collected a total of 960 observations. There was no communication with other participants during the experiment. Further, agents do not have any individual monitoring nor enforcing capability, that is, they cannot identify the individual strategies of other agents. Therefore they can neither punish not reward any fellow group member. However, after each round each agent obtains information about the total group investment in project C, and therefore can compare the quantity invested by the group with his own level of investment in project C and act strategically. The current set of experiments do not allow to analyze the effect of group members' communication on natural resource protection. We plan to analyze the effects of allowing agents to communicate on future research, especially in cases where the recovery of a natural resource requires reaching a threshold.[18]

On arrival, the subjects had to read the instructions. The instructions describe the situation, the exact size of each group, the number of decision rounds, the size of the natural resource stock, the personal endowment, the investment possibilities and the exchange rate from points to money. It was also explained that the donations that resulted from the game will be given to the SEO/Birdlife organization. We provided each participant with a calculator.

It is a repeated game; in each round each agent receives an endowment of $e = 20$ experimental points for personal investment. They can invest the endowment in project D or C. Those points invested in project C are represented by x_i, and those invested in project D are represented by $(20 - x_i)$. Moreover, the investment decisions alter a natural resource stock. Each point invested in project C increases the resource stock by $c = 1.5$ points; on the contrary, each point invested in project D reduces the resource stock by $d = 1$ points. The initial natural resource stock is $B_o = 80$ points.[19] Depending

[18]Some authors report cases where agent's communication improves contributions (See examples of experiments with communication in Krishnamurthy, 2001 and Haruvy, et. al, 2017). Moreover, Marco-Renau (2018) has developed a theoretical model where he demonstrated that social network could be crucial on determining the success of natural resource conservation.

[19]Note that with this parametrization, if all agents invest all the endowment in D, the resource will be extinct $dne = 80$.

on the group agents' investment decisions, at the end of each round the natural resource stock could be above, below or equal to the 80 initial points. We further assume that the environmental agency goal is satisfied if at least the natural resource stock remains constant, that is $B_o = 80$.

In the basic game, each point invested in project C has a constant return of $\alpha = 1$ points. That is, for example, if an agent invests 20 points in project C their payoff will be $1 \cdot 20 = 20$ points. Moreover, each point invested in project D has a constant return of $\omega = 3$ points. That is, for example, if an agent invests 20 points in project D their payoff will be $3 \cdot 20 = 60$ points. Additionally, in the individual and in the collective provision point mechanism games, the agency introduces a conditional subsidy that is granted to agent i only if agent i contributed to project C. The environmental agency allocates a budget of 128 points, per round, to pay these subsidies. We use an exchange rate of 4 $points = 1$ $euro$.

In the individual provision point mechanism, every agent receives a constant subsidy $\kappa_i = 32$ points if their contribution to project C is at least equal to threshold $\bar{t}$.[20] We have fixed this threshold at $\bar{t} = 8$ points.[21] If every agent invests $x_i = 8$ points the amount that the group can obtain is $\kappa_i n = 32 \cdot 4 = 128$ points, and in this case the agency budget is exhausted. Moreover, the individual payoff will be determined by:

$$\pi_i = \left\{ \begin{array}{c} \pi_i = 3\,(e - x_i) + 1x_i \text{ if } x_i < 8 \\ \pi_i = 3\,(e - x_i) + 1x_i + 32 \text{ if } x_i \geq 8 \end{array} \right\} \tag{4.6}$$

In this setting, the optimal individual strategy is to invest 8 points in project C (see

[20]As each group has 4 agents we have $4 \cdot 32 = 128$.
[21]Note that, if all agents reach the threshold, then $n\bar{t} = \overline{T} = 32$ points.

Figure 4.1a). If all agents follow the optimal individual strategy, the individual payoff at the end of a round will be $\pi_i = 3 \cdot 12 + 1 \cdot 8 + 32 = 76$ points or, what is the same, 19€. Alternatively, if an agent invests 0 points in project C, their individual payoff at the end of a round will be $\pi_i = 3 \cdot 20 = 60$ points or, what is the same, 15€. Finally, if all agents follow the optimal social strategy and invest 20 points in project C, the individual payoff at the end of a round will be $\pi_i = 1 \cdot 20 + 32 = 52$ points or, what is the same, 13€.

On the other hand, in the collective provision point mechanism, agents are granted a collective payment of $S_G = 128$ points only if the group invests a minimum number of points in C. We have fixed this collective threshold at $\overline{T} = 32$ points invested in project C. Note that, in particular, this parametrization facilitates the comparison between the individual and the collective provision point mechanism. This investment assures that the natural resource is preserved.[22] Also, if the threshold $\overline{T} = 32$ points is reached, each agent receives $\alpha + \phi$ for each point invested in project C, where $\phi = \frac{128}{\sum_{i=1}^{n} x_i}$. Further, the individual payoff of agent i will be equal to:

$$\pi_i = \left\{ \begin{array}{c} \pi_i = 3\,(e - x_i) + 1x_i \text{ if } \sum_{i=1}^{n} x_i < 32 \\ \pi_i = 3\,(e - x_i) + \left(1 + \frac{128}{\sum_{i=1}^{n} x_i}\right) x_i \text{ if } \sum_{i=1}^{n} x_i \geq 32 \end{array} \right\} \tag{4.7}$$

In this setting, if the threshold were not reached, the individual optimal strategy would be to invest $x_i = 0$ points in project C, and the individual payoff at the end of a round will be $\pi_i = 3 \cdot 20 = 60$ points or, what is the same, 15€. This is not only an individually optimal strategy but also a Nash equilibrium strategy if the threshold were

[22]Recall that, $B_R = B_0 - d \sum_{i=1}^{n} (e - x_i) + c \sum_{i=1}^{n} x_i$ and then $B_R = 80 - 48d + 32c = 80$ points.

not reached. The maximum that an agent can earn is 60 points if the threshold is not reached.[23] As we just have shown, if the threshold is not reached and agent i invests $x_i = 0$, then they earn 60 points, but note additionaly, that if agent i invests $x_i = 0$ and the threshold is reached, they also earn 60 points. Therefore, investing 0 points in project C returns 60 points independently of the outcome of the collective provision point mechanism. Investing 0 points in project C always returns 60 points; it is a strategy that assures a return of 60 points. However, $x_i = 0$ is not the individual optimal strategy when the threshold is reached. That is, agents have to make a conjecture about fellow agents' investment decisions before choosing their strategies.

Recall further that, in the collective provision point mechanism, when the threshold is reached the return of each point invested in C depends on the total amount of points invested by group members; therefore, this is another reason for agents to make conjectures about fellow agents' investment decisions before choosing their strategies. A focal point of this game is for each agent to invest 8 points in project C; this will be the best symmetric strategy for an agent that expects the threshold to be reached. If each agent were to invest 8 points in project C (see Figure 4.1b), agent i's payoff at the end of the round will be $\pi_i = 3 \cdot 12 + \left(1 + \frac{128}{32}\right) \cdot 8 = 76$ points or, what is the same, 19€. If the game were symmetric, the optimal group strategy would coincide with the best individual strategy. Note that the optimal group strategy is to contribute a minimum of 32 points to project C and reach threshold $\overline{T}$, that is $\sum\limits_{i=1}^{n} x_i = 32$. Then, it is easy to see that investing 8 points in project C would be the individual optimal strategy and, therefore, would coincide with the group optimal strategy if the game were symmetric. Further, it also coincides with the minimum strong-sustainable strategy. However, investing $x_i = 8\ \forall i$ in project C is not a Nash equilibrium strategy. Agent i

[23]The retribution of 3 points per unit invested in project D is larger than any other retribution that can be obtained if the threshold is not reached, that is 1 point per unit invested in project C.

could increase their payoff by increasing their investment in project C given that the other group members keep investing 8 points each in that project. That is, if agent i were to invest $x_1 = 9$, their profits would be equal to $\pi_i = 3 \cdot 11 + \left(1 + \frac{128}{33}\right) \cdot 9 = 76.9$ or, what is the same, 19.2€.[24]

However, if each agent invests 12 points in project C, then $\alpha + \frac{S_G}{\sum_{i=1}^{n} x_i^m} \left(1 - \frac{x_i^m}{\sum_{i=1}^{n} x_i^m}\right) = 1 + \frac{128}{48}\left(1 - \frac{12}{48}\right) = 3$ and it is equal to ω, that is investing $x_i = 12\ \forall i$ is a Nash equilibrium. The individual payoff at the end of a round would be $\pi_i = 3 \cdot 8 + \left(1 + \frac{128}{48}\right) \cdot 12 = 68$ points or, what is the same, 17€. That is, we reach a tragedy of the commons type of situation where, with the optimal group strategy, each agent invests $x_i = 8$ in project C, but this strategy it is not a Nash strategy and agents are driven to increase their contribution to project C. Moreover, these focal points arise when we consider only the symmetrical equilibria but agent strategies do not need to be symmetric in our game.

Finally, if all agents follow the socially optimal strategy, that is to invest 20 points in project C, the individual payoff at the end of a round will be $\pi_i = \left(1 + \frac{128}{80}\right) \cdot 20 = 52$ points or, what is the same, 13€. At the end of each round agents are informed about the total investments in project C, the gains of investing a point in project C, the total individual gains and the final natural resource stock level. In addition, only the results of one specific round are transformed into real private or social gains. This round, called t^*, is randomly chosen at the end of the game. After all investment decisions have been taken, t^* is chosen and each agent is paid for their individual gains associated with period t^*. At the end of round t^* a monetary donation, G, is granted to the SEO/Birdlife organization; the amount of this donation depends on the remaining

[24]Also, if agent i invests 16 in project C while others invest 8, then $\pi_i = 3 \cdot 4 + \left(1 + \frac{128}{40}\right) \cdot 16 = 79.2$. It will be the same if i invests 20 in project C while others invest 8, then $\pi_i = 3 \cdot 0 + \left(1 + \frac{128}{44}\right) \cdot 20 = 78,18$.

fund level.[25] Those agents that have invested in project C in round t^* are given a certificate acknowledging that the donation to the SEO/Birdlife organization has been made. Finally, at the end of the game, participants have to answer a questionnaire.[26] See in Tables 4.1 all strategies that agents can follow in the basic, individual and collective game, respectively, and their associated natural resource stock and contribution level, assuming symmetry.[27]

4.2.5 Hypothesis to test

As we pointed out in the introduction, our goal is to show that agents under the collective provision point mechanism contribute (invest in project C) more than agents in the other two settings. In the collective mechanism, there are multiple equilibria and agents have to coordinate to assure that the threshold is reached. If the threshold is not reached, the individual optimal strategy is $x_i = 0$. It is a Nash equilibrium (See point I_1 in Figure 4.2), but the natural resource is not preserved. However, if the threshold is reached, the Nash equilibrium is an allocation $(x_1, ...x_n)$ where $\omega = \alpha +$

[25]The donation is obtained from $B_R = B_0 - d\sum_{i=1}^{n}(e - x_i) + c\sum_{i=1}^{n} x_i$. If, for example, $\sum_{i=1}^{n} x_i = 32$ then $B_R = 80 - 1(80 - 32) + 1.5 \cdot 32 = 80$ points, that is a donation of $\frac{80}{4} = 20$ *euros*. Note that this is a situation in which the fund is kept constant at its initial amount, that is 80 points.

Moreover, if $\sum_{i=1}^{n} x_i = 10$, then $B_R = 80 - 1(80 - 10) + 1.5 \cdot 10 = 25$ points. Note that this is a situation in which the fund has decreased by 55 points $(80 - 25)$ with respect to its initial amount of 80 points. The donation will be $\frac{25}{4} = 6.25$ *euros*.

Finally, if $\sum_{i=1}^{n} x_i = 80$, then $B_R = 80 - 1(80 - 80) + 1.5 \cdot 80 = 80 + 30 = 200$. Note that this is a situation in which the fund has increased by 120 points with respect to its initial amount of 80 points, and the donation will be $\frac{200}{4} = 50$ *euros*.

[26]We present the instructions for each treatment and the questionnaire in appendix 4.6.3.

[27]Recall that the minimum strong-sustainable strategy is obtained as follows $\sum_{i=1}^{n} x_i = \frac{dne}{(d+c)} = \frac{1 \cdot 4 \cdot 20}{(1+1.5)} = 32$; if we assume symetry this is $t = \frac{32}{4} = 8$ *points* invested by each agent.

	Basic Game		Individual provision point mechanism		Collective provision point mechanism			
					When threshold is not reached		When threshold is reached	
	Contribution to project C	N.resource stock	Contribution to project C	N.resource stock	Contribution to project C	N.resource stock	Contribution to project C	N.resource stock
Nash equilibrium strategy							12	120
Individual optimal strategy	0	0	8	80	0	0		
Group optimal strategy							8	80
Minimum strong-sustainability strategy	8	80			8	80		
Socially optimal strategy	20	200	20	200	20	200	20	200
Equal average payoff strategy	–	–	–	–	–	–	16	160

Table 4.1: Contributions associated with the strategy followed by agents and related resource stock assuming symmetry.

$\frac{S_G}{\sum_{i=1}^{n} x_i^m}\left(1-\frac{x_i^m}{\sum_{i=1}^{n} x_i^m}\right)$, $\sum_{i=1}^{n} x_i^m > \overline{T}$, and the natural resource is preserved (See point I_2 in Figure 4.2). Typically, in threshold public goods experiments, contributions take place around the efficient Nash equilibrium (see Croson and Marks, 2000). Also, commonly in threshold public goods experiments, the efficient Nash equilibrium coincides with the threshold allocation, but in our case the efficient Nash equilibrium requires a larger investment in project C than the threshold allocation. Further, at allocation $\sum_{i=1}^{n} x_i^m = \overline{T}$, an agent i will have incentives to increase their investment in C up to the point that the marginal benefit of investing in C is equal to the marginal benefit of investing in D, that is up to the efficient Nash equilibrium. Therefore, the Nash equilibrium in the collective provision point mechanism could lead to a larger investment in C than the Nash equilibrium in an individual provision mechanism, that is when $x_i = t$.

In the individual provision point mechanism, the incentive is granted only if agent i individually reaches threshold t. Therefore, we are introducing a focal point, at $x_i = t$,where the individual optimal strategy is located. Note that the threshold is also a natural resource sustainable point (See point I/M in Figure 4.1b). From this, four hypotheses can arise.[28]

Hypothesis 1 Contributions to project C are larger in the collective provision point mechanism than in the individual provision point mechanism.

Hypothesis 2 Contributions to project C are larger in the individual provision point mechanism than in the basic game.

Hypothesis 3 In the individual provision point mechanism agents contribute ex-

[28]Kerr *et. al.* (2012) support the idea that incentives can promote agents' participation when people are uninterested. Moreover, there is considerable literature about economic incentives to promote pro-social behaviour in natural resource protection (See for example Wunder, 2005).

actly in the focal point of $x_i = t$.

Hypothesis 4 In the individual and in the collective provision point mechanisms the natural resource is preserved.

In the basic game, the individual optimal equilibrium is $x_i = 0\ \forall i$. Therefore, agents do not have economic reasons to contribute. Nevertheless, even when there are no economic reasons to contribute, it is known that voluntary donations and charity in public goods provision could lead agents to invest in project C.[29] However, these contributions do not necessarily assure the preservation of the natural resource. It could be the case that contribution efforts do not counterbalance the effect of investment efforts in project D and then the natural resource would not be protected. Therefore, our hypotesis is that:

Hypothesis 5 In the basic game agents contribute voluntarily to the natural resource; however, the natural resource is driven to extinction.

It seems clear that the collective provision point mechanism is where contributions to C are expected to be the largest; therefore, this would be the best mechanism assuring natural resource protection.

[29]People are willing to contribute because they care about the pool (Ariely *et al.*, 2009 and Banerjee and Shogren 2012) or in order to be well-valued by the community, for prestige and respect (Olson, 1965 and Ariely et al 2009).

4.3 Results

4.3.1 Basic Game

The average contribution in the basic game is 4.5 points (see Table 4.2), which differs significantly from zero according to the Wilcoxon test.[30] Each agent's endowment is 20 points; therefore agents, on average, contribute to project C around 22.5% of their total capacity. This average is calculated over the whole sample and without distinguishing among rounds. This percentage may seem quite high if we consider that agents do not receive any economic compensation for their contribution to project C. Nevertheless, the resource is driven to exhaustion. Further, we calculate the average contribution to project C round by round. In all rounds except for rounds 1 and 2 it is significantly lower than 8.[31] According to the Wilcoxon test, this average contribution differs significantly from the minimum strong-sustainable strategy (See in table 4.1 that $x_i = 8$). When the minimum strong-sustainable strategy is not reached, the resource is driven to exhaustion, the evolution of the average contribution and of the resource stock is presented in panels a and b of Figure 4.3. Summarizing, even if the average contribution is different from zero in each round, it reaches the minimum strong-sustainable strategy only in the first two rounds. That is, in the basic game agents contribute positively to project C; however, their contributions are not large enough to assure the natural resource recovery round after round.

Observation 1 *Agents contribute on average* 22.7% *of their capacity. However, this average contribution decreases steadily round after round.* See Figure 4.3

[30] We obtained the following statistics: $V = 211,115$ and $p < 0.000$. See also Table 4.6 in Appendix 4.7.3 to see the Wilcoxon tests results per round.

[31] See Table 4.6 in Appendix 4.7.3 to see the Wilcoxon tests results per round.

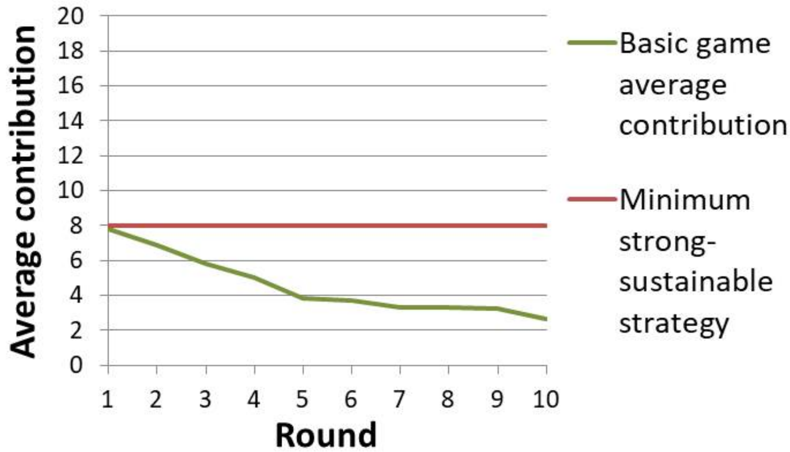


Figure 4.3: Average contributions per round in the basic game.

In addition, for a group to recover the resource in round t would mean that the group average contribution in round t is larger than 8 points. When we analyze the average contribution per group, we see that the percentage of groups that are able to recover the resource decreases from 62% in the first round to 0% in the last one. Therefore, the natural resource is driven to extinction by all groups in the last round. Furthermore, only three groups reach the minimum strong-sustainable contribution during a few initial rounds,[32] and some others reach the minimum strong-sustainable resource contribution sporadically in some intermediate rounds.[33] Furthermore, average contribution decreases round after round in all groups except for two where it remains almost constant.[34] In these cases, the constant trend is due to the presence of an agent in each group whose contributions present an increasing path that counterbalances other agents' contributions. Analyzing individual behaviour, we see that, although most agents tend to contribute to project C, they do so at a decreasing rate; agents keep contributing to C, but lowering the amount round after round.

[32]Those groups are 1, 2 and 3 in Figure 4.10 of Appendix 4.7.4.
[33]Those groups are 2, 5 and 6 in Figure 4.10 of Appendix 4.7.4.
[34]Those are groups 5 and 8 in Figure 4.10 of Appendix 4.7.4.

Observation 2 *On average, contribution is below the minimum strong-sustainable contribution and the natural resource is driven to extinction by all groups.*

Observation 3 *Group average contribution decreases steadily round after round in all groups except for two where it remains almost constant.*

We have classified agents in four types, strong-selfish, selfish, conservationists and strong-conservationists, according to their contribution level. We consider as strong-selfish those agents contributing $[0-4)$ points to project C. Further, we have classified those agents contributing $[4-8)$ points as selfish and those agents contributing $[8-16)$ as conservationists. Finally, those agents contributing 16 or more points to project C are considered strong-conservationists. We have calculated the percentage of each type of agent in our sample round by round. In Table 4.3, we present the percentage of each type of agent across all rounds and in the first and last rounds. On average, 53.4% of agents are strong-selfish, the most frequent strategy. However, the percentage of strong-selfish increases from 18.8% in the first round to 75% in the last round. Additionally, it can be pointed out that the percentage of conservationists decreases from 50% in the first round to 12.5% in the last. The percentages of selfish and strong-conservationists also decrease. Furthermore, 34.4% of agents start behaving as conservationists but end up behaving as strong-selfish. Further, 21.9% start behaving as selfish and end up behaving as strong-selfish. 18.7% are always strong-selfish and one agent (3.1%) starts behaving as a strong-conservationist but ends up behaving as strong-selfish.[35] [36]

Observation 4 *The most frequent type of agent is strong-selfish and this frequency increases round after round.*

[35] Also, 9.4% of agents start behaving as conservationists but end up behaving as selfish.

[36] See Figure 4.9 in Appendix 4.7.3 to see a graphical representation of the evolution of the four types of agents.

Additionally, we have calculated the percentage of agents that follow the optimal individual strategy - and contribute zero points to project C - across all rounds and in the first and in the last round. We present these results in Table 4.4, where the percentage of agents that follow the optimal individual strategy across all rounds is 35.9%. Only 2.8% and 4.7% of agents follow the social and the minimum strong-sustainable strategy. In the first round, only 15.6% of the agents follow the optimal individual strategy. Nevertheless, in the last round this percentage increases to 50%.

Observation 5 *The most followed strategy is the optimal individual strategy.*

	Basic Game		Individual provision point mechanism		Collective provision point mechanism	
	Average Contribution	N.resource recovered cases in %	Average Contribution	N.resource recovered cases in %	Average Contribution	N.resource stock
First Round	7.8 (±5.3)	37.5%	9.5 (±3.9)	87.5%	10.1 (±4.4)	87.5%
Last Round	2.6 (±4.5)	0%	8.9 (±2.7)	87.5%	10.5 (±4.7)	100%
Average	4.5 (±5.4)	15%	8.9 (±3.3)	78.7%	10.3 (±5.1)	91.2%

* standard errors in brackets.

Table 4.2: Descriptive analysis of contributions (means and standard errors) and percentage of cases in which the natural resource is recovered.

	Basic Game			Individual provision point mechanism			Collective provision point mechanism		
	Average	First Round	Last Round	Average	First Round	Last Round	Average	N.resource stock	Last Round
Strong-selfish	53.4%	18.8%	75%	4.7%	3.1%	3.1%	9.7%	6.25%	6.3%
Selfish	21.3%	25%	9.4%	4.7%	9.4%	0%	13.1%	6.25%	15.6%
Conservationist	20%	50%	12.5%	85.3%	78.1%	90.6%	60.6%	75%	65.6%
Strong-conservationist	5.3%	6.2%	3.1%	5.3%	9.4%	6.3%	16.9%	12.5%	12.5%

Table 4.3: Percentage of types of agents on average and in first and last rounds.

4.3.2 Individual provision point mechanism results

In this game, the average contribution to project C over the whole sample without distinguishing among rounds is 8.9 points, see table 4.2. Note that contributing exactly 8 points is a focal point where the optimal individual strategy and the minimum strong-sustainable strategy coincide. We calculated round by round the average contribution to project C and we did not find any significant differences between these average contributions and this focal point in 6 out of the 10 rounds, including the last one (see table 4.6 in Appendix 4.7.3). In all rounds the average contribution to project C across groups is slightly above or equal to 8, the minimum strong-sustainable strategy (see Figure 4.4) and, therefore, the natural resource would, on average, be recovered in all rounds.

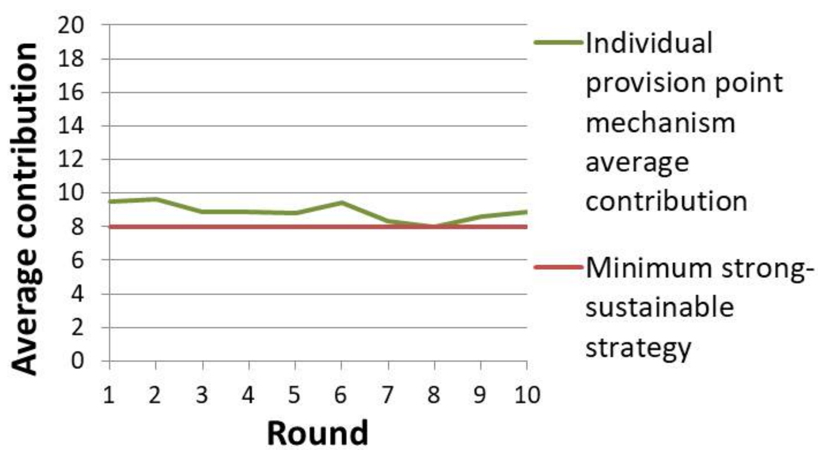


Figure 4.4: Average contributions per round in the individual provision point mechanism.

For a group to recover the resource in round t would require the group average contribution in round t to be equal to or larger than 8 points. We have observed that the group average contribution is larger than 8 in 63.7% of cases, and it is equal to 8 in 15% which, at least, manage to keep the resource stock constant. The percentage of

	Basic Game			Individual provision point mechanism			Collective provision point mechanism		
	Average	First Round	Last Round	Average	First Round	Last Round	Average	First Round	Last Round
Nash equilibrium strategy	35.9%	15.6%	50%	58.8%	40.6%	75%	6.2%	0%	9.4%
Individual optimal strategy							14%	7.1%	15.6%
Group optimal strategy									
Minimum strong-sustainability strategy	4.7%	12.5%	9.4%						
Socially optimal strategy	2.8%	6.3%	3.1%	2.5%	6.3%	0%	9.9%	7.1%	9.4%
Equal average payoff strategy	–	–	–	–	–	–	4.4%	0%	9.4%

* Average percentages in the collective provision point mechanism are obtained from those groups reaching the threshold in a specific round. This represents 91.2% of the sample or, what is the same, 292 cases. In these cases, the average contribution is 10.7 points.

Table 4.4: Percentage of optimal strategies followed by agents on average and in first and last rounds.

groups that are able to recover the resource across the whole sample is 78.7% (see table 4.2). Note also that the percentage of groups that are able to recover the resource in the first round is 87.5%. This is the same as in the last round, although the average contribution in the first round is larger than in the last round.

Observation 6 *The average natural resource is recovered in* 78.7% *of cases when the individual provision point mechanism is applied.*

Further, selfish agents have no incentives to contribute more than 8 points, as this allocation is also the optimal individual strategy; thus, agents contributing above 8 points could be motivated by altruism. The percentage of agents that in a given period t invest in C more than 8 is 31.9%. Moreover, the average contribution in the individual provision mechanism game is 8.9 points, which represents 44.5% of an agent i's investment capacity (which is 20 endowment points). If we assume that 40% of the investment is caused by the incentive (since 8 points represent 40% of the endowement), then we can say that agents only contribute 4.5% out of altruism (up to 8.9 points). Therefore, this percentage is lower than the percentage assigned to altruism, 22.5%, in the basic game.[37]

Observation 7 *Average contribution has a statistically significant difference and is above the optimal individual strategy.*

Analyzing agents' behaviour by group, we see that in all cases the average group contribution decreases, except for groups $2, 3$ and 8 where contributions tend to increase slightly. Nevertheless, the differences in the contribution trends in groups 2, 3 and 8 do not cause high differences in the natural resource preservation level compared with other groups (See Figure 4.11 in Appendix 4.7.4).

[37]Recall that in the basic game we assume all contributions are related to altruistic behaviour.

In addition, we classified agents as strong-selfish, selfish, conservationist and strong-conservationist, as we did in the basic game. In Table 4.3, we represent the percentage of each type of agent across the whole sample in all rounds and in first and last rounds specifically. We observed that only 4.7% of agents are strong-selfish; a similar percentage is selfish. Moreover, 85.3% of the agents have conservationist behaviour. That is, the most frequent type of agent is the conservationist. The percentage of conservationists increases from 78.1% in first round to 90.6% in round 10. Note that since the beginning of the game most agents behave as conservationists, and this percentage increases over time.[38]

Observation 8 *The most frequent type of agents in the individual game is the conservationist agent*

The percentage of times across the whole sample that the individual optimal strategy is followed by an agent i in period t is 58.8%, that is, agents contribute exactly 8 points to project C in 58.8% of cases. This percentage increases from 40.6% in the first round to 75% in the last round. Recall that this strategy coincides with the minimum strong-sustainable strategy (See Table 4.4).

Observation 9 *The most followed strategy is the individual optimal strategy or minimum strong-sustainable strategy.*

[38] See Figure A.9 in Appendix 4.6.3 to see a graphical representation of the evolution of the four types of agents.

4.3.3 Collective provision point mechanism results

We now present the results of applying the collective provision point mechanism. In this game, the optimal solution depends on whether or not threshold $\overline{T}$ is reached. A budget $S_G = 128$ is granted to the community of $n = 4$ agents only if a minimum number of $\overline{T} = 32$ points is invested in project C, that is if $\sum_{i=1}^{n} x_i \geqq 32$. In the individual provision mechanism, agent i receives the subsidy if they have invested $x_i \geq 8$, independently of other agents' behaviour. Now, however, the threshold is collective and being able to enjoy subsidy S_G depends on the investment decision of the other group members. A minimum of 32 points have to be invested in project C by the 4 members of the group for the subsidy S_G to be granted. Note that to enjoy the subsidy, on average, each group member has to contribute 8 points to project C, that is, in this collective provision point mechanism a certain degree of coordination is required to reach the collective threshold. Once S_G is granted, it is distributed among group members proportionally to their contribution to project C.

Our results show that the average individual contribution to project C across the entire sample is 10.3 points (see Table 4.2). This average contribution differs significantly (accordingly to the Wilcoxon test) from both the Nash equilibrium strategy (12 points) and the minimum strong-sustainable or group optimal strategy (8 points) of this game.[39] Recall that if all agents were using the same strategy, this equilibrium will also be the individual optimal strategy, where each agent will maximize their profits. Further, in 91.2% of rounds the threshold is reached and groups manage to sustain the resource.[40] Moreover, this percentage increases to 100% in the last round. Further note

[39]Results for the Wilcoxon test for the Nash equilibrium $V = 14,227$ and $p = 0.000$, and for the minimum strong-sustainable strategy $V = 28,698.5$ and $p = 0.000$.

[40] $\frac{\text{n}^o \text{ of rounds the threshold is reached}}{\text{n}^o \text{ de rounds}} * 100$

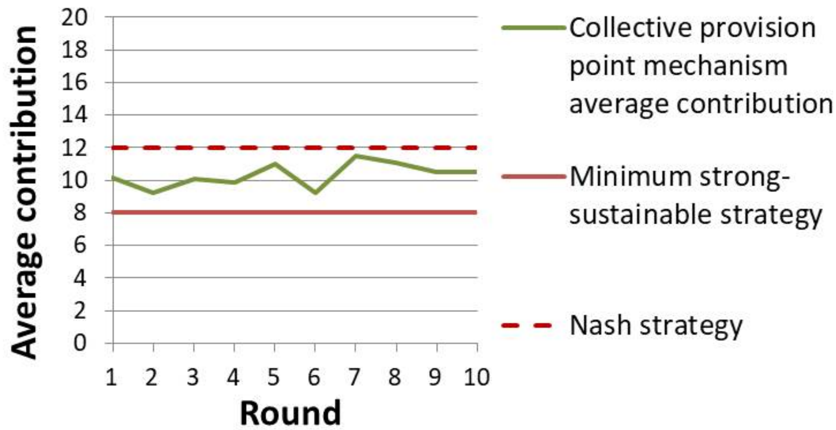


Figure 4.5: Average contributions per round in the collective provision point mechanism.

that the average contribution is always above the minimum strong-sustainable strategy in all rounds (see Figure 4.5) and, therefore, the natural resource stock would be sustainable in all rounds.

Observation 10 *Agents coordinate to reach the threshold.*

Observation 11 *The natural resource is recovered in* 91.2% *of cases.*

In this game, and contrary to what happens in the basic and individual provision point mechanism, the group average contribution tends to increase round after round, except for group 8 where it decreases (see Figure 4.12 in Appendix 4.7.4).[41] The increase rate is often small but systematic; only in group 4 the contribution rate increases strongly (Figure 4.12g). Agents' strategies differ among groups. In some groups, agents follow similar strategies, for example groups 2, 3 and 7. This behaviour starts in the very first rounds and prevails during all rounds for most agents and, therefore, the resource is always recovered (Figures 4.12c, 4.12e and 4.12m). On the other hand, group 4 members contribute a few points to project C in the first rounds but constantly

[41]And in group 2 it is kept constant (Figure 4.12c).

increase their contribution round after round. The natural resource is sustained after the $4th$ round because agents, from that round on, consistently contribute above the individually optimal strategy (see Figure 4.12). Additionally, agents in groups 1, 5, 6 and 8 follow very different strategies; however, they are also able to preserve the natural resource in most of the rounds (see panels a, i, k and o of Figure 4.12). That is, despite the high differences in agents' behaviour, the natural resource is preserved in most rounds, that is, in $91,2\%$ of rounds.[42]

Observation 12 *Despite the high differences in individual strategies, agents tend to coordinate to reach the collective threshold.*

Further, in this collective provision mechanism, only in 9.7% of rounds (across the whole sample) agents behave as strong-selfish and in 13.1% of rounds as selfish (see Table 4.3). On the other hand, in 60.6% of rounds agents follow conservationist behaviour. Therefore, conservationist is the most frequent type of agents' behaviour. Also, only in 16.9% of rounds agents present strong-conservationist behaviour. Although, since the first round, agents tend to the behave as conservationists, this percentage decreases up to the $5th$ round, and from then on it increases again (Figure 4.9 in Appendix 4.7.3). 75% of times, agents behave as conservationists in round 1; this percentage decreases to 46.8% in round 5 and then increases to 65.6% in the last round. The percentage of strong conservationists is the same in the first and last rounds. After being conservationist in the first round, it seems that agents experiment with their contributions and round after round learn that the best strategy is to coordinate and reach the threshold.

Observation 13 *The most frequent type of agents' behaviour in the collective provision point mechanism game is to behave as a conservationist.*

[42] $\frac{\text{n}^o \text{ of rounds the n.resource is preserved}}{\text{n}^o \text{ de rounds}} * 100$

Recall that in this setting optimal and Nash strategies differ depending on whether or not the threshold is reached. The groups reach the threshold in 91.2% of the rounds, that is, they do not reach it in only 8.8% of the rounds.[43]

Observation 14 *In most cases,* 91.2% *of the rounds, the threshold is reached in the collective provision point mechanism experiment.*

Recall that, in this setting, the individual optimal and the Nash strategies differ depending on whether or not the threshold is reached (see Table 4.1). We have calculated the percentage of agents that follow each strategy, taking into account whether or not the threshold was reached. That is, we can see in Table 4.4 that 6.2% of times agents follow the symmetric Nash equilibrium strategy (i.e. contributing 12 points to project C) in cases in which the threshold is reached, which include 91.2% of the rounds of the sample. In the case that the threshold were not reached, agents follow the Nash strategy in 25% of rounds; recall however that only in 8.8% of rounds the threshold is not reached. Also note that in 14% of rounds agents follow the symmetric individual optimal strategy that coincides with the minimum strong-sustainable strategy, and the group optimal strategy, when the threshold is reached. This is the most frequently followed strategy in the whole sample; however, the percentage in which agents follow this strategy is quiet small, 14%. Finally, we expected that the allocation where the average payoff of investing in C equals the average payoff of not investing at all in C could become a focal point; however, it was not since only in 4.4% of cases agents follow this strategy.

Observation 15 *The most frequently followed strategy in the collective provision point mechanism experiment when the threshold is reached is the focal point where the*

[43]Only two groups do not reach the threshold in rounds 2 and 3. And one group in rounds 1, 6 and 8. The average investments in these cases is $5,8$ points. In all the other cases, the threshold is reached.

individual optimal, the group optimal and minimum strong-sustainable strategy coincide.

Our results show that the average individual contribution to project C across all the sample is 10.3 points (see Table 4.2). This average contribution differs significantly (according to the Wilcoxon test) from both the Nash equilibrium strategy (12 points) and the minimum strong-sustainable or group optimal strategy (8 points) of this game.[44] However, 38.8% of the agents' contributions fall between these two numbers.

Furthermore, in this game an agent could be contributing to project C for two reasons, one to recover the resource and the other to obtain the largest possible retribution. If each agent invests 8 points in C, they would sustain the resource (they would reach the minimum strong-sustainable strategy), and they would maximize each agent's individual profits. However, the average individual contribution to project C across the entire sample is 10.3 points which is significantly larger than 8. We believe that several factors can explain this larger than expected contribution. First, conservationist agents that want to assure the protection of the resource can overcontribute to project C to make up for other agents that may undercontribute. Conservationist agents overinvest to assure that the goal is reached. Also, agents that do not care about the resource but want the threshold to be reached can behave similarly, overinvesting in C to make up for other agents that make insufficient contributions to C.[45] Note that, in both cases and independently of the agents' reasons, the setting of the game facilitates the overinvestment in project C; the agency goal to recover the resource is attained more frequently than in the previous settings.

Further, note that for a person who does not want the resource to recover, then a

[44] Results for the Wilcoxon test and for the Nash equilibria $V = 14,227$ and $p = 0.000$, and for the minimum strong-sustainable strategy $V = 28,698.5$ and $p = 0.000$.

[45] In both cases this behaviour can be due to some type of risk aversion.

possible strategy is to assure that the threshold is not reached, and thus to invest x_i in C. An investment $0 < x_i < 8$ has some doubts about the outcome of the game and does not want to be left out of the gains to be earned if the threshold is reached. Investing few points in C allows the earnings to be increased if the threshold is reached but it has a cost, the earnings lost if finally the threshold is not reached. If the threshold were not reached and that agent had invested $x_i = 0$, they would have earned 60 points; therefore, any gain below this implies some loss for the agent. Furthermore, contributing less than 8 makes no sense if the agent has a taste for nature and cares about the sustainability of the natural resource, $x_i = 8$ is the individual optimal strategy and there is no point in trying to free ride and expect others to contribute a number of points larger than 8 because, if the threshold is reached, they would earn less than they would have earned if they had invested $x_i = 8$.

4.4 Games comparison

Let us now compare the three settings. One of our main hypotheses is that the collective provision mechanism is more reliable in assuring the sustainability of the natural resource than the basic and the individual provision mechanisms, that is, we expect contributions to project C to be larger with this mechanism than in both basic and individual provision mechanisms. We first compared the games by pairs and we observed that the difference in the average contribution to project C between basic and individual provision point mechanisms is statistically significant ($W = 79,837.5$, $p = 0.000$ according to Mann–Whitney–U test). Further, we also found statistically significant differences between the average contributions in the basic game and in the collective provision point mechanisms ($W = 81,471$, $p < 0.000$, Mann–Whitney–U test) and also between the average contributions in the individual provision point mechanism and in the collective provision point mechanism ($W = 39,751.5$, $p < 0.000$, Mann–Whitney–U test). Further, it is easy to see in Figure 6a that the average contribution to project C in the collective provision point mechanism is the largest of the three games, followed by the average contribution of the individual provision mechanism and, finally, the average contribution of the basic game.

Additionally, we use the Kruskal–Wallis to test whether the results obtained from the three games present a different underlying distribution. Our results show that these differences are statistically significant ($\chi^2_{df=2} = 228.87$ and $p < 0.000$), we can reject the null and accept that at least one of the games presents a different underlying distribution. Further, we apply the Jonckheere test for ordered alternatives that is similar to the Kruskal–Wallis test but allows the ordering of the populations from which the samples are obtained to be taken into account. We can accept our hypothesis that the experiment with higher contributions is the collective provision point mechanism, followed by the individual provision point mechanism and the basic game ($JT = 83,243$ and $p = 1$).

Therefore, we accept the hypothesis that the average contributions to project C differ among the three games and that the collective provision point mechanism presents the largest contributions among the three mechanisms considered. In fact, it is larger than the individual provision point mechanism which, in turn, is also larger than that obtained from the basic game. This also means that the game with higher natural resource recovery levels is the collective provision point mechanism (Fig 4.6). Introducing this coordination game increases the chances of resource sustainability. Further, note that although in the three settings agents contribute to the natural resource, only agents under the individual and the collective provision point mechanisms reach the

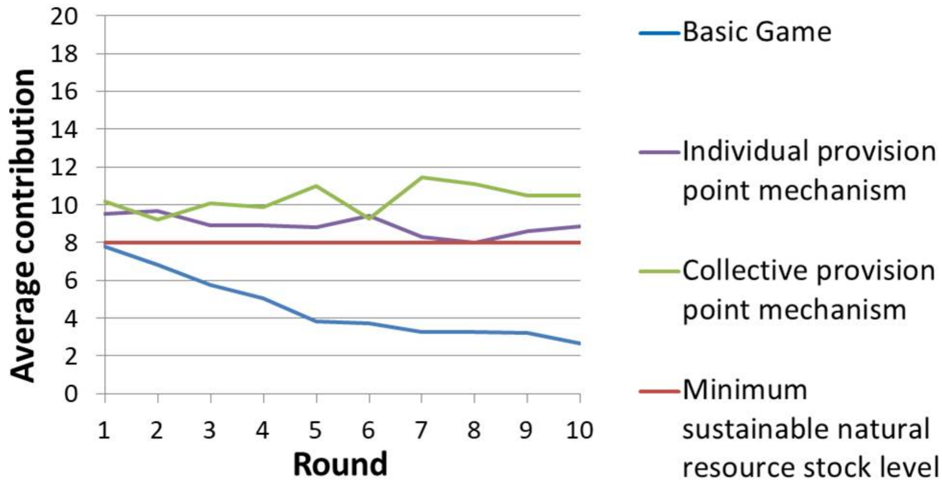


Figure 4.6: Average contribution per round.

sustainble stock level often.

Observation 16 *The average contributions to project C are larger when subjects participate in a collective provision point mechanism game. In particular, the average investment in project C is larger than the average investment in the individual provision point mechanisms, which in turn is larger than average contributions in the basic game.*

Observation 17 *The investment decision of agents that participated in a collective provision point mechanism allows the natural resource to be sustainable in* 91.2% *of the cases, which is more often than the individual provision mechanism which does so in* 78.7% *of the cases. The basic game only allows the recovery of the resource in* 15% *of the cases. Therefore, under the same budget, the collective provision point mechanism allows the natural resource to be recovered more often than the individual provision point mechanism.*

We also compare the collective provision point mechanism with other similar experiments from the existing literature. To do this comparison we consider the Step Return

(SR) indicator, developed by Croson and Marks (2000) and defined as the aggregate group payoff from the contributions to project C divided by the agents total contribution to project C. Under our setting, SR range from 5 to 2.6.[46] As our results show, the collective mechanism is successful in 91.2% of cases. Croson and Marks (2000) performed a threshold public good experiment in which agents can choose to contribute any part of a private endowment towards the provision of a public good. The public good was provided if agents coordinate and reach a threshold (that was to invest 45% of the endowment in the public good); then agents received a constant extra amount. On the contrary, if the threshold were not reached, contributions were returned to agents. Three cases were analyzed, $SR = 1.2$, $SR = 2$ and $SR = 3$, and the public good was provided in 33%, 69% and 63% of cases, respectively. Even though our collective mechanism reaches a larger rate of resource recovery we have to take in to account that our SR is larger than in the Croson and Marks experiments. In addition, Suleiman and Rapoport (1992) reached a maximum contribution success rate of 85% when $SR = 5$, still our rate of success is larger. Therefore, comparing our results with these literature, we see that our collective provision point mechanism presents a higher percentage of success. This could be caused, among other reasons, by the efficient Nash equilibrium allocation.[47]

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[46]Note that $SR = \frac{\text{aggregate group payoff from contributions to C}}{\text{total contribution in C}} = \frac{n \cdot \left(1 + \frac{128}{\frac{n}{\sum_{i=1}^{n} x_i}}\right) x_i}{\sum_{i=1}^{n} x_i}$; therefore, if the threshold is reached that is $\sum_{i=1}^{n} x_i = 32$ then $SR = 5$ and if contributions are the maximum possible then $\sum_{i=1}^{n} x_i = 80$ and $SR = 2.6$.

[47]In Croson and Marks, 2000 the SR is constant; however, in our experiment the SR is decreasing once the threshold has been reached. Recall that the agents contribution at the Nash equilibrium is larger than the agents contribution at the Optimal Individual strategy. As the contribution level increases, the extra payoff received by an agent decreases.

4.5 The role of agents' characteristics in investment decisions: A regression analysis

Finally, we use regression analysis to isolate the effect of agents' personal characteristics in the investment decisions. We consider two groups of characteristics, a first group that included the straightforward features of agents, such as gender, education and age, among others, and a second group that comprises behavioural traits of agents, such as attitudes towards recycling, concern for the environment and behavioural responses to other agents' investment strategies.

We use a regression analysis in which our dependent variable, x_{ikt}, represents the quantity contributed to project C by individual i of group k during round t and where our independent variables represent agents' characteristics. At the end of the game, each subject had to answer a questionnaire in which the agent had to state their personal characteristics and answer questions that allow their behavioural traits to be estimated. For example, questions were asked about the agent's recycling behaviour or their knowledge about climate change.[48]

We do not have a clear hypothesis about the role of gender in the propensity to invest in project C; studies present contradictory results. For example, Solow and Kirkwood (2002) reported cases where males tend to cooperate more than females. On the other hand, Nowell and Trinkler (1993) estimate than females present a more cooperative behaviour than males. There are even studies supporting the idea that females and males cooperate to the same degree (Cadsby and Maynes, 1998). We conducted this test to clarify the role of gender in our results. To carry out our test we defined

[48]The complete text of the questionaire can be found in Appendix 4.7.5

dummy variable $DGen_i$ that takes value 1 when agent i is female and 0 otherwise. Furthermore, we expected agents with economic knowledge to be more familiar with this type of games and, therefore, more likely to behave strategically and to follow more economically oriented strategies. Some studies have shown that economists tend to free ride more than others agents, *i.e.*, Carter and Irons (1991) and Gerlach (2017). Therefore, we also singled out agents that have studied or are studying economic science from the rest of participants. We define the variable $DEcon_i$ that takes value 1 when agent i has studied or is studying economics and 0 otherwise. Similarly, we identified those agents coming from families with a farming background. Farmers are more used to environmental subsidies than other professionals. Also, we expect agents with such a background to have a broader knowledge of this type of policy mechanism than other agents and that this expertise could lead to different behaviour. Moreover, it has also been reported that farmers are more risk averse than other agents (see, for example, Sulewski and Kloczko-Gajewskaulewski, 2014). Therefore, to clarify these differences we define dummy variable $DAgri_i$ that takes value 1 when agent i indicates that their family has a direct relation with a farming activity and 0 otherwise. This allowed us to test whether agents from families with a farming background behave in a significantly different manner to others. We further ask for agents' age and we identify it in variable Age_i. There is evidence that older agents contribute more than young (List, 2004). Although we only have a 10-year age range, our hypothesis is that contributions are larger in older agents. We included this set of variables in our estimated regressions but the only variable that was significant in most regressions was $DGen_i$; therefore, we dropped the rest of variables. The variable $DGen_i$ was always positive and often significant in most regressions, meaning that females tend to invest more in project C than males.

Our agents participated in three different games; to isolate any systematic game characteristics we defined a set of three dummy variables to distinguish and compare the behaviour of agents across games. Variable $DBas_i$ takes value 1 when agent i has participated in the basic game and zero otherwise. Similarly, variable $DInd_i$ takes value 1 when agent i has participated in the individual provision point mechanism and zero otherwise and, finally, $DColl_i$ takes value 1 when agent i has participated in the collective provision point mechanism and zero otherwise. The estimated coefficients of these variables allow us to distinguish the investment in project C among games. We have estimated our models introducing variables $DBas_i$ and $DInd_i$, that is, choosing as a reference group the data from the collective provision point mechanism. In all regressions these two variables were negative and significant, showing that the agents that participated in the collective provision point mechanism games invest a larger amount in project C than the agents that participated in the basic and individual provision point mechanism games. Furthermore, the absolute value of the parameter of variable $DInd_i$ was larger than the parameter of variable $DBas_i$ showing that the investment in project C was the lowest in the case of the basic game.

At the end of the session, agents were asked several questions that allowed us to measure the agents' degree of both environmental knowledge and of environmental awareness. Variable $DKnow_i$ indicates the degree of agent i's knowledge about environmental problems. Agents were asked four questions about the environment and a point was assigned for each correct answer.[49] The variable $DKnow_i$ is the sum of the correct answers of agent i, variable $DKnow_i$ takes integer values between 0 and 4, where 0 represents the case of the lowest level of environmental knowledge (no correct answer was given by agent i) and 4 the highest (when agent i answered all four environmental

[49]See the questionnaire in Appendix 4.7.5.

questions correctly). Similarly, the variable $DAware_i$ indicates the degree of agent i's awareness of current environmental problems. Agents were asked four questions about their engagement in environment protection actions (such as recycling) and a point was assigned for each positive answer.[50] The variable $DAware_i$ is the sum of the positive answers of agent i. Variable $DAware_i$ takes integer values between 0 and 4, where 0 represents the case of the lowest level of environmental engagement (agent i does not engage or participate in any environmental protection action) and 4 the highest (when agent i has engaged in all listed actions). This variable takes integer values between 0 and 4, where 0 represents the lowest level of environmental awareness and 4 the highest. Moreover, we expect that the more knowledgeable a person is about existing environmental problems, the more willing to contribute to project C they will be. Similarly, we also expect that the more aware a person is about current environmental problems, both global and local, the more likeky to contribute to project C they would be. Therefore, we expect the estimated coefficients of both variables to be positive and significant. We included both variables in our models. Variable $DKnow_i$ was consistently non-significant in all estimated models; on the contrary, variable $DAware_i$ was positive and significant in all estimated models, meaning that people that engage in environmental protection initiatives tend to invest more in project C than other agents.

Finally, in order to investigate whether appropriation is affected by time evolution, we included a set of dummies that identified the round number in which the investment decision was taken. We define these variables as $DPeriod_s$ so that $DPeriod_s = 1$ if $s = t$ and zero otherwise. These variables allow us to test whether investment in one round significantly differed from that in any other period.

Furthermore, we wanted to test whether a variation in the resource stock in round

[50]See the questionnaire in Appendix 4.7.5.

$t-1$ had an effect on agents' strategies in round t. In each round, the resource stock could increase or decrease, and at the end of each round agents were informed about the resource stock level attained after all agents had made their decisions. Therefore, this information allowed us to test whether the agent's investment decision in x_{ikt} was related to changes in the resources stock in period $(t-1)$. We create two variables, first, variable $RIncrease_{ik(t-1)}$ to capture the effect of an increase in the resource stock at the end of period $(t-1)$. We defined as $RIncrease_{ik(t-1)} = (c+b)\sum_{i=1}^{n} x_{ik(t-1)} - cne$ whenever $(c+b)\sum_{i=1}^{n} x_{ik(t-1)} > cne$ and 0 otherwise. Where $x_{ik(t-1)}$ represents the investment decision of all agents belonging to community k during period $(t-1)$. If the regression coefficient of this variable is positive and significant, it will imply that an increase in the resource stock size in round $(t-1)$ is followed by an increase in the investment decisions in round t. That is, an increase in $RIncrease_{ik(t-1)}$ is followed by an increase in x_{ikt}. Agents' behaviour will tend to support the increase in resource stock size in the previous round. If the regression coefficient of this variable is negative and significant, it would imply that an increase in the resource stock is followed by a decrease in the investment in project C. That is, an increase in $RIncrease_{ik(t-1)}$ is followed by a decrease in x_{it}. Agents' behaviour will tend to erode the increase in resource stock size in the previous round. The estimated coefficients of this variable were positive and significant in the basic game, in the individual and collective game were non-significant.

Similarly, we define $RDecrease_{ik(t-1)}$ as the variable that captures the negative variation in the natural resource stock. It measures the decrease in the resource stock during round $(t-1)$. It is equal to $RDecrease_{ik(t-1)} = \left| cne - (c+b)\sum_{i=1}^{n} x_{ik(t-1)} \right|$ whenever $cne > (c+b)\sum_{i=1}^{n} x_{ik(t-1)}$ and 0 otherwise. If the regression coefficient of this variable is positive and significant, this would mean that a reduction in the resource in round $(t-1)$ is followed by an increase in the investment in project C in round t. Agents' behaviour will tend to counterbalance the decrease in resource stock size in the previous round. A reduction in the resource stock size could be offset by an increase in the investment decisions in the following round. However, if the regression coefficient of this variable is negative and significant, it would mean that a reduction in the resource in round $(t-1)$ is followed by a decrease in the investment in project C in round t. Agents' behaviour will tend to keep eroding and exacerbate the reduction in resource stock. The estimated coefficients of this variable were negative and significant in the basic game, in the other games were non-significant.

On the other hand, we introduce another set of explanatory variables to capture the influence of other agents' investments on agent i's decisions. When agent i from group k takes their investment decision in period t, they are aware of the average contribution of their group companions in period $(t-1)$. We distinguish between two types of agents, low and high contributors. First, if agent i in period $(t-1)$ has contributed less than the average of their group k, then agent i is a low contributor $(LC_{ik(t-1)})$. That is, if the difference $\left(x_{ik(t-1)} - \overline{x}_{k(t-1)}\right) < 0$ then agent i in period $(t-1)$ is a low contributor. We define variable low contributor as $LC_{ik(t-1)} = \left|\left(x_{ik(t-1)} - \overline{x}_{k(t-1)}\right)\right|$ whenever $\left(x_{ik(t-1)} - \overline{x}_{k(t-1)}\right) < 0$ and 0 otherwise. This variable captures the behaviour of agents who in a given round contributed below the average of their group. If the regression coefficient of this variable is positive and significant, this would mean that a lower than the mean investment in period $(t-1)$ is followed by an increase in the investment in project C in round t. Agents tend to counterbalance their behaviour in the previous round. If the regression coefficient of this variable is negative and significant, this would mean that a lower than the mean investment in period $(t-1)$ is followed by a decrease in the investment in project C in round t. Agents tend to keep underinvesting in project C. And, second, if agent i in period $(t-1)$ has contributed more than the average of their group k, then agent i is a high contributor $(HC_{ik(t-1)})$. That is, if the difference $\left(x_{ik(t-1)} - \overline{x}_{k(t-1)}\right) > 0$ then agent i in period $(t-1)$ was a high contributor. We define variable high contributor as $HC_{ikt} = \left(x_{ik(t-1)} - \overline{x}_{k(t-1)}\right)$ whenever $\left(x_{ik(t-1)} - \overline{x}_{k(t-1)}\right) > 0$ and 0 otherwise. This variable captures the behaviour of agents in round $(t-1)$. If the regression coefficient of this variable is positive and significant, this would mean that a high contribution in period $(t-1)$ is followed by an increase in the investment in project C in round t. If the regression coefficient of this variable is negative and significant, this would mean that a high contribution in period $(t-1)$ is followed by a decrease in contributions in project C in round t. Agents' behaviour will tend to counterbalance their behaviour in the previous round. Our regression analysis are summarized in Tables 4.5 and 4.6.

The regression analysis results show that variables $DBas_i$ $DInd_i$ are negative and significant, that is, the average investment in project C is significantly lower in the basic game and in the individual provision point mechanism game than in the collective provision point mechanism game (see estimated coefficients of variables $DBas_i$ $DInd_i$ in Table 4.5 and 4.6).

Furthermore, the variable $DGen_i$ is clearly significant and positive in the basic game but neither in the individual provision nor in the collective provision mechanism. In these games, the variable $DGen_i$ is clearly non-significant. Something similar ocurrs with the variable $DAware_i$ which is clearly significant and positive in the basic game but not in the others.

Therefore, in the basic game females and those environmentally aware agents tend to contribute in a larger proportion than others, that is they are more altruistic. Nevertheless, in the individual provision point mechanism, agents' characteristics could be

Estimate				
	(a)	(b)	(c)	(d)
$DBas_i$	-3.289 (0.000)***	–	–	–
$DInd_i$	-0.907 (0.008)**	–	–	–
$DGen_i$	0.461 (0.099)*	1.428 (0.011)**	0.146 (0.701)	-0.188 (0.767)
$DAware_i$	0.478 (0.009)**	0.678 (0.067)*	0.305 (0.355)	0.332 (0.192)
$RIncrease_{ik(t-1)}$	0.021 (0.097)*	0.073 (0.005)**	-0.010 (0.671)	0.010 (0.571)
$RDecrease_{ik(t-1)}$	-0.065 (0.000)***	-0.074 (0.000)***	-0.031 (0.444)	-0.039 (0.447)
$HC_{ik(t-1)}$	0.580 (0.000)***	0.362 (0.010)**	0.442 (0.001)*	0.842 (0.000)***
$LC_{ik(t-1)}$	-0.383 (0.000)***	-0.661 (0.000)***	2.272 (0.085)*	-0.354 (0.020)***
_cons	8.263 (0.000)***	4.886 (0.002)**	7.607 (0.000)***	8.709 (0.000)***
R^2	0.4660	0.4712	0.0712	0.3276
N	864	288	288	288

* Significance codes *** 1per cent level **5per cent level and *10 per cent level.
* p-values in brackets.
* (a) All games (b) Basic game (c) Individual provision point mechanism (d) Collective provision point mechansim

Table 4.5: Robust regression analysis.

banished because there is a clear focal point where both the natural resource protection goal and the largest payoff are reached. Further, in the collective provision point mechanism there is not a focal point but a coordination problem, and thus agents could be more focused on coordinating than on other reasons for contributing, such as altruism.

Observation 18 *Women contribute more than men in the basic game.*

Further, with a significance at the 5-per cent level, there is a positive correlation between agents with environmental awareness and contributions to the natural resource

	Estimate							
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
$DBas_i$	−5.852 (0.000)***	−3.133 (0.000)***						
$DInd_i$	−0.944 (0.007)**	−0.958 (0.014)*						
$DGen_i$	0.481 (0.119)	0.906 (0.006)**	2.212 (0.000)***	3.237 (0.000)***	0.140 (0.710)	0.198 (0.610)	−0.187 (0.764)	−1.041 (0.157)
$DAware_i$	0.632 (0.000)***	0.745 (0.000)***	1.309 (0.000)***	1.117 (0.003)**	0.316 (0.285)	0.254 (0.408)	0.344 (0.253)	1.045 (0.003)**
$RIncrease_{ik(t-1)}$		0.022 (0.027)*		0.078 (0.000)***		0.016 (0.329)		0.020 (0.217)
$RDecrease_{ik(t-1)}$		−0.068 (0.000)***		−0.061 (0.000)***		0.008 (0.843)		−0.025 (0.509)
$HC_{ik(t-1)}$	0.725 (0.000)***		0.732 (0.000)***		0.418 (0.000)***		0.852 (0.000)***	
$LC_{ik(t-1)}$	−0.196 (0.003)**		0.000 (0.996)		0.241 (0.040)*		−0.343 (0.001)**	
_const	7.746 (0.000)***	7.731 (0.000)***	−0.803 (0.356)	1.918 (0.029)*	7.456 (0.000)***	8.022 (0.000)***	8.833 (0.000)***	8.413 (0.000)***
R^2	0.4148	0.329	0.3029	0.3423	0.05588	−0.005738	0.3107	0.02701
N	864	864	288	288	288	288	288	288

* Significance codes *** 1per cent level **5per cent level and *10 per cent level.

* p-values in brackets.

* (a) and (b) All games, (c) and (d) Basic game, (e) and (f) Individual provision point mechanism (g) and (h) Collective provision point mechansim.

Table 4.6: Other robust regression analysis.

preservation, that is agents that have some environmental conscience tend to contribute more than those that do not.

Observation 19 *Agents with some kind of environmental awareness contribute more than those without in the basic game.*

Additionally, the variables $RIncrease_{ik(t-1)}$ and $RDecrease_{ik(t-1)}$ also present a similar pattern to the variables presented above. These variables are significant in the basic game but neither in the individual nor in the colective provision mechanism game. That is, $RIncrease_{ik(t-1)}$ is positive and significant in the basic game, meaning that an increase in the resource stock size in round $(t-1)$ is followed by an increase in the investments in project C in round t. Also, $RDecrease_{ik(t-1)}$ is negative and significant in the basic game, meaning that a reduction in the resource in round $(t-1)$ is followed by a decrease in the investment in project C in round t. That is, both in the case of an increase in the resource stock and in the case of a decrease in the resource stock, agents tend to support the directon of the variation in the resource stock size. Agents do not tend to counterbalance previous rounds' behaviour.

Observation 20 *Agents behavior will tend to support the variation in the natural resource stock size in the previous round.*

Finally, this is a repeated game and we can also test whether agents adapt their behaviour to other agents' behaviour. The only pair of variables that are consistently significant in the three games are $HC_{ik(t-1)}$ and $LC_{ik(t-1)}$. The variable $HC_{ik(t-1)}$ is positive and significant in the three games, meaning that if an agent was a high contributor in period $(t-1)$, it keeps behaving as such in round t. On the other hand, variable $LC_{ik(t-1)}$ is negative and significant in the basic and the collective mechanism game, but is positive but hardly significant in the individual mechanism game. In fact, the only explanatory variable that is clearly significant in the individual game is $HC_{ik(t-1)}$ and the overall explanatory power of our regressions is very small in this game. This is contrary to what occurs in the basic and collective mechanism games, where the explanatory power of our regressions is high with $R^2 = 0.4712$ in the basic game and $R^2 = 0.3276$ in the collective mechanism game. One reason could be that there is a clear focus point $x_{ikt} = 8$ and agents follow this strategy independently of their characteristics.

Observation 21 *Agents tend to imitate other agents' strategies in all games.*

4.6 Conclusions

The collective provision point mechanism is successful in recovering the resource in 91.3% of cases. This is a large success percentage compared with the individual provision point mechanism and with the basic game. It also represents a large success if we compare it with other threshold public good experiments from the existing literature (see the Croson and Marks (2000) literature review). We think this larger success could be motivated by the efficient Nash equilibrium allocation. If a group reaches the threshold allocation, each of the agents could be willing to increase their investment in C because on increasing in it they could obtain, ceteris paribus, a larger payoff. In addition, risk aversion attitudes can play a role in reaching the efficient Nash equilibrium allocation. For example, those agents with some kind of risk aversion will contribute above the threshold to assure the threshold is reached to counterbalance other agents' low contributions. Also, agents could overinvest in C for altruistic reasons and not necessarily in risk averse situations.

All these factors affecting agents' decision-making process should be isolated. A topic for future research could go in this direction, to try to differentiate overinvestment for risk averse or altruistic reasons. We could run the same collective provision mechanism game but without introducing the natural resource framework. Moreover, another alternative would be to introduce a risk aversion measurement method before the experiment is run. There are several methods to measure risk preference of individuals (See Charness *et al.,* 2013). On doing this, we could determinate how individual risk preferences affect contribution levels. Further, recall that our results seem to indicate that agents tend toward the Nash equilibrium round after round; therefore, if this were the case, that would mean that agents tend toward the efficient Nash equilibrium independently of where the threshold is located. It also could be interesting to analyze the effect of different levels of SR in the individual and the collective game on the natural resource provision's success.

In addition, other hypotheses can arise. In the basic game, as we have already said, agents could invest in project C due to some altruistic type of behaviour. However, if we introduce a rewarding mechanism, agents would have not only altruistic reasons to preserve the environment but also an economic motivation, which is the incentive. Cases have been reported in which contributions decrease after an incentive is introduced; this phenomenon is consistent with Frey's (1997) crowding theory (Frey, 1997 and Frey and Oberholzer-Gee, 1997), which argues that although external incentives increase the economic reasons to contribute, they can reduce altruist motivations. That is, economic incentives can destroy agents' trust in the recipient or can change agents' individual decision from a social frame to an economic frame.[51] However, other ap-

[51]For a further explanation, see Deci, (1975); Fehr and Falk (2002), Heyman and Ariely, (2004) and Falk and Kosfeld, (2006).

proaches, such as Andreoni's impure altruism models,[52] would predict that the added incentive should not affect the contributions of pro-social behaviour in large economies, that is the so-called "warm glow of giving" (Andreoni, 1990). Also, the basic game is the simplest of the three games and, therefore, it is much easier for the players of this game to identify the different strategies. It could also be the case that there were more conservative agents playing in the basic game. Moreover, in the individual provision point mechanism, agents could feel that they are contributing enough to the threshold individually, because the natural resource would be protected and additional voluntary donations would not be necessary. However, in the basic game voluntary donations are necessary to protect the resource. The effect of incentives on alturistic motivations to contribute could be better analyzed if a basic game with a constant subsidy (without threshold) were considered.[53]

Finally, note that what determines the sustainability of the natural resource is the intrinsic natural resource characteristics. In the individual provision point mechanism, if the threshold was located at a point where contributions were not enough to assure the natural resource's sustainability, the incentive would be a waste of economic resources. A focal point has the advantage that it is easy for the agency to design but it can go against natural resource recovery if it is fixed below the minimum strong-sustainable point. Contrarily, we could also be wasting economic resources if voluntary donations were enough to assure the natural resource conservation but an incentive was introduced. Therefore, knowing the natural resource characteristics is an important factor on designing natural resource preservation policies. According to our parameterization, the natural resource is recovered if contributions reach 40%, that is

[52] Givers are not only motivated by the interest in welfare of the recipient, which is pure altruism, but also by their own welfare in the act of giving. That is impure altruism (Andreoni (1989).

[53] Note that if we call this incentive ϕ, it must satisify $\omega > \alpha + \phi$ and different results could be obtained depending on ϕ level.

an individual contribution of 8 points. It could be interesting to apply the basic game and the individual provision point mechanism with natural resources that recover with different contribution levels, such as, for example, a natural resource able to recover with contribution efforts below 22.5%, which is the alltrusim level reached in the basic game.

4.7 Appendix

4.7.1 Another possible experimental design and procedure

Individual provision point mechanism

In the individual provision point mechanism, if $(\omega - \alpha)\,\bar{t} = \kappa$ to invest $x_i = \bar{t}$ points in project C and $(e - x_i) = (e - \bar{t})$ in project D is an individual Nash Equilibrium, then the best individual strategy would be $x_i = \bar{t}\ \forall i$. This equilibrium grants agent i the same individual benefits as the full non-conservationist equilibrium, and $x_i = 0$ is also the best individual strategy (See points I_1 and I_2 in Figure 4.7a). If $(\omega - \alpha)\bar{t} > \kappa$, the best strategy for any agent i is always to invest their whole endowment in project D, that is $x_i = 0$, regardless of whether the threshold was reached. In this case, $x_i = 0$ is always an individual Nash Equilibrium (See point I in Figure 4.7b).

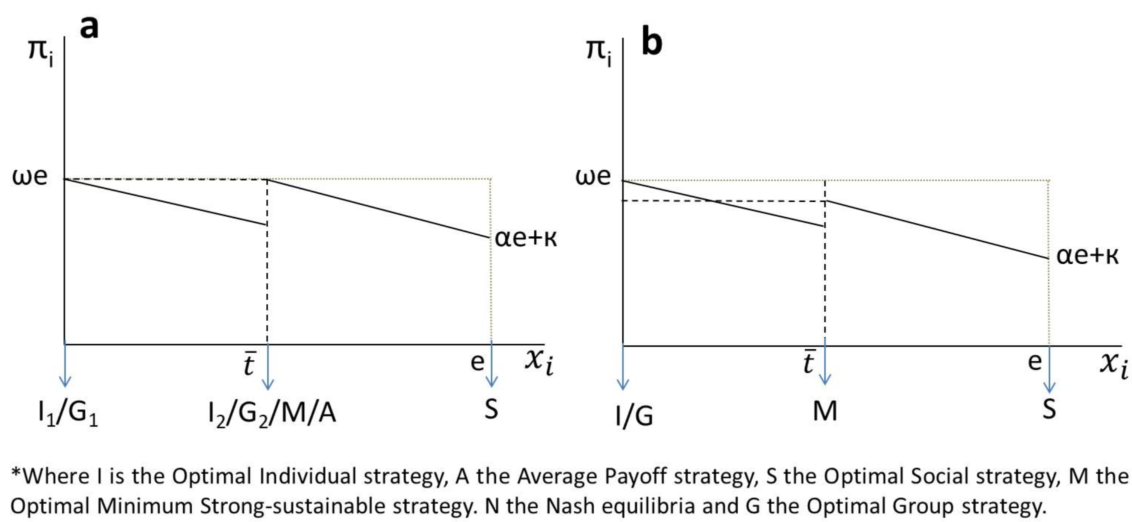

Figure 4.7: Another individual provision point mechanism. Average payoff (AP)

Collective provision point mechanism

In the collective provision point mechanism, four other situations are possible. First, a case where $\overline{T}\,(\omega-\alpha) > S_G$ (Figure 4.8a) and a case where $\overline{T}\,(\omega-\alpha) = S_G$ (Figure 4.8b). Note in Figures 4.8a and 4.8b that, once the threshold is reached, the group/individual optimal strategy and the Nash equilibrium are located at $\sum_{i=1}^{n} x_i = T$.[54] On the contrary, if the threshold is not reached, the Nash and the group/individual optimal are both located at $\sum_{i=1}^{n} x_i = 0$. Moreover, if $\overline{T}\,(\omega-\alpha) < S_G$ and there is a point such as $\sum_{i=1}^{n} x_i^* = \sum_{i=1}^{n} x_i^m = \overline{T}$ where it holds that $\omega = \alpha + \frac{S_G}{\sum_{i=1}^{n} x_i^m}\left(1 - \frac{x_i^m}{\sum_{i=1}^{n} x_i^m}\right)$ then this point is also both a group/individual optimal strategy and a Nash equilibrium (See Figure 4.8c). At this point, no agent will have incentives to increase or decrease their investment in C. Note that all these cases (Figures 4.8a, 4.8b and 4.8c) represent a situation where the Nash is exactly located on the threshold, as occurs with the majority of threshold public good experiments. Finally, the fourth case is when $\overline{T}\,(\omega-\alpha) < S_G$

[54] Assuming symmetry.

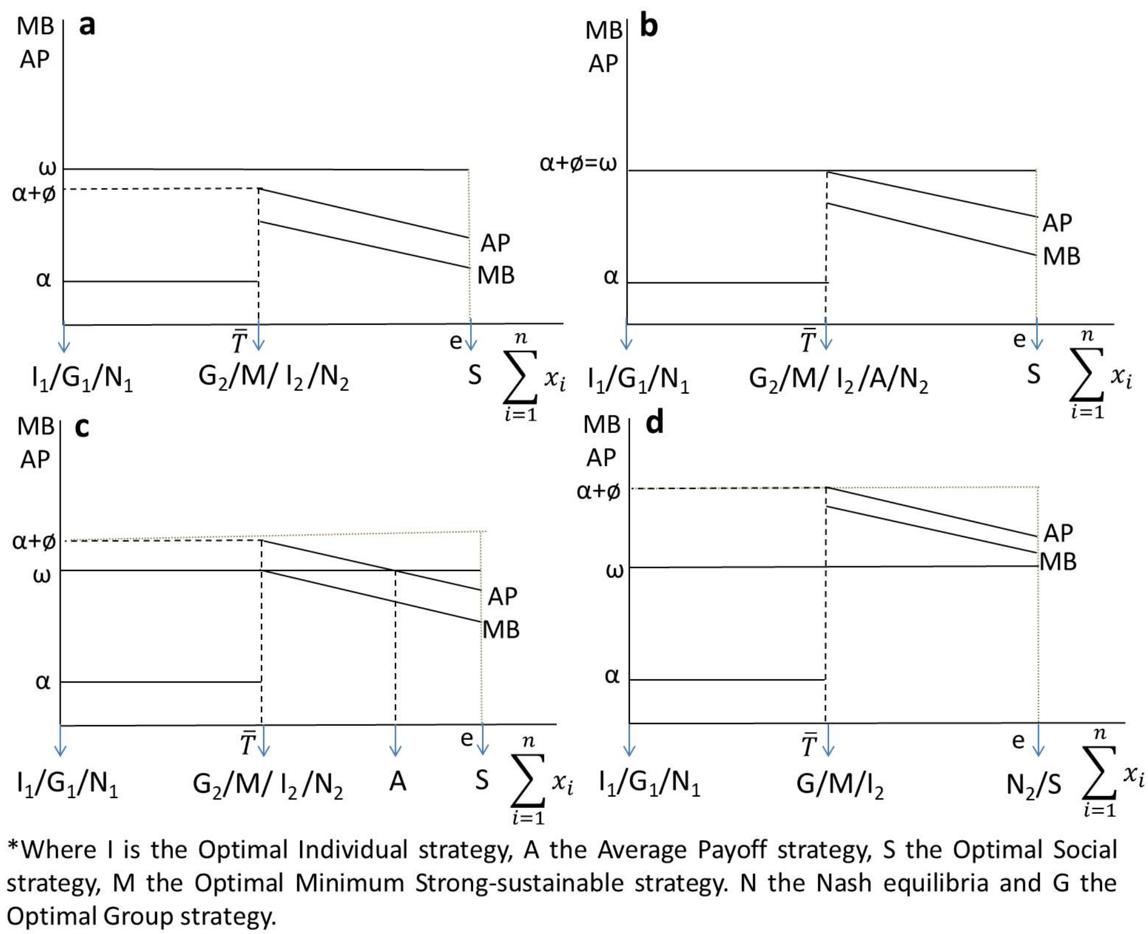

Figure 4.8: Another collective provision point mechanism. Average Payoff (AP) and Marginal net Benefits (MB).

and there is not any point where $\omega = \alpha + \frac{S_G}{\sum_{i=1}^{n} x_i^m}\left(1 - \frac{x_i^m}{\sum_{i=1}^{n} x_i^m}\right)$ for any $\sum_{i=1}^{n} x_i$. In this case, the Group/Individual optimal strategy will be $\sum_{i=1}^{n} x_i. = T$; however, the Nash optimal strategy will be $\sum_{i=1}^{n} x_i. = ne$ (See Figure 4.8d).

4.7.2 Agents' behaviour assuming symmetry

A rational subject maximizes their individual payoff function represented by equation $\pi_i = \omega\left(e - x_i\right) + \alpha x_i + \frac{S_G}{\sum\limits_{i=1}^{n} x_i} x_i$ when the threshold is reached. The first order condition is

$$\frac{\partial \pi_i}{\partial x_i} = -\omega + \alpha - \frac{S_G}{\sum\limits_{i=1}^{n} x_i}\left[\frac{x_i}{\sum\limits_{i=1}^{n} x_i} - 1\right] = 0$$

Note that this is the maximization function for one agent. Nevertheless, we have n agents and, therefore, a system with n equations and n unknown that need to be solved simultaneously. Solving this system could be quiet challenging. Assuming symmetry, we can represent the maximization function as;

$$\frac{\partial \pi_i}{\partial x_i} = -\omega + \alpha - \frac{S_G}{n x_i}\left[\frac{1}{n} - 1\right] = 0$$

Solving this equation we obtain

$$\begin{aligned}
\frac{\partial \pi_i}{\partial x_i} &= -\omega + \alpha - \frac{S_G}{n x_i}\left[\frac{1}{n} - 1\right] = 0 \\
\frac{\partial \pi_i}{\partial x_i} &= -\omega + \alpha - \frac{S_G}{n^2 x_i} + \frac{S_G}{n x_i} = 0 \\
\frac{\partial \pi_i}{\partial x_i} &= n^2 x_i\left(-\omega + \alpha\right) - \frac{S_G n^2 x_i}{n^2 x_i} + \frac{S_G n^2 x_i}{n x_i} = 0 \\
\frac{\partial \pi_i}{\partial x_i} &= n^2 x_i\left(-\omega + \alpha\right) - S_G + S_G n = 0 \\
n x_i &= \frac{S_G}{(-\omega + \alpha)}\left(\frac{1}{n} - 1\right) \\
n x_i &= \frac{S_G}{(\omega - \alpha)}\left(1 - \frac{1}{n}\right)
\end{aligned}$$

Therefore, we have a unique solution such that $\sum\limits_{i=1}^{n} x_i = x_i = \frac{S_G}{n(\omega - \alpha)}\left(1 - \frac{1}{n}\right)$, that is

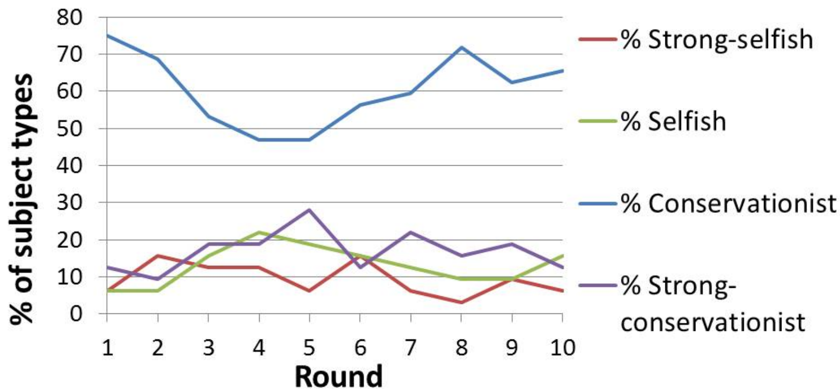

Figure 4.9: Percentage of agent types per round in the basic game (a), in the individual provision point mechanism (b) and in the collective provision point mechanism (c)

the symmetric Nash equilibrium investment.

4.7.3 Complementary results information

		Round 1	Round 2	Round 3	Round 4	Round 5	Round 6	Round 7	Round 8	Round 9	Round 10
Basic Game	Average contribution	7.8	6.8	5.8	5	3.8	3.7	3.3	3.3	3.2	2.6
	Wilcoxon test. The null hypothesis is that average contribution is equal to zero	$V = 378$ (0.000)	$V = 276$ (0.000)	$V = 276$ (0.000)	$V = 253$ (0.000)	$V = 253$ (0.000)	$V = 190$ (0.000)	$V = 190$ (0.000)	$V = 153$ (0.000)	$V = 153$ (0.000)	$V = 136$ (0.000)
	Wilcoxon test. The null hypothesis is that average contribution is equal to eight	$V = 164$ (0.371)	$V = 205$ (0.267)	$V = 137.5$ (0.017)	$V = 127$ (0.017)	$V = 60.5$ (0.000)	$V = 60.5$ (0.000)	$V = 36$ (0.000)	$V = 39.5$ (0.000)	$V = 50.5$ (0.000)	$V = 33.5$ (0.000)
Individual provision point mechanism	Average contribution	9.5	9.6	8.9	8.9	8.8	9.4	8.3	8	8.6	8.9
	Wilcoxon test. The null hypothesis is that average contribution is equal to eight	$V = 150$ (0.025)	$V = 139$ (0.002)	$V = 85$ (0.377)	$V = 89$ (0.274)	$V = 68$ (0.114)	$V = 72$ (0.009)	$V = 42$ (0.421)	$V = 31$ (0.858)	$V = 43$ (0.014)	$V = 31$ (0.068)
Collective provision point mechanism	Average contribution	10.1	9.2	10.1	9.9	10.9	9.2	11.5	11.1	10.5	10.5
	Wilcoxon test. The null hypothesis is that average contribution is equal to eight	$V = 336.5$ (0.000)	$V = 197.5$ (0.173)	$V = 291.5$ (0.043)	$V = 331$ (0.102)	$V = 296.5$ (0.009)	$V = 254$ (0.244)	$V = 363$ (0.001)	$V = 305$ (0.000	$V = 299$ (0.007)	$V = 304.5$ (0.005)
	Wilcoxon test. The null hypothesis is that average contribution is equal to twelve	$V = 123.5$ (0.008)	$V = 86$ (0.004)	$V = 134$ (0.070)	$V = 156.5$ (0.043)	$V = 202.5$ (0.371)	$V = 105$ (0.008)	$V = 166.5$ (0.587)	$V = 175$ (0.150)	$V = 159$ (0.079)	$V = 132$ (0.063)

* p-values in brackets.

Table 4.7: Average contribution and Wilcoxon test per round.

4.7.4 Results per group

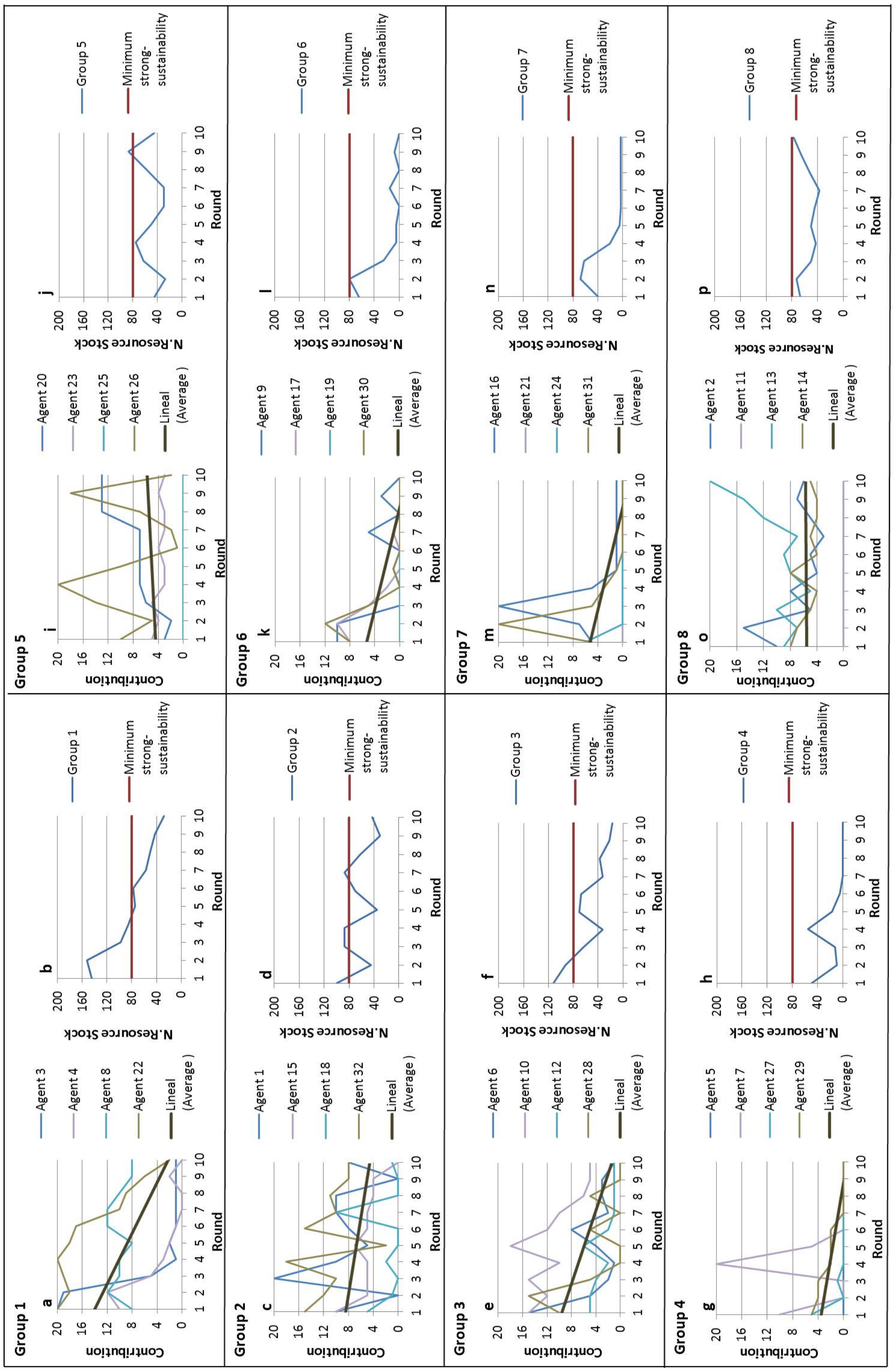

Figure 4.10: Basic game. Agents' contribution and average natural resource recovery per round.

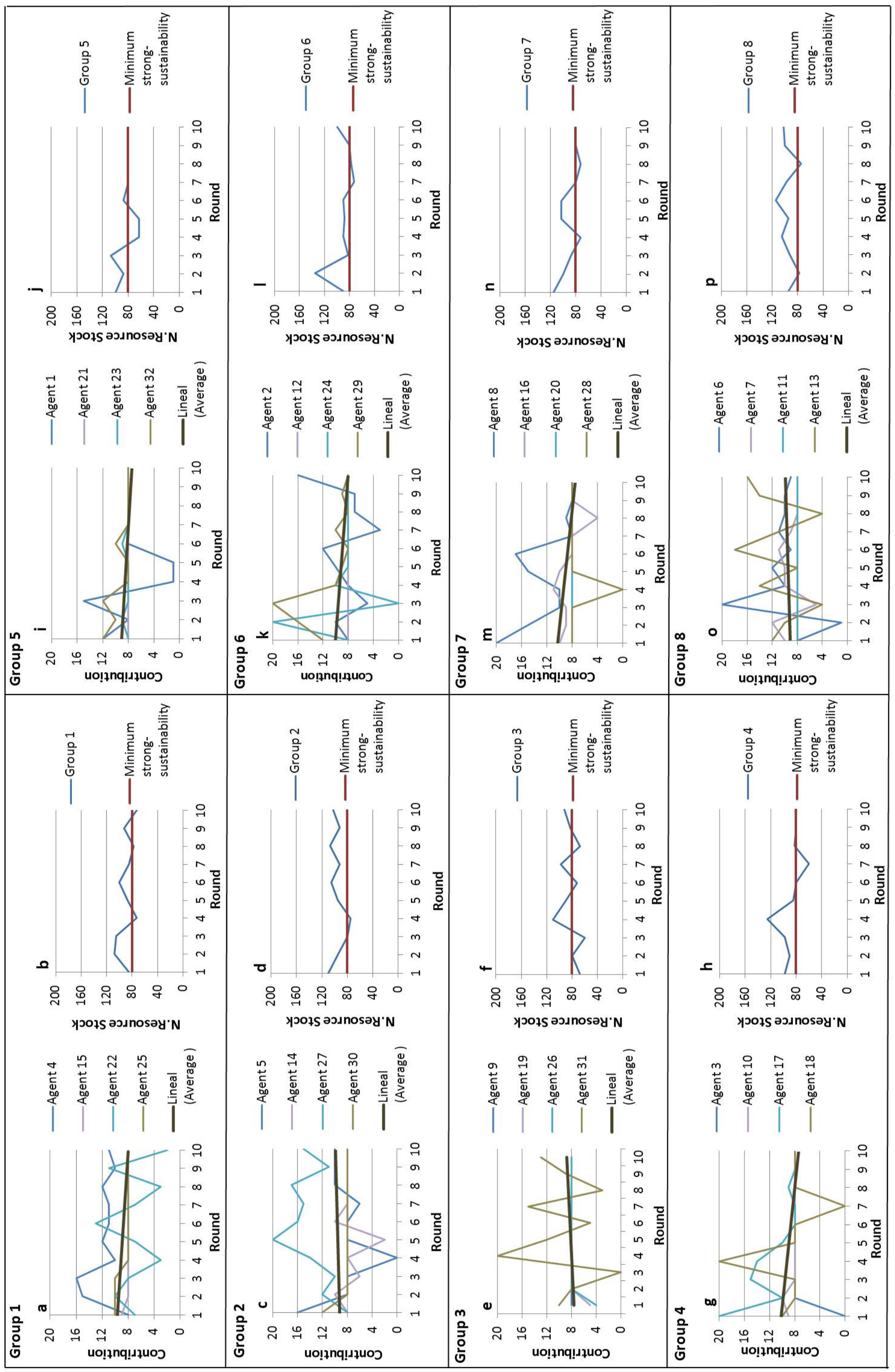

Figure 4.11: Individual provision point mechanism. Agents' contribution and average natural resource recovery per round.

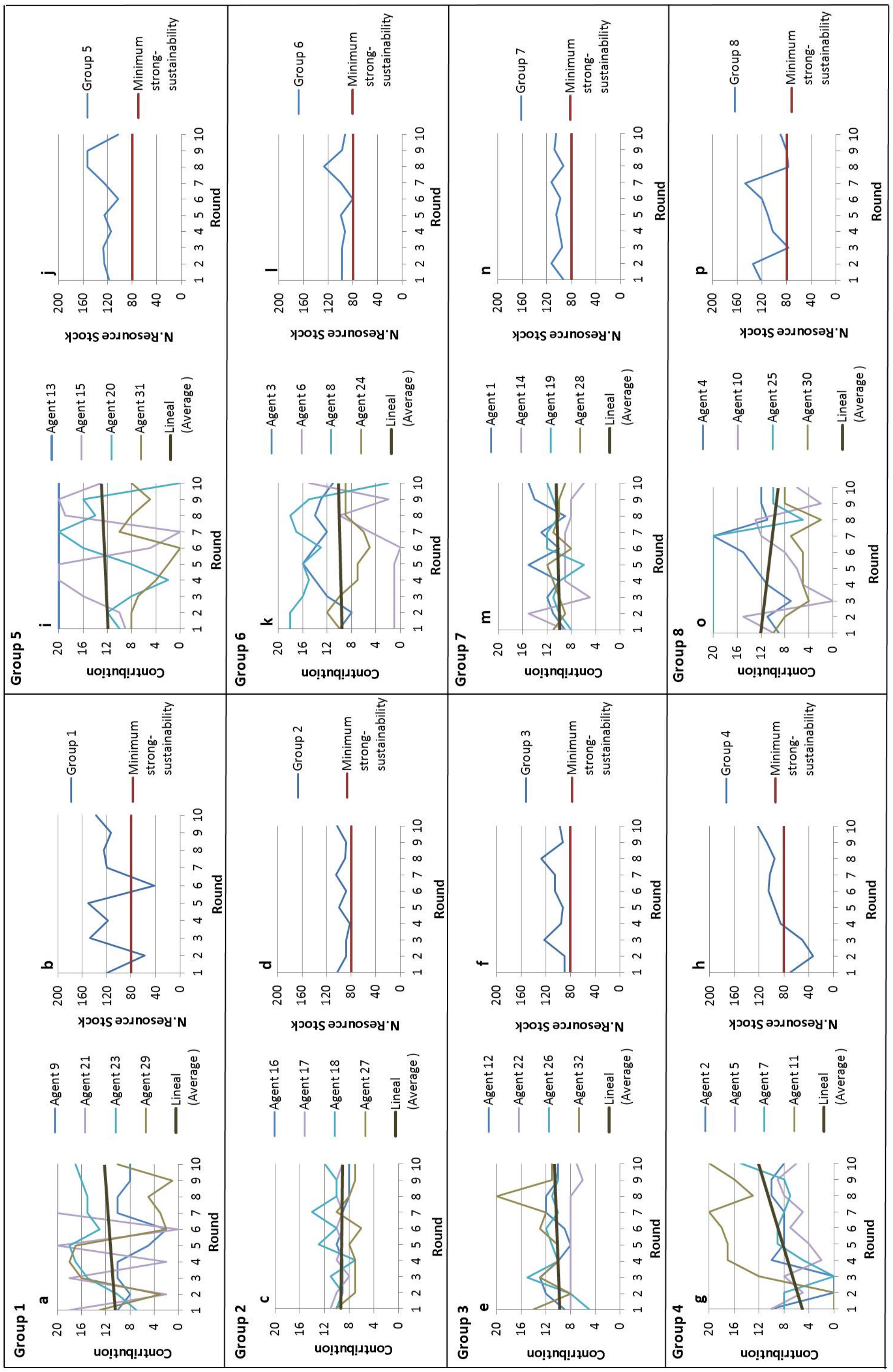

Figure 4.12: Collective provision point mechanism. Agents' contribution and average natural resource recovery per round.

4.7.5 Instructions (originally in Spanish)

Basic Game

WELCOME TO THE EXPERIMENT

This experiment studies the decision-making process in an economic environment. In this instruction, you will find information about the decisions you can make and about their consequences.

With your decisions you can earn money that you will receive at the end of the experiment. During the experiment, we are not going to talk about Euros but points. Points will be converted into Euros at the end of the experiment in accordance with the exchange rate below:

4 points = 1 Euro

THE EXPERIMENT

This experiment is split into 10 rounds; in each one you have to make an investment.

You are in a **4-member group**, that is, the group is composed of you and 3 other persons present here. Your group members are the same during the 10 rounds; however, you will not at any time know who is part of your group. Your investment results will depend both on the decisions you will take and on the decisions taken by the other members of your group.

Investment decisions

At the beginning of each round, your group has an **80-point fund.** All your investment decisions can have an effect on this fund. What there is in the fund after investments is going to be donated to the SEO/BirdLife (Spanish Society of Ornithology) association, **whose mission is to conserve biodiversity.**

Moreover, at the beginning of each round you receive 20 points. We call these points your endowment. You have to decide how many of these points you want to invest in project D and how many in project C, so that the investment in D plus the investment in C is equal to 20.

On the **screen**, you will have to key in how many points you invest in project C. The rest of your endowment (e.g. 20-investment in C) is automatically invested in D.

The **earnings** you obtain at the end of each round depend on these investments. What remains in the fund for the environmental association also depends on these investments.

The consequences of investing in Project D

1. Earnings for you

For each point invested in Project D you obtain 3 points.

1 point in D = 3 points for you

2. Fund for the environmental association

For each point invested in Project D the fund for the environmental association is reduced by 1 point.

1 point in D = 1 point less in the fund

The consequences of investing in Project C

1. Earnings for you

For each point invested in Project C you obtain 1 point.

1 point in C = 1 point for you

2. Fund for the environmental association

For each point invested in Project C the fund for the environmental association is increased by 1.5 points.

1 point in C = 1.5 more points for the fund

Your total earnings in the round

Your total earnings in the round are the sum of your earnings from Project D plus your earnings from Project C.

$$\boxed{\textbf{(3}\times\textbf{your investement in D) + (1}\times\textbf{your investment in C)}}$$

The income of each participant is calculated in the same way.

Fund for the environmental association at the end of the round

The fund for the environmental association at the end of the round depends on the group investments in D and in C. The points of the fund are:

$$\boxed{\textbf{80-1}\times\textbf{Total investement in D+1.5}\times\textbf{Total investement in C}}$$

Information at the end of each round

At the end of each round you obtain on the screen the following information about what happened in that round:

Your investment in project C.

Your group total investment in project C.

Your earnings in that round.

The remaining fund for the environmental association.

At the start of a new round, your group receives a new fund for the environmental association of 80 points and you receive a new endowment of 20 points and the opportunity to re-invest in project D or project C.

At the end of the game, one of the 10 rounds will be randomly selected. Each player will be paid the earnings obtained in the chosen round. The environmental fund corresponding to that round will be donated to the SEO / BirdLife environmental association. Each of you will receive a notification that the donation has been made.

FINAL EARNINGS

At the end of the game, one of the 10 rounds will be randomly selected.

Each player will be paid the earnings obtained in the chosen round.

The environmental fund corresponding to that round will be donated to the SEO / BirdLife environmental association. Each of you will receive a notification that the donation has been made.

Individual provision point mechanism

WELCOME TO THE EXPERIMENT

This experiment studies the decision-making process in an economic environment. In this instruction, you will find information about the decisions you can make and about their consequences.

With your decisions you can earn money that you will receive at the end of the experiment. During the experiment, we are not going to talk about Euros but points. Points will be converted into Euros at the end of the experiment in accordance with the exchange rate below:

4 points = 1 Euro

THE EXPERIMENT

This experiment is split into 10 rounds; in each one you have to make an investment.

You are in a **4-member group**; that is, the group is composed of you and 3 other persons present here. Your group members are the same during the 10 rounds; however, you will not at any time know who is part of your group. Your investment results will depend both on the decisions you take and on the decisions taken by the other members of your group.

Investment decisions

At the beginning of each round, your group has an **80-point fund**. All your investment decisions can have an effect on this fund. What is in the fund after investments is going to be donated to the SEO/BirdLife (Spanish Society of Ornithology) association, **whose mission is to conserve biodiversity.**

Moreover, at the beginning of each round you receive 20 points. We call these points your endowment. You have to decide how many of these points you want to invest in project D and how many in project C, so that the investment in D plus the investment in C is equal to 20.

On the **screen**, you will have to key in how many points you invest in project C. The rest of your endowment (e.g. 20-investment in C) is automatically invested in D.

The **earnings** you obtain at the end of each round depend on these investments. What remains in the fund for the environmental association also depends on these investments.

The consequences of investing in Project D

1. Earnings for you

For each point invested in Project D you obtain 3 points.

1 point in D = 3 points for you

2. Fund for the environmental association

For each point invested in Project D the fund for the environmental association is reduced by 1 point.

1 point in D = 1 point less in the fund

The consequences of investing in Project C

1. Earnings for you

For each point invested in Project C you obtain 1 point.

1 point in C = 1 point for you

Moreover, if your investment in Project C is equal to or **higher than 8 points** you receive **32 additional points.**

2. Fund for the environmental association

For each point invested in Project C the fund for the environmental association is increased by 1.5 points.

1 point in C = 1.5 more points for the fund

Your total earnings in the round

Your total earnings in the round are the sum of your earnings from Project D plus your earnings from Project C.

If **your investment in C is below 8 points**, your total earnings are:

$$\boxed{\textbf{(3}\times\textbf{your investement in D) + (1}\times\textbf{your investment in C)}}$$

If **your investment in C is equal to or above 8 points**, your total earnings are:

$$\boxed{\textbf{(3}\times\textbf{your investement in D) + (1}\times\textbf{your investment in C)+32}}$$

The income of each participant is calculated in the same way.

Fund for the environmental association at the end of the round

The fund for the environmental association at the end of the round depends on the group investments in D and in C. The points of the fund are:

$$\boxed{\textbf{80-1}\times\textbf{Total investement in D+1.5}\times\textbf{Total investement in C}}$$

Information at the end of each round

At the end of each round you obtain on the screen the following information about what happened in that round:

Your investment in project C.

Your group total investment in project C.

Your earnings in that round.

The remaining fund for the environmental association.

At the start of a new round, your group receives a new fund for the environmental association of 80 points and you receive a new endowment of 20 points and the opportunity to re-invest in project D or project C.

FINAL EARNINGS

At the end of the game one of the 10 rounds will be randomly selected.

Each player will be paid the earnings obtained in the chosen round.

The environmental fund corresponding to that round will be donated to the SEO / BirdLife environmental association. Each of you will receive a notification that the donation has been made.

Collective provision point mechanism

WELCOME TO THE EXPERIMENT

This experiment studies the decision-making process in an economic environment. In this instruction, you will find information about the decisions you can make and about their consequences.

With your decisions you can earn money that you will receive at the end of the experiment. During the experiment, we are not going to talk about Euros but points.

Points will be converted into Euros at the end of the experiment in accordance with the exchange rate below:

4 points = 1 Euro

THE EXPERIMENT

This experiment is split into 10 rounds; in each one you have to make an investment.

You are in a **4-member group**, that is, the group is composed of you and 3 other persons present here. Your group members are the same during the 10 rounds; however, you will not at any time know who is part of your group. Your investment results will depend both on the decisions you take and on the decisions taken by the other members of your group.

Investment decisions

At the beginning of each round, your group has an **80-point fund**. All your investment decisions can have an effect on this fund. What is in the fund after the investments is going to be donated to the SEO/BirdLife (Spanish Society of Ornithology) association, **whose mission is to conserve biodiversity.**

Moreover, at the beginning of each round you receive 20 points. We call these points your endowment. You have to decide how many of these points you want to invest in project D and how many in project C, so that the investment in D plus the investment in C is equal to 20.

On the **screen**, you will have to key in how many points you invest in project C. The rest of your endowment (e.g. 20-investment in C) is automatically invested in D.

The **earnings** you obtain at the end of each round depend on these investments. What remains in the fund for the environmental association also depends on these investments.

The consequences of investing in Project D

1. Earnings for you

For each point invested in Project D you obtain 3 points.

1 point in D = 3 points for you

2. Fund for the environmental association

For each point invested in Project D the fund for the environmental association is reduced by 1 point.

1 point in D = 1 point less in the fund

The consequences of investing in Project C

1. Earnings for you

What you obtain for each point invested in Project C depends on what you and the other 3 members of your group do. The following table shows the earnings per point invested in C according to the total investment of your group in C.

Group total investement in C	Your earnings for each point invested in C	Group total investement in C	Your earnings for each point invested in C	Group total investement in C	Your earnings for each point invested in C	Group total investement in C	Your earnings for each point invested in C
1	1	21	1	41	4.1	61	3.1
2	1	22	1	42	4.0	62	3.1
3	1	23	1	43	4.0	63	3.0
4	1	24	1	44	3.9	64	3.0
5	1	25	1	45	3.8	65	3.0
6	1	26	1	46	3.8	66	2.9
7	1	27	1	47	3.7	67	2.9
8	1	28	1	48	3.6	68	2.9
9	1	29	1	49	3.6	69	2.9
10	1	30	1	50	3.5	70	2.8
11	1	31	1	51	3.5	71	2.8
12	1	32	5.0	52	3.4	72	2.8
13	1	33	4.9	53	3.4	73	2.8
14	1	34	4.8	54	3.3	74	2.7
15	1	35	4.7	55	3.3	75	2.7
16	1	6	4.6	56	3.2	76	2.7
17	1	37	4.5	57	3.2	77	2.7
18	1	38	4.4	58	3.2	78	2.6
19	1	39	4.3	59	3.1	79	2.6
20	1	40	4.2	60	3.1	80	2.6

2. Fund for the environmental association

For each point invested in Project C the fund for the environmental association is increased by 1.5 points.

1 point in C = 1.5 more points for the fund

Your total earnings in the round

Your total earnings in the round are the sum of your earnings from Project D plus your earnings from Project C.

(3×your investment in D) + (table value×your investment in C)

The income of each participant is calculated in the same way.

Fund for the environmental association at the end of the round

The fund for the environmental association at the end of the round depends on the group investments in D and in C. The points of the fund are:

80-1×Total investement in D+1.5×Total investement in C

The following examples can help you to understand the experiment.

Example 1: Suppose that you invest 11 points in project D and 9 points in project C; if the total amount of points that your group has invested in C (including your investment) is of 27 points, your earnings will be of 42 points. $(3 * 11) + (1 * 9) = 42$.

In this case, the environmental fund will be of 67.5 points. $80-(1*53)+(1.5*27) =$ 67.5 points.

Example 2: Suppose that you invest 11 points in project D and 9 points in project C; if the total amount of points that your group has invested in C (including your investment) is of 67 points, your earnings will be of 59.1 points $(3*11)+(2,9*9) = 59,1$.

In this case, the environmental fund will be of 167.5 points.$80-(1*13)+(1.5*67) =$ 167.5 points.

Information at the end of each round

At the end of each round you obtain on the screen the following information about what happened in that round:

Your investment in project C.

Your group total investment in project C.

The earnings for each point invested in project C.

Your earnings in that round.

The remaining fund for the environmental association.

At the start of a new round, your group receives a new fund for the environmental association of 80 points and you receive a new endowment of 20 points and the opportunity to re-invest in project D or project C.

FINAL EARNINGS

At the end of the game one of the 10 rounds will be randomly selected.

Each player will be paid the earnings obtained in the chosen round.

The environmental fund corresponding to that round will be donated to the SEO / BirdLife environmental association. Each of you will receive a notification when the donation has been made.

Questionnaire

1. Age:

   a. Open answer

2. Gender

   a. Female b. Male

3. With whom do you live?

   a. With my parents b. With my partner c. In a student flat

   d. In a residence e. Alone

4. What are you currently studying?

   a. Open answer

5. Are you also working during your studies?

   a. Yes, occasionally b. Yes, continuously c. No

   d. (I am not studying)

6. Are you a member of an association for the protection of nature?

   a. Yes b. No

7. Do you have your own vehicle?

   a. Yes b. No

8. Is there any member of your family dedicated to agriculture?

   a. Me b. No one c. Parents d. Grandparents

   e. Siblings f. Others

9. Do you usually recycle paper, glass or plastic?

a. Yes b. No

10. In what container does the paper go?

a. Blue b. Yellow c. Green

11. What transport do you use to go to classes?

a. Car/Motorcycle b. Bicycle c. By foot d. Public transport

12. What is compost?

a. Garbage b. Organic matter c. Chemical compound

13. What is the main cause of climate change?

a. Fossil fuels b. Use of aerosols c. Deforestation

14. Around how many species of fauna and flora do you think are currently endangered in Spain?

a. 200 species b. 2,000 species c. 20,000 species

15. Are you in favour of limiting the circulation of private vehicles in the city in order to reduce air pollution?

a. Yes b. No

16. Do you usually buy organic products?

a. Yes b. No

Afterword

Biodiversity conservation in agricultural land usually requires the performance of a series of conservationist practices that are costly for farmers. Therefore, and as we have demonstrated in the co-evolutionary model developed in chapter one, farmers' participation in conservationist programmes requires the introduction of economic incentives through agri-environmental schemes. Knowing which agri-environmental schemes promotes farmers' conservationist behaviour and under which circumstances it is crucial in order to environmental agencies to be able to design mechanisms that allow to protect natural resources and for farmers' economical sustainability. In this respect, in the second chapter we have developed three different agri-environmental scheme models; the subsidies scheme (constant and collective) and the price differentiation scheme, and we have demonstrated that any of them could be useful to protect natural resources on farmland. In particular, we have shown that all the agri-environmental schemes allows for stable equilibria where conservationist and non-conservationist coexist and where the natural resource is sustained. We conclude that subsidies and price differentiation schemes are able to protect natural resources on farmland.

Some differences appear when we work in the field. In chapter 3 we have observed, with the Little bustard simulation example, that although all models could allow the same stable equilibria, they present differences in their basins of attraction. That is, differences among models are found out of the equilibria. In particular, we have demonstrated that the price differentiation scheme could present larger basins of attraction than any subsidy scheme. In addition, the damage caused by birds to the conservationists' harvest function is crucial to determine the existence of a stable equilibrium point and to determine the budget and the prices needed to reach it.

Finally, in the last chapter we have shown how different threshold incentives perform when a natural resource requires a minimum stock level to be sustained (as occurs in our theoretical model). From the experiments we know that, first, threshold incentives are useful on protecting natural resources because they make it possible to increase contribution levels up to the natural resource sustainability threshold. Second, the collective threshold mechanism presents larger contribution levels than the individual threshold mechanisms; that is, partnership and collaboration among farmers could improve contributions. In addition, in this last chapter we show the importance of knowing the natural resource characteristics in order to design the best incentive mechanism. Finally, further research should be done to better determine the farmers' decision-making process, especially in collective subsidies which is when the threshold incentive becomes a coordination problem.

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