Modelling environmental effects of agriculture
The case of organic rye and grey partridge

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MODELLING ENVIRONMENTAL EFFECTS OF AGRICULTURE

THE CASE OF ORGANIC RYE AND GREY PARTRIDGE

Abstract

Our optimal control model identifies economic reasons as to why farmland bird populations have dramatically declined in modern agricultural landscapes. By integrating recreational wildlife values into farm level decision-making on arable crop choice and herbicide use, we derive those economic instruments needed for creating suitable conditions for game bird species on farmland. Based on the Finnish data available on the grey partridge (*Perdix perdix*), we illustrate how the optimal acreage subsidy for organically-grown areas, herbicide tax rates and the hunting licence fee could be estimated in monetary terms. Finally, we discuss the benefits and costs of cultivating organic cereals which will enhance preservation of the grey partridge.

Keywords: environmental benefits, grey partridge, herbicides, optimal control, rye

JEL classification: Q57, Q18, H41

1. Introduction

The positive environmental benefits of agriculture include preservation of such public goods as farmland biodiversity and agricultural landscapes. However, agricultural intensification and specialisation, along with the decline of livestock farming and the cultivation of winter cereals have clearly caused the loss of wildlife habitats. An alarming indicator for biodiversity in agricultural ecosystems is the decreasing abundance of farmland birds. In particular, the grey partridge (*Perdix perdix*), a typical game bird of open arable landscapes, has been adversely affected by the modification of the agricultural landscape. Since the 1930s European grey partridge populations have declined remarkably, and the bird is currently listed among species with an unfavourable conservation status. (Hietala-Koivu, 2002; Miettinen *et al.*, 2004; Pimentel and Greiner, 1997; Heath and Rayment, 2003; Potts, 1986; De Leo *et al.*, 2004; Hagemeijer and Blair, 1997).

As rapid changes in land use curtail environmental benefits, effective measures to conserve wildlife in agricultural areas become necessary (see, *e.g.*, Lowe and Whitby, 1997). In this paper, we address the positive and negative effects of cereals cultivation and the associated economic costs of environmentally benign agricultural practices. We utilise the grey partridge stock as a biodiversity indicator for illustrating the effects of the crops and herbicides the farmers choose to use. In our framework, we also take into account hunters' recreational hunting decisions, and the fact that the partridge stock provides welfare beyond simply recreational hunting.

There is an extensive and increasing volume of literature concerning agri-environmental schemes and policies for multifunctional agriculture (*e.g.*, Dobbs and Pretty, 2004). For example, Boisvert (2001) examined the implications of joint production of private and public goods in farm production, in which two agricultural commodities are produced along with landscape amenities and an environmental residual. In addition, management of biodiversity aspects are increasingly considered in the analyses (*e.g.*, van Wenum *et al.*, 2004). However, there are few economic studies analysing the dynamics of bird species in this context despite the wide use of farmland birds as biodiversity indicators. The most closely related approach to ours originates from the study by Hammack and Brown (1974) who investigated the optimal allocation of the prairie wetlands in North America. They analysed the conflicting economic and ecological interests when the drainage of marshes and ponds increases the supply of arable land, and eliminates the costs of tilling around potholes, but at the same time decreases the nesting areas and the stock of waterfowl. Our modelling owes much to the inspiring work of Hammack and Brown, and to other studies on unpriced environmental input where the ecological function affects the growth rate of a renewable stock over time (*e.g.* a wetland supporting a fishery as outlined in Barbier and Strand 1998, and Barbier 2000; see also Ellis and Fisher 1987). The main contribution of our application is on elaborating economic incentives to achieve a socially optimal level of a bird species and corresponding input uses in crop production.

In our model, the environmental externalities lead to a socially inefficient allocation of arable land, non-optimal use of herbicides and over-exploitation of partridge stock, since private valuations of inputs and outputs are different from their social valuations. We develop first-best policy instruments to internalise bird fauna values in farm level decision making. To date the pricing of biodiversity has focused on the valuation of individual species using contingent valuation and other methods of stated preferences (Montgomery *et al.*, 1999, Loomis and White 1996). The results of our empirical illustration show that government intervention can be justified even with conservative value estimates of game birds.

The paper is structured as follows. We develop a framework of cereals cultivation and partridge hunting, and study how the government may intervene optimally by subsidising organic crop farming, taxing herbicide use and imposing a hunting licence fee in such a way that the externalities are internalised. We introduce some background information on both the cultivation of winter cereals and on grey partridges in Finland to provide an empirical illustration of the use of biodiversity values in the design of individual policy measures. The framework applied and empirical results give useful insights into the ongoing process of shaping policies to implement and improve agri-environmental schemes in the EU.

2. Analytical framework

In this section, we introduce a theoretical framework for crop production and partridge hunting. First, we study the underlying assumptions, find the social and private optima of arable land allocation, farm capital investments, herbicide use and partridge hunting bag.

Let us assume that the total area of homogenous agricultural land in the economy is A, which is a constant upper limit on land for farming in the long run. The social planner allocates agricultural land between two bread grain cereal crops. Crop 1 is organically-grown rye and crop 2 is spring wheat. Both variables are functions of continuous time, but we suppress the time argument (t) and denote the area devoted to crop 1 by a_1 and the area devoted to crop 2 by a_2. By assuming that all fixed amounts of agricultural land are used at any time, we have $a_1 + a_2 = A$. This assumption implies that the price or rental value of land will be captured by the Lagrangian multiplier for the land constraint in the optimisation problem.

The dynamic production function of organic crop 1, $y_1 = f(a_1, K_1)$, is assumed to be strictly concave with respect to a_1 and K_1. Sector-specific know-how and (human) capital invested in the chosen agricultural technology, organic or conventional, is denoted by K_i (i = 1,2). The production function of conventional crop 2, $y_2 = g(a_2, K_2, h)$, contains three arguments. The last of these, h, represents the amount of herbicides used in weed control. The marginal products of all three inputs are assumed to be positive and diminishing.

Capital formation and (gross) investment, I_i, are related by the following differential equation

$$\dot{K}_i = I_i - \delta K_i \qquad i = 1,2$$

where $\dot{K}_i = dK_i / dt$, and δ represents the constant depreciation rate of capital. The cost of an investment is denoted by $c^{I_i}(I_i)$, which is an increasing function of investment, or $\partial c^{I_i}(I_i)/\partial I_i \equiv c^{I_i}_{I_i}(\cdot) > 0$ and $\partial^2 c^{I_i}(I_i)/\partial I_i^2 \equiv c^{I_i}_{I_i I_i}(\cdot) > 0$. Furthermore, farmers operate in competitive product and factor markets, and we denote the market price of crop 1 by p^1, the market price of crop 2 by p^2, and the unit price of herbicide by p^h.

We assume that the herbicide damage is a flow variable, *i.e.*, that herbicide residues do not accumulate in the environment and build up into a persistent stock. Direct adverse effects of herbicides to humans, typically poisonings and related illnesses, are denoted by $D(h)$, which is the monetary equivalent of the disutility. The social costs of herbicide use in agriculture to human well-being may also include consumers' disutility from the potential risk of herbicide residues in food, water and the atmosphere (Pimentel and Greiner, 1997). It is assumed that an increase in the use of herbicides in crop production generates direct disutility at an increasing rate. Therefore we have $D_h(\cdot) > 0$ and $D_{hh}(\cdot) > 0.$ In addition, indirect effects from the use of herbicides are also considered. We assume that the use of herbicides in weed control reduces the growth rate of partridge stock, because herbicides decrease the supply of insect food and increase partridge chick mortality (Potts, 1986).

The partridge stock is replenished by growth, which depends positively on the size of the partridge population, B, and the area under organic rye (crop 1), and negatively on the amount of herbicides used. The bird stock is reduced by hunting. The amount of partridges shot is denoted by X. Furthermore, the parameter α measures the constant natural mortality rate of partridges. The relationships above can be summarised as

$$\dot{B} = e(B, a_1, h) - X - \alpha B$$

where $e(\cdot)$ denotes the natural production function with $e_B(\cdot) > 0,$ $e_{a_1}(\cdot) > 0,$ and $e_h(\cdot) < 0.$

We assume that hunters generate their recreational hunting experience. The amount of partridges shot is X. The variable also measures the amount of partridge bag, since we assume that the proportion of birds shot but not retrieved is negligible. The net benefits of recreational partridge hunting are given in monetary units by

$$p^R X - c^X(B)X$$

where p^R is a total hunting value attributed to a bagged partridge. The total hunting value consists mainly of recreational benefits that are typically much larger than the value of meat received from the hunting bag. The unit hunting cost, $c^X(B),$ depends negatively on the size of the partridge stock, B, since hunters must allocate more time and effort when the partridge population is low (cf. Clark and Munro, 1975). Therefore we have $c_B^X(\cdot) < 0$ and $c_{BB}^X(\cdot) < 0.$ Thus, the net hunting benefits increase as the bird stock increases.

Since many people who do not hunt may value and derive utility from the continued presence of partridges, we assume that the partridge stock provides welfare above and beyond hunting. The non-use values attached to the stock of partridges are given in monetary units by the function $W(B)$. Furthermore, we assume that $W_B(\cdot) > 0$ and $W_{BB}(\cdot) < 0.$

2.1 Social planner's problem

The objective of the social planner is to maximise discounted social welfare by allocating the arable area between crops optimally, finding the optimal investments and choosing the optimal amounts of herbicide used and partridges shot

$$Max \int_0^\infty \left[p^1 f(a_1, K_1) + p^2 g(a_2, K_2, h) - c^{I_i}(I_i) - p^h h - D(h) + p^R X - c^X(B)X + W(B) \right] e^{-\rho t} dt$$

$$s.t. \quad \dot{K}_i = I_i - \delta K_i \qquad K_i(0) = K_{i0} > 0 \qquad i = 1,2$$

$$\dot{B} = e(B, a_1, h) - X - \alpha B \qquad B(0) = B_0 > 0$$

$$a_1 + a_2 = A$$

Thus there are six control variables, a_1, a_2, I_i $(i = 1,2)$, h, and X, and three state variables, the stock of capital, K_i (i = 1,2), and the stock of partridges, B, in the optimal control model above. ρ ($\geq$ 0) is the rate of discount, K_{i0} refers to the initial stock of sector specific capital, and B_0 denotes the given initial size of the partridge population.

The current-value Lagrangian function (*i.e.* the current-value Hamiltonian augmented with the constraint $a_1 + a_2 = A$) is

$$\ell_c = p^1 f(a_1, K_1) + p^2 g(a_2, K_2, h) - c^{I_i}(I_i) - p^h h - D(h) + p^R X - c^X(B)X + W(B)$$
$$+ l\left[I_i - \delta K_i\right] + m\left[e(B, a_1, h) - X - \alpha B\right] + n\left[A - a_1 - a_2\right]$$

where l is the shadow price of capital, m is the shadow price of partridge stock B, and the Lagrangian multiplier n is the shadow price of arable land A.

The maximum-principle conditions are

$$\frac{\partial \ell_c}{\partial a_1} = p^1 f_{a_1}(\cdot) + m e_{a_1}(\cdot) - n = 0 \tag{1}$$

$$\frac{\partial \ell_c}{\partial a_2} = p^2 g_{a_2}(\cdot) - n = 0 \tag{2}$$

$$\frac{\partial \ell_c}{\partial I_i} = -c_{I_i}^{I_i}(\cdot) + l = 0 \tag{3}$$

$$\frac{\partial \ell_c}{\partial h} = p^2 g_h(\cdot) - p^h - D_h(\cdot) + m e_h(\cdot) = 0 \tag{4}$$

$$\frac{\partial \ell_c}{\partial X} = p^R - c^X(\cdot) - m = 0 \tag{5}$$

including the equations of motion for the state and the costate variables

$$\dot{K}_i = \frac{\partial \ell_c}{\partial l} = I - \delta K_i \tag{6}$$

$$\dot{B} = \frac{\partial \ell_c}{\partial m} = e(\cdot) - X - \alpha B \tag{7}$$

$$\dot{l} = -\frac{\partial \ell_c}{\partial K_i} + \rho l = -p^1 f_{K_1}(\cdot) - p^2 g_{K_2}(\cdot) + l\left[\delta + \rho\right] \tag{8}$$

$$\dot{m} = -\frac{\partial \ell_c}{\partial B} + \rho m = c_B^X(\cdot) X - W_B(\cdot) + m\left[\alpha + \rho - e_B(\cdot)\right] \tag{9}$$

plus the infinite-horizon transversality conditions (Seierstad and Sydsaeter, 1987)

$$\lim_{t\to\infty} l(t) \geq 0 \qquad (= 0, \text{if } \lim_{t\to\infty} K_i(t) > 0) \quad \textit{and} \quad \lim_{t\to\infty} m(t) \geq 0 \qquad (= 0, \text{if } \lim_{t\to\infty} B(t) > 0)$$

We assume interior solutions and focus on their interpretation. Rearranging the first two maximum-principle conditions (equations (1) and (2)) yields the following socially optimal arable land allocation

$$p^1 f_{a_1}(\cdot) + m e_{a_1}(\cdot) = p^2 g_{a_2}(\cdot)$$

Thus at the social optimum, when both crops are cultivated, the sum of the values of marginal products of arable area devoted to the production of crop 1 and partridges is equal to the value of the marginal product of arable land under crop 2.

Equation (3) directs increasing the investments up to the point where the marginal adjustment cost is equal to the shadow price of capital. Equation (4) shows that at the social optimum, the value of marginal product of herbicide used net of the marginal social damages done and partridge growth loss incurred equals the unit price of herbicide, *i.e.*, the marginal cost. Finally, equation (5) implicates that the social planner should increase the hunting bag to the point where the net benefits of recreational hunting are equal to the marginal current value of an additional partridge.

The steady state for capital stocks is characterised by the equality of investment and depreciation of farm equipment capital. Respectively, when $dB/dt = 0$, equation (7) can be written as $e(\cdot) = X + \alpha B$, implicating simply that the biological growth and reduction rates of the partridge stock are equal in the steady state. Furthermore, when $dl/dt = 0$, the equation of motion for the costate variable *l* can be written as $l(\delta + \rho) = p^1 f_{K_1}(\cdot) + p^2 g_{K_2}(\cdot)$ implicating that the marginal user cost of capital should be equal to the value of the marginal product of farm capital. Finally, when $dm/dt = 0$, equation (9) can be solved for *m*, *i.e.*

$$m = \frac{W_B(\cdot) - c_B^X(\cdot)X}{\rho + \alpha - e_B(\cdot)}$$

which implicates that in the steady state the shadow price of partridge stock, *m*, is equal to the ratio between the marginal contribution of partridge stock to current social welfare, $W_B(\cdot) - c_B^X(\cdot)X$, and the marginal contribution of partridge stock to future social welfare, $\rho + \alpha - e_B(\cdot)$. From (5) we have $m = p^R - c^X(B)$. If we make this substitution into equation (9), we have in the optimal steady state

$$p^R - c^X(\cdot) = \frac{e_B(\cdot)[p^R - c^X(\cdot)]}{\rho + \alpha} - \frac{c_B^X(\cdot)X}{\rho + \alpha} + \frac{W_B(\cdot)}{\rho + \alpha} \tag{10}$$

The left-hand side of the equation (10) can be considered as the marginal opportunity cost of not hunting. The right-hand side consists of the marginal incentives to postpone hunting, which include partridge capital gains, $e_B(\cdot)[p^R - c^X(\cdot)]$, the marginal decrease in unit hunting cost due to increased partridge stock, $c_B^X(\cdot)X$, and the marginal welfare effect of the increased partridge stock, $W_B(\cdot)$. Because of the accumulation phenomenon, the instantaneous incentives have to be discounted by dividing with the sum of the rate of discount and the natural mortality rate, $\rho + \alpha$.

Let us next differentiate $m = p^R - c^X(B)$ with respect to time to get $\dot{m} = -c_B^X(B)\dot{B}$. Equating this expression with (9) and substituting $p^R - c^X(B)$ for *m* yields

$$-c_B^X(B)\left[e(B, a_1, h) - X - \alpha B\right] = c_B^X(B)X - W_B(B) + [p^R - c^X(B)]\left[\alpha + \rho - e_B(B, a_1, h)\right]$$

which, when simplified and rearranged, gives

$$\rho = e_B(\cdot) - \alpha - \frac{c_B^X(\cdot)\left[e(\cdot) - \alpha B\right]}{p^R - c^X(\cdot)} + \frac{W_B(\cdot)}{p^R - c^X(\cdot)} \tag{11}$$

and with $x = e(\cdot) - \alpha B$ defines the modified golden-rule value of the socially optimal steady-state partridge stock *B*. The equation (11) states that the rate of discount, *ρ*, equals the own rate of return of the partridge stock. The latter consists of two components: the net marginal productivity of the resource stock, $e_B(\cdot) - \alpha$, and the marginal stock effect, which also consists of two components. The components of the marginal stock effect are the decreased unit hunting cost,

$c_B^X(\cdot)[e(\cdot)-\alpha B]/[p^R-c^X(\cdot)]$, and increased social welfare from the stock benefits, $W_B(\cdot)/[p^R-c^X(\cdot)]$. Thus, the hunting rate is socially optimal when the net product of the partridge stock is equal to the discount rate.

2.2 Representative farmer's private optimum

In this section, we consider a representative farmer whose objective is to maximise profit from the cultivation of arable crops. The profit maximisation problem of the farmer is thus

$$Max \int_0^\infty \left[p^1 f(a_1,K_1)+p^2 g(a_2,K_2,h)-c^{I_i}(I_i)-p^h h\right]e^{-\rho t}dt$$

$$s.t.\quad \dot{K}_i = I_i-\delta K_i \qquad K_i(0)=K_{i0}>0,\quad i=1,2 \qquad a_1+a_2=A$$

The current-value Lagrangian function is

$$\ell_c = p^1 f(a_1,K_1)+p^2 g(a_2,K_2,h)-c^{I_i}(I_i)-p^h h+l\left[I_i-\delta K_i\right]+n\left[A-a_1-a_2\right]$$

and the maximum-principle conditions are

$$\frac{\partial \ell_c}{\partial a_1}=p^1 f_{a_1}(\cdot)-n=0 \tag{12}$$

$$\frac{\partial \ell_c}{\partial a_2}=p^2 g_{a_2}(\cdot)-n=0 \tag{13}$$

$$\frac{\partial \ell_c}{\partial I_i}=-c_{I_i}^{I_i}(\cdot)+l=0 \tag{14}$$

$$\frac{\partial \ell_c}{\partial h}=p^2 g_h(\cdot)-p^h=0 \tag{15}$$

$$\dot{K}_i=\frac{\partial \ell_c}{\partial l}=I_i-\delta K_i \tag{16}$$

$$\dot{l}=-\frac{\partial \ell_c}{\partial K_i}+\rho l=-p^1 f_{K_1}(\cdot)-p^2 g_{K_2}(\cdot)+l\left[\delta+\rho\right] \tag{17}$$

The maximum-principle condition (14) indicates that the optimal investment in farm equipment, and thus the optimal capital path, is the same as at the social optimum (cf. equation (3)). Instead, the maximum-principle conditions for a farmer's use of arable land and of herbicides differ from the social optimum, because the representative farmer does not take into account the beneficial environmental effects of rye cultivation nor the adverse effects of herbicides. This can be seen by comparing the equations (12), (13) and (15) with equations (1), (2) and (4).

2.3 Representative hunter's private optimum

Game populations are regulated using closed seasons and hunting can be scaled in accordance with game stocks. Here, we assume that hunters act as sole owners of the partridge stock, and that they maximise the net hunting benefits. The maximisation problem of the representative hunter is thus

$$Max \int_0^\infty \left[p^R X-c^X(B)X\right]e^{-\rho t}dt$$

$$s.t.\quad \dot{B}=e(B,a_1,h)-X-\alpha B \qquad \text{and} \qquad B(0)=B_0.$$

The current-value Hamiltonian function is

$$H_c = p^R X - c^X(B)X + m^H\left[e(B,a_1,h) - X - \alpha B\right]$$

and the maximum-principle conditions are

$$\frac{\partial H_c}{\partial X} = p^R - c^X(\cdot) - m^H = 0 \tag{18}$$

$$\dot{B} = \frac{\partial H_c}{\partial m^H} = e(\cdot) - X - \alpha B \tag{19}$$

$$\dot{m}^H = -\frac{\partial H_c}{\partial B} + \rho m^H = c_B^X(\cdot)X + m^H\left[\alpha + \rho - e_B(\cdot)\right] \tag{20}$$

When comparing the above maximum-principle conditions with the maximum-principle conditions of the social planner, there exists a difference between equations (9) and (20) because hunters do not take into account the fact that the natural biological stock also provides economic welfare to society above and beyond hunting, $W(B)$. Therefore, we indicate the shadow price of the partridge stock in the representative hunter's private solution with m^H.

2.4 Corrected solutions

In this section, we use market-based instruments to correct the externalities. There are three externalities in the framework presented: 1) The cultivation of rye positively affects the growth rate of the partridge stock. 2) The use of herbicides in crop production negatively affects the growth rate of the partridge stock and causes damage and disutility to humans. 3) Recreational hunting excessively reduces the level of the partridge stock and leads to loss of stock benefits.

By comparing the farmer's private optimum with the social optimum, one may notice that the area under crop 1 is too small from a social point of view. Therefore, the government may subsidise the production of crop 1 and impose the crop-specific area payment *s*. Furthermore, when finding the private optimum, the farmer also neglects the social costs engendered by herbicide use. The social damages can be internalised by imposing a Pigouvian tax, *t*, to a farmer's use of herbicides.

In the presence of acreage subsidy, *s*, and Pigouvian tax, *t*, the current-value Lagrangian function of the representative farmer's maximisation problem becomes

$$\ell_c = p^1 f(a_1,K_1) + p^2 g(a_2,K_2,h) - c^{I_i}(I_i) - p^h h + s a_1 - th + l\left[I_i - \delta K_i\right] + n^F\left[A - a_1 - a_2\right]$$

and the relevant maximum-principle conditions are

$$\frac{\partial \ell_c}{\partial a_1} = p^1 f_{a_1}(\cdot) + s - n^F = 0 \tag{21}$$

$$\frac{\partial \ell_c}{\partial a_2} = p^2 g_{a_2}(\cdot) - n^F = 0 \tag{22}$$

$$\frac{\partial \ell_c}{\partial h} = p^2 g_h(\cdot) - p^h - t = 0 \tag{23}$$

By comparing the equations (21) – (23) with the corresponding maximum-principle conditions of the social optimum (1), (2) and (4), it is self-evident that the level of the acreage subsidy, *s*, depends on the product of the shadow price of the partridge stock and the marginal growth effect of a_1. Therefore, the socially optimal subsidy for the rye acreage has to be

$$s = m e_{a_1}(\cdot) \tag{24}$$

The similar reasoning results in that the optimal herbicide tax rate has to equal

$$t = D_h(\cdot) - me_h(\cdot) \tag{25}$$

The herbicide tax internalises both direct and indirect effects of herbicide use. The latter consists of the reduced partridge productivity caused by the herbicides and it is weighted with the shadow price of the partridge stock. Furthermore, it is important to note that both the optimal first-best acreage subsidy and the first-best herbicide tax change over time, because they are functions of the shadow price of the partridge stock, m.

Let us next consider the representative hunter's private optimum. We know from the maximum-principle condition (18) that hunters increase harvesting to the point where $p^R - c^X(\cdot) = m^H$. Substituting the above result into (20), yields in the steady state

$$p^R - c^X(\cdot) = \frac{e_B(\cdot)[p^R - c^X(\cdot)]}{\rho + \alpha} - \frac{c_B^X(\cdot)X}{\rho + \alpha}$$

Since $W_B(\cdot)$ is not accounted for by hunters, the marginal benefits of delaying hunting are smaller compared with equation (10). For this reason the steady-state partridge stock, the size of which is defined in the equation

$$\rho = e_B(\cdot) - \alpha - \frac{c_B^X(\cdot)\left[e(\cdot) - \alpha B\right]}{p^R - c^X(\cdot)} \tag{26}$$

is too small compared with the social optimum, which is defined by the equation (11) and the steady-state hunting bag, $x = e(\cdot) - \alpha B,$ is thus unoptimally large.

To prevent over-exploitation of the partridge stock, the government may introduce a hunting licence fee, z, for the hunter, after which the hunter's current-value Hamiltonian function becomes

$$H_c = p^R X - c^X(B)X - zX + m^H\left[e\left(B, a_1, h\right) - X - \alpha B\right]$$

The maximum-principle conditions are

$$\frac{\partial H_C}{\partial X} = p^R - c^X(\cdot) - z - m^H = 0 \tag{27}$$

$$\dot{B} = \frac{\partial H_c}{\partial m^H} = e(\cdot) - X - \alpha B \tag{28}$$

$$\dot{m}^H = -\frac{\partial H_c}{\partial B} + \rho m^H = c_B^X(\cdot)X + m^H\left[\alpha + \rho - e_B(\cdot)\right] \tag{29}$$

After substituting $m^H = p^R - c^X(\cdot) - z$ into (29), we have in the steady state

$$p^R - c^X(\cdot) = \frac{e_B(\cdot)[p^R - c^X(\cdot)]}{\rho + \alpha} - \frac{c_B^X(\cdot)X}{\rho + \alpha} + z \tag{30}$$

Thus it is easy to see by comparing (30) with (10) that the partridge hunting fee is made internal to the representative hunter's decision, if we set

$$z = \frac{W_B(\cdot)}{\rho + \alpha} \tag{31}$$

i.e., the hunting licence fee equals the present value of the marginal stock benefits.

3. Empirical illustration

In this section, we demonstrate our analytical findings with an empirical illustration of the impacts of farming decisions on the grey partridge population in Finland. First, we give some background on the grey partridge and the cultivation of rye in Finland. Second, we discuss the population dynamics of the grey partridge by developing a physical balance equation to illustrate grey partridge population relationships. We utilise previous valuation studies to approximate the use value of a bagged partridge and the non-use value of a partridge stock in monetary terms to find suitable estimates for m and $W_B(\cdot)$. Our ultimate purpose is to assess the components of those policy instruments derived in the previous section to gain insight into how to estimate, in monetary terms, the optimal rye acreage subsidy and herbicide tax rates and the hunting licence fee. Finally, we discuss the benefits and costs of organic rye cultivation which enhances the preservation of the grey partridge.

3.1 Background

Today, the grey partridge is classified as a near-threatened species in Finland (Rassi *et al*., 2001). If no additional measures are taken, it is predicted that the current agricultural policies will lead to further decline in the species. The present size of the breeding population is 4,000 pairs, and the winter population is approximately 20,000 individuals. In the 1950s, the size of the breeding partridge stock was estimated to be 15,000 pairs (Väisänen *et al.*, 1998). The reasons for the decline of the species in Finland include reductions in the area under winter cereals as well as adverse effects of agricultural pesticides which decrease the supply of insect food and increase chick mortality. The range of the grey partridge covers the west coast of Finland and the southern and south-western parts of Finland. (Tiainen and Pakkala, 1996)

In Finland, there are nearly 300,000 registered hunters, which is a total of 6% of the Finnish population. Hunters belong to hunting clubs which lease land and water areas for hunting. Leases are often nominal. Land owners and hunting clubs grant or sell hunting permits for areas in their possession. For state-owned lands, hunting permits are sold by the Finnish Forest and Park Service. In northernmost Finland, local inhabitants have free hunting rights on public lands. Moose and deer hunters must purchase a hunting licence. (Hunters' Central Organisation, 2004). There are regional restrictions on partridge hunting, and hunting is concentrated in western Finland. According to statistics produced by the Finnish Game and Fisheries Research Institute (2004), the size of the annual partridge bag has been approximately 1,000 kg in the past twenty years.

Rye is a winter cereal and its shoots provide grey partridges, pheasants and brown hares with vegetation during winter and early spring (Lindén *et al.*, 1996). In contrast to central and western Europe, winter cereal fields in Finland provide better habitats for farmland birds than spring cereal fields. This is because the vegetation in Finnish winter cereal fields is sparse and low during the breeding season of birds (Piha *et al.*, 2003). In addition, rye is suitable for organic farming in which chemical pesticides and fertilisers are not used at all. In 2002, over 20% of Finland's rye area was organically farmed (Plant Production Inspection Centre, 2003). Also the need for herbicides in conventionally farmed rye fields is smaller than, for example, in spring wheat fields, because winter cereal fields have fewer weeds than spring cereal or hay fields (Raatikainen *et al.*, 1978). This benefits the environment, since herbicides also reduce the availability of food for invertebrates and birds.

Although the cultivation of rye provides several environmental benefits as described above, Finnish farmers typically incur relatively high opportunity costs if they cultivate rye. This is because the producer price for rye has not been significantly higher compared to prices for other cereals, and the per-hectare yields in rye production have been smaller than, for example, in spring wheat production. Furthermore, the risk of crop failure is higher in winter cereal production than in spring cereal production. Since those farmers who cultivate rye bear the costs of producing positive environmental effects but do not share the benefits, they do not have an economic incentive to cultivate rye. The lack of incentives reduces the rye area and may also decrease crop diversity, not to mention the partridge stock and hunters' partridge bags. Thus, it is hardly surprising that the arable area under rye in Finland in past decades has typically been less than 3% of the total cereal area (Information Centre of the Ministry of Agriculture and Forestry, 2003). Furthermore, as a result of the CAP reform, agreed on June 2003 in Luxembourg, rye will be excluded from the intervention system of the European Union (Council, 2003). According to Lehtonen *et al.* (2004), this will make rye a relatively unprofitable crop to cultivate in Finland if no other production-linked support for rye is established.

3.2 Physical balance equation

Bearing in mind that we assumed earlier the following equation of motion for the partridge stock

$$\dot{B} = e(B, a_1, h) - X - \alpha B$$

We modify the production function to explicitly include the size of the breeding population $(1-\alpha)B$.

$$\dot{B} = e\big((1-\alpha)B, a_1, h\big) - X - \alpha B$$

Hence B is the size of the winter population and parameter α now measures the overwinter mortality rate of partridges.

To provide a solution for the annual net production of grey partridges, we assume that the partridge stock is currently in the long run equilibrium (*i.e.* $\dot{B} = 0$). The size of the steady-state (winter) population, B^s, in Finland is currently 20,000 birds (Väisänen *et al.*, 1998). We assume that the overwinter mortality of partridges is 0.60. This is a moderate mortality rate compared to Potts (1986) who reported $\alpha = 0.76$. The size of the breeding population is 8,000 $[= (1-\alpha)B^s = 0.4 \times 20{,}000]$ birds and the number of breeding pairs is simply assumed to be 4,000. In recent years, the annual partridge bag, X, has been approximately 2,000 birds (Finnish Game and Fisheries Institute). If 12,000 partridges die during the winter and 2,000 are killed by hunters, the annual net production of partridges has to be 14,000 in order to maintain the balance.

For future reference, we assume that each pair has an average of seven chicks of which half will survive. Hence in the steady state the annual net production of partridges is $0.5 \times (4{,}000 \times 7) = 14{,}000$ and the gross production is 28,000 immature birds.

3.3 Valuation of grey partridges

Since there is no market price for a grey partridge, the minimum value of a bagged partridge is assumed to be €5. This estimate is based on the statistics of the Finnish Game and Fisheries Institute reporting annually the calculatory values of annual hunting bags. The basis for valuation is the value of the meat received from the hunting bag, and this can be used as a minimum estimate for economic value.

Besides the value of meat, hunting has a significant recreational component. Using the contingent valuation method, Ovaskainen *et al.* (1992) found that the value of meat accounted for only 11-12% of the total hunting value of grouse (*Tetraonidae*) in Finland. If this is generally true for all Finnish game birds, the recreational value of a bagged partridge would be about €45. Also, the existence value derived from the very presence of grey partridges might be significant, since the grey partridge is classified as a near-threatened species in Finland, but without any research results it is difficult to estimate how much people would be willing to pay to ensure the continued presence of the grey partridge. Our upper limit for the total hunting value of a grey partridge is thus €45.

3.4 Optimal policy instruments

Rye subsidy rate
In the natural production function of grey partridges, $e((1-\alpha)B, a_1, h)$, the area under rye, a_1, supports the growth of the grey partridge population. In the distribution area of grey partridges, the average area under rye has been approximately 18,300 hectares during 1995-2003. Therefore one additional rye hectare increases the annual net production of grey partridges (14,000 birds) on average by $e_{a_1}(\cdot) = 14{,}000/18{,}300 \approx 0.8$ bird/ha. This corresponds well with the documented partridge density in the UK during the first half of the 20th century when herbicides and pesticides were not used intensively (De Leo *et al.*, 2004). Given our earlier assumption that the shadow price of an additional partridge lies between €5 to €45 per bird, we can approximate the optimal support to be

$$s \quad = \quad me_{a_1}(\cdot) \quad = \quad (5 \to 45) \times 0.8 \quad = \quad 4 \to 36 \qquad (24')$$

The per hectare support to rye should be €4-36 /ha depending on the value of the grey partridge.

Herbicide tax rate
Let us then suppose that the use of pesticides in Finland has been completely abolished. We assume that as a result of this, the fraction of immature birds that survive will increase from 0.5 to 0.6. This is based on a Danish study (Hald (2002) referred in Schou *et al.*, 2002) according to which even 6 metre wide pesticide free margins in cereal fields increase the survival of partridge chicks by 10 percentage points.

The net production of partridges will, in the following year, increase from 14,000 birds to 16,800 birds (*i.e.* by 2,800 partridges per annum) as a result of the increase in the survival fraction. In per hectare terms this yields $e_h(\cdot) = 2{,}800/18{,}300 \approx 0.15$ bird/ha. Furthermore, according to Siikamäki (1997), a Finnish consumer would be willing to pay annually €69 if the use of pesticides in agriculture was completely abolished. The total willingness to pay is then approximately €250 million. Since the total arable land area under cultivation in Finland is about 2.2 million hectares, this yields $D_h(\cdot) = 114$ €/ha. Therefore, the herbicide tax rate per hectare

$$t \quad = \quad D_h(\cdot) - me_h(\cdot) \quad = \quad 114 + [(5 \to 45) \times 0.15] \quad = \quad 114.75 \to 120.75 \qquad (25')$$

lies within the range of 115 €/ha and 121 €/ha depending on the partridge value.

Optimal hunting licence fee
The value of grey partridges to humans includes stock benefits, which are sensitive to changes in the total size of the population. We showed earlier that the optimal hunting licence fee equals the present value of the marginal stock benefits. Hence the hunting licence fee is 8 to 69 €/bird.

$$z \quad = \quad \frac{W_B(\cdot)}{\rho + \alpha} \quad = \quad \frac{(5 \to 45)}{0.05 + 0.60} \quad = \quad 7.69 \to 69.23 \qquad (31')$$

All in all, we have been able to value, in monetary terms, the socially optimal policy instruments needed for correcting for the market optimum. We are fully aware that we have made certain bold assumptions to derive the results, but our purpose has been to show how the process of choosing the optimal levels for policy instruments should be carried out if authorities were considering intervention. This procedure is applicable for many components of agri-environmental support schemes implemented throughout the European Union.

Evaluation of non-market benefits and opportunity costs of organic rye cultivation
Using the figures derived above we can summarise the non-market benefits of organic rye cultivation supporting the grey partridge population as depicted in Table 1. It must be remembered that we assume the average area under organic rye yields roughly one bird (0.8 + 0.15) per hectare.

Table 1. Per hectare non-market benefits of organic rye cultivation (€/ha)

Value of a rye hectare supporting grey partridge hunting if the use of pesticides in agriculture is abolished	€5 – 43/ha
Consumers' willingness to pay for the abolishing of the use of pesticides in agriculture[a]	€114/ha

[a]Siikamäki, 1997 (Includes other values than the valuation of impacts on the grey partridge stock).

The non-market benefits should be compared with the opportunity costs of organic rye cultivation. The average producer prices of rye and spring wheat have been almost equal during Finland's EU membership. However, there has been a big difference between the productivity of these two cereals. During 1995-2003, the average market price of wheat (converted into the price level for 2000 by the agricultural price index, cereals) has been €141.15 per tonne. In the same period, the average market price of rye has been €140.96/tonne. In the distribution area of grey partridges, the average annual per hectare yield of spring wheat (weighted by regional output volumes) has been 3,328kg/ha. The corresponding figure for rye is 2,359kg/ha. Since, according to the statistics produced by the Plant Production Inspection Centre, the hectare yields of rye in organic production during 1999-2002 have been approximately 67% of the yields in conventional production, we assume that the hectare yield of rye in organic production is 1,573kg/ha. As both the price and the average per hectare yield of spring wheat are higher than those for rye, the farmer loses sales revenues amounting to €240 per hectare if he cultivates organic rye instead of conventionally cultivated spring wheat. Similarly, the opportunity cost is € 110, if organic rye is compared with conventional rye.

The calculated opportunity cost of €110-240 is an upper bound for opportunity costs, because the annual support for organic production has been €102.59ha^{-1} following a two-year conversion period. Given the consumers' strong support for organic farming measured by their willingness to pay (Siikamäki 1997) the subsidy seems to be well justified if the benefits received from grey partridge hunting are included as well. In fact, since rye fields also offer food and shelter to pheasants and brown hares, one should also include the benefits received from those species when evaluating the welfare contribution of organic rye cultivation. However, one should be careful not to double-count the benefits when valuing individual species separately.

5. Conclusions

We investigated the link between agricultural production and commodity and non-commodity outputs of agricultural production. By using the dynamic framework, we showed that the uncontrolled economy leads to too small a cultivation area of rye, an excessive use of herbicides in weed control, and overly large partridge hunting bags, compared to the socially optimal situation. The area under rye remains too small because farmers, when making their crop choices, do not consider that rye cultivation adds social welfare by increasing the reproduction rate of the partridge stock, from which humans derive welfare. Equally, farmers also ignore the harmful effects of herbicides. This implies welfare losses in the form of direct adverse effects to humans and reductions in hunting bags, as well as in other benefits derived from the partridge stock, because herbicides decrease the biological growth of the partridge population. We also demonstrated that the private optimum is realised at the lower partridge stock level and the hunting rate is excessively high, because hunters maximise their net recreational hunting benefits but do not cater for the stock benefits that accrue for society at large.

The above findings justify government intervention to internalise biodiversity benefits in the economic decision-making of farms. In Finland, the annual area support to organic production has been €102.59ha^{-1} after a two-year conversion period. Our empirical illustration shows that the subsidy per hectare seems to be well justified by the benefits derived from grey partridge hunting, given consumers' overall support for organic farming. However, simply launching area support does not provide the proper incentives, so an input tax on herbicides is required. Hunting of the grey partridge should be controlled by hunting fee which would become very high when the size of the population approached a critically low, predetermined risk level.

In spite of recent pro-environmental change, the multifunctional character of agriculture necessitates lateral thinking for policymakers, because even a small change in agricultural support may sometimes significantly affect the provision of public goods from agriculture. Since the marginal value of the partridge stock is a function of time, optimal agri-environmental policy also includes dynamic characteristics. Therefore, the levels of subsidy and tax would vary according to the shadow price of the partridge stock. This feature adds complexity not only to the theoretical analyses, but also to agri-environmental policy design and implementation.

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