Managing Multiple Ecosystem Services Provision: Cereal Production, Soil Quality and Habitat Preservation

Maria A. Cunha-e-Sá*
NOVA School of Business and Economics
Universidade Nova de Lisboa
Portugal

Rui Pedro Mota*
NOVA School of Business and Economics
Universidade Nova de Lisboa
Portugal

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Abstract

We develop a model for the optimal management of multiple ecosystem services provision, namely, of cereal production, soil quality and habitat preservation for an endangered species (in general, biodiversity preservation) in a cereal steppe area. When ecosystem services are jointly produced, paying for only one service may be detrimental to the whole system. The interactions between these three ecosystem services provide interesting insights, given the presence of trade-offs. As land is privately owned there is scope for intervention. We compare the social planner's solution with the regulated one. While private landowners do not internalize the habitat preservation yet they take into account the effect of their decisions on soil quality. Thus, we identify the optimal mix of instruments (taxes and subsidies) required to implement the social optimum. We show that only one instrument is not enough (as it is currently applied in the case study area). We derive the optimal policy instruments at the optimum, as well as along the optimal path. Policy implications are derived.

Keywords: multiple ecosystem service provision; joint production; agriculture; soil erosion; habitat preservation; optimal policy.

JEL Classification #: Q01, Q24, Q57

1. Introduction

The Millenium Ecosystem Assessment has concluded that over the past 50 years, 60% of all ecosystem services (ES) have declined as a direct result of the growth of agriculture, forestry, fisheries, industries and urban areas. While markets exist for the

* Mailing Address: Campus de Campolide P-1099-032, Lisboa, Portugal. Emails: mcunhasa@novasbe.pt, rui.mota@novasbe.pt. Phone Number: 351213801600.

* Mailing Address: Campus de Campolide P-1099-032, Lisboa, Portugal. Emails: mcunhasa@novasbe.pt, rui.mota@novasbe.pt. Phone Number: 351213801600.

products of agriculture, fisheries, and forestry, the benefits from watershed protection, climatic regulation, pest and disease regulation, and habitat provision, among others, are largely unpriced. These public benefits are known as ecosystem services (ES).

Private landowners typically undersupply most ecosystem services and biodiversity since they do not have a market price to reflect the benefits they provide to society. Therefore, market prices may be distorted below the social values. Without a mechanism to internalize the nonmarket values of ecosystems, ecosystem services will be suboptimally provided, becoming eventually unsustainable. Some recent studies have developed economic-ecological models to illustrate these market outcomes, such as Eichner and Pethig (2006), and Finnoff and Tischhart (2008), among others. Thus, there is scope for intervention.

Governments and regulatory agencies have produced legislation to affect land use and thus the ecosystem services that land provides. Effective mechanism design requires understanding of both the linkages among biodiversity, ecological functioning and ecosystem services and the incentives for private provision of these resources, given their public good nature.

The main mechanisms aiming at motivating economic agents to provide for those services range from regulation and penalty (e.g., zoning restrictions, Endangered Species Act (ESA)), cap and trade (e.g. carbon markets), direct payments to services providers, to self-regulation. In fact, recently, cap and trade and direct payments have emerged as the preferred mechanisms. However, mechanisms addressing multiple ES, as in Sanchirico and Springborn (2011), have been seldom considered in the literature. Often, incentives that encourage production of one service may have a negative impact on the others. Hence, the interdependence between services, such as in the case of joint production, cannot be ignored as it may generate feedback effects that offset each

others' impact. Therefore, payment schemes should capture all the effects of ecosystem management, that is, should include the multiple services that are affected.

The purpose of this paper is to develop a bioeconomic model of a cereal-grazing steppe system. The cereal steppe is an example of a multi-functional rural landscape that besides agricultural and livestock products provides habitat for several endangered species of birds. The results are discussed for the Castro Verde steppe region located in the South of Portugal.

The private landowner maximizes the present value of profits from growing cereal and raising cattle over time by optimally allocating the land between cereal and grazing at each period, as well as by deciding on optimal cattle density on grazing land. On the other hand, agricultural productivity is negatively affected by soil erosion on cropland, reducing soil productivity. However, private landowners take into account soil losses when deciding on their management practices, the impact on habitat preservation is not internalized. While enlarging the land area allocated to cereal growth impacts positively on biodiversity, it has a negative impact on soil productivity by increasing soil erosion (Goetz, 1997). Moreover, given that the land endowment constraint is binding, when increasing land allocated to cereal, land area allocated to grazing land decreases, which has a negative impact on profits from grazing. Hence, landowners have an incentive to increase cattle density in the current period which has a negative impact on habitat preservation in the future. Thus, the trade-offs eventually generated by joint production of multiple ecosystem services cannot be ignored when designing payment schemes.

As the land is privately owned there is scope for intervention. Therefore, we compare the social planner's solution with the regulated one. While private landowners do not internalize the habitat preservation, yet they take into account the effect of their

decisions on soil quality. Thus, we identify the optimal mix of instruments (taxes and subsidies) required to implement the social optimum. We show that a sole instrument is not enough (as it is currently applied in Castro Verde). We derive the optimal policy at the optimum, as well as along the optimal path. Policy implications are derived.

The rest of the paper is organized as follows. Section 2 describes the case study, Section 3 presents the analytical bioeconomic model. Both the social planner's and the regulated problems are described. Section 4 develops the numerical simulation for the calibrated model to the Castro Verde region and discusses the results and policy implications. Finally, section 5 offers the main conclusions.

2. Case Study: Brief Description of Castro Verde Area

The cereal steppe in the municipality of Castro Verde occupies around 80% of the total area. The landscape of the cereal steppe is a space-temporal mosaic composed of cereal, stubble (recently harvested), fallow and ploughed fields. Typically, the fallow land occupies a large part of the total area, ranging from around 50% to 80% depending on the time of the year (Moreira et al., 2004). The soil in the municipality of Castro Verde is mostly derived from schist and is characterized by thinness and low drainage (Marta-Pedroso, 2007). Thus, there is a high risk of erosion determining low agricultural capabilities.

For several decades, land management practices in the region of Castro Verde have been characterized by periodic rotations between winter cereals growing for 1 to 2 years, followed by fallowing periods of 2 to 3 years (Marta-Pedroso et al., 2007). Fallow refers to land that is idled as part of a shifting cultivation system after being planted with annual or short-term perennial crops, accumulating nutrient-rich biomass that can serve as fertilizer when the land is brought back to cultivation. It is a worldwide

used land regeneration practice mainly in regions of low soil quality, providing on-site benefits such as soil regeneration, weed control, and reducing the negative effects on soil erosion.

Besides increasing soil productivity by protecting from soil erosion, the land under fallow is used as grazing land to raise sheep, which generates a higher yield per hectare than growing cereal, making the former activity more attractive from a private perspective. Moreover, stubbles are also used for livestock grazing.

The cereal steppe is an example of a multi-functional rural landscape that besides agricultural and livestock products constitutes habitats for several endangered species of birds, of which the great bustard (*Otis Tarda*) is the most important. For this reason the cereal growing lands in that region of southern Portugal have a high biodiversity value.

The population of *Otis Tarda* in Portugal is the fourth most important at the European scale. Its trend for the period 1980-2002 was analysed by Pinto et al. (2005). After a significant decline in 1984-1995, a fast increase was observed after 1995 on, mostly due to the increase of suitable habitats in the region of Castro Verde. A positive trend for the concentration of the population of *Otis Tarda* in Castro Verde was also observed. In 2002, the Portuguese population of *Otis Tarda* was estimated in 1 150 birds of which 912 were located in Castro Verde. In 1980, 50% of the total Portuguese population was in Castro Verde. For the time period analysed by Pinto et al. (2005) eight local extinctions were documented. A threshold of 30 birds was reported as the minimum viable population of *Otis Tarda*, below which the probability of extinction drastically increased (Pinto et al., 2005). In fact, eight of ten populations where initial population size was less than 30 individuals became extinct in the 22-year period.

Moreover, it was observed a trend for faster decline in areas with smaller numbers of birds.

The choice of habitats by the *Otis Tarda* in the region of Castro Verde was investigated in Moreira et al. (2004). The authors concluded that different habitats are used for feeding, male display and female nesting, depending on the season considered (i.e., winter, breeding and post-breeding). Bustards use fallow during all seasons, mainly for sources of food and breeding displays. Cereal fields are used for nesting and stubbles for food during post-breeding.

Thus a mosaic of habitat types seems to be essential for maintaining the *Otis Tarda* population. The occurrence of lek grounds is the main reason for conservation. Fallow fields should be maintained for displaying males, cereal fields for nesting females and stubble fields as foraging areas.

The mosaic that composes the cereal steppe of Castro Verde results from a low profitability rotational crop system that is maintained by subsidizing farmers to keep their land under extensive cereal cultivation and to adopt farming practices according to the bird species' life cycles (agri-environmental measures) (Marta-Pedroso et al., 2007). In fact, the timing of the Castro Verde increase in *Otis Tarda* population can be related to a Life project that started in 1993 which resulted in the acquisition of 2000 ha of land that included the main lekking grounds. The threat to conservation at the regional scale (the Castro Verde municipality in Alentejo) led to the acquisition at a local scale of a few farms by an environmental NGO (LPN), using funds at both the EU scale (Life program) and national scale (corporate and individual donors). The strategy was then to obtain public funds to grant subsidies to farmers to adopt practices compatible with nature conservation. The farms have been rented to local farmers, conditional on their compliance with strict regulations related to the protection of animal species.

In 1995, the Zonal Plan with European Union agri-environmental measures (EEC regulation 2078/92) has started to promote management actions on 60 000 ha in Castro Verde. Subsidies were granted to promote rotational crop with fallow and dry cereals, low livestock densities as well as to limit the use of chemicals (Pinto et al, 2005). In 1999, 61% of the Zonal Plan area presented agri-environmental schemes in place whereas in 2003 only 34% followed the promoted actions. As farmers became less willing to participate, an increase in pasture areas and livestock density is expected, as well as a negative impact on the recent observed evolution on *Otis Tarda* population. This decrease in farmers' uptake (around 40%) can be related to delays in subsidies payments followed by a substantial decrease in financial support (Pinto et al., 2005).

The Castro Verde Zonal Plan was ineffective in preventing soil erosion and desertification. In spite of the reported positive effects of the Zonal Plan of Castro Verde on target bird populations, the occurrence of soil erosion caused by cereal farming is an important drawback of this program, which has not been taken into account in past program evaluations (Marta-Pedroso, 2007). Although some measures adopted by farmers under the agri-environmental scheme do contribute to soil protection (e.g. longer periods of fallow), they do not prevent the continuing soil erosion associated with cereal cultivation. On the other hand, the livestock grazing areas can be considered as negligible contributors to soil erosion.

Summing up, cereal and sheep are the two market goods, on which the local economy is based. While enlarging the land area allocated to cereal growth provides a positive environmental externality by impacting positively on biodiversity, it has a negative impact on soil productivity by increasing soil erosion. While the increase in soil productivity is a pecuniary positive externality, thus captured by the private

landowner as the land becomes more productive, the impact on biodiversity is a public good, and, therefore is not internalized by private actions.

The following bioeconomic model describes the optimal management of an area with two uses – agriculture and grazing – when the soil quality and the existence of an endangered species are taken into account. The preservation of the endangered species and of the cereal steppe for habitat purposes has the trade-off of increasing soil erosion in the region that ultimately, if no actions are taken, will render the area irreversibly inappropriate for cultivation of cereals.

3. The Bioeconomic Model

The total area in Castro Verde is fixed and approximately equal to the sum of the areas allocated to rotational cereal land and permanent pastures land. The area defined as rotational cereal land includes areas of cereals that rotate with fallow used for grazing. As described in the previous section, one important trade-off is the choice between maintaining permanent pasture areas or a rotational crop system of cereals. The shares of the total area available to the rotational crop system and permanent pastures can be interchanged instantaneously and infinitesimally (continuously), and are decision variables of the landowners at each time period. Moreover, we assume that there are no costs associated to land use changes.

Each land type provides ecosystem services: direct human use (food – cereals and sheep products) and habitat preservation services for endangered species (e.g., *Otis Tarda*). Cereal fields provide cereals for food and habitat for *Otis Tarda* (nesting and food), while fallow land provides grazing areas for sheep and habitat for *Otis Tarda* (display areas and food). Depending on the time of the year, the *Otis Tarda* occupies the area under rotational cereal crops and permanent pasture areas in varying proportions. As described in the previous section, the soil quality is an important state variable for

this system. Although the model is general enough to treat different levels of soil quality, in the particular case of Castro Verde the soil is considered to be of poor quality and in need of preservation. To include the impacts of soil erosion on the optimal decision of agents, we associate a rate of soil erosion to each type of area and an index of soil quality to the total area of Castro Verde.

The local economy can be represented by two production functions that characterize the production technology for each activity. Hence, output per hectare is given as follows:

$$\pi^i(t) = \pi^i(\mu^i(t), l^i(t), q^i(z(t);\bar{a})) = f^i(\mu^i(t), z(t), l^i(t);\bar{a}) - C^i(\mu^i(t), l^i(t)) \quad (1)$$

for $i = c, g$, where the superscripts c and g stand, respectively, for rotational cereal crops and for permanent pastures (or grazing) areas., Also, $\mu^i(t)$ represents an index of intensity of production in output *i*, $l^i(t)$ is the land area allocated to output *i*, and $q(z(t);\bar{a})$ characterizes local soil productivity where $z(t)$ is soil depth. Finally, $\bar{a}$ represents (exogenous) local soil characteristics. The production in each site depends on the index of inputs, the land area available and soil quality. $C^i(\mu^i(t), l^i(t))$ represents the cost function of area with use *i*, and it depends on the inputs to production and on the area available.

Note that as long as we assume that there is a continuum of land that interchanges between cereal growing and grazing land, the local soil productivity, and, therefore, soil depth, are undistinguishable between the land areas allocated to the two different uses. In what follows, we assume that intensity of production is only a practice on the permanent grazing land, and we denote it by sheep density by hectare, *d*. Thus, we have that $\mu^c(t) = 0$, and $\mu^g(t) = d(t)$. Moreover we assume that the cost function of the permanent grazing area only depends on the sheep density.

Since soil depth depends on current management practices, it cannot be assumed as constant. Therefore, the intertemporal change of the soil depth at time t is represented by the following differential equation:

$$\frac{dz(t)}{dt} = s - h\left(\mu^i(t), z(t), l^i(t); \bar{a}\right)$$

where s stands for exogenous the rate of soil formation and $h(t)$ the rate of soil erosion, respectively. Note that the rate of soil erosion may depend on the management practices adopted by each activity, as well on intensity practices. In what follows the evolution of soil depth over time is given by

$$\frac{dz}{dt} = s - h^c(l^c) - h^g(l^g) = s - h(l^c, l^g) \tag{2}$$

Therefore, we assume that density in grazing land does not affect the rate of soil erosion.

Assuming a given endowment of land, $\bar{l}$, we may write:

$$l^c(t) + l^g(t) = \bar{l} \tag{3}$$

where $\bar{l}$ is allocated between the two uses of land, that is, rotational cereal crops and grazing land, for all *t*.

Given the biophysical functions (1), and (2), a landowner ‘s decision on the intensity of cultivation has an impact upon the instantaneous level of the corresponding output, the rate of soil erosion, the soil depth, and future output levels of both activities.

Finally, the dynamics of the birds’ population is given by

$$\frac{dO}{dt} = g(O, K(l^c, l^g)) - D(d)l^g \tag{4}$$

where O is the number of endangered birds per hectare, $g(O, K(l^i))$ is the growth function of birds and $D(d)l^g$ represents the decrease in birds population due to sheep density per hectare of grazing land. The density of sheep has a negative impact on birds’

development and cannot be ignored in the dynamics of the population. Therefore, it depends on the stock of the population at each time period, as well as on the carrying capacity of the land, which depends on the amount of land allocated to each activity. Besides, intensity of production per hectare affects negatively the evolution of the population as accounted by the damage function $D(d)$ in (4) which depends on sheep density in grazing land.

3.1 The Social Planner's Problem

In this section, we model a benevolent social planner's decision problem. This problem consists of maximizing the present value of revenues from growing cereal, and sheep raising, as well as the social benefits derived from birds' preservation, as follows:

$$\underset{\{l^c,l^g,d\}}{Max}\, V^s(O,z,d,l^c,l^g;\bar{a},p^i,c^i,r)=\int_0^\infty (\sum_{i=c,g}\pi^i + B(O)e^{-rt}dt \tag{5}$$

s.t.

$l^i(t)\geq 0,\ \mu^g(t)\geq 0,$

(2), (3) and (4), given $\overline{O},\bar{z}$.

Moreover, from (1), we have that

$$\sum_{i=c,g}\pi^i=\sum_{i=c,g}p^i y^i(t)-c^c l^c(t)-c^g d(t)\,. \tag{6}$$

and $B(O(t))$ represents the social benefits from preservation of the bird species at time t.

The social planner's problem is an autonomous infinite horizon optimal control problem, where the state variables are $z(t)$, soil depth, and the stock of the birds'

population, $O(t)$, while the control variables are the amount of land allocated to each activity, $l^i(t)$, and sheep density in grazing land, $d(t)$.[1]

Assuming an interior solution for both land allocation and density, using Pontryagin's Maximum Principle, we may state the current value Hamiltonian as follows:

$$H = \sum_{i=c,g} \pi^i + B(O) + \lambda_z \left[s - h(l^c, l^g) \right] + \lambda_O \left[g(O, k(l^c, l^g) - D(d) l^g \right] \tag{7}$$

Subsituting l^g by $\bar{l} - l^c$, the necessary first-order conditions for an interior solution are given by:

$$\frac{\partial H}{\partial l^c} = \frac{\partial \pi^c}{\partial l^c} - \frac{\partial \pi^g}{\partial l^g} + \lambda_z \frac{\partial h}{\partial l^c} + \lambda_O \left[\frac{\partial g}{\partial K} \frac{\partial K}{\partial l^c} + D(d) \right] = 0 \tag{8}$$

$$\frac{\partial H}{\partial d} = \frac{\partial \pi^g}{\partial d} + \lambda_O l^g D' = 0 \tag{9}$$

$$\frac{d\lambda_z}{dt} = r\lambda_z - \frac{\partial \pi^c}{\partial z} \tag{10}$$

$$\frac{d\lambda_O}{dt} = \left(r - \frac{\partial g}{\partial O} \right) \lambda_O - B' \tag{11}$$

$$\frac{dz}{dt} = \frac{\partial H}{\partial \lambda_z} = s - h^c(l^c) - h^g(l^g) \tag{12}$$

$$\frac{dO}{dt} = \frac{\partial H}{\partial \lambda_O} \tag{13}$$

as well as the initial conditions for the state variables and the conventional transversality conditions. $\lambda_z(t)$ represents the current value shadow price or the marginal user cost of soil depth, while $\lambda_O(t)$ is the current value shadow price or the marginal user cost of birds' stock, and r is the discount rate.

[1] If the nonnegativity constraints can be binding, the corresponding Lagrangean problem should be stated instead. In this case, the Lagrange multipliers associated with the nonnegativity constraints are introduced in the model as additional variables.

According to (8), land is optimally allocated between the two activities when the marginal net benefits are the same, that is, if the marginal profit on cereal production plus the intertemporal benefit on the carrying capacity of birds net of the intertemporal opportunity cost on soil depth from currently allocating an additional hectare to cereal production equals the marginal loss in current profits from grazing plus the reduced intertemporal opportunity cost on soil depth and on birds' population, as the land allocated to grazing decreases. Moreover, from (9), we may conclude that the optimal density level in grazing land is such that the increase in the marginal profit from currently increasing density should compensate for the intertemporal opportunity cost imposed on birds' population. Finally, (10) and (11), the two co-sate equations, describe the dynamics of the marginal user costs associated with soil depth and birds' population, respectively.

Optimal Interior Steady-State

The equations that correspond to an interior steady-state solution are given as follows:

$$\frac{\partial \pi^c}{\partial l^c} - \lambda_z \frac{\partial h^c}{\partial l^c} + \lambda_O \frac{\partial g}{\partial K}\frac{\partial K}{\partial l^c} = \frac{\partial \pi^g}{\partial l^g} - \lambda_z \frac{\partial h^g}{\partial l^g} + \lambda_O \left[\frac{\partial g}{\partial K}\frac{\partial K}{\partial l^g} - D(d)\right] \tag{14}$$

$$\frac{\partial \pi^g}{\partial d} = -\lambda_O(\bar{l} - l^c)\frac{\partial D}{\partial d} \tag{15}$$

$$\lambda_z = \frac{\partial \pi^c / \partial z}{r} \tag{16}$$

$$\lambda_O = \frac{B'}{r - \partial g / \partial O} \tag{17}$$

$$s = h^c(l^c) + h^g(l^g) \tag{18}$$

$$g(O, K(l^c, l^g) = D(d) l^g \tag{19}$$

Substituting (16) and (17) into (14) and (15), and given (18) and (19), we may obtain the social optimal decision rules for the control variables, land allocation to each activity and density, as a function of the state variables soil depth and the stock of birds' population, given the parameters of the model.

Moreover, at the steady-state, we have that

$$\lambda_O = \frac{\frac{\partial \pi^c}{\partial l^c} - \frac{\partial \pi^g}{\partial l^c} - \frac{\partial \pi^c / \partial z}{r}\frac{\partial h}{\partial l^c}}{-\frac{\partial g}{\partial K}\frac{\partial K}{\partial l^c} + D(d)} = -\frac{\partial \pi^g / \partial d}{l^g D'} = \frac{B'}{r - \partial g / \partial O} \tag{20}$$

given (16)

$$\lambda_z = \frac{\partial \pi^c / \partial z}{r} \tag{21}$$

and (15)

$$\lambda_O = -\frac{\partial \pi^g / \partial d}{l^g D'} \tag{22}$$

3.2 The Regulated Problem

In this section, we consider the case of the private landowner. Given (2), we observe that the soil depth influences the productivity of cereal production. Therefore, the private landowner internalizes the impact of his decisions on soil depth. However, he does not take into account the effect of his decisions on birds' population, as in the case of the social planner's problem. Given that society values birds' preservation in this region, which requires habitat preservation, a subsidy per hectare of cereal, $\eta^c(t)$, has been granted to landowners that allocate to cereal production an amount of land at least as large as a certain threshold level. Assuming that this threshold is not binding, the problem of the private landowner consists of maximizing the present value of the flow of profits from both activities and the granted subsidies over time, as follows:

$$\underset{\{l^c(t),l^g(t),d(t)\}}{Max} V^p(z,O,l^c,l^g,d;\bar{a},p^i,c^i,r)=\int_0^\infty(\sum_{i=c,g}\pi^i+\eta^c l^c)e^{-rt}dt \tag{23}$$

s.t.

$$l^i \geq 0\,,\ d \geq 0\,, \tag{24}$$

(2) and (3), given $\overline{O},\bar{z}$.

The problem is also an infinite horizon optimal control problem. For an interior solution, the Hamiltonian can also be obtained as before. The first-order conditions in this case are given as follows:

$$\frac{\partial H^p}{\partial l^c}=\frac{\partial \pi^c}{\partial l^c}+\eta^c(l)-\frac{\partial \pi^g}{\partial l^g}-\lambda_z\frac{\partial h}{\partial l^c}=0 \tag{25}$$

$$\frac{\partial H^p}{\partial d}=\frac{\partial \pi^g}{\partial d}=0 \tag{26}$$

$$\frac{d\lambda_z^p}{dt}=r\lambda_z^p-\frac{\partial \pi^c}{\partial z} \tag{27}$$

$$\frac{dz}{dt}=\frac{\partial H^p}{\partial \lambda_z}=s-h^c(l^c)-h^g(l^g) \tag{28}$$

as well as the initial conditions for the state variables.

Therefore, by comparing (26) with (14), the optimal subsidy at the regulated optimum steady state is given by

$$\eta^{c*}=\lambda_O^*\left[\frac{\partial g}{\partial K}\left(\frac{\partial K^*}{\partial l^c}-\frac{\partial K^*}{\partial l^g}\right)+D(d^*)\right] \tag{29}$$

as long as the right-hand side of (29) is positive. If this is the case, the optimal subsidy is given by the marginal net impact of a hectare of land allocated to cereal on carrying capacity of birds' population and on sheep density on grazing land over time. This net impact is evaluated at the marginal social benefit discounted at the net social rate ($r-\partial g/\partial O$), and it is assumed to be positive. However, as it is clear by comparing (26) to (15), this subsidy is not enough to implement the social optimum. In fact, sheep

density per hectare of grazing land affects negatively birds' population, which is not captured by the subsidy to cereal land, and, therefore is not internalized by private landowners. Hence, at the optimum, this activity should be taxed as follows:

$$\eta^{g*} = \lambda_O^* l^{g*} D'(d^*) \tag{30}$$

where $\lambda_O{}^*$ is given by (20). This is equivalent to reducing the revenues of the owner of grazing land in proportion to the animal density. This way, the optimal tax provides the incentive to the private landowner to internalize in his management practices the negative impact of increasing sheep density on birds' population, evaluated at the present value of the optimal marginal social benefit of birds. Hence, at the social optimum density should be decreased relative to the regulated case. Therefore, we may conclude that the subsidies that are granted to landowners according to current regulations are not enough to implement the social optimum. The landowners only devoted to grazing should be taxed by the amount of the impact cattle density has in increasing mortality of birds. This can be easily understood if one recalls that we are in presence of two externalities, one related to the preservation of the cereal/grazing rotation landscape for habitat, and the other to the need to regulating cattle density, given its impact on birds' growth rate.

The instruments (29) and (30) discussed above were obtained for the steady state of the optimal system. To completely characterize the regulatory instruments along the optimal path we compare the optimal dynamical system in the regulated and social problems. Taking the time derivative of (8) and (9) and eliminating the shadow prices by making use of the Euler equations (10) and (11) we obtain two equations, that together with (12) and (13) represent the optimal system.

Following the same procedure for the regulated problem, and including an instrument to regulate the choices of sheep density, comparing the two optimal systems yields the following expressions for the dynamics of the optimal instruments,

$$\frac{d\eta^c}{dt} - \eta^c\left(\rho + \hat{h}_{l^c}\right) = -B'\left(g_{l^c} + D\right) - \frac{\frac{\partial \pi^g}{\partial d}\left(\frac{\partial g}{\partial l^c} + D\right)}{D' l^g}\left(\frac{\frac{d}{dt}\left(\frac{\partial g}{\partial l^c} + D\right)}{g_{l^c} + D} - \frac{\partial g}{\partial O} - \hat{h}_{l^c}\right) \tag{31}$$

$$\frac{d\eta^g}{dt} - \eta^g\left(\rho - g_O + \frac{dD' l^g / dt}{D' l^g}\right) = B' D' l^g \tag{32}$$

where $\hat{h}_{l^c}$ is the growth rate of $\partial h / \partial l^c$. Evaluating the above expressions at the steady state yields, as expected, the instruments (29) and (30). To obtain the instruments for the entire optimal path, equations (31) and (32) are solved. Further, assuming that the birds' carrying capacity and the erosion functions depend linearly on land, and that $D(d^*)$ is also linear on cattle density, the following expressions for the taxes/subsidies at time t are obtained.

$$\eta^c(t) = \int_t^\infty \frac{\frac{\partial \pi^g}{\partial d}\left(\frac{\partial g}{\partial l^c} + D\right)}{D' l^g} \frac{\partial g}{\partial O} e^{-rs}\, ds + \int_t^\infty B'\left(\frac{\partial g}{\partial l^c} + D\right) e^{-rs}\, ds \tag{33}$$

$$\eta^g(t) = -\int_t^\infty B' D' l^g e^{-\int_t^s r - \frac{\partial g}{\partial O} - i^g / l^g \, d\tau}\, ds \tag{34}$$

These expressions represent present the value of the marginal external effects (positive and negative) along the optimal regulated path. Assuming that the ecosystem is in a state of insufficient cereal land for habitat, increasing the area of cereal rotation increases the carrying capacity for birds (i.e., $g_{l^c} > 0$), implying that the right hand side of (33) is positive. This implies that the cereal landowner must be subsidized. In the case of the owner of permanent pastures, the right hand side of (34) is negative, thus

representing a tax. The owner of permanent pasture land faces a disincentive to have more land due to the negative impact that sheep density has on birds' mortality. This tax corresponds to the decrease on birds' population due to the increase in one unit of sheep density ($D'l^g$), and it is priced at the marginal value of birds to society (B'). To obtain the present value, future external effects are discounted at the social net discount rate, that is, the private discount rate, *r*, net the marginal change on birds' population growth and the growth rate in permanent grazing land. This is in contrast with the subsidy in (33) that is only discounted at the private discount rate.

Regarding the rotational cereal crops, (33) represents a compensation for positive external effects on the preservation of birds' habitat. The second term on the right hand side of (33) represents the compensation for the increase in birds' carrying capacity, $\partial g/\partial K\, \partial K/\partial l^c$, plus the compensation for avoiding that permanent pastures have a negative impact on birds' population due to increases in cattle density to compensate for the decreased profit in grazing land as cereal land is increased. These effects are priced at the marginal value of birds to society (B').The first term of the subsidy in (33) provides an incentive to prevent the private landowner from increasing the permanent pasture area.

If the area of rotational cereal crops increases, implying that the area of permanent pasture decreases, then along the optimal path, the landowner will increase the sheep density to compensate for that that loss in grazing area. This can be seen from either one of the first order conditions of the social planner's problem, (8) or (9). For instance, (9) defines an implicit function of l^c, λ_O and d. Taking the implicit derivative $\partial d/\partial l^c$ we get,

$$\partial d/\partial l^c = -\frac{-\partial \pi^g/(\partial d \partial l^c) + \lambda_O D'}{\partial^2 \pi^g/\partial d^2 - \lambda_O D'' l^g}.$$

The sign of the denominator is negative and the denominator is positive in case land area and sheep density are substitutes in the profit function π^s, which implies that along the optimal path changes in land devoted to rotational cereal crops move in the same direction as changes in sheep density.

So an incentive to increase the area devoted to rotational cereal crops also creates an incentive to increase sheep density, which, although increasing profits for the private landowner, decreases the growth rate of birds' population that society values positively. Therefore, to prevent the landowner to increase sheep density a compensation is required. This compensation is given weighted by the ratio between marginal benefits and costs indirectly associated with changes in land areas, which corresponds to the first term of the subsidy in (33).

4. Conclusions

In this paper we develop a model for the optimal management of multiple ecosystem services, which has seldom been considered in the literature. When ecosystem services are jointly produced, paying for only one service may be detrimental to the whole system.

We consider the services of cereal production, soil quality and habitat preservation for an endangered species (in general, biodiversity preservation) for a given land area. The land is allocated to two different uses, cereal and grazing, which are both essential to preserve the habitat for an endangered bird species, the *Otis Tarda*. The interactions between these three ecosystem services provide interesting insights, given the presence of trade-offs. By granting subsidies to increase the area allocated to cereal in order to preserve biodiversity, soil erosion increases reducing the capability of the system to produce cereal in the future, preventing the preservation of suitable habitat

for the endangered species. Moreover, when more land is allocated to cereal, less land is allocating to grazing in the current period, with negative impact on future profits of this activity. Therefore, landowners have an incentive to increase cattle density in the current period, which impacts negatively on the quality of birds' habitat over time.

As the land is privately owned there is scope for intervention. Therefore, we compare the social planner's solution with the regulated one. While private landowners do not internalize the habitat preservation, yet they take into account the effect of their decisions on soil quality. Thus, we identify the optimal mix of instruments (taxes and subsidies) required to implement the social optimum. We show that only one instrument is not enough (as it is currently applied in Castro Verde). We derive the optimal policy at the optimum, as well as along the optimal path. Policy implications are derived.

In what concerns future work, the numerical analysis of the model calibrated to the Castro Verde region will be provided, and policy implications discussed.

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