

Pest Resistance Regulation and Pest Mobility

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Abstract

We examine the regulations for managing pest resistance to pesticide variety in a spatially-explicit analytical framework. We compare the performance of the EPA's mandatory refuges and a tax on pesticide variety under several biological assumptions on pest mobility and farmer's pest vulnerability. We find that the tax tends to be more efficient if farmers are sufficiently heterogeneous with regard to their pest vulnerability within the area in which pests move. On the other hand, the refuge is more efficient for low pest mobility or if each farmer's impact on his own pest resistance is negligible. Our result sheds light on the choice of regulatory instruments for common-pool resource regulations where spatial localization matters.

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1 Introduction

Resistance to pest damage is embedded in some crop varieties, which thereby have an economic advantage over their conventional non-resistant counterparts. But this advantage may be lost over time, as selection pressure causes pest populations to adapt to this resistance. A similar phenomenon is the erosion of the efficacy of chemical pesticides as pests become immune to them. Natural resistances have always existed in crop varieties, and some of them are selected deliberately through conventional crop breeding. The field of pest resistance management has received new and increased scrutiny with the advent

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of insect-resistant genetically modified crops, in which resistance to one major target pest (or more recently two pests) has been inserted through genetic engineering.

To date, all commercialized insect-resistant transgenic crops have obtained this resistance through the insertion and expression of the toxins of a soil bacterium, *Bacillus Thuringiensis* (*Bt*). Commercialization of these crops in the United States has raised concerns about adaptation build-up, especially among environmentalist groups, because organic farmers use *Bt* sprays for pest control. Largely due to active pressure by these groups, but also to the involvement of scientists calling for regulation, the large-scale adoption of *Bt* crops in the United States has been accompanied by the most impressive mandatory system ever developed for pest resistance management (EPA 2001, Bourguet et al. 2005). In 1995 for *Bt* cotton and in 2000 for *Bt* corn, the US Environmental Protection Agency has demanded that all farmers growing a *Bt* crop devote a given percentage of their farm surface to a non-GM non-insect-resistant variety. These non-GM areas are called refuges. They are designed to maintain a pool of susceptible insects to delay the buildup of adaptation to *Bt* crops in target insect populations. The regulation specifies the size of the refuge and a maximal distance between *Bt* and refuge fields.

This mandatory refuge system has been motivated by a market failure due to the fact that pest resistance is a common-pool resource exploited under open access by farmers. As pointed out by the earlier literature on pest resistance to chemical pesticides (Hueth and Regev 1974, Regev et al. 1983, Lazarus and Dixon 1984, Clark and Carlson 1990, Bromley 1990)¹, the use of pesticides (or, equivalently, what we call *pesticide varieties* such as *Bt* corn) has two impacts on farmers' profit. The first is the immediate benefit due to the reduction of the pest population and, therefore, of pest damages. It is individual since each farmer enjoys the benefit of pesticides applied on his own field. The second is the future decrease of susceptibility to the pesticide (chemical or variety) in the pest population, which reduces its beneficial use. For the latter impact, since pests are mobile on larger scales than single farms (which is the case for all target pests of *Bt* crops), pest susceptibility is a common-pool resource shared by all farmers in the area. Since the benefits of pesticides are individual but the costs in term of future development of pest resistance are collective, the market provides farmers with incentives to over-use pesticides. Hence, there is scope for regulation to improve crop production efficiency.

It is not however clear that a uniform mandatory refuge is the best regulatory instrument to manage pest resistance. The literature on common-pool resources and environmental regulation stresses that market-based regulations such as taxes and subsidies or tradable emissions permits are more efficient when agents (e.g. farmers) are heterogeneous. The reason is that market forces tend to assign the costs of reducing

¹See Miranowski and Carlson (1986) for a review and discussion on this literature.

pollution or resource over-use to the more efficient agents (see e.g. Baumol and Oates 1998, Kolstad 2000). In the case of pesticide use, different farmers usually face different pest vulnerabilities. A tax on pesticides would assign the reduction of pesticide use mostly to farmers less vulnerable to pest attacks.

However, a particular feature of pest resistance management mitigates this usual preference for market-based instruments: pest mobility is limited, because a pest is more likely to move to fields close by than to those far away. In other words, pest susceptibility is a common-pool resource that is scattered unevenly in the crop fields. This spatial externality among farmers implies that conventional variety fields should be located close enough to pesticide fields to serve as a refuge. Therefore, not only the costs and benefits of pesticide use matter for an efficient pest resistance management, but also the localization of pesticide use. The desirable localization of resource use is not necessarily linked with the value of this resource, and therefore is not necessarily implemented with market-based instruments. For instance, if all farmers whose opportunity cost to give up pesticide use were located in the same place, a tax on the pesticide variety would concentrate conventional fields close to one another, far away from the pesticide fields. Therefore, pests originating from those conventional fields would hardly cross with resistant pests emerging from pesticide crops since they would have a low probability of reaching them. In that case, a “command-and-control” regulation that restricts these places in which pest susceptibility is extracted, such as mandatory refuges, might be more appropriate. In this context, the aim of this paper is to compare the efficiency of the two aforementioned regulatory instruments, i.e. a mandatory refuge and a tax on pesticide variety, to mitigate the development of pest resistance, under several assumptions on pest mobility and farm heterogeneity.

The advent of *Bt* crops and the adoption of the refuge policy in the US have triggered a wave of studies and research on pest resistance management (see Hurley 2006 for a review). The first involvement of economists in the design of this policy has been to provide calibrated simulations, in collaboration with population biologists, in order to determine economically optimal refuge sizes (Hurley et al. 2001, Hurley et al. 2002) and the costs of alternative refuge configurations (Hyde et al. 2001). This initial work has been extended in various directions. Laxminarayan and Simpson (2002) examine how the optimal refuge size should change over time. Livingston et al. (2004) posit a simulation model for examining *Bt* resistance and insecticide resistance together, and assessing the effect of spraying refuges with insecticides or not. Mitchell et al. (2002) examine the effects of several incentive instruments to secure grower compliance with the uniform refuge requirement: a refuge insurance potentially coupled with a subsidy, a direct refuge subsidy along with inspection and return of the subsidy by non-compliant

growers, a mandatory insurance or a combination of fines and monitoring. Frisvold and Reeves (2006) show how providing multiple refuge options (e.g. a large refuge sprayed with a chemical pesticide versus a small unsprayed refuge) reduces regulatory costs.

The choice of the instrument itself was first questioned by Secchi and Babcock (2003). The authors apply a dynamic and spatially explicit simulation model calibrated on *Bt* corn to show that non-*Bt* fields planted near *Bt* fields significantly delay the resistance buildup, even with low levels of insect mobility across fields. They argue that if pest mobility is high enough, tradable refuges between neighbors may be superior to in-field mandatory refuges, although they do not analyze this alternative regulation in their simulations. In addition, they do not consider the impact of pest resistance regulations on farmers' variety choice since this choice is exogenous in their simulation. The present paper fills this gap by comparing the impact of mandatory refuges and a tax (which has the same flavor as tradable refuges) with endogenous farmers' variety choice.

In the same vein as Secchi and Babcock, Vacher et al. (2006) also use simulations and push the analysis further by making growers' variety choices endogenous, and by considering a fee on the *Bt* seed as an alternative to refuges, to decrease *Bt* areas and therefore delay the evolution of resistance. However, they assume that farmers are myopic, in the sense that they do not consider their own impact on pest resistance. In contrast, in this paper each farmer takes into account how his own actions affect resistance development. In Vacher et al. (2006) as in our paper, farmers are sorted geographically and face heterogeneous pest attacks. The fee strategy alone, in the absence of mandatory refuges, leads to a spatial segregation of *Bt* and conventional corn. Whether the non-*Bt* area serves as a natural refuge for the *Bt* area and contains the evolution of resistance depends on pest dispersal between the two patches and on the heterogeneity between farmers. The simulations in Vacher et al. (2006) suggest that the fee strategy alone would not work for *Bt* corn in the US Cornbelt, but could dominate the refuge strategy for a smaller and more heterogeneous ecosystem.

The present paper tackles the same issue as Vacher et al. (2006), using a different methodology. We design a spatially-explicit model of crop production with pest resistance in which farmers make crop variety choices. Instead of relying on simulations on calibrated dynamic models which lack of generality and transparency in the mechanisms at play, we use a stylized representation of the problem from which we are able to derive analytical solutions. We analyze the impact of two key parameters pointed out in Vacher et al. (2006): pest mobility and farm heterogeneity. Depending on the levels of these parameters, we assess whether a refuge or a tax on *Bt* seed can restore efficiency and, if not, how each of these instruments performs in managing the evolution of pest resistance.

Our approach is more in line with the mainstream environmental regulation literature, which attempts to design instruments that decentralize the efficient outcome (e.g. resource extraction or pollution reduction) in equilibrium. We first describe explicitly the efficient localization and size of crop varieties: what we call the efficient pest resistance management strategy. We then examine under which assumptions on pest mobility and farm heterogeneity a mandatory refuge or a tax on the pesticide variety lead to the efficient outcome in equilibrium. Next, we compare the performance of both instruments when they lead to second-best outcomes in equilibrium, to establish how the choice between the refuge and the tax varies when the degrees of pest dispersal and farm heterogeneity vary.

Apart from pest resistance management, the paper contributes to the literature on the choice of regulatory instruments when the spatial localization of the resource matters. Examples include fisheries, water, bio-diversity and pollution. For those resource and environmental problems, the market-based instruments fail to implement the first-best solution since the value of the resource is not necessarily related to its optimal spatial distribution. For instance, protecting some animal or vegetal species requires forest areas of specific form and size. The private property of land does not necessarily lead to forest areas of these forms and sizes (see Parkhurst and Shogren, 2005). For fisheries, the imperfect mobility of fish species in the ocean might provide a rationale for spatial enclosures such as marine reserves instead of tradable quotas or landing taxes (Chakravorty and Nemoto, 2000; see Janmaat, 2005, for a review).

The rest of the paper proceeds as follows. Section 2 presents the model. Section 3 describes the optimal and equilibrium outcomes in the general case, that is, without any specific assumption on pest mobility and farmer's pest vulnerability. It shows that the inefficiency of the equilibrium outcome is due to pest mobility. The next two sections analyze the decentralization of the efficient outcome (pest resistance management) with regulations under specific assumptions on pest mobility and farmer's pest vulnerability. Section 4 shows that a tax on the pesticide variety implements the efficient outcome if pests are perfectly mobile across fields and if farmers have a negligible impact on resistance. Section 5 shows that if farmers face same pest vulnerability then a refuge implements the first-best. It can also be implemented with a tax but only if farmers have a non-negligible impact on resistance. Section 6 compares the performance of the two regulations under alternative assumptions on pest mobility and farmer's pest vulnerability in implementing a second-best outcome.

2 Model

Although resistance build-up is a dynamic problem, we summarize the cumulated effect of the use of the resistant variety over time in a one-period problem. Farmers make their variety choice at the beginning of the period with rational expectations on future pest resistance. They obtain their profit at the end of the period. This short-cut allows us to keep the model tractable, to focus on one important side of the problem that has received less attention in previous papers: its spatial dimension.²

We rely on a spatially explicit framework in which we assume that farmers are spatially sorted, from those who face the fewest pest attacks to those who face the most (a sorting that could result from a climatic gradient). Due to pest mobility, resistance at each location is influenced by crop choices at other locations. This formalization allows us to capture the effect of pest dispersal in the long run when farmers make an initial crop variety choice and stick to it. In addition, we abstract from other issues that are of importance for pest resistance management but that appear less central for the choice of instruments in the first place: for example, we do not consider the possibility of applying a chemical pesticide on the non-resistant areas; nor do we consider strategic behavior from seed suppliers (we keep the seed prices as exogenous).

We consider a set Ω of $2I - 2$ farmers facing heterogeneous pest attacks. Producers are equidistant on a circle and located according to their ranking (i.e. for every $i \in \{2, \dots, 2I - 3\}$, farmer i has neighbors $i - 1$ and $i + 1$, and farmers 1 and $2I - 2$ are neighbors). Farmer 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 $i \in \{1, \dots, I\}$), and non-increasing in i on the second half of the circle. Moreover, we assume a symmetric distribution of n_i on both halves of the circle (i.e. $n_{2I-i} = n_i$ for every $i \in \{2, \dots, I - 1\}$), with $\max_{i \in \{1, \dots, I\}} n_i = n_I \leq 1$. Each farmer has a fixed area of land that is planted either with a pesticide variety or with a conventional variety that shows no resistance to the pest considered.

In the absence of pest attacks, the unit profit on the conventional variety is assumed to be constant and normalized to 1. All pests survive and cause crop damage on the conventional variety. Profit losses caused by pest attacks of intensity n_i are equal to n_i . The pesticide variety is available with an over-cost (or opportunity cost) c compared to the conventional variety. Only resistant pests survive to cause crop damage on the pesticide variety. The farmer's unit profit at location i is:

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

²The drawback is that we cannot analyze the dynamics of farmers' variety choices across time with resistance build-up.

where x_i is the proportion of surface area planted with a pesticide variety and w_i is the average long-run proportion of resistant pests.³

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

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

where $\delta_{i-j} = \delta_{j-i}$ captures the impact of farmer j 's crop on resistance at i (δ_0 is the effect of a farmer on his own resistance level) and γ quantifies the magnitude of resistance development, with $0 < \gamma < 1$. We assume $\delta_0 = 1$ and $\delta_j \leq \delta_k$ for $j < k$. This assumption implies that a farmer's impact on resistance at another location is decreasing with the distance.⁴

A pest resistance management strategy (PRM) $\mathbf{x} = (x_1, \dots, x_{2I-2})$ is a vector of resistant area proportions (or variety choice) x_i for every farmer $i \in \Omega$. In what follows, we successively examine the efficient PRM strategy, denoted as \mathbf{x}^* , and the equilibrium PRM strategy in the absence of regulation, denoted as \mathbf{x}^e , in the general case. Then, for specific assumptions on pest dispersal and farm heterogeneity, we examine these two strategies as well as the performance of two types of regulation, a mandatory refuge and a uniform tax on the seeds of the resistant variety.

3 Optimal and equilibrium outcomes

In our set-up, total welfare is measured by the sum of profits from crop production. Therefore, the socially optimal PRM strategy \mathbf{x}^* maximizes $\sum_{i \in \Omega} \pi_i(x_i, w_i, n_i, c)$, subject $0 \leq x_i \leq 1$ to every $i \in \Omega$. Denote $\underline{\lambda}_i^*$ and $\bar{\lambda}_i^*$ the multipliers associated with the respective constraints $x_i \geq 0$ and $x_i \leq 1$, for any $i \in \Omega$. The optimal PRM strategy \mathbf{x}^* satisfies the following first-order conditions:

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

³Immediate observation shows that: $\partial \pi_i / \partial x_i = n_i(1 - w_i) - c$: all other things being equal, 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 . This unit profit level decreases with the level of resistance w_i , as pest control then decreases on the resistant area. It decreases with the intensity of pest attacks n_i .

⁴At each location, choices of other farmers influence only resistance. We do not account for the fact that choices made at other locations may also influence the intensity of pest attacks at each location (pesticide plantings may decrease the whole pest population and therefore decrease the pest pressure at each location, i.e. each n_i could also be modelled a function of other farmers' planting strategies x_j).

for every $i \in \Omega$. In (3), the marginal benefit of the pesticide variety (left-hand side) is equalized to its marginal cost (right-hand side) net of the shadow costs of the constraints at any location i . 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 farmers* $j \neq i$, formally $\frac{\partial w_j}{\partial x_i}$.

Let us now examine the equilibrium PRM strategy $\mathbf{x}^e = (x_1^e, \dots, x_{2I-2}^e)$ defined as the planting strategies selected by farmers in the Nash equilibrium without regulation. Each farmer i maximizes his own profit $\pi_i(x_i, w_i, n_i, c)$ subject to $0 \leq x_i \leq 1$. Denoting $\underline{\lambda}_i^e$ and $\bar{\lambda}_i^e$ the multipliers associated with the respective constraints $x_i \geq 0$ and $x_i \leq 1$, the (only) solution x_i^e , satisfies the following first-order condition:

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

According to (4), each farmer 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 farmer incurs only the cost of the PRM strategy on his 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 farmers' profits.

It is easy to show that in our model the inefficiency of the equilibrium PRM strategy comes from the spatial externality among farmers. If pests are immobile from one farm to the next, formally if $\delta_k = 0$ for $k \neq 0$, then (2) simplifies to $w_i = \gamma x_i$ and, therefore, $\frac{\partial w_j}{\partial x_i} = 0$. Substituting in (3) and (4) leads to the same first order conditions for the optimal and equilibrium PRM strategies. Therefore if pests are immobile the PRM strategies selected by profit maximizer farmers are optimal.

In what follows, we compare the efficient and equilibrium PRM strategies under several assumptions on pest mobility and on the heterogeneity of pest attack intensity among farmers. Whenever the equilibrium is not optimal, we assess the performance of two regulations, a uniform mandatory refuge and a tax on the pesticide variety. With a (uniform mandatory) refuge, each farmer is allowed to plant at most a given proportion, let's say \bar{x} , of his area with the pesticide variety. Producer i then chooses x_i to maximize $\pi_i(x_i, w_i, n_i, c)$ subject to $x_i \in [0, \bar{x}]$. A tax τ on pesticide increases the over-cost of the pesticide seed from c to $c + \tau$. Therefore, farmer i chooses x_i to maximize $\pi_i(x_i, w_i, n_i, c + \tau)$ subject to $x_i \in [0, 1]$. In the next two sections we explicitly formulate \mathbf{x}^* and \mathbf{x}^e and analyze whether one or both instruments allow for efficiency to be restored, for extreme assumptions on pest dispersal rates and heterogeneity of pest attacks.

4 Perfectly mobile pests

We consider here the extreme case where pest dispersal is uniform: resistance development is determined by decisions made on all farms, no matter where they are located in relation to one another. Formally, we assume $\delta_k = 1$ for every distance k . All farmers then face the same externality and therefore the same resistance level,

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

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

The first-order condition of the efficient PRM strategy (3) becomes:

$$n_i(1 - w^*) + \underline{\lambda}_i^* = c + \frac{\gamma n_i}{N} \sum_{j \in \Omega} n_j x_j^* + \bar{\lambda}_i^*, \quad (5)$$

whereas the first-order condition of the equilibrium PRM strategy (4) yields:

$$n_i(1 - w^e) + \underline{\lambda}_i^e = c + \frac{\gamma n_i}{N} n_i x_i^e + \bar{\lambda}_i^e. \quad (6)$$

The next proposition describes and compares the efficient and equilibrium PRM strategies. It highlights the inefficiency of the “laissez faire” PRM strategy in this case.

Proposition 1 *With perfectly mobile pests, the efficient PRM strategy requires that farmers facing pest attacks up to a threshold n^* plant only the conventional variety while those facing pest attacks higher than n^* plant only the pesticide variety. In equilibrium PRM, farmers facing pest attacks lower than a threshold $n_1^e < n^*$ plant only the conventional variety. Depending on the model parameter values, those with pest attacks higher than n_1^e either all plant both varieties, or plant both varieties up to a threshold $n_2^e > n_1^e$, while those with attacks higher than n_2^e plant only the pesticide variety.*

The thresholds n^* and n_1^e are defined by $n^* \equiv \frac{c}{1-2w^*}$ and $n_1^e \equiv \frac{c}{1-w^e}$. The definition of n_2^e and the proofs are found in the Appendix.

With perfectly mobile pests, distances between farmers do not matter; only pest attack intensities n_j and farmers' planting strategies do. There is no cost of concentrating the pesticide variety in one area and the conventional variety in another. The pesticide variety is thus optimally planted where pest attacks are the highest. Since vulnerability to pests increases as one moves along the two halves of the circle of farmers, the optimal PRM strategy divides farmers into two neighboring groups: those more vulnerable to pests, who should plant only the pesticide variety, and the others who should rely on the conventional one.

In the “laissez faire” equilibrium also, farmers who use the pesticide seed are those more vulnerable to pests. Among them, some create a refuge zone to reduce resistance in their own fields because their own PRM strategy impacts the level of pest resistance on their own fields. Due to the open-access nature of pest resistance as a common-pool resource, the pesticide variety is overused in equilibrium: farmers whose pest attacks range between n_1^e and n^* plant the pesticide variety while it is efficient for them to plant only the conventional one.

We now examine whether the optimal PRM strategy may be implemented with regulation. A uniform mandatory refuge would never lead to the optimum, because it would force all farmers planting the pesticide variety to plant at least the mandatory refuge with the conventional variety, while the optimal PRM strategy requires that farmers specialize in pesticide or conventional variety.⁵ A tax on the pesticide seed $\tau > 0$ increases the overcost of the pesticide variety from c to $c + \tau$. The tax level may be chosen so as to provide incentives to farmers with pest attacks $n_i \in [n_1^e, n^*]$ to turn to the conventional variety. Yet as long as farmers internalize the impact of their variety choice on pest resistance in their own fields, they will devote part of their fields to the conventional variety. Therefore, the tax may implement the first-best only if each farmer plants only one of the two varieties. This happens if all farmers consider that their own variety choice has an infinitesimal impact on pest resistance. There could be two reasons for that: either the number of farmers N is very large, i.e. $\frac{n_i}{N}$ tends to 0; or farmers are “myopic” (in the sense that they ignore their impact on resistance when they choose their plant varieties). We now examine these two cases in more detail.

In both cases, profits π_i being linear in x_i for every i , each farmer i compares the return on pesticide variety, $1 - n_i w^e - c$ (with the equilibrium level of resistance w^e), with the return of the conventional variety, $1 - n_i$. Hence, farmers with low pest attacks $n_i < n_1^e \equiv \frac{c}{1-w^e}$ plant only the conventional variety (formally for those farmers $x_i^e = 0$), and those with $n_i > n^e$ plant only the pesticide variety (i.e. $x_i^e = 1$). Therefore, as with the optimal PRM strategy, the equilibrium threshold n_1^e divides each half circle of farmers $i = 1, \dots, I$ between those whose pest attacks are lower than n_1^e (who plant only the conventional variety) and the others (who plant only the pesticide variety). No farmer creates a refuge, but still, the area including farmers with pest attacks lower than n_1^e acts as a refuge area for the other farmers. It reduces resistance no matter where farms are located, given that pests are perfectly mobile. But in this laissez-faire equilibrium, farmers do not internalize their impact on resistance when they plant the

⁵Note that the optimal PRM strategy could be implemented by a “command-and-control” regulation different from mandatory refuges, by forcing farmers with $n_i \leq n^*$ to plant only the conventional variety. But this would require the inference of pest attack intensities n_i for every $i \in \Omega$ which is likely to be farmers’ private information.

pesticide variety, and therefore they rely too much on it. More precisely, all farmers with pest attacks n_i between n_1^e and n^* plant only the pesticide variety whereas they should plant the conventional one. By increasing the pesticide variety overcost from c to $c + \tau$, a tax τ switches the threshold pest attack sensitivity to $n^e(\tau) \equiv \frac{c+\tau}{1-w^e(\tau)}$. As τ increases, $n^e(\tau)$ increases since more farmers switch to the conventional variety. The optimal PRM strategy is implemented with a tax τ^* so that $n^e(\tau^*) = n^* \equiv \frac{c}{1-2w^*}$ and $w^e(\tau^*) = w^*$ which leads to $\tau^* = n^*w^*$. Therefore, we have established the following result.

Proposition 2 *When pests are perfectly mobile, if each farmer has a negligible impact on resistance, or if each farmer ignores his own impact on resistance development, farmers facing pest attacks up to n_1^e plant the conventional variety whereas those facing pest attacks higher than n_1^e plant the pesticide variety. Efficiency can be restored with a tax on the pesticide variety $\tau = n^*w^*$ where $w^* = \sum_{j \in \Omega, n_j \geq n^*} n_j$, which induces farmers facing pest attacks n_1^e up to n^* to turn to the conventional variety. Uniform refuge zones do not allow for efficiency to be restored.*

The equilibrium PRM strategy is inefficient because a farmer who plants the pesticide variety does not bear the full cost of the development of resistance resulting from his planting. A tax on the pesticide variety increases the over-cost of planting this variety. The proposed tax τ^* equalizes this over-cost to the aggregate losses resulting from the increase of resistance development for the farmer facing the threshold level of attacks n^* . As long as farmers consider that they have no impact on resistance development, this tax provides them with an incentive to select seed varieties efficiently, and yields an efficient resistance level.

5 Imperfectly mobile pests with homogeneous pest attacks

Having examined the two extreme assumptions of the absence of pest mobility and of perfect pest mobility, we now turn to the more realistic but complex assumption of imperfect pest mobility across farms. To obtain tractable results, we simplify the analysis by assuming homogeneous vulnerability to pests. Formally, we assume that $\delta_k > \delta_{k+1}$ for every k but $n_i = n_{i+1} = n$ for every $i \in \Omega$. In this case of imperfect mobility but homogeneous farmers, pest resistance at i as defined in (2) can be simplified as:

$$w_i = \frac{\gamma}{K} \sum_{j \in \Omega} \delta_{i-j} x_j, \quad (7)$$

with $K = \sum_{j \in \Omega} \delta_{i-j}$. Therefore, the marginal impact of any farmer j on pest resistance w_i at location i is $\frac{\partial w_i}{\partial x_j} = \frac{\gamma}{K} \delta_{i-j}$. It is decreasing with the distance $|i - j|$ between i 's and j 's fields.

For the optimal PRM strategy, substituting in (3), we obtain the following first-order condition:

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

which, using the definition of w_i in (7), simplifies to

$$n(1 - w_i^*) + \underline{\lambda}_i^* = c + nw_i^* + \bar{\lambda}_i^*. \quad (8)$$

The second-order condition which ensures that the optimal PRM strategy \mathbf{x}^* is unique, implies that the optimal variety choices x_i^* must be the same around the circle.⁶ This implies that pest resistance w_i^* will be the same everywhere. As before, corner solutions may occur. On the one hand, no pesticide seed is planted if $n \leq c$ since the loss due to pest attacks does not compensate for the overcost of the pesticide variety. On the other hand, it is optimal not to plant any conventional variety if $n(1 - 2\gamma) \geq c$. An interior solution occurs if $n(1 - 2\gamma) < c < n$, as none of the constraints is binding in that case. Then, condition (8) yields $w^* = \frac{1}{2} \left(1 - \frac{c}{n}\right)$. Using (7), we compute the optimal PRM strategy defined by $x_i^* = x^* = \frac{w^*}{\gamma} = \frac{1}{2\gamma} \left(1 - \frac{c}{n}\right)$ for every $i \in \Omega$. It prescribes the planting of a positive share of the field $1 - x_i^*$ with the conventional variety to reduce the development of resistance.

For the equilibrium PRM strategy, condition (4) yields:

$$n(1 - w_i^e) + \underline{\lambda}_i^e = c + \frac{\gamma}{K} \delta_0 n x_i^e + \bar{\lambda}_i^e. \quad (9)$$

Here, each farmer considers only the impact $\frac{\gamma}{K} \delta_0$ of his variety choice x_i^e on his own resistance w_i , thereby ignoring the impacts $\frac{\gamma}{K} \delta_{i-j}$ on all other farmers $j \neq i$'s resistance w_j . For an equilibrium resistance w_i^e at farm i , the share of pesticide plants on this farm is:

$$x_i^e = \frac{K}{\gamma \delta_0} \left(1 - w_i^e - \frac{c}{n} + \frac{\lambda_i^e - \bar{\lambda}_i^e}{n}\right). \quad (10)$$

We now investigate whether the efficient PRM strategy may be implemented in equilibrium through regulation. First, a mandatory refuge regulation restores efficiency. Suppose that farmers are constrained to plant at most a proportion $\bar{x} = x^*$ with the pesticide variety. Expecting a resistance equilibrium level w^* , condition (10) shows that

⁶Otherwise, moving the localization of \mathbf{x}^* by any positive number $k < I$ to the left or to the right along the circle would yield same total profit and therefore would also be optimal.

i would like to plant $x_i^e = \max\{\frac{K}{2\gamma\delta_0}(1 - \frac{c}{n}), 1\} > x^*$ with the pesticide variety and thus would reach the upper bound x^* . Second, a tax τ on the pesticide seed would increase its opportunity cost from c to $c + \tau$. Therefore, assuming that no constraint is binding (i.e. $\underline{\lambda}_i^e = \bar{\lambda}_i^e = 0$), the equilibrium variety choice in (10) yields an equilibrium PRM strategy:

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

The tax level that restores efficiency is such that $x_i^e = x^*$ if $w_i^e(\tau)$ is replaced by w^* in the above equation. This tax level is:

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

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). Note that it achieves $x_i^e = x^*$ only if $\frac{\delta_0}{K} \neq 0$, i.e. if each farmer has a non-negligible impact on resistance or if farmers are not myopic. Otherwise, as with perfectly mobile pests, farmers plant only one variety on all their land. With homogeneous farmers, as assumed, the equilibrium PRM strategy with a tax leads them all to choose only the conventional or the pesticide variety. We have thus established the following result.

Proposition 3 *With imperfectly mobile pests and homogeneous farmers, 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 farmer's impact on resistance is negligible, or each farmer ignores his own impact on resistance development.*

6 Comparison of refuge and tax under alternative assumptions on pest mobility and heterogeneity of pest attacks

We now turn to the case where pest mobility is imperfect and where producers face heterogeneous pest attacks. Analytical analysis is not tractable then, and we use numerical simulations to assess how pest mobility and producers' heterogeneity affect the efficiency of the two regulations. We assume that $I = 3$: four producers are located equidistantly on a circle and face pest attacks n_i with $n_1 \leq n_2 \leq n_3$ and $n_2 = n_4$. We set $\gamma = 0.8$ and $c = 0.1$. We model pest dispersal by $\delta_1 = h_\delta$ and $\delta_2 = (h_\delta)^2$, and pest attacks by $n_1 = 0.5(1 - h_n)$, $n_2 = n_4 = 0.5$ and $n_3 = 0.5(1 + h_n)$, letting the parameters h_δ and h_n vary from 0 to 1 by range of 0.1. This parameterization encompasses the extreme cases of immobile pests ($h_\delta = 0$), perfect pest mobility ($h_\delta = 1$), homogeneous pest attacks

($h_n = 0$) and maximum heterogeneity ($h_n = 1$). Letting h_δ increase between 0.1 and 0.9 simulates higher degrees of pest mobility, while letting h_n increase between 0.1 and 0.9 simulates increasing degrees of heterogeneity.⁷ As h_n and h_δ vary between 0 and 1, for each couple (h_n, h_δ) , we use numerical constrained optimization to determine the optimum and the equilibria without regulation, with the optimal tax level and with the optimal uniform refuge.

Table 1 below indicates which of the two instruments, tax or refuge, performs best (if needed) depending on pest mobility h_δ and farmers' heterogeneity h_n . The results are divided into four quartiles depending on welfare differences.⁸

[Insert Table 1]

Consistent with our theoretical results, we find that both the tax and the refuge allow the optimum to be implemented if producers are homogeneous ($h_n = 0$). There is no other simulation in which either the tax or the refuge implements the optimum. Table 1 then illustrates the relative performance of the two instruments. As long as pest dispersal and/or heterogeneity between farms remain small (more or less, above the dotted line in Table 1), the two instruments perform very similarly. With low pest mobility, farmers internalize a lot of their own effect on the evolution of resistance. Consequently, not much regulation is warranted, and not much difference appears in the profits obtained with the two instruments. With low heterogeneity between farms, the tax and the refuge perform fairly similarly since they are equivalent with homogeneous farmers.⁹ When either pest dispersal h_δ or heterogeneity between farms h_n , or both, become high, i.e. below the dotted line in Table 1, the gap in the performance between the two instruments becomes significant. With high pest mobility, we find that the tax dominates the refuge, a result that is in conformity with our theoretical findings for perfect mobility. The results are less clear-cut for a high farm heterogeneity. With low pest mobility and high farm heterogeneity, the refuge strategy dominates the tax strategy.

⁷Our multiplication formulation of pest dispersal encompasses both extreme cases of pest immobility ($\delta_1 = \delta_2 = 0$) and perfect mobility ($\delta_1 = \delta_2 = 1$) and reflects the empirical observation that pest dispersal decreases more than linearly with the distance. Our additive formulation of heterogeneity in pest attacks yields the same difference between n_2 and n_3 as between n_1 and n_2 , and models maximum heterogeneity in a simple way (with $h_n = 1$, we have $n_1 = 0$, $n_2 = 0.5$ and $n_3 = 1$). For these reasons, we use a different formulation for pest dispersal and for heterogeneity of pest attacks. In the extreme case where $n_1 = 0$ and pests are immobile, we assume that farmer 1 grows only the conventional crop without using equation 2 (formally, resistance at location 1 is undefined).

⁸Note that when a tax is used, aggregate profits (the welfare) include the tax revenue, assumed to be redistributed to producers in a lump-sum way. The welfare values are provided in the Appendix.

⁹Note that if farmers' impact on resistance is not nil, both regulations implement the first-best with homogeneous farmers.

Interestingly, the relative performance of the two instruments does not change monotonically with pest dispersal or farm heterogeneity. For some values of the dispersal parameter h_δ , the best regulatory instrument is the refuge, then the tax, then again the refuge, as the heterogeneity of pest attacks h_n increases. Symmetrically, for some values of the heterogeneity parameter h_n , the best instrument is the tax, then the refuge, then the tax, as pest dispersal h_δ , increases.¹⁰ This point is illustrated in Figure 1 (respectively Figure 2) in which we plot the welfare (aggregate producers' profit) at the optimum and equilibrium with each regulation as a function of farmers' heterogeneity h_n fixing pest dispersal at $h_\delta = 0.4$ (respectively pest dispersal h_δ fixing farmers' heterogeneity at $h_n = 0.1$).¹¹

[Insert Figure 1 and 2]

It is also interesting to investigate how the results change if we assume that farmers are “myopic” in the sense that they do not account for their own effect of resistance development – since this assumption is often retained in simulation models of pest resistance management (e.g. Vacher et al., 2006). Table 2 below shows the relative performance of the two instruments when farmers are myopic.

[Insert Table 2]

Results are much more clear-cut then. The refuge is more efficient than the tax for low and intermediate pest dispersal. On the other hand, the tax performs better than the refuge for high pest dispersal. Also, with myopic farmers, the tax tends to dominate more often since farmers respond less to tax incentives. The difference between Tables 1 and 2 suggests that we should be careful when comparing regulations with simulations if we ignore the farmer's perception of his own choice on pest resistance. As long as farmers have a non-infinitesimal impact on resistance at their own location – either because they are not too numerous, or because pest mobility is limited – they are not “resistance takers”. We should take into account the strategic interactions among them and therefore focus on the Nash equilibrium of the game, not the competitive equilibrium.

Altogether, these simulations suggest that the important parameter for the choice of regulatory instruments is pest mobility: the tax should be implemented with highly

¹⁰The welfare is around 2.4 in the collective optimum, and the maximum deviation from this optimum is 0.015 in the graphs, therefore the refuge and the tax perform quite close to the social optimum.

¹¹Note that the increase of welfare (total profits) at the optimum with pest dispersal and/or farmers' heterogeneity is due the pesticide variety fix cost c . As heterogeneity and pest dispersal increase, less farmers plant pesticide varieties but those who do plant a higher share, thereby minimizing fix total costs.

mobile pests, while mandatory refuges are better adapted for less mobile pests, even with high farm heterogeneity.

7 Conclusion

How should pest resistance to pesticide seeds be regulated? The paper illustrates the trade-off between a “command-and-control” instrument, which imposes the localization of resource uses and/or externalities, and a “market-based instrument” which delegates this choice to the agents (here, farmers). It highlights that the choice of regulatory instruments depends on pest mobility and on the heterogeneity of farmers’ vulnerability to pests. We provide analytical and simulation insights on this choice using a stylized model where the latter features are two parameters. We find that the first-best pest resistance management can be achieved (i) with a tax on pesticide seeds if pests move uniformly across fields and each farmer has a negligible impact on resistance development; (ii) with a mandatory refuge or a tax on pesticide seeds if farmers are homogeneous – provided that each farmer has a non-negligible impact on resistance in his own field for the tax. In the more general case of heterogeneous farmers and non-uniform (or imperfect) pest mobility, we compare the performance of the two instruments on welfare using simulations in an example. We find that neither instrument can restore efficiency, and that their relative performances differ significantly if either pest mobility or farmers’ heterogeneity is high. As long as pests are highly mobile across fields, the tax dominates the refuge. However, if pest mobility is more geographically restricted but farmers’ heterogeneity is high, the refuge dominates.

Environmental economists like market-based instruments such as taxes (or tradable permits or quotas) because market forces lead to an efficient assignment of the burden of resource use, or pollution reduction, among agents. Therefore, market-based instruments tend to minimize the costs to reduce resource use or pollution when those costs are agents’ private information. This paper shows that when localization matters, those who reduce resource use or pollution are not always located in the right place. Hence, minimizing the cost of reducing resource use (or pollution) does not necessarily imply an efficient localization of this reduction and, therefore, does not lead to the first-best. The performance of each instrument type (market-based or command-and-control) in implementing a second-best solution depends on the relative importance of two sources of efficiency gain. Market-based instruments are good at minimizing the opportunity costs of reducing resource use (or pollution), while command-and-control instruments are good at localizing resource use (or pollution) efficiently. In our set-up, the more pests move across heterogeneous farms, the higher the gains from minimizing pollution

(or resource use) reduction costs will be. On the other hand, if pest move less, their spatial localization has a higher impact on the welfare and the command-and-control instruments consequently dominate.

Another line of research would be to design a regulatory instrument to improve efficiency compared to the tax alone or the refuge alone options, when pest mobility is non-uniform and farmers are heterogeneous (as the refuge and tax both fail to implement the first-best in this case). A solution could be a market-based instrument with a spatial component. In the field of biodiversity protection, one such instrument is an agglomeration bonus which subsidizes contiguous conservation lands and therefore increases the value of private land if protected areas are agglomerated (Parkhurst and Shogren, 2005). Another is a tradable market for mandatory forest areas on agricultural land, which Chomitz (2004) analyses under several assumptions on the territorial size of the market in Brazil. In both cases a spatial dimension (the bonus or the territorial size) is added to the market-based instrument (private property for land or tradable mandatory forest areas) in order to favor the concentration of protected biodiversity areas. In contrast, for pest resistance management, regulation should favor the break-up and dispersion of refuge areas.

A Proof of Proposition 1

First, we identify the efficient PRM strategy \mathbf{x}^* . Since $w^* = \frac{\gamma}{N} \sum_{j \in \Omega} x_j^* n_j$, for every $i \in \Omega$, the first order condition (5) may be written:

$$n_i(1 - w^*) + \underline{\lambda}_i^* = c + n_i w^* + \bar{\lambda}_i^*, \quad (11)$$

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 (11), 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, $n_i > n^*$.

Second, we examine the equilibrium PRM strategy \mathbf{x}^e . Define $\Delta = (1 - w^e)^2 - 4\frac{\gamma c}{N}$. In (6), 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 $\frac{\gamma}{N} n_i^2 - n_i(1 - w^e) + c < 0$ (inequality A).

If $\Delta \leq 0$, inequality A never holds, therefore there is no farmer with $x_i^e = 1$.

If $\Delta > 0$, inequality A holds for $n_i \in (n_2^e, n_3^e)$, with $n_2^e = \frac{N}{2\gamma} (1 - w^e - \sqrt{\Delta})$ and $n_3^e = \frac{N}{2\gamma} (1 - w^e + \sqrt{\Delta})$.

Assuming that $\Delta > 0$, one easily checks that $n_I < n_2^e \iff \sqrt{\Delta} < 1 - w - \frac{2\gamma n_I}{N} \iff 1 - w > \frac{2\gamma n_I}{N}$ and $\Delta < \left(1 - w - \frac{2\gamma n_I}{N}\right)^2 \iff$ condition A holds. Therefore if $\Delta > 0$ and if condition A holds, there is no farmer i with $x_i^e = 1$ (farmers with $x_i^e = 1$ should be such that $n_i \in (n_2^e, n_3^e)$, but $n_I < n_2^e$).

Assuming that $\Delta > 0$, one easily checks that $n_3^e < n_I \iff \sqrt{\Delta} < \frac{2\gamma n_I}{N} - (1 - w)$ which implies that $1 - w < \frac{\gamma n_I}{N} + \frac{c}{n_I}$ (inequality B). But if $n_3^e < n_I$ then inequality A does not hold for n_I , therefore necessarily $x_I^e < 1$ and $\underline{\lambda}_I^e = 0$. From the Lagrangean (6) this implies $n_I(1 - w^e) < c + \frac{\gamma n_I^2}{N}$ which contradicts inequality B. Therefore we cannot have that $n_3^e < n_I$.

From (6), the proportion of pesticide variety for a farmer planting both varieties is given by $x_i = \frac{(n_i(1-w^e)-c)N}{\gamma n_i^2}$. Assuming that farmers i and $i+1$ plant both varieties, we obtain that $x_{i+1} - x_i$ is of the sign of $c(n_i + n_{i+1}) - (1 - w^e)n_i n_{i+1}$, which is indeterminate.

Third, we show $n^* > n_1^e$. Consider first the case $\Delta > 0$. Suppose $n^* \leq n_1^e$. 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 contradictory consequences, namely $w^* \geq w^e$ and $w^* < w^e$, which shows that the reverse assumption must hold. The proof is similar in the case where $\Delta \leq 0$, or in the case where $\Delta > 0$ and condition A does not hold.

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Table 1. Simulation results: which regulation performs best?

		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	h_δ
0	no	P _{opt}	P _{opt}	P _{opt}	P _{opt}	P _{opt}	P _{opt}	P _{opt}	P _{opt}	P _{opt}	P _{opt}	P _{opt}	
0.1	no	T	R	R	R	R	R	R	T	T*	T*	T**	
0.2	no	T	T	R	R	R	T	T*	T**	T**	T**	T***	
0.3	no	T*	T	R	R*	R	T*	T**	T**	T**	T***	T***	
0.4	no	T*	T*	T	T	T*	T**	T***	T***	T***	T***	T***	
0.5	no	T	T*	T*	T**	T**	T***	T***	T***	T***	T***	T***	
0.6	no	R	T	T**	T**	T***	T***	T***	T***	T***	T***	T***	
0.7	no	R	T*	R*	R**	R**	R*	R*	T**	T**	T**	T***	
0.8	no	R*	R*	R*	R**	R**	R*	T	T**	T***	T***	T***	
0.9	no	R	R*	R**	R**	R**	R*	T*	T**	T**	T***	T***	
1	no	R	R*	R**	R**	R**	R*	T*	T**	T**	T***	T***	
h_n													

Note: This table provides simulation results with h_δ in columns and h_n in lines. It indicates one of four possible situations: no regulation is warranted ("no"); each of the two instruments, tax or refuge, may restore the optimum ("P_{opt}"); a tax does better than a refuge, but does not restore the optimum ("T"); a refuge does better than a tax, but does not restore the optimum ("R"). Results for situations T and R are divided in four quartiles, depending on the absolute value of the difference in aggregate producers' profits with the optimal tax and the optimal refuge. The 25 simulations with the lowest difference in aggregate profits with these two instruments are indicated with no star, the 25 simulations with an intermediate low difference with one star, the 25 simulations with an intermediate high difference with two stars, and the 25 simulations with the highest difference in profits with three stars.

Figure 1. Welfare as a function of h_n , for a given h_δ

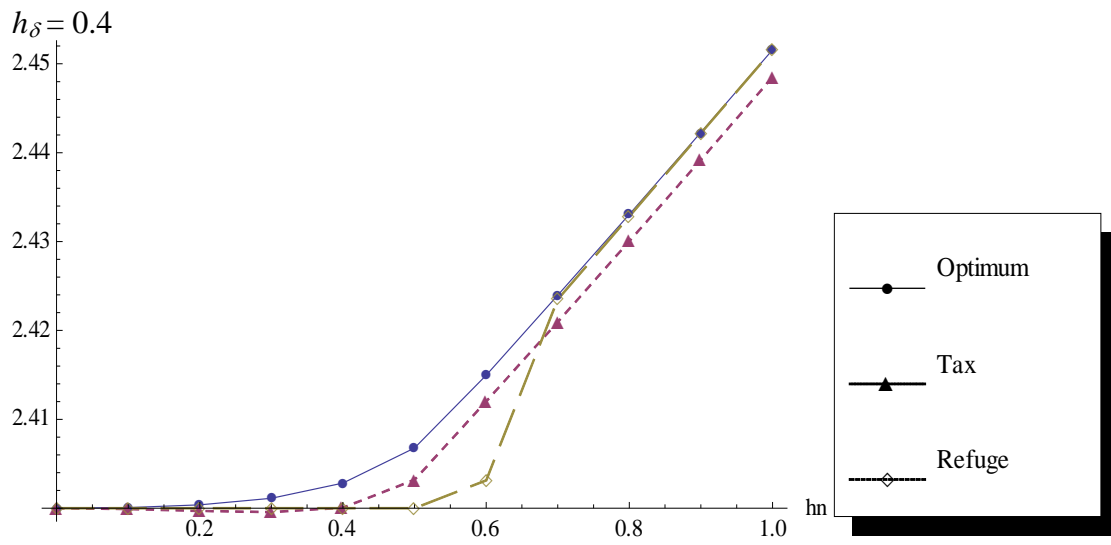


Figure 2. Aggregate welfare as a function of h_δ , for a given h_n

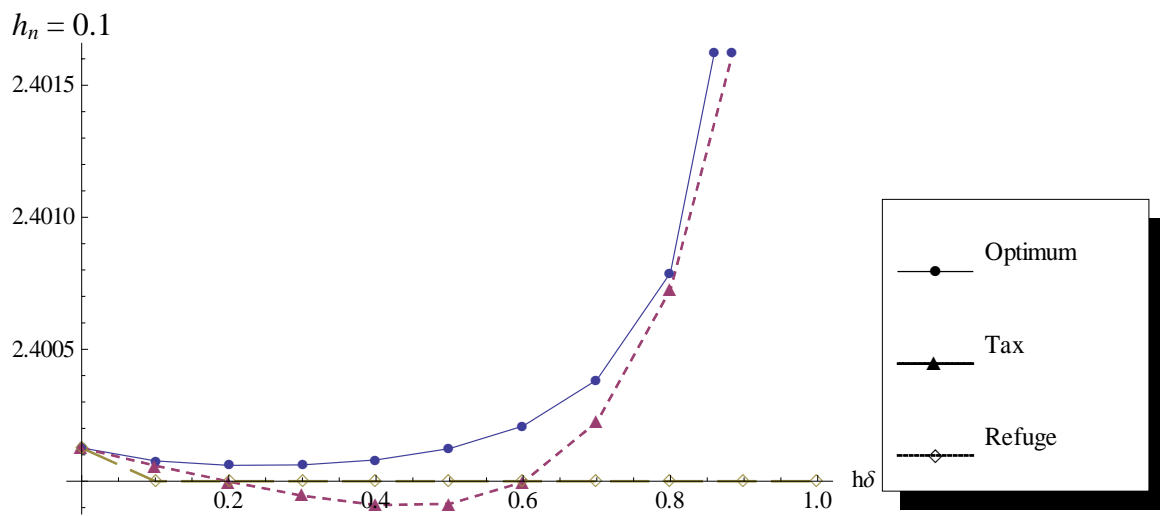


Table 2. Simulation results: which regulation performs best if farmers are myopic?

	h_δ										
h_n	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	P_{opt}	P_{opt}	P_{opt}	P_{opt}	P_{opt}	P_{opt}	P_{opt}	P_{opt}	P_{opt}	P_{opt}	P_{opt}
0.1	R	R	R	R	R	R	R*	R*	R*	R	T
0.2	R	R*	R*	R*	R**	R*	R**	R*	R	T	T*
0.3	R*	R**	R**	R**	R**	R**	R*	R*	T	T*	T*
0.4	R***	R**	R**	R**	R***	R**	R*	R	T	T*	T**
0.5	R**	R**	R***	R***	R***	R**	R*	R	T*	T*	T***
0.6	R**	R**	R***	R***	R***	R**	R*	T	T*	T**	T**
0.7	R**	R**	R***	R***	R***	R***	R**	R*	R	T*	T*
0.8	R**	R***	R***	R***	R***	R***	R**	R*	T	T*	T**
0.9	R***	R***	R***	R***	R***	R***	R**	R*	T	T*	T**
1	R***	R***	R***	R***	R***	R***	R**	R*	T	T*	T**

Note: same as in Table 1.