How to regulate pest resistance management depending on pest mobility

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Pest Resistance Regulation and Pest Mobility

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Abstract

We use a spatially-explicit analytical framework to compare mandatory refuges and a tax on the resistant variety as regulation instruments for pest resistance management. Because the extraction of the common-pool pest susceptibility resource depends on the spatial pattern of pest dispersal, we find that the usual preference for market-based environmental instruments does not necessarily apply to pest resistance management. Mandatory refuges are preferred to a tax on the resistant variety for some assumption sets on heterogeneity between farms and pest dispersal distances.

1 Introduction

More than 20% of genetically-modified crops currently grown are insect-resistant through the expression of insecticidal proteins of Bacillus thuringiensis (*Bt*). The evolution of insect pest resistance will imperil the efficiency of these transgenic insect-resistant crops. The currently advised strategy to delay resistance evolution is to require Bt growers to plant non-*Bt* refuges in close proximity to *Bt* plants and to control their compliance with this requirement (see Hurley et al. 2001 and 2002, Mitchell et al. 2002). We suggest that an alternative strategy to induce growers to plant non-toxic crops is to make Bt seed more expensive by instituting a user fee.

Pest management in agricultural production by use of chemical pesticides or pest-resistant varieties (e.g. *Bt* crops) exerts a selection pressure on pest populations. Over time, the ability of chemicals or resistant varieties to prevent crop damages decreases as resistance to these pesticides by the pests increases. In economic terms, the stock of pest susceptibility to a given pesticide is a non-renewable resource (Hueth and Regev 1974). Farmers might use pest resistance strategies to exhaust this resource (pest susceptibility) at an efficient rate. For instance, they might devote part of their crop to conventional varieties (or without pesticide), thereby creating refuges for pests. Yet, since pest are mobile from one crop to another, pest susceptibility is a common-pool resource for farmers. Since farmers bear the full cost of reducing growth of pest susceptibility but share the benefits, they have an incentive to under-invest in pest resistance management strategies. As a consequence, farmers tends to exhaust the stock of susceptibility at a higher rate than the optimal rate. In other words, the laissez-faire management of pest susceptibility leads to the famous tragedy of the commons, thereby providing a rationale for regulation (Regev et al. 1983).

In this paper we contribute to the economic literature on pest resistance management

by taking explicitly into account farm localisation and pest dispersion to examine the choice of regulation instruments for pest resistance management. More precisely, we compare two regulatory instruments: (uniform) mandatory refuges and a tax/subsidy scheme (a tax on resistant varieties and a subsidy on conventional varieties). Mandatory refuges have been implemented in the U.S. for Bt corn through the so-called insect resistance management plan. Taxes and subsidies might provide farmers with incentives to plant more of the conventional variety, thereby reducing pest resistance evolution.

Vacher et al. (2006) used simulations to compare these two instruments in a spatially-explicit, population genetics model of *Bt* corn in the United States. Their approach conveys the usual advantages and limitations of simulation models, i.e. careful calibration to real-world data, versus lack of generality and lack of transparency in the mechanisms. To get additional insights into this problem, we build a spatially-explicit framework with heterogenous farmers and we examine analytically how differences in pest attacks across farms and mobility of pests across farms affect the ranking of the two instruments.

2 Model

We consider a set of $2I - 2$ producers facing heterogenous pest attacks. This set is denoted $\Omega = 1, ..., 2I - 2$. Producers are located on a circle, according to their ranking (i.e. for every $i \in \{2, .., 2I - 3\}$, producer i has neighbors $i - 1$ and $i + 1$, and producers 1 and $2I - 2$ are neighbors). Producer i faces an intensity of pest attacks n_i. To avoid edge effects, we assume that n_i is non-decreasing in i on the first half of the circle (i.e. $n_{i+1} \geq n_i$ for every $i \in \{1, ..., I\}$), and non-increasing in i on the second half of the circle with a symmetric distribution of n_i on both halves of the circle (i.e. $n_{2I-i} = n_i$ for every $i \in \{2, ..., I - 1\}$). Moreover, we assume that $\max_{i \in \{1, ..., I\}} n_i = n_I \leq 1$. Each producer has a fixed area of land that is planted either with a pest-resistant variety (latter denoted as "pesticide variety") or with a conventional variety that shows no resistance to the pest considered. Although resistance buildup is a dynamic problem in essence, we summarize here its cumulated effect over time in a one-period problem. Such a simple formalization allows to capture the effect of pest dispersion at the long run when producers make an initial crop variety choice and stick on it.

In the absence of pest attacks, the unit profit on the conventional variety is assumed constant and normalized to 1. All pests survive and cause crop damages on the conventional variety. Profit losses caused by pest attacks of intensity n_i are equal to n_i.[1] The pesticide variety is available with an overcost c compared to the conventional variety

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[1] For simplification matters we do not consider the possibility of applying a chemical pesticide on the area sown with the conventional variety.

(i.e. the cost of the conventional variety is normalized to 0). This cost will be kept constant in our analysis (in other words, we do not consider any strategic behavior from the suppliers of this technology in this paper). Only resistant pests survive to cause crop damages on the pesticide variety. The producer's unit profit at location i takes the form:

$$\pi_i(x_i, w_i, n_i) = x_i(1 - n_i w_i - c) + (1 - x_i)(1 - n_i), \qquad (1)$$

where x_i is the proportion of area planted with a pesticide variety and w_i is the average long run level of resistant pests.[2]

The proportion of resistant pests at farm i depends on the other farmers' planting strategies x_j for $j \neq i$ as follows:

$$w_i = \gamma \frac{\sum_{j \in \Omega} \delta_{i-j} x_j n_j}{\sum_{j \in \Omega} \delta_{i-j} n_j}, \qquad (2)$$

where $\delta_{i-j} = \delta_{j-i}$ captures the impact of producer j's crop on resistance at i and γ quantifies the magnitude of resistance development, with $0 < \gamma < 1$. We assume $\delta_j \leq \delta_k$ for $j < k$. This assumption implies that a producer's impact on resistance at another location is decreasing with the distance. δ_0 captures the impact of a producer on its own resistance level.

A pest resistance management strategy (PRM) $\{x_i\}$ is a set of pesticide area proportions x_i for every producer $i = 1, ..., I$. In what follows, we successively examine the efficient PRM strategy, denoted $\{x_i^*\}$, and the equilibrium PRM strategy, denoted $\{x_i^e\}$, in the general case and then for specific assumptions on pest dispersion.

3 Optimal and producers' PRM strategy

We first consider the optimal strategy at the collective level, assuming that the welfare is aggregate producers' profits. The socially optimal PRM strategy $\{x_i^e\}$ solves the maximization program $\max_{\{x_i^*\}} \sum_{j \in \Omega} \pi_i(x_i, w_i, n_i)$, subject to: $\forall x_i \in X, \ x_i \in [0, 1]$.

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[2]Immediate observation shows that: $\partial \pi_i / \partial x_i = n_i(1 - w_i) - c$; $\partial \pi_i / \partial w_i = -n_i x_i$; $\partial \pi_i / \partial n = -x_i w_i - (1 - x_i)$. Given the level of resistance w_i, the unit profit level at location n_i increases with the resistant area proportion if and only if the additional number of pests that are controlled by the resistant technology, i.e. the number of susceptible pests, $n_i(1 - w_i)$, is higher than the unit cost of the resistant technology, c. Given any positive pest-resistant area x_i, the unit profit level at location i decreases with the level of resistance w_i, as pest control then decreases on the resistant area. And for a given level of resistance and a given resistant area proportion, the unit profit level decreases with the intensity of pest attacks.

Denote $\underline{\lambda}_i^*$ and $\bar{\lambda}_i^*$ the multipliers associated to the respective constraints $x_i \geq 0$ and $x_i \leq 1$, for any x_i for $i \in \Omega$. For every i, the solution $\{x_i^*\}$ to the above program satisfies the following first-order condition:

$$n_i(1 - w_i^*) + \underline{\lambda}_i^* = c + \sum_{j \in \Omega} n_j x_j^* \frac{\partial w_j}{\partial x_i} + \bar{\lambda}_i^*, \tag{3}$$

with the complementarity slackness conditions

$$\underline{\lambda}_i^* \geq 0 \qquad x_i^* \geq 0 \qquad \underline{\lambda}_i^* x_i^* = 0,$$

$$\bar{\lambda}_i^* \geq 0 \qquad x_i^* \leq 1 \qquad \bar{\lambda}_i^*(1 - x_i^*) = 0.$$

Equation (3) equalizes the marginal benefit of the pesticide variety (left-hand side) to its marginal cost (right-hand side) net of the shadow costs of the constraints. The marginal cost of pesticide variety includes the impact of i's area of the pesticide variety on its own resistance level w_i (formally $\frac{\partial w_i}{\partial x_i}$) as well as on resistance levels w_j of *other producers* $j \neq i$, i.e. $\frac{\partial w_j}{\partial x_i}$.

Let us now examine the PRM strategy of producers without regulation. The program of producer i is $\max_{x_i} \pi_i(x_i, w_i, n_i)$, subject to $x_i \in [0, 1]$. Denoting $\underline{\lambda}_i^e$ and $\bar{\lambda}_i^e$ the multipliers associated to the respective constraints $x_i \geq 0$ and $x_i \leq 1$, the (unique) solution x_i^e, satisfies:

$$n_i(1 - w_i^e) + \underline{\lambda}_i^e = c + n_i x_i^e \frac{\partial w_i}{\partial x_i} + \bar{\lambda}_i^e \tag{4}$$

with the complementarity slackness conditions:

$$\underline{\lambda}_i^e \geq 0 \qquad x_i^e \geq 0 \qquad \underline{\lambda}_i^e x_i^e = 0$$

$$\bar{\lambda}_i^e \geq 0 \qquad x_i^e \leq 1 \qquad \bar{\lambda}_i^e(1 - x_i^e) = 0$$

Here too, each producer equalizes the marginal benefit of pesticide variety (left-hand side) to its marginal cost (right-hand side) net of the shadow cost of the constraints. However, since the producer incurs only the cost of the PRM strategy on its own profit, he ignores the impact of his PRM strategy on his neighbor's profits. Therefore, in contrast to the optimal PRM strategy, the right-hand term in (4) includes only the impact of i's PRM strategy on his profit, not on the other producers' profits.

Substituting for the partial derivatives, the first-order conditions (3) and (4) become

$$n_i(1 - w_i^*) + \underline{\lambda}_i^* = c + \gamma n_i \sum_{j \in \Omega} n_j x_j^* \frac{\delta_{i-j}}{D_j} + \bar{\lambda}_i^* \tag{5}$$

and

$$n_i(1 - w_i^e) + \underline{\lambda}_i^e = c + n_i^2 x_i^e \frac{\gamma \delta_0}{D_i} + \bar{\lambda}_i^e, \tag{6}$$

with $D_j = \sum_{k \in \Omega} \delta_{j-k} n_k$ for every $j \in \Omega$. From condition (5) it appears clearly that the optimal PRM strategy X^* depends on pest dispersion rates δ_{j-k} for every $k \in \Omega$. Condition (6) shows that a producer i's PRM strategy depends on its pest attack n_i, the equilibrium resistance level w^e and on the impact of its PRM decision on its resistance level, namely $\gamma n_i \frac{\delta_0}{D_i}$. We will be able to formulate explicitly $\{x^*\}$ and $\{x^e\}$ for extreme assumptions on dispersion rates in Sections 4 and 5.

4   Immobile pests

As a benchmark, we first consider the case of no externalities between producers. We assume $\delta_0 > 0$ and $\delta_t = 0$ for $t \neq 0$: the resistance level at one location depends only on the PRM strategy at this location. In other words, pests are immobile from one producer to the other. Formally, we assume $w_i = \gamma \frac{\delta_0 n_i x_i}{\delta_0 n_i} = \gamma x_i$.

In this case $\frac{\partial w_j}{\partial x_i} = 0$ for $j \neq i$ and the efficient first-order condition for i (3) simplifies to:

$$n_i(1 - w_i^*) + \underline{\lambda}_i^* = c + n_i x_i^* \frac{\partial w_i}{\partial x_i} + \bar{\lambda}_i^*, \tag{7}$$

which is equivalent to the producer's first-order condition (4) for every $i \in \Omega$. Since the resistance level at i depends only on producer i's PRM strategy, each producer i has an incentive to select the efficient PRM strategy at i, i.e., $x_i^e = x_i^*$ for every $i \in \Omega$. In other words, the equilibrium "laissez-faire" situation is optimal. No regulation for resistance management is warranted.

Substituting for the partial derivative and the value of w_i^* in the efficient first order conditions (7) yields:

$$n_i(1 - \gamma x_i^*) + \underline{\lambda}_i^* = c + n_i \gamma x_i^* + \bar{\lambda}_i^*,$$

which simplifies to:

$$x_i^* = \frac{1}{2\gamma}(1 - \frac{c}{n_i} + \frac{\underline{\lambda}_i^* - \bar{\lambda}_i^*}{n_i}). \tag{8}$$

When no constraint is binding, i.e. $\underline{\lambda}_i^* = \bar{\lambda}_i^* = 0$, then $x_i^* = \frac{1}{2\gamma}(1 - \frac{c}{n_i})$. The area planted with the pesticide variety is increasing in the intensity of pest attacks n_i. It is decreasing in the pesticide variety overcost c and in the magnitude of resistance development γ. If the lower bound constraint of efficiency program is binding then $x_i^* = 0$, $\underline{\lambda}_i^* > 0$ and

$\bar{\lambda}_i^* = 0$. Condition (8) shows that it implies $n_i < c$. The upper bound constraint is binding for $\frac{1}{2\gamma}(1 - \frac{c}{n_i}) > 1$, which yields $\gamma < \frac{1}{2}$ and $n_i > \frac{c}{1-2\gamma}$. We have proved the following results.

Proposition 1 *With immobile pests, the producer's PRM strategies are efficient. As-suming that $\gamma < \frac{1}{2}$ and $n_I > \frac{c}{1-2\gamma}$, they are defined as follows.*

    a. *All producers i facing pest attacks $n_i \leq c$ plant only the conventional variety.*

    b. *All producers i facing pest attacks $n_i \in \left(c, \frac{c}{1-2\gamma}\right)$ plant both the conventional variety and the pesticide variety, and for these producers the pesticide area proportion x_i^* increases with i.*

    c. *All producers i facing pest attacks $n_i > \frac{c}{1-2\gamma}$ plant only the pesticide variety.*

When pests are only mobile inside of each farmer's production area, the pest suscepti-bility to the pesticide variety is a resource owned privately by each producer. Therefore, each producer takes into account the effect of its varietal choice on the evolution of resistance. The pesticide variety is not profitable for producers facing low pest attacks, i.e. for whom $n_i \leq c$, because the gains it procures in terms of increased pest control do not outweigh its additional technology cost. On the opposite, the pesticide variety is profitable for producers facing high pest attacks, i.e. for whom $n_i > c$. Whether or not all these producers find it profitable to plant also the conventional variety on some part of their acreage (with this area acting as a refuge to decrease the level of resistance) then depends on the magnitude of γ, i.e. the magnitude of resistance development due to pesticide variety plantings.

5   Perfectly mobile pests

In the extreme case of perfectly mobile pest (or uniform pest dispersion) then $\delta_t = \delta_{t+1} = \delta$ for every distance t. All producers then face the same resistance level,

$$w = \frac{\gamma}{N} \sum_{j \in \Omega} x_j n_j,$$

with $N = \sum_{j \in \Omega} n_j = \frac{D_i}{\delta}$.

The first-order condition of the efficient PRM strategy (5) becomes:

$$n_i(1 - w^*) + \underline{\lambda}_i^* = c + \frac{\gamma n_i}{N} \sum_{j \in \Omega} n_j x_j^* + \bar{\lambda}_i^*, \tag{9}$$

whereas the first-order condition of the equilibrium PRM strategy (6) yields:

$$n_i(1 - w^e) + \underline{\lambda}_i^e = c + \frac{\gamma n_i}{N} n_i x_i^e + \bar{\lambda}_i^e \qquad (10)$$

A producer takes into account the impact of his PRM strategy on his profit via the resistance level, formally $\frac{\gamma n_i}{N} n_i x_i^e$, whereas he should consider his whole impact on the economy, formally $\frac{\gamma n_i}{N} n_i x_i^e$. With perfectly mobile pests, distances between producers do not matter: only pest attack intensities n_j do. They are normalized by the overall intensity N.

The next proposition describes and compares the efficient and equilibrium PRM strategies. It highlights the inefficiency of the "laisser faire" PRM strategy with mobile pests.

Proposition 2 *With perfectly mobile pests, we have:*

a. The efficient PRM strategy requires that producers $n_i < n^*$ plant only the conventional variety while producers $n_i > n^*$ plant only the pesticide variety, with $n^* = \frac{c}{1-2w^*}$.

b. Producers plant only the conventional variety for $n_i \leq n_1^e$, both varieties (with resistant area proportion x_i^e increasing with n_i) for $n_i \in (n_1^e, n_2^e)$, only the pesticide variety for $n_i \geq n_2^e$, with $n_1^e = \frac{c}{1-w^e}$ and $n_2^e = \frac{N}{2\gamma}\left(1 - w^e - \sqrt{(1-w^e)^2 - 4\frac{\gamma c}{N}}\right)$ and assuming that $n_2^e < n_I$.

c. $n^* > n_1^e$.

Since vulnerability to pest increases moving along the two halves of the circle of producers, the optimal PRM strategy divides producers into two neighbor groups: those more vulnerable to pests, who should plant only the pesticide variety, and the others who should rely on the conventional one.[3] Since pests are perfectly mobile, distance does not affect the impact of producers' planting strategies on resistance at other locations. There is no cost of concentrating the pesticide variety is one area and the conventional variety in another. The pesticide variety is thus optimally planted where it is the most useful.

In the "laisser faire" equilibrium, producers who use the pesticide seed are also those more vulnerable to pests. Among those producers, some create a refuge zone by themselves to reduce resistance. This is because their own PRM strategy impacts the level of pest resistance in their field. They devote part of their area to the conventional variety when the benefit of this PRM strategy outweighs its cost. The last result of Proposition 2 shows that producers whose pest attacks range between n_1^e and n^* plant

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[3]Notice that producers facing pest attacks n^* if they exist might choose any strategy x_i.

the pesticide variety while it is efficient to plant the conventional one. This is due to the common property nature of pest resistance which gives an incentive to overuse the pesticide variety.

We now compare further the efficient and equilibrium outcomes with perfectly mobile pests, assuming that each producer has a infinitely small impact on pest resistance w. It might be so because each producer owns a very small area in this agricultural region (I tends to infinity). Or, alternatively, producers might by myopic regarding their impact on resistance w. Formally, this means $\frac{\partial w_i}{\partial x_i} = 0$ in the equilibrium first-order condition (4), or, that $\frac{n_i}{N}$ tend to 0 in the first-order condition (10), which becomes:

$$n_i(1 - w^e) + \underline{\lambda}_i^e = c + \bar{\lambda}_i^e.$$

In this case, it is straightforward to show (as in proof of Proposition 2) that the threshold $n^e \equiv \frac{c}{1-w^e}$ divides the segment of producers between those whose pest attacks are lower than n^e (who plant only the conventional variety) and the others (who plant only the pesticide variety). Due to the infinitesimal impact of each producer's PRM strategy on resistance, no producer creates a refuge zone. Nevertheless, the area including producers with pest attacks lower than n^e acts as a refuge area for the other producers. With perfectly mobile pests, it reduces resistance equally everywhere. But it is not planted for pest resistance management purposes. It is just planted because at these locations pest attack intensity is too low to outweigh the overcost of pesticide variety. In particular, no producer plants the conventional seed if $n^e \leq n_1$.

Clearly, $n^* > n^e$. Producers facing pests attacks between n^e and n^* plant only the pesticide variety but should use only the conventional one. As a consequence, the resistance level is too high: $w^e > w^*$. Proposition 3 below posits a regulatory instrument that restores efficiency.

Proposition 3 *When each producer's impact on resistance is negligible, producers facing pests attacks n_1 up to n^e plant the conventional variety whereas those facing pests attacks higher than n^e plant the pesticide variety. Efficiency can be restored with a tax on the pesticide variety $\tau = n^* w^*$ where $w^* = \sum\limits_{j \in \Omega, n_j \geq n_i^*} n_j$, which induces producers facing pest attacks n^e up to n^* to turn to the conventional variety. Uniform refuge zones do not allow to restore efficiency.*

The equilibrium PRM strategy is inefficient because producers do not bear the full cost of planting the pesticide variety on producer's profits through pest resistance development. A tax on the pesticide variety increases the overcost of planting this variety. The proposed tax τ equalizes this overcost to the profit loss of all producers due to the

increase of resistance development. It provides producers with an incentive to select seed varieties efficiently. The resistance level is thus efficient.

6 Imperfectly mobile pests with homogeneous pest attack

In the previous sections, we have considered successively two extreme assumptions. First, we have assumed no pest mobility so that pest resistance developed in one farm has no impact its neighborhood. Second, we have assumed perfect pest mobility so that resistance developed at any location is perfectly diffused elsewhere in this region. In this section, we consider a more realistic but more complex assumption on imperfect mobility of pests across farms. On the other hand, to obtain tractable results, we simplify the analysis by assuming homogeneous vulnerability to pests. Formally, we assume that $\delta_t > \delta_{t+1}$ for every t but yet $n_i = n_{i+1} = n$. In this case of imperfect mobility but homogeneous farmers, pest resistance at i as defined in (2) simplifies to:

$$w_i = \gamma \frac{\sum_{j \in \Omega} \delta_{i-j} x_j}{\sum_{j \in \Omega} \delta_{i-j}}.$$

Since $\sum_{j \in \Omega} \delta_{i-j}$ does not depend on i, we denote it K. The resistance level at i becomes:

$$w_i = \frac{\gamma}{K} \sum_{j \in \Omega} \delta_{i-j} x_j.$$

The first-order condition of the efficient PRM strategy (5) writes

$$n(1 - w_i^*) + \underline{\lambda}_i^* = c + \frac{n\gamma}{K} \sum_{j \in \Omega} \delta_{j-i} x_j^* + \bar{\lambda}_i^*.$$

Since $\delta_{j-i} = \delta_{i-j}$ for every $i, j \in \Omega$, using the definition of w_i^*, it becomes

$$n(1 - w_i^*) + \underline{\lambda}_i^* = c + n w_i^* + \bar{\lambda}_i^*,$$

which, using the definition of w_i^*, yields:

$$w_i^* = \frac{1}{2} \left(1 - \frac{c}{n} + \frac{\underline{\lambda}_i^* - \bar{\lambda}_i^*}{n} \right). \tag{11}$$

The equilibrium PRM strategy satisfies (4) which, with imperfectly mobile pests and homogeneous producers, yields:

$$n(1 - w_i^e) + \underline{\lambda}_i^e = c + \frac{\gamma}{K} \delta_0 n x_i^e + \bar{\lambda}_i^e. \tag{12}$$

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Therefore, we have:

$$w_i^e = 1 - \frac{c}{n} - \frac{\gamma\delta_0}{K}x_i^e + \frac{\underline{\lambda}_i^e - \bar{\lambda}_i^e}{n},$$

and

$$x_i^e = \frac{K}{\gamma\delta_0}\left(1 - w_i^e - \frac{c}{n} + \frac{\underline{\lambda}_i^e - \bar{\lambda}_i^e}{n}\right),$$

for every $i \in \Omega$.

It is immediate that efficient and equilibrium resistance levels and proportions of pesticide variety plantings have to be equal everywhere, i.e. $w_i^* = w^*, x_i^* = x^*, w_i^e = w^e$ and $x_i^e = x^e$ for every $i \in \Omega$.

We now investigate the implementation of an efficient PRM strategy in equilibrium through regulation. We focus on the case where it is efficient to plant both the conventional and the pesticide variety at each location (i.e. the case where $\underline{\lambda}_i^* = \bar{\lambda}_i^* = 0$ for every $i \in \Omega$). From (11), the optimal resistance level is given by $w^* = \frac{1}{2}(1 - \frac{c}{n})$ at each location. Since $x_i^* = x^*$ for every $i \in \Omega$, then $w^* = \gamma x$ and, therefore, $x^* = \frac{1}{2\gamma}(1 - \frac{c}{n})$ at each location.

First, a mandatory refuge regulation restores efficiency. Suppose that producers are obliged to plant at most a proportion x^* with the pesticide variety. Expecting a resistance equilibrium level w^*, i would like to plant $x_i^e = \frac{K}{2\gamma\delta_0}(1 - \frac{c}{n}) > x^*$ with the pesticide variety and thus would reach the upper bound x^*.

Second, a tax τ on the pesticide variety yields an equilibrium PRM strategy (assuming that no constraint is binding):

$$x_i^e = \frac{K}{\gamma\delta_0}\left(1 - w_i^e - \frac{c+\tau}{n}\right).$$

It restores efficiency if there exists a tax level τ that achieves $x_i^e = x^*$ if w_i^e is replaced by w^* in the above equation. This tax level is:

$$\tau^* = \left(\frac{1}{2} - \frac{\delta_0}{2K}\right)(n - c).$$

It is strictly positive because $K > \delta_0$ and $n > (1 - w^*)n \geq c$ (the marginal benefit of the pesticide variety exceeds its overcost). It achieves $x_i^e = x^*$ only if $\frac{\delta_0}{K} > 0$, i.e. if each producer has a non-negligible impact on resistance. We thus have established the following result.

Proposition 4 *With imperfectly mobile pests and homogeneous producers, equilibrium refuge zones are sub-optimal. Efficiency can be restored by uniform mandatory refuges. It can also be restored by a tax on the pesticide variety, unless each producer's impact on resistance is negligible.*

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Condition (11) shows that it is the case when the constraints are not binding, i.e. when i is such that $\underline{\lambda}_i^* = \bar{\lambda}_i^* = 0$. In this case, $w_i^* = \frac{1}{2}(1 - \frac{c}{n})$. Suppose that there exist k and i such that $w_k^* > w_i^* = \frac{1}{2}(1 - \frac{c}{n})$ for one k at least. Then (11) and the slackness conditions show that $\bar{\lambda}_k^* = 1$ and $x_k^* = 1$. Due to the symmetry of the circle, optimality implies simply $\pi_k(1, w_k^*, n) + \pi_i(x_i^*, w_i^*, n) \geq \pi_k(x_i^*, w_i^*, n) + \pi_i(1, w_k^*, n)$, which is equivalent to $n(w_i^* - w_k^*)(1 + x_i^*) \geq 0$. It implies $w_i^* \geq w_k^*$ which contradicts our starting assumption $w_k^* > w_i^*$. A similar proof shows that we cannot have k and i such that $w_k^* < w_i^* = \frac{1}{2}(1 - \frac{c}{n})$. Hence, we have shown that the optimal resistance level is the same w^* everywhere. It is equal to $w^* = \frac{1}{2}(1 - \frac{c}{n})$ if no constraints are binding. In this case, since $x_i^* = x^*$ for every $i \in \Omega$, then $w^* = \gamma x$ and, therefore, $x^* = \frac{1}{2\gamma}(1 - \frac{c}{n})$. Otherwise, either all the upper bound constraints are binding, and then $x_i^* = 1$ for every $i \in \Omega$ and $w^* = \gamma$. Or all the lower bound constraints are binding and then to $x_i^* = 0$ for every $i \in \Omega$ and $w^* = 0$.

7 Conclusion

We show that the efficient management of pest resistance can be achieved (i) with mandatory refuges if farmers face identical pest attacks or if pests are not mobile across farms, (ii) with a tax/subsidy scheme if farmers face heterogeneous pest attack and pest are perfectly mobile.

The case of heterogeneous pest attacks and imperfectly mobile pests is left for future research. Simulations will be used to study this case, for which results are theoretically undetermined. For this last case, we expect the optimal regulation instrument to depend on the degree of pest mobility. If pest are highly mobile, thereby moving across heterogeneous farms, we expect that a tax/subsidy regulation type is more appropriate. Otherwise, mandatory refuges are likely to be better instruments to manage pest resistance efficiently.

A conclusion of this paper is that the market-based management fee strategy of common property resources may be dominated by the command-and-control refuge rule in this model with imperfect dispersion rates of pests. Therefore, the usual preference for market-based environmental instruments (Baumol et Oates 1988, Kolstad 2000) does not necessarily apply to pest resistance management, because the state of the common-pool resource does not depend on global but rather on local exploitation rates.

Beyond our specific case of pest resistance management, our paper sheds a new light on the choice of environmental instruments for the management of other common-pool resources whereby localisation and dispersion are important, such as biodiversity in forests (Chomitz 2004) or fisheries (Janmaat 2005).

8 References

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9 Appendix

9.1 Proof of Proposition 2

a. Substituting for $w^* = \frac{\gamma}{N} \sum_{j \in \Omega} x_j^* n_j$, the first order conditions (9) become:

$$n_i(1 - w^*) + \underline{\lambda}_i^* = c + n_i w^* + \bar{\lambda}_i^*, \tag{13}$$

for $i = 1, ..., I$. Define $n^* \equiv \frac{c}{1 - 2w^*}$. If the lower bound constraint $x_i \geq 0$ is binding, then $\underline{\lambda}_i^* > 0$, $x_i^* = 0$ and $\bar{\lambda}_i = 0$ which, combined with (13), imply that $n_i < n^*$.

Symmetrically, if the upper bound constraint is binding, then $\underline{\lambda}_i^* = 0$, $\bar{\lambda}_i > 0$ and $x_i^* = 1$ and, thus, $n_i > n^*$.

b. In (10), if the lower bound constraint $x_i \geq 0$ is binding, then $\underline{\lambda}_i^e > 0$, $x_i^e = 0$ and $\bar{\lambda}_i^e = 0$, which implies that $n_i < \frac{c}{1-w^e} \equiv n_1^e$. If the upper bound $x_i \leq 1$ is binding,

then $\underline{\lambda}_i^e = 0$, $\bar{\lambda}_i^e > 0$ and $x_i^e = 1$, which implies that $\frac{\gamma}{N}n_i^2 - n_i(1 - w^e) + c < 0$. Assuming that $(1 - w^e)^2 > \frac{4\gamma c}{N}$, this inequality holds for $n_i \in (n_2^e, n_3^e)$, with $n_2^e = \frac{N}{2\gamma}\left(1 - w^e - \sqrt{(1 - w^e)^2 - 4\frac{\gamma c}{N}}\right)$ and $n_3^e = \frac{N}{2\gamma}\left(1 - w^e + \sqrt{(1 - w^e)^2 - 4\frac{\gamma c}{N}}\right)$.

c. Propositions 2a and 2b imply that $w^* = \frac{\gamma}{N}(x^* n^* + \sum_{j\in\Omega, n_j > n^*} n_j)$ and $w^e = \frac{\gamma}{N}(\sum_{j\in\Omega, n_j \in (n_e^1, n_e^2)} x_i^e n_i + \sum_{j\in\Omega, n_j > n_e^2} n_i)$. Suppose that $n^* \leq n_1^e$. First, it implies that $\sum_{j\in\Omega, n_j > n^*} n_j \geq \sum_{j\in\Omega, n_j > n_1^e} n_j$. Therefore, from the above definitions of w^* and w^e, $w^* \geq w^e$. Second, by definition, it is equivalent to $\frac{c}{1-2w^*} \leq \frac{c}{1-w^e}$, which implies $w^* < w^e$. Thus the starting assumption $n^* \leq n_1^e$ leads to two contradicted consequences, namely $w^* \geq w^e$ and $w^* < w^e$, which shows that the reverse assumption must hold.

9.2 Proof of Proposition 3

A tax $\tau > 0$ on the pesticide variety increases its overcost to $c + \tau$. The equilibrium first-order condition (4) with $w_i = w$ and $\frac{\partial w}{\partial x_i} = 0$ becomes

$$n_i(1 - w^e) + \underline{\lambda}_i^e = c + \tau + \bar{\lambda}_i^e. \tag{14}$$

The threshold level n^e is defined by the first-order condition (14) when $\underline{\lambda}_i^e = \bar{\lambda}_i^e = 0$:

$$n^e(1 - w^e) = c + \tau. \tag{15}$$

Producers with $n_i < n^e$ satisfy (14) with $\underline{\lambda}_i^e > 0$ and $\bar{\lambda}_i^e = 0$ and thus select $x_i^e = 0$. Those with $n_i < n^e$ satisfy (14) with $\underline{\lambda}_i^e = 0$ and $\bar{\lambda}_i^e > 0$ and therefore choose $x_i^e = 1$.

Besides, we know from Proposition 2 that the efficient threshold satisfies

$$n^*(1 - 2w^*) = c$$

The above equality and equation (15) show that a tax implements the optimal outcome, formally $n^e = n^*$ and therefore $n^e = n^*$, for $\tau = n^* w^* = \sum_{j\in\Omega, n_j \geq n^*} n_j$.