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Biosecurity in agriculture: an economic analysis of coexistence of professional and hobby production*

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One component of biosecurity is protection against invasive alien species, which are one of the most important threats worldwide to native biodiversity and economic profitability in various sectors, including agriculture. However, agricultural producers are not homogeneous. They may have different objectives and priorities, use different technologies, and occupy heterogeneous parcels of land. If the producers differ in terms of their attitude towards invasive pests and the damages they cause, there are probably external effects in the form of pest spread impacts and subsequent damages caused. We study such impacts in the case of two producer types: profit-seeking professional producers and utility-seeking hobby producers. We show that the hobby producer, having first set a breeding ground for the pest, under-invests in pest control. We also discuss potential policy instruments to correct this market failure and highlight the importance of considering different stakeholders and their heterogeneous incentives when designing policies to control invasive alien species.

Key words: biosecurity, hobby production, invasive alien species.

1. Introduction

Invasive alien species and exotic diseases threaten the environment, health, and production systems worldwide (e.g. Vitousek *et al*. 1996). Such biosecurity hazards are causing harm to human health and potentially large economic losses to agricultural producers in the regions tainted with the pest or the disease. Besides affecting agricultural production and income of individual farmers, pest and disease epidemics are also capable of causing havoc in the agricultural market on a larger scale as well as threaten supply security and sustainability of production in vulnerable areas. In addition to supply-side effects, epidemics affect the demand for goods both directly (through price) and indirectly (through perceptions).

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Such effects may be sizable. For instance Pimentel *et al.* (2001) estimate the annual costs of arthropods on crops to be \$15.9 billion in the US, \$0.96 billion in the UK, \$0.94 billion in Australia, \$1.0 billion in South Africa, \$16.8 billion in India and \$8.5 billion in Brazil. Invasions are thus costly, occur on a global scale and will continue rapid increase due to interactions with other global changes such as increasing globalisation of markets and increases in global trade, travel and tourism. In the northern regions climatic changes are predicted to increase invasion attempts of alien species, including those detrimental to agriculture (Jeffree and Jeffree 1996). Biosecurity policies aim to protect production, ecosystems and human health from exotic pests and diseases. Such policies have previously often been on *ad hoc* basis, tailored for an individual problem at hand, but several pest and disease outbreaks in recent years have forced the decision makers to begin looking at the issue more systematically, allowing for a more integrated and cost-efficient policy making (Biosecurity Council 2003).

Another trend affecting the invasive species issue is the increasing heterogeneity of farmers and rural people as a whole and increasing specialisation of agricultural enterprises. Nowadays producers are often specialising in only one type of crop or animal and may lose interest and skills needed in other forms of production. The agricultural sector has evolved also in numbers: there are very few professional farmers in the western countries whereas the number of semi-professional, hobby and life-style farmers has remained high if not increased.

In New Zealand, the large agricultural reform in the 1980s induced land prices to decrease and the number of hobby farmers to increase. In the European Union, the movement from production-related to de-coupled support has made it attractive in some cases to turn to semi-professional or hobby farming. Additionally, in some countries there has always been active backyard gardening and for instance chicken houses, which, from the point of view of biosecurity, need to be taken as seriously as professional production.

Increasing need for biosecurity and rise in hobby farming mandate consideration of new issues when designing biosecurity policies for the future. Agricultural policies have traditionally been directed towards professional farmers. However, in the case of biosecurity policies hobby producers must also be accommodated in policy design and implementation. This requires differentiated policies and tools as well as more work in policy design and construction of the incentive structures. Consequently, more analysis on pest control policy decisions including both hobby and professional producers is needed.

We study producer behaviour analytically in the case of agents with differing objectives, and illustrate the analytical results using the case of Colorado potato beetle (CPB) in Finland. Instead of one profit-seeking producer type who may choose from alternative production technologies, we deal explicitly with two producer types: (i) a profit-seeking professional producer and (ii) a utility-seeking hobby producer. The two main policy alternatives studied include (i) decentralised policy where decision making is left to producers themselves; and (ii) socially coordinated policy. In the first case, each producer may choose their own actions according to their preferences, characterised by their privately optimal Nash equilibria. The hobby group, even after identifying the presence of the pest, may choose not to act, in essence setting a feeding and breeding ground for the pest. In the case of the coordinated policy the state decides upon the optimal levels of control by hobby and professional producers, characterised by the socially optimal outcome (maximisation of joint welfare).

We extend existing discussion on invasive species by addressing the coexistence of two different producer types with differing attitudes towards pest control by applying an ecological economic model. We extract some stylised results, illustrating the importance of accounting for different stakeholder objectives in invasive alien species control. We highlight the fact that having heterogeneous producers requires differentiated policies and discuss some potential policy instruments that may be used to attain a socially optimal outcome.

The article is organised as follows. Section 2 discusses the basic background issues, including biosecurity and the coexistence of professional and hobby producers. Section 3 presents the analytical model, first discussing the objectives of the hobby and professional producers, followed by optimisation of joint welfare. Section 4 presents the numerical illustration and Section 5 concludes.

2. Biosecurity and hobby production

Biosecurity deals with the exclusion, eradication, or effective management of risks posed by pests and diseases to the economy, environment and human health (Biosecurity Council 2003). One element of biosecurity is protection against invasive alien species.

In case where pre-emptive control measures have failed, reactive control can be used to reduce the damages. Reactive pest control may consist of, for instance, chemical, biological or physical control, field isolation distances and other buffer zones, crop rotation systems and genetic technologies. Stakeholders' incentives are an important factor in determining the magnitude and quality of cooperation authorities can rely on in control policy, and what in reality happens as a result of implementing a specific policy. For instance, in the case of invasive species that threaten agricultural production, cooperation from professional producers may be readily available, whereas the public at large may not be as dependable. The circle of relevant stakeholders may be large. For instance, in New Zealand the primary stakeholders in biosecurity are thought to include primary producers, the public, environmental interest groups, indigenous peoples, scientists, regional councils, the public health sector, industry sectors, and the government (Biosecurity Council 2003).

The aggregate level of pest control is complicated by the fact that producers are not homogeneous. They may have different objectives and priorities, use different technologies, and occupy heterogeneous parcels of land. It is in the interests of professional production-orientated producers to carefully monitor and manage activities related to pest control. In contrast, a significant number of hobby producers are not as clearly interested in profit maximisation through production. Instead, they concentrate on production as a hobby where utility is derived primarily from the work input and from the existence value of the farming activity itself (Mishra *et al.* 2002; Blank 2005). It is presumed that the hobby group is not as interested (or may be disinterested) in pest control activities, and in the absence of specific incentives invests fewer resources in pest control.

If the producers differ in terms of their attitude towards the pest, there are likely to be external effects in the form of pest spread impacts and subsequent damages to the production process. In practice the farmers and the hobby group coexist in a geographically determined area, and the different attitude towards biosecurity may cause one group to affect the economic profitability or utility of the other group. Such impacts are not uncommon. They have been reported for instance in Australia in relation to pig diseases (Schembri *et al.* 2006) and fruit flies (ABC 2003), as well as in Italy (Capua *et al.* 2002) and Denmark (Danish Veterinary and Food Administration 2003) in relation to Newcastle disease.

Our numerical illustration of the CPB provides a similar setting. In the major invasions in Finland (1998 and 2002) 81–83 per cent of the invaded plots were hobby producer plots. The relationship between potato production and the CPB can be considered as a two-step process: (i) by deciding to plant potatoes on a field, a producer practically provides a feeding and breeding ground for the CPB and (ii) by carrying out appropriate pest control practices, the producer attempts to keep the beetle population from growing and thus reduces the spread pressure. If a producer is simply interested in the first part of the production process (planting), and is cavalier about taking care of the corrective action (pest control), s/he as a net effect produces a negative impact on other growers in the area.

Hence, the privately optimal behaviour of different agents needs to be accounted for in policy-making. As for instance Shogren (2000) and Finnoff *et al.* (2005) note, when agents adapt assuming otherwise may lead to biased results. It is thus important to note that the hobby producers do adapt, but not necessarily to the full extent desired by the society. In this paper we assume that the land allocation decisions of both groups, and thus the potato area, are exogenously given and therefore we focus on the second step (the control decisions). This approach has three advantages: (i) it reduces the number of decision variables and simplifies the analytical model; (ii) it enables us to illustrate clearly the problem of under-investment in pest control by hobby producers; and (iii) it highlights the importance of considering the heterogeneity of agents when designing corrective policies. The effects of changes in potato area are subsequently explored through a sensitivity analysis.

We concentrate on the problem of under-investment in pest control by hobby producers, ignoring potential under-investments among professional producers themselves, due to two factors: the high level of contract production with a given set of production rules, and the environmental support programme (covering 95 per cent of Finnish farms) which requires good production practices. By having to follow good production practices the professional producers end up behaving more or less as if they would co-operate on the issue of plant protection, although there are no formal or informal agreements inducing co-operation. Hobby producers on the other hand have different production incentives, are not trained for plant protection, and are very heterogeneous and spatially scattered.

A somewhat similar study to ours is Jakus (1994), which discusses homeowner control decisions regarding tree quality in the homeowner's lot, which in part determines the tree quality in the neighbourhood. The study differs from ours in that the homeowner's actions will not affect any other optimisation decisions, and the homeowner gets utility from neighbourhood tree quality.

3. Analytical model

An analytical model is used to analyse the behaviour of two types of producers and how that behaviour is affected by the presence of the pest. The producer is assumed to account only for the impacts that affect his/her own production, not the external impacts on any neighbouring farms. For simplicity we assume that regardless of the extent of crop damage, the producer price of the agricultural product remains unaffected (small-country assumption).

Professional producers are dealt with using standard production and profit functions. Hobby production is modelled such that the members of the group receive additional utility according to time they spend on production activities. However, time is money and has an opportunity cost, and after a certain point additional time (required to control the pest) yields lower or negative utility.

3.1 Hobby producer: the Nash equilibrium

The hobby producer is a utility maximiser and behaves only in his/her own interest. The situation is characterised as Nash equilibrium. We assume that the preferences of hobby producers can be represented by a single utility function defined over the aggregate consumption of goods (x), the aggregate level of pest control (z_h) applied, and the aggregate time spent on growing the crop (t_p). For simplicity and computational purposes a functional form with a constant elasticity of substitution (CES) is assumed. Parameter σ represents the elasticity of substitution between the different determinants of the utility function. Utility of the hobby producers is given by

$$U(x, z_h, t_p) = \frac{(x^\rho + z_h^\rho + t_p^\rho)}{\rho} \tag{1.a}$$

$$\rho = \frac{\sigma - 1}{\sigma} \leq 1 \tag{1.b}$$

Hobby producers maximise their utility subject to two constraints: the budget constraint $x + cz_h = (1 - \gamma)(M + w\bar{t}_w)$ and the time constraint $t_x + t_z + t_p + \bar{t}_w = T$. The budget constraint determines that the money spent on goods (where the price of goods is normalised to one) plus the money spent on pest control measures with a unit price of c has to be equal to the non-saved share $(1 - \gamma)$ of wealth (M) plus the salary from the fixed time spent working ($\bar{t}_w$) at the hourly wage rate (w). The time constraint determines that the total time spent on consumption of goods (t_x), undertaking pest control (t_z), undertaking crop production and working cannot be greater than the total time available (T). All the variables represent the aggregate values over all hobby producers. For simplicity we also assume that $t_x = x$ and $t_z = z_h$, which imply that one unit of goods and one unit of control substances are consumed per each unit of time, respectively. By solving the budget constraint with respect to x, using the time constraint and the two relationships above, we obtain an expression for t_p. Substituting x and t_p into the utility function (1.a) yields a new utility function, defined over the aggregate level of hobby producers' pest control (z_h)

$$\begin{aligned} V(z_h) = \frac{1}{\rho}\{[(1-\gamma)(M + w\bar{t}_w) - cz_h]^\rho + (z_h)^\rho \\ + [T - (1-\gamma)M - (1+\gamma w - w)\bar{t}_w + (c-1)z_h]^\rho\} \end{aligned} \tag{2}$$

Numerical illustration reveals that the properties of this utility function are such that $\mathrm{d}V/\mathrm{d}z_h <=> 0$ and $\mathrm{d}^2V/\mathrm{d}z_h^2 < 0$. The economic problem of the hobby producer can then be stated as maximisation of Expression (2), using z_h as the decision variable. The first order necessary condition requires

$$\begin{aligned} \frac{\mathrm{d}V}{\mathrm{d}z_h} = -c[(1-\gamma)(M + w\bar{t}_w) - cz_h]^{\rho-1} + (z_h)^{\rho-1} \\ + (c-1)[T - (1-\gamma)M - (1+\gamma w - w)\bar{t}_w + (c-1)z_h]^{\rho-1} = 0 \end{aligned} \tag{3}$$

The solution of Expression (3) yields the demand function for pest control by the hobby producers on aggregate (z_h^N). We use the N superscript to stress that this is Nash equilibrium (i.e. a private optimum). The expression is solved numerically later in the article. Notice that the demand for pest control only depends on the hobby producer's preferences and on the parameter values and that potential consequences of pest control do not affect the hobby producer's decision. Also notice that since the pest damage does not affect the hobby producers, we are dealing with a unidirectional externality.

3.2 Professional producer: the Nash equilibrium

The professional producer is a profit maximiser, or equivalently a damage minimiser, and takes the amount of pest control exerted by the hobby producer as given. We consider professional producers as an aggregate and in doing so ignore – as discussed earlier – the fact that each individual grower might under-invest in pest control. Damage (D) depends on the proportion of the production area invaded by the pest (A). Professional producers can reduce the damage by applying pest control (z_p). A convenient way to represent the damage function is then

$$D(A, z_p) = kA^{\beta}(1 + z_p)^{\theta}, \qquad \text{wiht } 0 \leq A \leq 1,\ k > 0,\ \theta < 0,\ \beta \geq 1. \tag{4}$$

Expression (4) is essentially of the Cobb-Douglas form (e.g. Mitchell *et al.* 2004). The damage function includes a measure of maximum possible damage (k) that occurs when the entire production area is invaded and the pest is not controlled at all ($A = 1$ and $z_p = 0$). Parameter θ reflects the effectiveness of pest control in reducing damage and parameter β the elasticity of damage with respect to the proportion of the invaded area. Expression (4) suggests that when no pest control is applied ($z_p = 0$) the full damage occurs, and that when the proportion of invaded area is nil ($A = 0$) no damage occurs. D is decreasing in β and increasing in k and θ.

Since the extent of the invaded area affects producer welfare, we need to account for the dynamics of the pest spread. The dynamics of the invaded area are represented as follows

$$\dot{A} = sA(1 - A) - h(z_p + \eta z_h)A \tag{5.a}$$

$$h = \frac{e}{H_p + H_h} \tag{5.b}$$

$$s > 0,\ e > 0,\ 0 < \eta < 1 \tag{5.c}$$

Expression (5.a) implies that the dynamics of A are the result of two elements. The first term on the right hand side reflects the 'natural' rate of change of A, which is a function of the proportion of the invaded area (A) and the non-invaded area ($1 - A$). The spread rate (s) represents the instantaneous rate of change of A. The use of a logistic spread function is supported by the large amount of literature on agricultural pests and diseases (e.g. Eiswerth and Johnson 2002; Kompas *et al.* 2006).

The use of pest control by both professional (z_p) and hobby producers (z_h) slows down the natural dynamics of A. We assume that the hobby producers are less effective than the professional producers ($0 < \eta < 1$) per unit of control in slowing down the dynamics of A. This may be due to, for instance, lack of interest, knowledge, time or inferior equipment. The effect of z is proportional to the magnitude of A and to effectiveness of pest control in reducing the growth rate of the invaded area (h). $\dot{A}$ is decreasing in h, z and η and increasing in s and in A over the region $0 \leq A \leq 0.5$.

Expression (5.b) implies that the magnitude of h is decreasing in the total crop area (professional producer area H_p plus hobby producer area H_h). This is plausible because expression (5.a), in fact, describes the dynamics of the proportion of the invaded area as a function of the absolute level of pest control. The larger the crop area the larger should be the absolute level of pest control necessary to keep the proportion of the invaded area at the same level. Finally, note that hobby producer control affects only the dynamics of the invaded area, but not the instantaneous damages. This is because possible pesticide drifts are ignored, and the pest damage to the hobby producer's crop is irrelevant as s/he gains utility from production, not from the final crop.

The economic problem of the professional producer with a long-term perspective can be represented as follows

$$\underset{z_p}{\text{Min}} \int_0^\infty \{D(A, z_p) + cz_p\} e^{-\delta t} \mathrm{d}t \tag{6}$$

subject to Expressions (5.a, b and c) and given $z_p \geq 0$, $A(0) > 0$ and $z_h = z_h^N$. Expression (6) entails the minimisation of costs associated with the damage by the pest (D) and its control (cz_p), by choosing the amount of control (z_p), given the dynamics of the invaded area (A) and the privately optimal amount of control exerted by the hobby producers (z_h^N). The current value Hamiltonian for the problem is

$$\tilde{H} = D(A, z_p) + cz_p + \mu[sA(1-A) - h(z_p + \eta z_h^N)A], \textit{ with } \mu \geq 0. \tag{7}$$

Together with Expression (5.a) the first order necessary conditions are

$$\tilde{H}_{z_p} = D_{z_p} + c - \mu hA = 0 \tag{8.a}$$

$$\dot{\mu} - \delta\mu = -\tilde{H}_A = -D_A - \mu[s(1-2A) - h(z_p + \eta z_h^N)] \tag{8.b}$$

By applying standard calculus we can obtain an expression for the privately optimal dynamics of pest control

$$\dot{z}_p = \frac{1}{D_{z_p z_p}}\{(D_{z_p} + c)(\delta + sA) - D_A hA - D_{z_p A} A[s(1-A) - h(z_p + \eta z_h^N)]\} \tag{9}$$

Expressions (9) and (5.a) can be solved in steady-state and yield the solution A^N and z_p^N, where the superscript N again indicates that this is a Nash equilibrium.

3.3 The cooperative outcome: maximisation of joint utilities

To model the problem from the perspective of the social planner, we look at the maximisation of the joint utility of the hobby and professional producers – equivalent to the optimal policy. The profit function of the professional producer is transformed into a utility function by assuming that his/her utility (disutility) function is monotonically decreasing (increasing) in the damage and the control costs. The social utility (W) gives equal weight to hobby and professional producers, and is given by $W(z_h, z_p, A) = V(\bullet) - D(\bullet) - cz_p$, which suggests that W is determined by the utility to the hobby producers (V) minus the disutility of the pest damage to professional producers (D) and the cost of control adopted by the professional producers (cz_p). Hence the damage and the costs of control are measures of the disutility and not monetary values as in (6). This implies that the professional producer is risk-neutral, i.e. the disutility is a linear function of the damage and the costs of control.

The economic problem consists in the maximisation of the social welfare function through the choice of the optimal levels of pest control by both hobby and professional producers, given the constraints posed by the dynamics of the invaded area. The problem can formally be represented as

$$\underset{z_h, z_p}{\text{Max}} \int_0^{\infty} [W(z_h, z_p, A)] e^{-\delta t} \mathrm{d}t \tag{10}$$

subject to Expressions (5.a, b and c) and given $A(0) > 0$. The current value Hamiltonian for the problem is given by

$$\tilde{H} = V(z_h) - D(z_p, A) - cz_p + \mu[sA(1 - A) - h(z_p + \eta z_h)A], \quad \text{with } \mu \le 0 \tag{11}$$

Note that the shadow price (μ) is now negative. Recall that μ represents the marginal value of releasing the constraint (5.a). If this constraint is released (i.e. faster growth of the invaded area or higher equilibrium value of A in steady state) the effect will be a reduction in social utility. The first order necessary conditions for Expression (11) are

$$\tilde{H}_{z_h} = V_{z_h} - \mu h \eta A = 0 \tag{12.a}$$

$$\tilde{H}_{z_p} = -D_{z_p} - c - \mu h A = 0 \tag{12.b}$$

$$\dot{\mu} - \delta\mu = -\tilde{H}_A = D_A - \mu[s(1 - 2A) - h(z_p + \eta z_h)] \tag{12.c}$$

By comparing Expressions (12.a) and (3), and taking into account $\mu \le 0$, it is evident that, compared to the private optimum, the hobby producer invests more resources in control at the social optimum. This can be stated as follows: $z_h^S \ge z_h^N$, where the superscript S denotes the social optimum. Expressions (13.a, b and c) below present the socially optimal dynamics of pest control and invaded area, which can be solved in a steady-state to yield the solution z_h^S, z_p^S and A^S.

$$\dot{z}_h = \frac{1}{V_{z_h z_h}} \{V_{z_h}(\delta + sA) + \eta D_A h A\} \tag{13.a}$$

$$\dot{z}_p = \frac{1}{D_{z_p z_p}}\{(D_{z_p+c})(\delta + sA) - D_A hA - D_{z_p A}A[s(1-A) - h(z_p + \eta z_h)]\} \tag{13.b}$$

$$\dot{A} = sA(1-A) - h(z_p + \eta z_h)A \tag{13.c}$$

4. Numerical illustration

The properties of the analytical model can best be described through a numerical illustration. Our objective is to supplement the analytical model by extracting some stylised results, presenting the qualitative impacts of changes in the parameters, rather than to provide accurate predictions. We illustrate the model using the case study of Colorado Potato Beetle (*Leptinotarsa decemlineata*) and potato production in Finland. This choice is motivated by the existence of extensive hobby potato production that coexists with professional potato production in Finland. The species can cause severe difficulties for the potato producers, and the potential for its range expansion to Finland has been shown by genetic (Boman *et al.* 2006) and climatologic (Jeffree and Jeffree 1996) studies. We assume that a viable invasion takes place and reactive control must be adopted.

4.1 Parameter values and basic assumptions

The two types of potato producers are the professional producers (H_p = 30 000 ha) and the hobby producers (area unknown, but likely to be around H_h = 10 000 ha). Production areas are located randomly and any short-distance pest spread is equally likely to target either of the areas. The small country assumption allows us to ignore consumer surplus impacts and estimate the elasticity of damage with respect to the invaded area (β) to be 1.00. Maximum damages (k) of 117.1 million euros are assumed to ensue when the pest causes 80 per cent crop losses within the entire professional production area.

Saving rates over 2001–2006 have ranged between – 2.6 and +2.1 per cent, with an average of 0.03 per cent (Statistics Finland 2008). In our application we assume the saving rate (γ) to be null. The discount rate (δ) used is 0.03. Direct estimation of utility functions would require an ad hoc study, and given the absence of studies estimating the utility of hobby farmers in a context sufficiently similar to ours, we parameterise the utility function so as to generate sensible results and assume the elasticity of substitution (σ) to be 2. For the spread rate (s), no direct estimations are available. We set the spread rate equal to 0.3, which would lead to all the potato area (40 000 ha) to be affected in about 30 years if no control were applied. Parameter e is set at 0.01 primarily to produce plausible spread scenarios. Given the lack of information about the effectiveness of professional and hobby control on the dynamics of CPB, it is very difficult to identify appropriate values for these parameters. In their study on the control of insect-transmitted diseases Brown *et al.* (2002) use a base-case value of 0.05 for the effectiveness of control on pest dynamics. Parameter θ is set equal to –0.05 primarily to obtain plausible damage scenarios. Impacts of wealth are ignored ($M = 0$). Total time available for activities (T) is set at 8 weeks (CPB high season) and time spent working (t_w) at 40 h per week at the wage rate (w) of 15 euros per hour (Statistics Finland, www.stat.fi). Pest control unit is chosen to equal one hour of work in pest control, including any control substances used within this period, and cost per unit of control (c) is set at 50 euros (Heikkilä and Peltola 2007). The hobby producers are assumed less effective than the professional producers ($\eta = 0.5$) per unit of control in slowing down the dynamics of the invaded area.

To measure the consumer price for goods consumed we compute a normalisation factor. Total household expenditure is divided by the average number of people per household, giving the average consumption per person (12 037 euros) (Statistics Finland, www.stat.fi). This is divided by the estimated total amount of consumption hours per year (4320), giving 2.78 that we approximate to 3.00. The normalised control cost, wage rate and maximum damages can then be computed by dividing the non-normalised costs by three.

4.2 Results and sensitivity analysis

We first calculate the disjoint (Nash) equilibrium in which the hobby producers and the professional producers choose their actions without coordination (private optimum). We then calculate the joint equilibrium in which the total welfare of the society is maximised (social optimum) and show that there may be substantial losses in the case of the disjoint solution. The effects of changes in the parameter values are explored through a sensitivity analysis.

The basic results and the sensitivity analysis are shown in Table 1. All monetary values are expressed in normalised euros, and pest control in hours/ha/week. At the Nash equilibrium the hobby producers spend 13.16 h/ha/week and professional producers 0.85 h/ha/week controlling the pest. The corresponding level of invaded area stands at 32 per cent (13 000 ha). The economic damage ($C = D + cz_p$) to professional producers exceeds 10.2 million euros/year (about 21 per cent of the total output value). If hobby producers decide not to apply any control at all (e.g. they are averse to pest control), the privately optimal level of professional pest control is 1.67 h/ha/week, the proportion of invaded area 50 per cent (20 000 ha) and the corresponding level of damage is about 16.9 million euros/year (35 per cent of total output value).

At the social optimum, hobby producers invest more resources in pest control in the base case (18 h/ha/week) and professional producers are able to reduce their pest control effort to 0.44 h/ha/week. The proportion of the invaded area is significantly lower (23 per cent, equivalent to 9200 ha) and the corresponding level of damage stands at around 6.8 million euros/year (14 per cent of total output value). Table 1 reveals that the steady-state invaded area is always lower at the social optimum compared to the Nash

Table 1 Basic results and sensitivity analysis (Nash equilibrium and social optimum) with elasticities in brackets

Cases	Solution	z_p (ε_{zp}) (hours/ha/week)	z_h (ε_{zh}) (hours/ha/week)	A (ε_A) (proportion)	C (ε_C) (million euros/year)
Base	Nash	0.85	13.16	0.32	10.2
	S.O.	0.44	18.00	0.23	6.8
k + 10%	Nash	1.10 (2.91)	13.16 (0.00)	0.26 (1.88)	9.8 (0.39)
	S.O.	0.56 (2.84)	18.00 (0.00)	0.20 (1.30)	6.6 (0.29)
k – 10%	Nash	0.62 (2.79)	13.16 (0.00)	0.37 (1.56)	10.4 (0.20)
	S.O.	0.33 (2.52)	18.00 (0.00)	0.25 (0.87)	6.9 (0.15)
h + 10%	Nash	0.87 (0.19)	13.16 (0.00)	0.24 (2.50)	8.6 (1.57)
	S.O.	0.35 (1.87)	18.00 (0.00)	0.17 (2.61)	5.2 (2.35)
h – 10%	Nash	0.77 (1.03)	13.16 (0.00)	0.40 (2.50)	11.6 (1.37)
	S.O.	0.47 (0.77)	18.00 (0.00)	0.30 (3.04)	8.4 (2.35)
s = 0.4	Nash	0.66 (0.68)	13.16 (0.00)	0.52 (1.88)	13.8 (1.06)
	S.O.	0.50 (0.44)	18.00 (0.00)	0.41 (2.35)	10.9 (1.81)
s = 0.2	Nash	0.37 (1.70)	13.16 (0.00)	0.14 (1.69)	4.6 (1.65)
	S.O.	0.0001 (3.00)	17.80 (0.03)	0.0002 (3.00)	0.007 (3.00)
H_h + 10%	Nash	0.84 (0.17)	11.97 (0.91)	0.34 (0.63)	10.6 (0.39)
	S.O.	0.45 (0.32)	16.36 (0.91)	0.25 (0.87)	7.3 (0.74)
H_h – 10%	Nash	0.87 (0.18)	14.60 (1.09)	0.30 (0.63)	9.8 (0.39)
	S.O.	0.42 (0.37)	20.00 (1.11)	0.21 (0.87)	6.3 (0.74)
η + 10%	Nash	0.70 (1.81)	13.16 (0.00)	0.30 (0.63)	9.2 (0.98)
	S.O.	0.27 (3.81)	18.00 (0.00)	0.20 (1.30)	5.6 (1.76)
η – 10%	Nash	1.00 (1.70)	13.16 (0.00)	0.33 (0.31)	11.0 (0.78)
	S.O.	0.62 (4.22)	18.00 (0.00)	0.26 (1.30)	8.0 (1.76)

equilibrium. Also the hobby (professional) level of pest control is always higher (lower) at the social optimum.

The damage is always higher at the Nash equilibrium than at the social optimum. Table 1 shows how the damage is highest (lowest) when the spread rate is highest (lowest). Also, the damage is lower when the value of the maximum damage (k) is higher. This result follows from the fact that higher values of k imply a higher marginal return from pest control. As a consequence professional producers have a stronger incentive to control the pest (compare the level of pest control in the two cases k + 10 and k – 10 per cent), which in turn will affect the steady-state invaded area. Increasing the effectiveness of hobby producers (η) also helps to reduce the level of damages. An increase in the hobby production area (H_h), keeping the number of producers fixed, also unambiguously increases the steady state invaded area in both Nash equilibrium and social optimum. Further analysis, not presented here, reveals that the level of professional producer pest control first increases with the hobby production area, but after a certain threshold begins to decrease. This suggests that when the hobby area is relatively large, professional producers' incentives to control the pest are lowered.

In order to assess the sensitivity of the results with respect to the parameter values, Table 1 also reports the elasticities of the solution values of A, z_h, z_p and C with respect to changes in h, k, s, H_h and η. In particular the spread

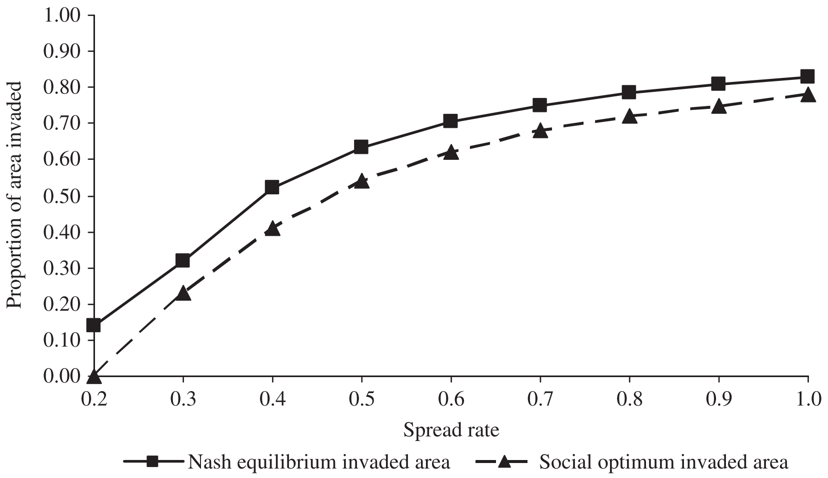

Figure 1 Impact of spread rate(s) on proportion of invaded area (A) in Nash equilibrium and social optimum.

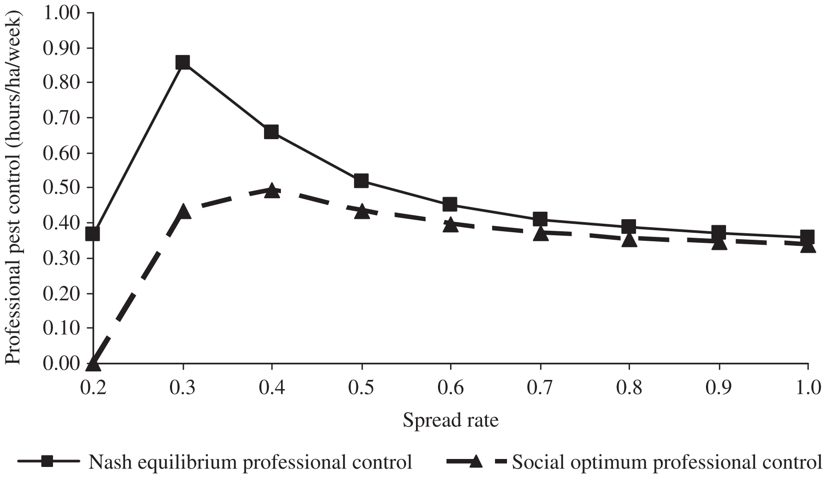

Figure 2 Impact of spread rate(s) on professional producers' pest control (z_p) in Nash equilibrium and social optimum.

rate (s) and the effectiveness of hobby producers (η) are among the parameters that exert the largest effect on the equilibrium values of A and z_p. A 10 per cent increase in η generates a reduction in z_p of 38 and 18 per cent, respectively, at the social optimum and at the Nash equilibrium. A 33 per cent reduction in s generates a reduction in A of 99.9 and 56 per cent, respectively.

Figure 1 illustrates that an increase in the spread rate leads to a higher proportion of the area being invaded. On the other hand the effect on pest control effort is not monotonic (Figure 2). For spread rates below $s = 0.3$–0.4 an increase in the spread rate will lead to an increase in professional pest control, both in the Nash and in the social optimum case. However, for spread rates above $s = 0.4$, further increases will lead to a reduction in professional

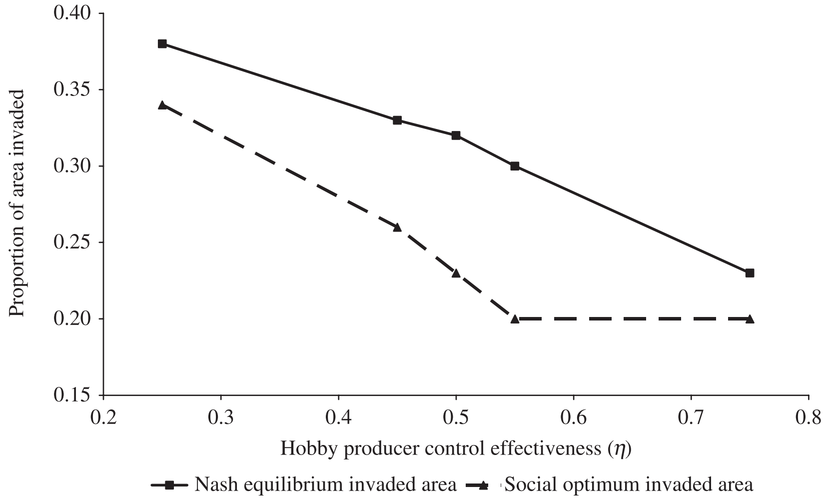

Figure 3 Impact of hobby farmers' pest control effectiveness (η) on proportion of invaded area (A) in Nash equilibrium and social optimum.

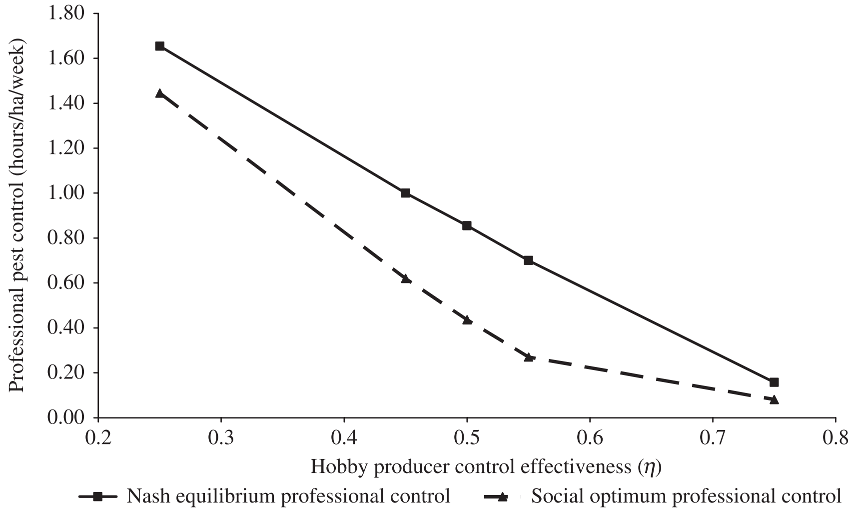

Figure 4 Impact of hobby farmers' pest control effectiveness (η) on professional producers' pest control (z_p) in Nash equilibrium and social optimum.

pest control. Intuitively this suggests that if the pest spreads too rapidly, producers' incentives to control are weakened.

The effect of hobby farmers' effectiveness in pest control (η) on the invaded area and professional farmer's pest control at the Nash equilibrium and social optimum are illustrated in Figures 3 and 4.

In the base case the reduction in the damage associated with a move from the Nash to the social optimum ($\Delta C = C^N - C^S$, the cost of non-cooperation) stands at around 33 per cent. The gains from a socially optimal policy could

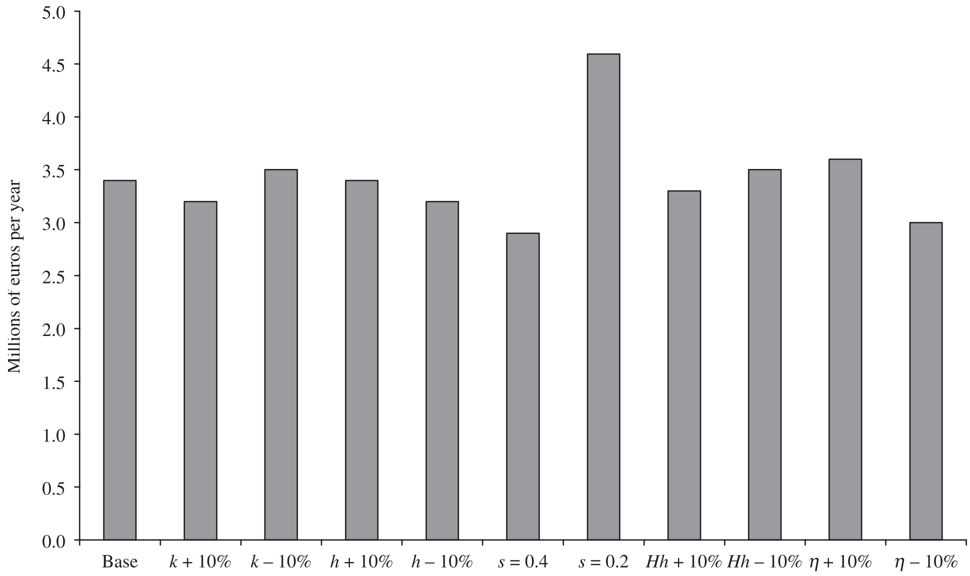

Figure 5 Cost of non-cooperation: the cost to professional producers (damage and pest control) from not being at the social optimum.

thus be sizable for professional producers. Since any policy aiming to move from the Nash to the social optimum will have an associated cost, ΔC provides an indication of the opportunity to regulate as illustrated in Figure 5 for different parameter values.

In our model the gains from including hobby producers in the regulation of the externality are highest when

- The spread rate is low ($s = 0.2$): the benefits of regulation are 99 per cent of the damage (4.6 million euros/year).
- The effectiveness of hobby farmer control is high ($\eta + 10$ per cent): the benefits are 40 per cent of the damage (3.6 million euros).
- The effectiveness of pest control in general is high ($h + 10$ per cent): the benefits are 40 per cent of the damage (3.4 million euros).

On the other hand, the benefits of regulation are lowest when

- The spread rate is high ($s = 0.4$): the benefits are 21 per cent of the damage (2.9 million euros).
- The effectiveness of hobby farmer control is low ($\eta - 10$ per cent): the benefits are 27 per cent of the damage (3 million euros).

The model could be generalised by including the heterogeneous objectives and possible spillovers among the professional producers, as well as by using more general functional forms for the hobby producer utility function and crop damage. The assumptions on utility function are particularly important, because the analytical solution depends strongly on the functional form. In a real-life situation targeted surveys, aiming to assign monetary values to hobby producers' welfare changes, could be used to inform a political debate to determine what kind of obligations (if any) hobby producers should comply with. For example, a mandatory policy similar in magnitude to the one resulting from our exercise (37 per cent increase in hobby producers' pest control effort) would be socially desirable if hobby producers' willingness to pay to avoid such regulation plus the costs of its implementation are less than 3.4 million euros annually (ΔC).

5. Discussion

We show how the heterogeneity of the incentive structure in farm level biosecurity management between hobby and professional producers leads the former to under-invest in pest control. By concentrating on the pest control decision instead of the land allocation decision, we can clearly illustrate how the hobby producers will under-invest in pest control activities, since they do not take into account its effects on professional producers. Once the effect of hobby producers' decision to grow the crop is accounted for, pest control decisions resemble abatement decisions by pollutant emitters. Since control, in our case, generates positive external benefits, from a social point of view the hobby producers will under-invest in control. As shown in the numerical illustration, the gains from a socially optimal policy could be sizable, but it is possible that the transaction costs of corrective policies may end up being prohibitively high. However, to devise a corrective policy, the fact that crop fields provide a breeding ground for the pest, and that hobby crop fields are more probable to stay invaded, cannot be ignored. The sensitivity analysis of the hobby production area clearly illustrates this point.

The current laws and regulations concerning invasive plant pest control reflect the view that producers have a right to a pest-free production environment. The current policy regarding certain quarantine plant pests, including the CPB, in the European Union allows the producers to get compensation for the lost production and eradication costs associated with the policy. However, two points should be taken into account. First, as Butler and Maher (1986) point out, compensation to the victims of an externality should not be based on uncorrected marginal damages, as this would induce the victims to undertake too little control. Second, the compensation policy applies to professional producers and does not take hobby production into account. Hence the Nash equilibrium levels of control need to be accounted for. So far, there has not been any differentiated policy towards hobby producers, perhaps partly because the true nature of a specific producer cannot be easily identified. Nonetheless, policies should be designed such that we can prevent the hobby producers from turning into sloppy producers.

Potential policies may be designed to either restrict setting up breeding grounds for the pests or to induce all producers to apply proper pest control. Cultivation could be regulated for instance through production permits, and the appropriate pest control decisions for instance through subsidies, liability or Coasian bargaining. The approaches are indeed complementary, the main difference being whether we wish to affect the planting decisions or the management decisions thereafter.

Regarding policies related to management decisions, the analytical model developed in this paper can provide some insights, for instance introduction of a pest control subsidy for hobby producers. The subsidy, however, presents at least two problems. First, it could lead to an increase in the hobby production area, with associated negative impacts. Second, it fails to recognise that the mere existence of hobby potato fields is an important component of the problem.

Another policy option could be based on liability, often discussed in the context of gm-crops, where hobby producers could be held liable for damages that their actions impose on other producers. A penalty based on the deviation of private hobby producers' pest control from the socially optimal level (however, determined) could be introduced (e.g. Xepapadeas 1997). The penalty would represent a strong incentive for hobby producers to either provide proper pest control or to abandon production altogether. The implementation of such a system is expensive as it would require monitoring hobby producers, but the penalty system could also be used as an incentive to promote a Coasian solution: a potential fine could induce hobby producers to actively search for collaboration with the professional producers in the area. Professional producers could find it in their interest to get together with the hobby producers and agree upon surveillance and control activities – or even to take care of pest control management of a few neighbouring hobby plots as well. The utility of the hobby producers would not be negatively affected if they outsourced pest control to professionals.

The actual policy instruments and their cost-effectiveness are beyond the scope of this study. We have sufficed ourselves here to highlighting the importance of considering two groups of stakeholders and their heterogeneous incentives. Some form of state participation in invasive species management is often warranted. This has been shown here to be the case with heterogeneous producers, highlighting the need for a holistic approach when designing biosecurity policies to counter invasive alien species.

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