Biodiversity and economic incentives in agriculture

Integrating bird fauna values into decision-making

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Abstract

Our optimal control model identifies economic reasons as to why several farmland bird populations have dramatically declined in modern agricultural landscapes. By integrating bird fauna values into decision-making on cereal crop choice, herbicide use and hunting bag size, we derive those economic instruments needed for enhancing biodiversity on farmland and reversing the decline of grey partridge (*Perdix perdix*) populations. Based on the Finnish data available, we illustrate how the optimal acreage subsidy for organically-grown rye areas, the herbicide tax rate and the grey partridge hunting licence fee could be estimated in monetary terms. The procedure to derive and value the first-best policy instruments is applicable for various components of agri-environmental schemes implemented throughout the European Union.

Keywords: grey partridge, herbicides, organic farming, recreational hunting, 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. In spite of this, agricultural intensification and specialisation, along with the decline of livestock farming have clearly caused the loss of wildlife habitats. An alarming indicator for the state of biodiversity in cereal ecosystems is the decreasing abundance of farmland birds. In particular, the grey partridge (*Perdix perdix*), a game bird of open arable landscapes which lives mainly in cereal crops, has been adversely affected by the intensification of agriculture throughout Europe. This is significant because more than any other bird species, the grey partridge can be considered to be an indicator of biodiversity in cereal ecosystems (Potts, 1986; Hagemeijer and Blair, 1997; Pimentel and Greiner, 1997; Potts, 1997; Sotherton, 1998; Chamberlain and Fuller, 2000; Heath and Rayment, 2003; De Leo *et al.*, 2004).

As rapid changes in land use curtail environmental benefits, effective measures to conserve wildlife in agricultural areas become necessary (*e.g.*, Lowe and Whitby, 1997; Weersink *et al*. 1998; Hanley and Oglethorpe, 1999). To date, the pricing of biodiversity has focused on the valuation of individual species using contingent valuation (CV) and other methods of stated preferences (Loomis and White, 1996; Montgomery *et al.*, 1999). 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 cereal crops and herbicides the farmers choose to use. We also take into account hunters' recreational hunting decisions, and the fact that the partridge stock provides welfare beyond recreational hunting. The primary purpose of this study is to demonstrate how to derive and value in monetary terms those policy instruments needed for adopting required environmental measures and agricultural practices to produce socially optimal amounts of commodity and non-commodity outputs of agriculture.

There is an extensive and increasing volume of literature concerning agri-environmental schemes and policies for multifunctional agriculture (*e.g.*, Peterson *et al*., 2002; Lankoski and Ollikainen, 2003; Dobbs and Pretty, 2004). In addition, aspects of biodiversity preservation and wildlife management in agriculture are increasingly considered in the analyses (*e.g.*, Wossink *et al*., 1999; Bulte and Horan, 2003; van Wenum *et al.*, 2004). However, there are only a 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. The studies of Hyde (1989) and Montgomery *et al*. (1994) construct marginal cost curves of forest bird species and treat abundance of birds as an alternative of timber production. 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 the socially optimal level of farmland biodiversity and corresponding input uses in cereals crop production.

In our framework, the environmental externalities lead to a socially inefficient allocation of arable land, excess use of herbicides and over-exploitation of partridge stock, since private valuations of inputs and outputs are different from their social valuations. We develop the first-best policy instruments to internalise bird fauna values in the economic decision-making of farmers and hunters. 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. In the second section, we introduce some background information on grey partridges, recreational hunting and cultivation of cereals in Finland. In the third section, 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. In the fourth section, we provide an empirical illustration of the use of biodiversity values in the design of individual policy measures. We also value the socially optimal policy measures in monetary terms. Concluding remarks are provided in the last section. The applied framework and produced empirical results give useful insights into the ongoing process of shaping policies to implement and improve agri-environmental schemes in the European Union (EU).

2. Background

European grey partridge populations have declined remarkably since the 1930s, and the bird is currently listed among species with an unfavourable conservation status (Potts, 1986; De Leo *et al*., 2004). If no additional measures are taken, it is predicted that the current agricultural policies will lead to further decline in the species. In Finland, the grey partridge is classified as a near-threatened species (Rassi *et al*., 2001). The present size of the breeding population is only 4,000 pairs. In the 1950s, the breeding population size 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 (Tiainen and Pakkala, 1996).

In Finland, there are nearly 300,000 registered hunters, 6% of the whole Finnish population (Hunters' Central Organisation, 2005). 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. Game populations are regulated using closed seasons, and hunting is scaled in accordance with game stocks. There are regional restrictions on grey partridge hunting which is concentrated in western Finland. According to statistics produced by the Finnish Game and Fisheries Research Institute (2004), the size of the annual grey partridge bag has been approximately 1,000 kg (2,000 birds) in the past twenty years.

In the EU, rye is cultivated mainly in Poland and Germany. In Finland, 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 (Piha *et al.*, 2003). This is because the vegetation in Finnish winter cereal fields is sparse and low during the breeding season of birds. 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, bird densities and hunters' grey 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 Common Agricultural Policy reform, agreed on June 2003 in Luxembourg, rye will be excluded from the intervention system of the EU (Council, 2003). According to Lehtonen *et al.* (2004), this will make rye a relatively unprofitable cereal to cultivate in Finland if no other production-linked support for rye is established.

3. Analytical framework

In this section, we introduce a theoretical framework for cereals production and grey 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. Then we develop the first-best policy instruments to internalise the externalities.

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. Agricultural land is allocated 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 farmland will be captured by the Lagrangian multiplier for the arable land constraint in the optimisation problem.

Sector-specific know-how and physical and human capital invested in the chosen agricultural technology, organic or conventional, is denoted by K_i (i = 1,2). The 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. 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.

In both agricultural sectors, 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 sector-specific investment, *i.e.* $\partial c^{I_i}(I_i)/\partial I_i \equiv c^{I_i}_{I_i}(\cdot) > 0$ and $\partial^2 c^{I_i}(I_i)/\partial I_i^2 \equiv c^{I_i}_{I_i I_i}(\cdot) > 0$. Furthermore, farmers are assumed to 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.

The application of herbicides in agriculture may expose humans to poisonings and related illnesses. The (direct) adverse effects of herbicides are denoted by $D(h)$, and we assume that $D_h(\cdot) > 0$ and $D_{hh}(\cdot) > 0.$ 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).

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 the amount of partridges shot, *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 parameter *α* measures the constant natural mortality rate of grey 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 own recreational hunting experience. The total hunting value of a bagged grey partridge consists mainly of recreational benefits that are typically much larger than the value of meat received from the hunting bag. The benefits of hunting, net of hunting costs, are given by *R*(*X*) so that $R_X(\cdot) > 0$ and $R_{XX}(\cdot) < 0$.

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*). We assume that $W_B(\cdot) > 0$ and $W_{BB}(\cdot) < 0$.

3.1 Social planner's problem

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

$$\text{Max} \int_0^\infty \left[p^1 f(a_1, K_1) + p^2 g(a_2, K_2, h) - c^{I_1}(I_1) - c^{I_2}(I_2) - p^h h - D(h) + R(X) + W(B) \right] e^{-\rho t} dt$$

$$\text{subject to} \qquad \dot{K}_i = I_i - \delta K_i \qquad K_i(0) = K_{i0} > 0 \qquad (i = 1,2)$$

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

$$\text{and} \qquad a_1 + a_2 = A$$

In the above optimal control problem, ρ (≥ 0) is the rate of discount, K_{i0} (i = 1,2) refers to the initial stock of sector-specific farm 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

$$\ell_c = p^1 f(a_1, K_1) + p^2 g(a_2, K_2, h) - c^{I_1}(I_1) - c^{I_2}(I_2) - p^h h - D(h) + R(X) + W(B)$$
$$+ l_1\left[I_1 - \delta K_1\right] + l_2\left[I_2 - \delta K_2\right] + m\left[e(B, a_1, h) - X - \alpha B\right] + n\left[A - a_1 - a_2\right]$$

where l_i (i = 1,2) is the shadow price of sector-specific 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

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

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

$$\frac{\partial \ell_c}{\partial I_i} = -c_{I_i}^{I_i}(\cdot) + l_i = 0 \quad (i = 1,2) \tag{3}$$

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

$$\frac{\partial \ell_c}{\partial X} = R_X(\cdot) - m = 0 \tag{5}$$

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

$$\dot{K}_i = \frac{\partial \ell_c}{\partial l_i} = I_i - \delta K_i \quad (i = 1,2) \tag{6}$$

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

$$\dot{l}_1 = -\frac{\partial \ell_c}{\partial K_1} + \rho l_1 = -p^1 f_{K_1}(\cdot) + l_1\left[\delta + \rho\right] \tag{8}$$

$$\dot{l}_2 = -\frac{\partial \ell_c}{\partial K_2} + \rho l_2 = -p^2 g_{K_2}(\cdot) + l_2\left[\delta + \rho\right] \tag{9}$$

$$\dot{m} = -\frac{\partial \ell_c}{\partial B} + \rho m = -W_B(\cdot) + m\left[\alpha + \rho - e_B(\cdot)\right] \qquad (10)$$

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

$$\lim_{t\to\infty} l_1(t) \geq 0 \;(=0, \text{ if } \lim_{t\to\infty} K_1(t) > 0), \lim_{t\to\infty} l_2(t) \geq 0 \;(=0, \text{ if } \lim_{t\to\infty} K_2(t) > 0) \text{ and } \lim_{t\to\infty} m(t) \geq 0 \;(=0, \text{ if } \lim_{t\to\infty} B(t) > 0)$$

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 cereals are cultivated, the sum of the values of marginal products of arable area devoted to the production of crop 1 and grey partridges is equal to the value of the marginal product of arable land under crop 2.

In both sectors, equation (3) directs increasing human capital, machinery and building investments to the point where the marginal adjustment cost is equal to the sector-specific 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. Equation (5) implicates that the social planner should increase the hunting bag to the point where the marginal net benefits of recreational hunting are equal to the marginal current value of an additional partridge.

According to equation (6), the steady state for farm capital stocks is characterised by the equality of sector-specific investment and sector-specific capital depreciation. 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 $dl_1/dt = 0$ $(dl_2/dt = 0),$ the equation of motion for the costate variable l_1 (l_2) can be written as $l_1(\delta + \rho) = p^1 f_{K_1}(\cdot)$ $\left(l_2(\delta + \rho) = p^2 g_{K_2}(\cdot)\right)$ implicating that the marginal user cost of sector-specific capital should be equal to the value of the marginal product of sector-specific capital. Finally, when $dm/dt = 0,$ equation (10) can be solved for *m*, *i.e.*

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

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, $W_B(\cdot)$, and the marginal contribution of partridge stock to future social welfare, $\rho + \alpha - e_B(\cdot)$. From (5) we have $m = R_X(\cdot)$. If we make this substitution into equation (10), we have in the optimal steady state

$$R_X(\cdot) = \frac{e_B(\cdot)\, R_X(\cdot)}{\rho + \alpha} + \frac{W_B(\cdot)}{\rho + \alpha} \tag{11}$$

The left-hand side of the equation (11) 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, $e_B(\cdot)\, R_X(\cdot)$, and the marginal welfare effect of the increased partridge stock, $W_B(\cdot)$. Because of the accumulation phenomenon, the instantaneous marginal incentives have to be discounted by dividing with the sum of the rate of discount and the natural mortality rate of grey partridges, $\rho + \alpha$.

Equation (11) can be solved for the rate of discount

$$\rho = e_B(\cdot) - \alpha + \frac{W_B(\cdot)}{R_X(\cdot)} \tag{12}$$

The equation (12) states that the rate of discount equals the own rate of return of the partridge stock. The latter has two components: the net marginal productivity of the resource stock, $e_B(\cdot) - \alpha$, and the marginal stock effect, $W_B(\cdot) / R_X(\cdot)$, which consist of increased social welfare from the stock benefits. Thus, the hunting rate is socially optimal when the net product of the partridge stock is equal to the discount rate. Along with $x = e(\cdot) - \alpha B$, equation (12) defines the modified-golden-rule value of the socially optimal steady-state partridge stock.

3.2 Representative farmer's private optimum

In this section, we consider a representative farmer whose objective is to maximise profit from the cultivation of cereal crops. The current-value Lagrangian function takes the form

$$\begin{aligned} \ell_c = {} & p^1 f(a_1, K_1) + p^2 g(a_2, K_2, h) - c^{I_1}(I_1) - c^{I_2}(I_2) - p^h h \\ & + l_1^F \left[I_1 - \delta K_1 \right] + l_2^F \left[I_2 - \delta K_2 \right] + n^F \left[A - a_1 - a_2 \right] \end{aligned}$$

where the shadow prices of sector-specific capital are indicated with l_i^F $(i = 1,2)$ and the shadow price of arable land is denoted by n^F.

We may list the following conditions by the maximum principle

$$\frac{\partial \ell_c}{\partial a_1} = p^1 f_{a_1}(\cdot) - n^F = 0 \tag{13}$$

$$\frac{\partial \ell_c}{\partial a_2} = p^2 g_{a_2}(\cdot) - n^F = 0 \tag{14}$$

$$\frac{\partial \ell_c}{\partial I_i} = -c_{I_i}^{I_i}(\cdot) + l_i^F = 0 \quad (i = 1,2) \tag{15}$$

$$\frac{\partial \ell_c}{\partial h} = p^2 g_h(\cdot) - p^h = 0 \tag{16}$$

$$\dot{K}_i = \frac{\partial \ell_c}{\partial l_i^F} = I_i - \delta K_i \quad (i = 1,2) \tag{17}$$

$$\dot{l}_1^F = -\frac{\partial \ell_c}{\partial K_1} + \rho l_1^F = -p^1 f_{K_1}(\cdot) + l_1^F \left[\delta + \rho\right] \tag{18}$$

$$\dot{l}_2^F = -\frac{\partial \ell_c}{\partial K_2} + \rho l_2^F = -p^2 g_{K_2}(\cdot) + l_2^F \left[\delta + \rho\right] \tag{19}$$

The maximum-principle condition (15) and the equations of motion (17-19) indicate that the optimal investment rules in sector-specific capital are the same as at the social optimum (cf. equations (3), (6), (8) and (9)). 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 (13), (14) and (16) with equations (1), (2) and (4). The organically-grown rye area will be smaller than socially optimal, and, since the land under agriculture is constant, the spring wheat area will be larger than socially optimal. Furthermore, at the representative farmer's private optimum, the herbicides are used excessively from the social point of view.

3.3 Representative hunter's private optimum

We approximate the Finnish situation and assume here that farmers do not charge for the rights to hunt[1]. Therefore, hunters act as sole owners of the partridge stock, and that they maximise the net hunting benefits subject to the equation of motion for the grey partridge stock.

[1] In the appendix we show the optimal solution whereby farmers have the property rights and they charge for hunting.

The current-value Hamiltonian function is

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

where the shadow price of the partridge stock is now indicated with m^H.

The maximum-principle conditions are

$$\frac{\partial H_c}{\partial X} = R_X(\cdot) - m^H = 0 \tag{20}$$

$$\dot{B} = \frac{\partial H_c}{\partial m^H} = e(\cdot) - X - \alpha B \tag{21}$$

$$\dot{m}^H = -\frac{\partial H_c}{\partial B} + \rho m^H = m^H \left[\alpha + \rho - e_B(\cdot)\right] \tag{22}$$

When comparing the above maximum-principle conditions with the maximum-principle conditions of the social planner, there is a difference between equations (10) and (22) because hunters do not take into account existence value and the fact that the natural biological stock also provides economic welfare to society above and beyond hunting.

We know from the maximum-principle condition (20) that hunters increase harvesting to the point where $R_X(\cdot) = m^H$. Substituting the above result into (22) yields in the steady state

$$R_X(\cdot) = \frac{e_B(\cdot) R_X(\cdot)}{\rho + \alpha}$$

Since $W_B(\cdot)$ is not accounted for by hunters, the marginal benefits of delaying hunting are smaller compared with equation (11). Therefore, the steady-state hunting bag, $X = e(\cdot) - \alpha B,$ is thus unoptimally large at the representative hunter's private optimum and the steady-state partridge stock, the size of which is defined by the equation

$$\rho = e_B(\cdot) - \alpha \tag{23}$$

is too small compared with the social optimum, which is defined by the equation (12) (cf. Li *et al*., 2001).

3.4 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

$$\ell_c = p^1 f(a_1, K_1) + p^2 g(a_2, K_2, h) - c^{I_1}(I_1) - c^{I_2}(I_2) - p^h h + s a_1 - th$$
$$+ l_1^F \left[I_1 - \delta K_1\right] + l_2^F \left[I_2 - \delta K_2\right] + n^F \left[A - a_1 - a_2\right]$$

The relevant maximum-principle conditions are

$$\frac{\partial \ell_c}{\partial a_1} = p^1 f_{a_1}(\cdot) + s - n^F = 0 \tag{24}$$

$$\frac{\partial \ell_c}{\partial a_2} = p^2 g_{a_2}(\cdot) - n^F = 0 \tag{25}$$

$$\frac{\partial \ell_c}{\partial h} = p^2 g_h(\cdot) - p^h - t = 0 \tag{26}$$

By comparing the equations (24) – (26) 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

$$s = m e_{a_1}(\cdot) \tag{27}$$

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

$$t = D_h(\cdot) - me_h(\cdot) \tag{28}$$

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 (27) and the first-best herbicide tax (28) change over time, because they are functions of the shadow price of the partridge stock, which is a function of continuous time.

Let us next consider the representative hunter's private optimum. To prevent over-exploitation of the partridge stock, the government may introduce a special hunting licence fee, *z*, for the grey partridge hunter, after which the hunter's current-value Hamiltonian function becomes

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

The relevant maximum-principle conditions are

$$\frac{\partial H_C}{\partial X} = R_X(\cdot) - z - m^H = 0 \tag{29}$$

$$\dot{m}^H = -\frac{\partial H_c}{\partial B} + \rho m^H = m^H\left[\alpha + \rho - e_B(\cdot)\right] \tag{30}$$

After substituting $m^H = R_X(\cdot) - z$ into (30), we have in the steady state

$$0 = (R_X(\cdot) - z)\left[\alpha + \rho - e_B(\cdot)\right]$$

Thus it is easy to see that the partridge hunting fee is made internal to the representative hunter's decision, if we set

$$z = R_X(\cdot) = m \tag{31}$$

i.e., the hunting licence fee equals the shadow price of partridge stock.

4. Empirical illustration

In this section, we demonstrate our analytical findings with an empirical illustration of the impacts of farming and hunting decisions on the grey partridge population in Finland. First, we discuss the population dynamics by developing a physical balance equation to illustrate grey partridge population relationships. We utilise statistics and previous valuation studies to approximate the use value of a bagged partridge and marginal social damages of herbicide use in monetary terms to find suitable estimates for *m* and $D_h(\cdot)$. 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 organic rye acreage subsidy and herbicide tax rates and the hunting licence fee. Finally, we discuss the benefits and costs of organic rye cultivation.

4.1 Physical balance equation

As mentioned, the size of the breeding population of the grey partridge in Finland is currently 4,000 pairs (Väisänen *et al.*, 1998). We presume that each pair has an average of four and half chicks of which 40% will survive. The annual net production of partridges is then $0.4 \times 4.5 \times 4{,}000 = 7{,}200$ immature birds.

We assume that the natural production function of grey partridges is additively separable, and derive a linear approximation of the production function around the steady state

$$e(\cdot) = e_B(\cdot)\,B + e_{a_1}(\cdot)\,a_1 - e_h(\cdot)\,h \tag{32}$$

The marginal product of a grey partridge, $e_B(\cdot)$, is assumed to be 0.23 and the size of the steady-state breeding population, *B*, simply 8,000 partridges.

In the natural production function of grey partridges, the area under rye supports the growth of the grey partridge population. In the distribution area[2] of grey partridges, the average area under rye, a_1, has been approximately 18,300 hectares during 1995-2003. Therefore, one additional rye hectare increases the annual net production of grey partridges (7,200 birds) on average by $e_{a_1}(\cdot) = 7{,}200/18{,}300 = 0.39$ bird/ha. This corresponds well with the documented partridge density in the UK during the first half of the 20th century when pesticides were not used intensively (De Leo *et al.*, 2004).

The use of herbicides decreases the supply of insect food and increases grey partridge chick mortality. Let us next suppose that the use of pesticides in Finland will be completely abolished. We assume that as a result of this, the fraction of surviving immature partridges will increase from 0.4 to 0.5. This is based on a Danish study (Hald, 2002, referred in Schou *et al.*, 2002) in which even 6 metre wide pesticide-free margins in cereal fields increased the survival of partridge chicks by 10 percentage points. As a result of the increase in the survival fraction, the net production of grey partridges will, in the following year, increase from 7,200 birds to 9,000 birds (*i.e.* by 1,800 partridges per annum). In per hectare terms, this yields $e_h(\cdot) = 1{,}800/18{,}300 = 0.10$ bird/ha.

The physical balance equation may be written in discrete time format as

$$B_{t+1} - B_t = e_B\, B_t + e_{a_1}\, a_{1t} - e_h\, h_t - X_t - \alpha\, B_t$$

In recent years, the annual partridge bag, X_t, has been approximately 2,000 birds (Finnish Game and Fisheries Institute, 2004). If we assume that the natural mortality rate of grey partridges, α, is 0.65 we may approximate the physical balance equation in the steady state as

$$0 = 1{,}800 + 7{,}200 - 1{,}800 - 2{,}000 - 5{,}200$$

4.2 Valuation of grey partridges and the marginal value of social damages of herbicides use

Since there is no market price for a grey partridge, the minimum value of a bagged grey partridge is assumed to be €5. This estimate is based on the statistics of the Finnish Game and Fisheries Institute reporting annually the value of the meat received from the hunting bags.

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*). If this is generally true for all Finnish game birds, the recreational value of a bagged partridge would be about €45. This is in accordance with Rosenberger and Loomis (2001) who in their annotated bibliography reported net economic recreation values which ranged from $9.81 to $30.82 for waterfowl hunting. Therefore, we assume that the shadow price of an additional partridge is €45.

Also, the existence value[3] derived from the very presence of grey partridges might be significant, since the grey partridge is classified as a near-threatened species in Finland. Unfortunately there are no research results on this subject. We know, however, that the value of a grey partridge in violation of the hunting right is €34. This value is determined on the basis of the guideline values for live game ratified by the Finnish Ministry of Agriculture and Forestry (2001).

According to the results of the CV study by 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.

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[2] 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). Thus the distribution area of grey partridge approximates to areas of six Employment and Economic Development Centres which comprise half of Finland's rye area and 86% of Finland's spring wheat area.

4.3 Optimal policy instruments

The values for socially optimal policy measures are summarised in Table 1.

Table 1. Monetary values of the first-best policy instruments

Rye subsidy rate, *s*	$s = m e_{a_1}(\cdot) = 45 \times 0.39 = €18/\text{ha}$
Herbicide tax rate, *t*	$t = D_h(\cdot) - m e_h(\cdot) = 114 + (45 \times 0.10) = €119/\text{ha}$
Hunting licence fee, *z*	$z = m = €45/\text{bird}$

Given that the shadow price of an additional partridge is €45 and that cultivation of rye enhances preservation of the grey partridge, we can approximate the optimal rye subsidy rate to be €18 per hectare.

The marginal value of direct adverse effects of pesticides is €114 per hectare (Siikamäki, 1997) and the marginal value of the indirect adverse effect of herbicides is €5 per hectare. Therefore, the socially optimal herbicide tax rate is €119 per hectare.

The optimal hunting licence fee is €45 per grey partridge, because we demonstrated that the optimal hunting licence fee equals the shadow price of grey partridge stock.

4.4 Evaluation of non-market benefits and opportunity costs of organic rye cultivation

We can approximate the non-market benefits of organic rye cultivation supporting the grey partridge population by using the figures derived above. According to our illustration, the organic rye area supports approximately a half (0.39 + 0.10) of a grey partridge per hectare. For that reason, if the use of herbicides in agriculture is abolished, the value of a rye hectare supporting grey partridge hunting is €22. In addition, the results obtained by Siikamäki (1997) indicate that the Finnish consumers are willing to pay €114 per hectare for the abolishment of the use of pesticides in agriculture. Therefore, the total non-market benefits of organic rye cultivation are €136 per hectare.

The non-market benefits should be compared with the opportunity costs of organic rye cultivation. According to the statistics produced by the Information Centre of the Ministry of Agriculture and Forestry, the average producer prices of rye and spring wheat have been almost equal during Finland's EU membership. Instead, there has been a large 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 (Statistics Finland, 2004)) has been €141.15 per tonne. In the same period, the average market price of rye has been €140.96 per tonne. In the distribution area of grey partridges, the average annual per hectare yield of spring wheat (weighted by

[3] Equation (10) can be solved for $W_B(\cdot)$ in the steady state, i.e. $W_B(\cdot) = m(\alpha+\rho-e_B(\cdot))$. If we use the figures utilised above and

regional output volumes) has been 3,328 kg/ha. The corresponding figure for rye is 2,359 kg/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 1,573 kg/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 €248 per hectare if he cultivates organic rye instead of conventionally cultivated spring wheat.

The calculated opportunity costs of organic rye cultivation are clearly greater than the estimated non-market benefits. Nevertheless, one should bear in mind that we have focused our attention on the grey partridge. Since rye fields also offer food and shelter to pheasants and brown hares, the benefits received from those species should be included, when evaluating the welfare contribution of organic rye cultivation. However, when valuing individual species separately, one should be careful not to double-count the benefits.

5. Conclusions

We used the grey partridge as an indicator for wildlife in the economic model of cereals cultivation. We showed that agricultural intensification and specialisation to spring cereals cultivation cause the loss of wildlife and farmland biodiversity in the cereal ecosystem. More specifically, our model of cereal crop cultivation and grey partridge hunting indicated that the uncontrolled economy leads to too small a cultivation area of organic rye (*i.e.* crop that produces environmental benefits), an excessive use of herbicides in weed control, and overly large partridge hunting bags compared to the socially optimal situation.

The area under organic rye remains too small because farmers, when making their crop choices, do not consider that organic 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 only maximise their net recreational hunting benefits but do not cater for the stock benefits that accrue for society at large.

The economic incentives that farmers and hunters face are inconsistent with biodiversity and wildlife conservation. Hence the above findings justify government intervention to internalise the externalities. Policy-makers should be able to reward farmers on the production of positive

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assume that the rate of discount is 0.05, we have $W_B(\cdot)$ = €45(0.65 + 0.05 – 0.23) = €21.

environmental benefits. Nowadays the agri-environmental support of the EU compensates predominantly the increased production costs and income losses that result from the implementation of policy measures.

The aim of our study was to derive and value in monetary terms the socially optimal policy instruments needed for correcting the market optimum. We are fully aware that we have made certain bold assumptions while deriving the results, but our purpose has been to demonstrate how the process of choosing the optimal levels for policy instruments should be carried out if the authorities were considering policy intervention. The procedure presented in this paper is also applicable for other situations where agricultural commodities are produced along with public goods.

In Finland, the annual area support to organic production has been €102.59 per hectare after a two-year conversion period during which the support is €147.16 per hectare. Instead, the herbicide use in conventional agriculture is not taxed. Our empirical demonstration suggests that the grey partridge alone justifies about 20 per cent of the organic production support. However, we also demonstrated that simply launching the area support for organic production does not provide the proper incentives for farmers, so a relatively high input tax on herbicides is also required. Since we have altogether three externalities, we also need three instruments to internalise them. Therefore, hunting of the grey partridge should be controlled by hunting licence fee which would become high if the size of the partridge population will approach a critically low, predetermined risk level. At present, there is no hunting licence fee for the grey partridge in Finland. The fee is collected only from the moose and deer hunters.

As the marginal value of the partridge stock is a function of time, optimal agri-environmental policy also includes dynamic characteristics. In addition, because of the joint production, the levels of different policy instruments are linked to each other. Therefore, the levels of rye subsidy, herbicide tax and hunting licence fee would vary according to the shadow price of the partridge stock. These features add complexity to agri-environmental policy design and implementation and make agri-environmental policy and management of game resources integrated.

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Appendix

A situation in which hunting rights belong to farmers who charge for partridge hunting

Let us suppose that the hunting rights of grey partridges belong to farmers who charge for the right to hunt. The partridges are then outputs for farmers and the area under rye and the amount of herbicides used are seen as inputs, since they affect the growth rate of partridges.

If we denote the hunting licence fee by p^X, the profit maximisation problem of a representative farmer is

$$\text{Max} \int_0^\infty \left[p^1 f(a_1, K_1) + p^2 (a_2, K_2, h) - c^{I_1}(I_1) - c^{I_2}(I_2) - p^h h + p^X X \right] e^{-\rho t} dt$$

$$\text{subject to} \qquad \dot{K}_i = I_i - \delta K_i \qquad K_i(0) = K_{i0} > 0 \qquad (i = 1,2)$$

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

$$\text{and} \qquad a_1 + a_2 = A$$

The current-value Lagrangian function is

$$\ell_c = p^1 f(a_1, K_1) + p^2 g(a_2, K_2, h) - c^{I_1}(I_1) - c^{I_2}(I_2) - p^h h + p^X X$$
$$+ l_1^A \left[I_1 - \delta K_1 \right] + l_2^A \left[I_2 - \delta K_2 \right] + m^A \left[e(B, a_1, h) - X - \alpha B \right] + n^A \left[A - a_1 - a_2 \right]$$

and the maximum-principle conditions are

$$\frac{\partial \ell_c}{\partial a_1} = p^1 f_{a_1}(\cdot) + m^A e_{a_1}(\cdot) - n^A = 0 \qquad \text{(A1)}$$

$$\frac{\partial \ell_c}{\partial a_2} = p^2 g_{a_2}(\cdot) - n^A = 0 \qquad \text{(A2)}$$

$$\frac{\partial \ell_c}{\partial I_i} = -c_{I_i}^{I_i}(\cdot) + l_i^A = 0 \quad (i = 1,2) \qquad \text{(A3)}$$

$$\frac{\partial \ell_c}{\partial h} = p^2 g_h(\cdot) - p^h + m^A e_h(\cdot) = 0 \qquad \text{(A4)}$$

$$\frac{\partial \ell_c}{\partial X} = p^X - m^A = 0 \qquad \text{(A5)}$$

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

$$\dot{K}_i = \frac{\partial \ell_c}{\partial l_i^A} = I_i - \delta K_i \quad (i = 1,2) \tag{A6}$$

$$\dot{B} = \frac{\partial \ell_c}{\partial m^A} = e(\cdot) - X - \alpha B \tag{A7}$$

$$\dot{l}_1^A = -\frac{\partial \ell_c}{\partial K_1} + \rho l_1^A = -p^1 f_{K_1}(\cdot) + l_1^A[\delta + \rho] \tag{A8}$$

$$\dot{l}_2^A = -\frac{\partial \ell_c}{\partial K_2} + \rho l_2^A = -p^2 g_{K_2}(\cdot) + l_2^A[\delta + \rho] \tag{A9}$$

$$\dot{m}^A = -\frac{\partial \ell_c}{\partial B} + \rho m^A = m^A[a + \rho - e_B(\cdot)] \tag{A10}$$

By comparing equations (A1) and (A2) to equations (1) and (2), it is self-evident that the areas under both cereals are similar to the social optimum. However, farmers use more herbicides than is socially optimal (equations (A4) and (4)) as they ignore the direct adverse effects of herbicides.

Farmers will set the partridge hunting licence fee, p^X, lower than $R_X(\cdot)$ in order to maximise their profits. From the social point of view, this will lead to an unoptimally low partridge stock and losses in stock benefits.