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Regulation of a spatial externality: Refuges versus tax for managing pest resistance

Stefan Ambec* and Marion Desquilbet†‡

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Abstract

We examine regulations for managing pest resistance to pesticide varieties in a temporally and spatially explicit framework. We compare the performance of the EPA's mandatory refuges and a tax (or subsidy) on the pesticide variety under several biological assumptions on pest mobility and the heterogeneity of farmers' pest vulnerability. We find that only the tax (or subsidy) restores efficiency if pest mobility is perfect within the area. If pest mobility is imperfect and when farmers face identical pest vulnerability, only the refuge might restore efficiency. With simulations we illustrate that complex outcomes may arise for intermediate levels of pest mobility and farmers' heterogeneity. Our results shed light on the choice of regulatory instruments for common-pool resource regulations where spatial localization matters.

JEL classification: Q16, Q18, D62.

Keywords: pest resistance, pesticides, transgenic crop, tax, refuge, spatial, externalities.

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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 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 acquired 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. Alternatively, since 2008, growers of some *Bt* cotton varieties in the southeastern US may utilize a natural refuge instead of a structured refuge for insect resistance management. This natural refuge may consist of weeds, wild hosts or other planted crops that can serve as alternate plant hosts for target insects of the *Bt* varieties (EPA, 2007).

In this paper, our aim is to assess to what extent, and how, plantings of pest-toxic varieties (that we call *pesticide varieties*) should be regulated, taking into account the benefits of such regulation only for the group of farmers using those varieties (and ignoring its benefits for non-users, like organic farmers using *Bt* sprays). As the earlier literature on pest resistance to chemical pesticides pointed out (Hueth and Regev 1974, Regev et al. 1983, Lazarus and Dixon 1984, Clark and Carlson 1990, Bromley 1990)[1], regulation is motivated by two market failures: the lack of property rights on the pest

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

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population and pest resistance. Both resources are commonly pooled and detrimental to all farmers. They are exploited under open access. In fact, the use of pesticide varieties has three 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 in the pest population level, which increases its beneficial use. Finally, the third impact is the future decrease in pest susceptibility to the pesticide which reduces its beneficial use. For the latter two impacts, since pests are mobile on larger scales than single farms (which is the case for all target pests of *Bt* crops), future pest population levels and pest susceptibility are common-pool resources shared by all farmers in the area. Since the immediate benefits of pesticides are individual but the benefits in terms of future pest population reduction and the costs in terms of future development of pest resistance are collective, the market provides farmers with incentives to under-use or 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 pollution or resource over-use to the more efficient agents (see e.g. Baumol and Oates 1998, Kolstad 2000). 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 economic 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

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mandatory refuges, might be more appropriate.

The aim of this paper is to clarify what determines the performance of the two aforementioned regulatory instruments namely a mandatory refuge and a tax or subsidy on the pesticide variety in mitigating the development of pest resistance. We highlight the fact that the choice between the two instruments depends on farmers' heterogeneity and pest mobility. To do so, we rely on a stylized model of crop choice with spatial externalities. To simplify, we reduce the time horizon to two periods. This allows us to capture how farm heterogeneity and pest dispersal interplay with analytical results. We are able to compute conditions describing the first-best and equilibrium outcomes under general assumptions on farm heterogeneity and pest dispersal. We use these conditions to analyze two cases analytically: perfectly mobile pests with heterogeneous farmers and imperfectly mobile pests with homogenous farmers. In each case we show that one of the two instruments implements the first-best while the other might not. We then provide a simulated example of the general model in which we vary heterogeneity and pest dispersal.

The rest of the paper proceeds as follows. Section 2 relates the paper to the economic literature on regulatory instruments with spatial externality and pest resistance management. Section 3 presents the model. Section 4 describes the optimal and equilibrium outcomes in the general case, that is, without any specific assumption on pest mobility and farmers' 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 5 shows that, unlike refuges, a tax on the pesticide variety restores efficiency if pests are perfectly mobile across fields. Section 6 shows that when farmers face the same pest vulnerability then a refuge restores efficiency. It can also be restored with a tax but only if farmers have a non-negligible impact on resistance. Section 7 compares the performance of the two regulations under alternative assumptions on pest mobility and farmers' pest vulnerability in implementing a second-best outcome.

2 Related literature

Our paper is related to two strands of the literature concerning, respectively, the choice of regulatory instruments under an economic environment with spatial externalities, and regulation strategies for reducing the development of pest resistance.

The development of pest resistance is a spatial-dynamic process. As noted above, pest resistance is a common-pool natural resource that spreads spatially over time. We

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can therefore borrow from the literature on the management and the regulation of other spatial-dynamic resources such as fisheries or endangered species (see Wilen (2007), Smith, Sanchirico and Wilen (2009), for recent reviews). We keep the temporal dimension of our model as simple as possible by summarizing the dynamics of the biological system in two periods. This simplifies the presentation considerably. Furthermore, we believe that it captures the main dynamic dimension of the problem since the time horizon for pesticide use is finite: at some point in time the pesticide seed will be useless either because most pests will become resistant or because another more efficient pesticide will be available. We devote more attention to the spatial dimension because our goal is to understand how the tax *versus* refuge regulations performs in mitigating the spatial externality problem. To this aim, we add more structure to the spatial model than is usually done in this literature. We assume that farmers are located along a circle and that their fields host pests, with different initial pest pressures and different pest growth rates due to climatic conditions. These initial pest pressures and growth rates evolve monotonically (at least weakly) moving along the circle. The fraction of pests that moves from one field to another is weakly decreasing with the distance between the two fields.

The most closely related paper to ours is Sanchirico and Wilen (2005). In an open-access spatial-dynamic fishery, these authors characterize the first-best outcome. They consider a tax regulation with only two patches, and show that the first-best can be decentralized with a spatial differentiated tax, while a uniform tax implements only a second-best. In fact, with a uniform tax, harvesting efforts are not allocated efficiently over space, since fishermen equalize after-tax marginal rents over all fishing patches, and therefore over-fish in low-cost patches and under-fish in high-cost patches. Here we consider another uniform regulation: a mandatory refuge. We compare the performance of the two uniform regulations in a richer spatial structure with more than two producers.

In the same vein, Janmaat (2005) analyzes the impact of resource dispersal in an open-access fishery. By comparing the optimal and equilibrium outcomes, he highlights the fact that increasing dispersal enhances the tragedy of the commons by reducing the steady-state resource stock, especially when dispersal is stock-dependent. Here we also consider resource dispersal and population as key parameters to manage pest resistance. We compare the performance of two policy instruments that improve efficiency in equilibrium: uniform mandatory refuges and uniform taxes.

Also on fisheries, Chakravorty and Nemoto (2000) compare the performance of several regulations in a spatial-temporal model calibrated on the Hawaii Longline fishery. They consider closure area policies and an increase of harvesting tax. Their policy conclusions are very specific to the parameters of the model they simulate and can,

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therefore, not be imported to different spatially explicit problems.

Our paper is also related to the literature on the design of natural reserves. A refuge and a natural reserve are both a share of land that is not fully exploited economically, for preservation purposes (pest resistance for the refuges and endangered species for natural reserves). Potts and Vincent (2007) use a spatially explicit model to analyze the localization and size of natural reserves. They find that aggregating reserves favors conservation. Some papers analyze specific regulations to implement natural reserves. Parkhurst and Shogren (2007) consider 'agglomeration bonuses' that subsidize aggregated conservation lands. They design a spatially explicit experiment to assess the performance of this regulation in implementing reserves of a specific form, e.g. a core or a corridor. Chomitz (2004) simulates markets in which farmers exchange mandatory forest protection areas on different geographical scales. The problem of biodiversity conservation is however different from pest resistance management, in that it leads to opposite predictions regarding the optimal spatial localization of refuges or natural reserves: they should be aggregated to protect biodiversity, but scattered across the landscape to be efficient in preserving pest resistance. It is therefore difficult to derive insights from this literature. More generally, policy recommendations from spatial-dynamic studies comparing regulations are often specific to the problem addressed. We complement this literature with a stylized temporal and spatial model of pest resistance management.

In the context of pest resistance, 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). Economists' first involvement in designing 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 regulatory 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).

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These 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 a similar approach to that of 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 of failing to consider their own impact on future pest population and resistance levels. In contrast, in our 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 Corn Belt, 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 two-period spatially explicit model of crop production with pest resistance in which farmers make crop variety choices. Instead of relying on simulations of calibrated dynamic models which lack 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 or subsidy on *Bt* seeds can restore efficiency and, if not, how each of these instruments performs in managing the evolution of pest resistance.

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3 Model

We rely on a temporally and spatially explicit framework in which, due to pest mobility, pest population levels and resistance at each location are influenced by crop choices at other locations in the former period.[2] For this purpose, we define a set Ω of $2I-2$ farmers that are equidistant on a circle and located according to their ranking (i.e. for every $i \in \{2,..,2I-3\}$, farmer i has neighbors $i-1$ and $i+1$, and farmers 1 and $2I-2$ are neighbors). In year t farmer i faces an intensity of pest attacks n_{it} and a pest resistance level w_{it}, both of which are affected by pest mobility from other locations. Each farmer has the same 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.

We define a biological model in discrete time, which represents a modified version of the pioneering work of Alstad and Andow (1995) on pest resistance management with transgenic *Bt* crops and refuge fields. To simplify, we reduce the time dimension to two periods, which is enough to capture the inter-temporal impact of pesticide plantings on pest attack intensity and pest resistance. The environment is assumed to be deterministic, with selection driving the evolution of a population of insects and of its genetic composition over time. In biological terms, we assume that resistance is determined by a single locus with two alleles, where an allele can either be susceptible (s) or resistant (r) to *Bt*.[3] In this diploid context, each insect inherits one allele from its father and one from its mother, and is thus either a resistant homozygote (rr), a susceptible homozygote (ss), or a heterozygote (rs).

We define the pest population at location i at the beginning of year t, n_{it}, as an average number of larvae per plant, which may be distributed unevenly over *Bt* and refuge fields. Omitting the indices, this average pest population is $n = n^{rr} + n^{ss} + n^{rs}$, where we let n^{rr}, n^{ss} and n^{rs} denote respectively the average number of resistant and susceptible homozygotes as well as heterozygotes, in terms of larvae per plant. The total number of alleles is $n^r + n^s = 2n$, among which $n^r = 2n^{rr} + n^{rs}$ are resistant and $n^s = 2n^{ss} + n^{rs}$ are susceptible. The average proportion of resistant alleles is defined by $w = n^r/(2n)$. We assume one generation of insects per year, with non-overlapping generations.

The initial pest attack n_{i1} is non-decreasing in i on the first half of the circle (i.e. $n_{i+1,1} \geq n_{i1}$ for every $i \in \{1,...,I-1\}$), which captures natural climatic and biological

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[2] 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 exogenous).

[3] As Roughgarden (1998) explains, "[F]or our purposes, a "locus" is a spot on a chromosome. Two different genes that can occupy the same spot are called "alleles"."

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conditions that favor the development of the pest population at i. To avoid edge effects, we assume that n_{i1} is 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. $n_{2I-i,1} = n_{i1}$ for every $i \in \{2, ..., I-1\}$). The initial pest resistance level is the same at each location (i.e. $w_{i1} = w$ for every $i \in \Omega$).

Each generation evolves along three successive stages: (1) genotype-induced mortality, (2) migration of emerging adults, and (3) reproduction and density dependence. We assume that there is random mating between all insects reproducing at any given location, and, that in each field, genotype proportions are not affected by density dependence. Therefore, at the beginning of each period the proportions of the three genotypes at each location are given by the Hardy-Weinberg ratios (Roughgarden, 1998).[4] The insect life cycle is detailed below.

3.1 The life cycle three stages

- **Stage 1**: genotype-induced mortality. We start year t with a resistance level w_{it} and a total population n_{it} in field i and with genotype populations $n_{it}^{rr} = {w_{it}}^2 n_{it}$, $n_{it}^{rs} = 2w_{it}(1-w_{it})n_{it}$ and $n_{it}^{ss} = (1-w_{it})^2 n_{it}$. We denote the proportion of area planted with a pesticide variety in year t as x_{it} (and therefore the proportion of refuge area as $1 - x_{it}$). The Bt toxin in the transgenic field causes all larvae of genotypes rs and ss to die, while it has no effect on larvae of genotype rr. At the end of stage 1, the weighted average population of each of the three genotypes $i = rr, rs$ and ss on the Bt and refuge fields is $n_{it,1}^{rr} = n_{it}^{rr}$, $n_{it,1}^{rs} = (1-x_{it})n_{it}^{rs}$ and $n_{it,1}^{ss} = (1-x_{it})n_{it}^{ss}$. At the end of stage 1, the average pest population is therefore $n_{it,1} = n_{it}\left(1 - x_{it}(1-w_{it}^2)\right)$. The number of resistant alleles is $2n_{it,1}^{rr} + n_{it,1}^{rs}$ and therefore the average resistance level is $w_{it,1} = \dfrac{w_{it}(1-x_{it}(1-w_{it}))}{1-x_{it}(1-w_{it}^2)}$.

- **Stage 2**: migration of emerging adults. Larvae pupate and hatch as adult moths which migrate. We assume that a proportion δ_{i-j} of moths emerging from location i migrates to location j (a proportion δ_0 stays at the same location), with $\sum_{j\in\Omega} \delta_{i-j} = 1$. We assume that the parameter δ_{i-j} increases weakly with the distance between i and j (formally, $\delta_{i-j} \geq \delta_{i-k}$ for $j < k$) and that $\delta_{i-j} = \delta_{j-i}$. This assumption implies that the migration rate only depends on the distance

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[4] The probability that an allele of type i is paired with an allele of type j ($i, j = r$ or s) is determined under the assumption that alleles collide with one another randomly. For example, the probability that a larva is of type rr is the probability that the first allele is of type r, w, times the probability that the second allele is of type r, w. The probability that a larva is of type rs is the probability that the first allele is of type r times the probability that the second one is of type s, $w(1-w)$, plus the probability that the first one is of type s times the probability that the second one is of type r, $(1-w)w$.

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and is decreasing with the distance. With these assumptions, the total population and the resistance level at location i at the end of stage 2 are given by $n_{it,2} = \sum_{j \in \Omega} [\delta_{i-j} n_{jt,1}]$ and $w_{it,2} = \frac{\sum_{j\in\Omega}[\delta_{i-j} w_{jt,1} n_{jt,1}]}{n_{it,2}}$.

- **Stage 3**: reproduction. Adult moths reproduce and lay eggs, then die. Eggs hatch as larvae, only some of which survives. As climatic conditions vary from one location to another, growth rates differ. The total population at location i at the end of stage 3 is given by $n_{it,3} = \gamma_i n_{it,2}$, where $\gamma_i > 1$ is the growth parameter of the pest population at i with $\gamma_{i+1} \geq \gamma_i$ for $i = 1, ..., I$ (that is, as n_{i1}, γ_i increases on the first half of the circle), while the resistance level is unchanged ($w_{it,3} = w_{it,2}$).[5]

3.2 The laws of motion of the biological model

At period t we define vectors of pest population levels, resistance levels and resistant area proportions for all farmers $i \in \Omega$, $\boldsymbol{y_t} = (y_{1t}, ..., y_{2I-2,t})$, for $y = n, w$ or x. Combining the evolution of the pest population over the three life cycle stages within year 1, we obtain the evolution of the pest population and of the resistance level:

$$n_{i2} = \gamma_i \sum_{j \in \Omega} \left[\delta_{i-j} n_{j1} \left(1 - x_{j1}(1 - w^2)\right)\right], \tag{1}$$

$$w_{i2} = \frac{\sum_{j\in\Omega} [\delta_{i-j} n_{j1} w \left(1 - x_{j1}(1-w)\right)]}{\sum_{j\in\Omega} [\delta_{i-j} n_{j1} \left(1 - x_{j1}(1-w^2)\right)]}. \tag{2}$$

The marginal impacts of farmer i's planting strategy x_{i1} in period 1 on pest population and resistance at j in period 2 are respectively:

$$\frac{dn_{j2}}{dx_{i1}} = -\gamma_j \delta_{j-i} n_{i1} (1 - w^2) \leq 0, \tag{3}$$

$$\frac{dw_{j2}}{dx_{i1}} = \frac{\delta_{j-i} n_{i1} (1-w) w^2 \displaystyle\sum_{k\in\Omega} \delta_{j-k} n_{k1}}{\left(\displaystyle\sum_{k\in\Omega} \delta_{j-k} n_{k1} (1 - x_{k1}(1-w^2)) \right)^2} \geq 0. \tag{4}$$

The marginal impact on pest population is strictly negative as long as $\delta_{i-j} > 0$ and $w < 1$: more pesticide plantings in i reduce the pest population in i, causing fewer insects to move from i to j. On the other hand, the marginal impact on resistance is strictly positive as long as $w < 1$: more pesticide plantings in i increase pest resistance in i and, since some insects move from i to j, they also increase pest resistance within the pest population in j in period 2.

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[5] For simplicity, we assume no density dependence, that is, we assume that the pest population could grow to infinity over time. This simplifying assumption has no consequence here because we solve the model for only two subsequent time periods.

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3.3 The economic objective

We assume that pest damages on crops occur after genotype-induced mortality and before migration, that profit losses caused by pest attacks of intensity n_{it} are equal to n_{it}, and that the pesticide variety is available with an over-cost (or opportunity cost) c compared to the conventional variety. The unit profit loss caused by pests at location i in period t is:[6]

$$l(x_{it}, w_{it}, n_{it}, c) = n_{it}\left(1 - x_{it}(1 - w_{it}^2)\right) + c x_{it}. \tag{5}$$

The economic objective is to minimize the discounted sum of profit losses (that is, of average yield losses encountered on the *Bt* and refuge fields and the over-cost of *Bt* plantings). We define $\boldsymbol{x_i} = (x_{i1}, x_{i2})$ as the vector of resistant area proportions (or variety choice) x_{it} for farmer i in periods $t = 1, 2$. A planting strategy $\boldsymbol{x} = (x_1, ..., x_{2I-2})$ is a vector of resistant area proportions x_i for every farmer $i \in \Omega$. In what follows, we successively examine the efficient planting strategy, denoted as $\boldsymbol{x}^*$, and the equilibrium planting strategy in the absence of regulation, denoted as $\boldsymbol{x}^e$, 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 or subsidy on the seeds of the resistant variety.

4 Optimal and equilibrium outcomes

Let ρ be the discount factor. In our set-up, the socially optimal planting strategy $\boldsymbol{x}^*$ minimizes the discounted sum of profit losses which, from equation (5) and given the initial conditions $\{n_{i1}\}_{i\in\Omega}$ and $w_{i1} = w$, may be written:

$$\begin{aligned}\min_{(\boldsymbol{x_1}, \boldsymbol{x}_2)} \quad & \textstyle\sum_{i\in\Omega}\left[n_{i1}\left(1 - x_{i1}(1 - w^2)\right) + c x_{i1}\right] \\ & + \rho \textstyle\sum_{i\in\Omega}\left[n_{i2}\left(1 - x_{i2}(1 - {w_{i2}}^2)\right) + c x_{i2}\right],\end{aligned}$$

subject to the dynamic motion equations (1) and (2), and subject to $0 \leq x_{it} \leq 1$, $\forall i \in \Omega, \forall t \in \{1, 2\}$.

Let $\underline{\lambda}^*_{it}$ and $\bar{\lambda}^*_{it}$ denote the multipliers associated to the constraints $x_{it} \geq 0$ and $x_{it} \leq 1$ respectively for $t = 1, 2$. The first-order conditions yield:

$$n_{i1}(1 - w^2) - \rho \sum_{j\in\Omega} \frac{dn_{j2}}{dx_{i1}}(1 - x_{j2}(1 - {w_{j2}}^2)) + \underline{\lambda}^*_{i1} = c + \rho \sum_{j\in\Omega} \frac{dw_{j2}}{dx_{i1}} 2 w_{j2} n_{j2} x_{j2} + \bar{\lambda}^*_{i1} \tag{6}$$

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[6] Immediate observation shows that: $\partial l(.)/\partial x_{it} = c - n_{it}(1 - {w_{it}}^2)$. All other things being equal, the unit profit loss at location i decreases with the resistant area proportion if and only if the additional number of pests that are controlled by the resistant technology, $n_{it}(1 - {w_{it}}^2)$, is higher than the unit cost of the resistant technology, c. This unit profit loss increases with the level of resistance w_i, as pest control then decreases on the resistant area. It increases with the intensity of pest attacks n_i.

$$\rho n_{i2}(1 - {w_{i2}}^2) + \underline{\lambda}_{i2}^* = \rho c + \bar{\lambda}_{i2}^* \tag{7}$$

The left-hand side and the right-hand side of (6) are respectively the marginal benefit and the marginal cost of pesticide plantings in the first period. The marginal benefit is in terms of current reduction in pest population at location i, and of pest population decrease in the next period at all locations $j \in \Omega$ (including location i). The marginal cost includes the over-cost of the pesticide variety, and the increase in the resistance level in the next period for all farmers $j \in \Omega$ (including i). In the second period, the marginal benefit of the pesticide variety (left-hand side in (7)) is only the reduction of current pest population while the marginal cost (right-hand side) is only the over-cost of the pesticide variety.

Let us now examine the equilibrium planting strategy $\boldsymbol{x}^e = (x_1^e, ...x_{2I-2}^e)$ defined as the planting strategies selected by farmers in the Nash equilibrium without regulation. In period 1, each farmer i chooses the two-period planting strategy (x_{i1}, x_{i2}) that minimizes his own discounted profit loss,

$$\min_{(x_{i1}, x_{i2})} \quad \left[n_{i1}\left(1 - x_{i1}(1 - w^2)\right) + cx_{i1}\right] \\ + \rho\left[n_{i2}\left(1 - x_{i2}(1 - {w_{i2}}^2)\right) + cx_{i2}\right],$$

subject to the dynamic motion equations (1) and (2), and subject to $0 \leq x_{it} \leq 1$ for $t = 1, 2$, given the planting strategies (x_{i1}^e, x_{i2}^e) selected by every other farmer $j \neq i$.

Let $\underline{\lambda}_{it}^e$ and $\bar{\lambda}_{it}^e$ denote the multipliers associated to the constraints $x_{it} \geq 0$ and $x_{it} \leq 1$ respectively for $t = 1, 2$. the first-order conditions yield:

$$\begin{aligned} n_{i1}(1 - w^2) - \rho\frac{dn_{i2}}{dx_{i1}}(1 - x_{i2}(1 - {w_{i2}}^2)) + \underline{\lambda}_{i1}^e &= c + \rho\frac{dw_{i2}}{dx_{i1}}2w_{i2}n_{i2}x_{i2} + \bar{\lambda}_{i1}^e && (8) \\ \rho n_{i2}(1 - {w_{i2}}^2) + \underline{\lambda}_{i2}^e &= \rho c + \bar{\lambda}_{i2}^e && (9) \end{aligned}$$

In each period, in (8) and (9), each farmer equalizes the marginal benefit of pesticide variety (left-hand side) to its marginal cost (right-hand side), net of the shadow costs of the constraints. Each farmer ignores the impact of his planting strategy on his neighbors' profits. Therefore, unlike the optimal planting strategy, equation (8) includes the impact of i's planting strategy on the pest population and resistance levels in the next period at his own location, not at other locations.

It is easy to show that in our model the inefficiency of the equilibrium planting strategy comes from the spatial externality among farmers. If pests are immobile from one farm to the next, formally if $\delta_{j-i} = 0$ for $j \neq i$ and $\delta_0 = 1$, then (3) and (4) simplify to $\frac{dn_{j2}}{dx_{i1}} = \frac{dw_{j2}}{dx_{i1}} = 0$ for every $j \neq i$. The first-order conditions are then the same

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for the optimal and equilibrium planting strategies: if pests are immobile, the planting strategies selected by profit- maximizing farmers are optimal.

As a benchmark, when pests are immobile, it is also interesting to consider the particular case of myopic farmers, in the sense that each farmer ignores his own impact on pest population and resistance in his own field in period 2 (we mention this particular case of myopic farmers in several instances below). In this case, $\frac{dn_{i2}}{dx_{i1}} = \frac{dw_{i2}}{dx_{i1}} = 0$, and, therefore, the equilibrium first-period first-order conditions simplify to $n_{i1}(1-w^2)+\underline{\lambda}^e_{i1} = c + \bar{\lambda}^e_{i1}$. Ignoring the marginal benefit of pesticide plantings in the first period on future pest population, $-\rho\frac{dn_{i2}}{dx_{i1}}(1-x_{i2}(1-{w_{i2}}^2))$, tends to make each farmer plant too little of the pesticide variety; whereas ignoring their marginal cost in terms of future resistance, $\rho\frac{dw_{i2}}{dx_{i1}}2w_{i2}n_{i2}x_{i2}$, tends to make them plant too much of the pesticide variety. Depending on which of these two effects are predominant the other, when pests are immobile, in equilibrium a myopic farmer may plant either too little or too much of the pesticide variety.

In what follows, we compare the efficient and equilibrium planting 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 implemented in period 1, a uniform mandatory refuge and a tax or subsidy on the pesticide variety. With a (uniform mandatory) refuge, each farmer is allowed to plant at most a given proportion, let's say $\overline{x}$, of his area with the pesticide variety. Producer i then chooses (x_{i1}, x_{i2}) to minimize $l(x_{i1}, w_{i1}, n_{i1}, c) + \rho l(x_{i2}, w_{i2}, n_{i2}, c)$ subject to $x_{i1} \in [0, \overline{x}]$ and $x_{i2} \in [0, 1]$. A tax $\tau > 0$ on pesticide seeds increases their over-cost from c to $c + \tau$ (while a subsidy $\tau < 0$ decreases their over-cost). Therefore, farmer i chooses (x_{i1}, x_{i2}) that minimizes $l(x_{i1}, w_{i1}, n_{i1}, c + \tau) + \rho l(x_{i2}, w_{i2}, n_{i2}, c)$ subject to $x_{it} \in [0, 1]$ for $t = 1, 2$. In the next two sections we analyze whether one or both instruments allow for efficiency to be restored under extreme assumptions on pest dispersal rates and on the heterogeneity of pest attacks.

5 Perfectly mobile pests

We consider here the extreme case where pest dispersal is uniform, and therefore where the relative location of farms does not matter. Formally, we assume that $\delta_k = \delta$ for every distance $k = 0, ..., I$. Then, $\sum_{i\in\Omega} \delta_{i-j} = \sum_{i=1}^{2I-2} \delta = 1$ for every $j \in \Omega$, and therefore $\delta = 1/(2I-2)$. Under our assumption of homogenous initial pest resistance ($w_{i1} = w$ for every i), the dynamics of the pest population and resistance levels between periods

1 and 2 simplify to:

$$n_{i2} = \frac{\gamma_i}{2I-2}D, \tag{10}$$

$$w_{i2} = w_2 = w\frac{\sum_{k\in\Omega}\left[n_{k1}\left(1-x_{k1}(1-w)\right)\right]}{D}, \tag{11}$$

where $D \equiv \sum_{k\in\Omega} n_{k1}(1-x_{k1}(1-w^2))$. With perfect pest mobility, the resistance level in the second period is the same at all locations along the circle ($w_{i2} = w_2$ for every $i \in \Omega$), while pest populations at different locations in period 2 differ only according the growth rate γ_i. The marginal impacts of the planting strategy in period 1 on the pest population and resistance levels in period 2 are:

$$\frac{dn_{j2}}{dx_{i1}} = -n_{i1}\frac{\gamma_j(1-w^2)}{2I-2},$$

$$\frac{dw_{j2}}{dx_{i1}} = n_{i1}\frac{(1-w)w^2N_1}{D^2},$$

where $N_1 \equiv \sum_{k\in\Omega} n_{k1}$ is the total pest population.

The planting strategy of any farmer has the same marginal impact everywhere: the pesticide variety planted in i impacts identically on the pest population and resistance levels in j and k for every j and k.

5.1 Optimum and equilibrium planting strategies

The optimum first-order conditions (6) and (7) become:

$$n_{i1}\left[1-w^2+\rho(A-B)\right]+\underline{\lambda}^*_{i1} = c+\bar{\lambda}^*_{i1}, \tag{12}$$

$$\rho n_{i2}(1-{w_2}^2)+\underline{\lambda}^*_{i2} = \rho c+\bar{\lambda}^*_{i2}, \tag{13}$$

where A and B are the two effects in period 2 of increased pesticide plantings at location i in period 1, a positive effect of decreased pest population at all locations,

$$A \equiv \frac{1-w^2}{2I-2}\sum_{j\in\Omega}\gamma_j(1-x_{j2}(1-{w_2}^2)), \tag{14}$$

and a negative effect of increased pest resistance level at all locations,

$$B \equiv 2\frac{(1-w)w^2N_1w_2}{D^2}\sum_{j\in\Omega}n_{j2}x_{j2}, \tag{15}$$

with A and B being common to all producers.

The first-order condition (13) implies that there exists a threshold pest population $n^*_2 = c/(1-{w^*_2}^2)$, so that all producers i with a pest population $n_{i2} < n^*_2$ should plant only the conventional variety ($x^*_{i2} = 0$), and all those with $n_{i2} > n^*_2$ should plant only

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the pesticide variety ($x^*_{i2} = 1$). In the first period, since the terms in brackets in (12) are the same for all producers, as long as the over-cost of the pesticide seed c is strictly positive, we can also define a threshold pest population

$$n^*_1 = \frac{c}{\left[1 - w^2 + \rho(A - B)\right]}, \tag{16}$$

such that $x^*_{i1} = 0$ for all producers with $n_{i1} < n^*_1$, and $x^*_{i1} = 1$ for other producers characterized by $n_{i1} > n^*_1$.[7] At each period $t = 1, 2$, if $n_{1t} < n^*_t < n_{It}$, since growth rates are ranked along the circle, conventional varieties are planted on the side of the circle characterized by low levels of pest attacks while the pesticide variety is located on the other side with high levels of pest attacks. The following proposition describes the optimum planting strategy with perfectly mobile pests.

Proposition 1 *With perfectly mobile pests, when pesticide seeds are more costly than conventional seeds, the efficient planting strategy requires that in each period ($t = 1, 2$), farmers facing pest attacks up to a threshold n^*_t plant only the conventional variety while those facing pest attacks higher than n^*_t plant only the pesticide variety.*

Under the "laisser faire" the first-order conditions (8) and (9) become:

$$n_{i1}\left[1 - w^2 + \rho\frac{1 - w^2}{2I - 2}\gamma_i(1 - x_{i2}(1 - w_2{}^2)) - \rho\frac{2(1 - w)w^2 N_1 w_2 n_{i2} x_{i2}}{D^2}\right] + \underline{\lambda}^e_{i1}$$
$$= c + \bar{\lambda}^e_{i1} \tag{17}$$
$$\rho n_{i2}(1 - w^2_2) + \underline{\lambda}^e_{i2} = \rho c + \bar{\lambda}^e_{i2} \tag{18}$$

We first describe the equilibrium planting strategy in the particular case where each farmer ignores his own impact on pest population and resistance in his field in period 2. This particular case may arise either because farmers are myopic, or because there is a large number of producers, so that a farmer's impact on his own field is negligible. Formally, the assumption of myopic or atomistic producers implies that $\frac{dn_{i2}}{dx_{i1}} = \frac{dw_{i2}}{dx_{i1}} = 0$, in which case the first-period first-order conditions simplify to:

$$n_{i1}(1 - w^2) + \underline{\lambda}^e_{i1} = c + \bar{\lambda}^e_{i1}. \tag{19}$$

As in the case of the efficient planting strategy, the second-period first-order conditions imply that there is a threshold pest population n^e_2 such that $x^e_{i2} = 0$ for all producers i with $n_{i2} < n^e_2$, and $x^e_{i2} = 1$ for all those with $n_{i2} > n^e_2$. In the same way, the equilibrium planting strategy in the first period at location i defines a threshold pest attack $n^e_1 = c/(1 - w^2)$, such that all farmers with lower pest attacks plant only the

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[7] The specific case where $c = 0$ is analyzed in the simulations.

conventional variety, while those facing higher pest attacks plant only the pesticide variety.

In this particular case of atomistic or myopic farmers, it is self-evident that the equilibrium differs from the first-best as long as farmers exhibit net externalities on each other. The ranking of n_1^* and n_1^e depends on the relative magnitudes of the positive externality on future pest populations and of the negative externality on future resistance levels. If the positive externality of pesticide plantings on future pest populations is greater than the negative externality on future resistance, formally if $A > B$, then $n_1^e > n_1^*$, which implies that in equilibrium there are not enough plantings of the pesticide variety. In the reverse case $A < B$ where the negative externality dominates the positive one, $n_1^e < n_1^*$, with too many farmers planting the pesticide variety in equilibrium.

In the general case where each farmer takes into account the impact of his planting strategy in period 1 on his own pest population and resistance levels in period 2, the equilibrium planting strategy is more complex because the term in brackets in (17) is producer-specific: it depends on the producer's planting strategy and pest population in the second period, x_{i2} and n_{i2}. In the Appendix, we show that the equilibrium strategy in this general case is similar to that described above in the particular case of atomistic or myopic producers. The only difference is the definition of the thresholds n_1^e and n_2^e. We summarize our results in the following Proposition.

Proposition 2 *In equilibrium, farmers facing pest attacks lower than a threshold n_t^e plant only the conventional variety, while those with pest attacks higher than n_t^e plant only the pesticide variety. The comparison of optimum and equilibrium thresholds depends on which externality ignored by farmers is predominant. When farmer are atomistic or myopic, $n_1^e > n_1^*$ if and only if $A < B$.*

With perfectly mobile pests, distances between farmers do not matter; only pest attack intensities 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 planted optimally where pest attack levels are the highest. Since vulnerability to pests increases as one moves along the two halves of the circle of farmers, the optimal planting 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 "laisser faire" equilibrium also, farmers who use the pesticide seed are those more vulnerable to pests. Due to the open-access nature of the pest population and resistance levels as common-pool resources, the pesticide variety is either overused or underused in equilibrium, depending on which externality is predominant.

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5.2 Optimal regulation

We now examine whether the optimal planting strategy may be implemented with regulation. Clearly, 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 planting strategy requires that farmers specialize either in the pesticide or in the conventional variety.[8] We examine below the effect of a tax or a subsidy on seeds of the pesticide variety.

A tax on the pesticide seed, $\tau > 0$, increases the over-cost of the pesticide variety from c to $c+\tau$, while a subsidy, $\tau < 0$, decreases this over-cost. The tax or subsidy level may be chosen to provide incentives to farmers with pest attack levels n_{i1} between n_1^e and n_1^* to opt for the conventional variety. Its sign depends on the relative magnitudes of the externalities on future pest populations and on future resistance levels. If decreasing future pest populations is more profitable than decreasing future pest resistance, then the net externality of the pesticide seed is positive, and the instrument should be a subsidy. In the reverse case, it should be a tax.

Formally, in the case of myopic or atomistic farmers, the equilibrium first-order conditions (19) with a tax or subsidy level τ that changes the pesticide seed over-cost from c to $c+\tau$ become:

$$n_{i1}(1-w^2) + \underline{\lambda}_{i1}^e = c + \tau + \bar{\lambda}_{i1}^e.$$

This equation defines a threshold pest population $n_1^e(\tau) = (c+\tau)/(1-w^2)$ for which all farmers with $n_{i1} > n_1^e(\tau)$ plant the pesticide seed while all those with $n_{i1} < n_1^e(\tau)$ plant conventional seed. The optimal tax level τ^* is such that the threshold pest population is the efficient one, i.e. $n_1^e(\tau^*) = n_1^*$. When farmers are myopic or atomistic, this is the case if and only if:

$$\tau^* = n_1^* \rho(B-A) = \frac{c\rho(B-A)}{1-w^2+\rho(A-B)}.$$

The tax τ^* is a Pigouvian tax, in the sense that it charges producer i the net impact of his variety choice on society (including himself if the producer is myopic) in the second period (a positive impact on future pest populations, a negative impact on future resistance levels). If the positive impact of a reduced pest population is greater than the negative impact of higher pest resistance, formally if $A > B$, then $\tau^* < 0$: pesticide seeds should be subsidized to provide incentives for farmers with pest attacks $n_{i1} \in [n_1^*, n_1^e]$ to

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[8] The optimal planting strategy could be implemented by a "command-and-control" regulation other than mandatory refuges, by forcing farmers with $n_{i1} \leq n_1^*$ to plant only the conventional variety. But this would require the inference of pest attack intensities n_{i1} for every $i \in \Omega$, which is likely to be farmers' private information.

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plant conventional varieties. In the reverse case where $A < B$, then $\tau^* > 0$: the negative impact of pest resistance is greater than the positive impact of the pest population on second-period profits, which leads to a positive tax to encourage farmers with pest attacks $n_{i1} \in [n_1^e, n_1^*]$ to plant conventional varieties.

In the more general case where each farmer takes into account the effects of his planting strategy in period 1 on his own population and resistance levels in period 2, the derivation of the optimal tax level is more complex. Since in this general case, the equilibrium is also one in which farmers with low levels of pest attacks, up to a threshold n_1^e, grow only the conventional variety, while farmers with high levels of pest attacks, above this threshold, grow only the pesticide variety, it is still possible to implement the optimum by a tax or a subsidy on pesticide seeds in equilibrium. The tax or subsidy basically moves the equilibrium threshold n_1^e to the efficient one n_1^*. This result is shown in Appendix. The next proposition summarizes the above results.

Proposition 3 *With perfectly mobile pests, the efficient planting strategy can be implemented in equilibrium by a tax or a subsidy on seeds of the pesticide variety, but not by a mandatory refuge.*

6 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 $\gamma_i = \gamma_{i+1} = \gamma$ for every $i \in \Omega$ and, therefore, $n_{i1} = n_{i+1,1} = n_1$ for every $i \in \Omega$, where n_1 denotes pest attack intensity at any location in the first period. The dynamics of the pest population and resistance levels between period 1 and 2 simplify to:

$$\begin{aligned} n_{i2} &= \gamma n_1 \sum_{j\in\Omega} \delta_{i-j}(1 - x_{j1}(1 - w^2)), \\ w_{i2} &= \frac{\displaystyle\sum_{j\in\Omega} \delta_{i-j} w(1 - x_{j1}(1 - w))}{\displaystyle\sum_{j\in\Omega} \delta_{i-j}(1 - x_{j1}(1 - w^2))}. \end{aligned}$$

With homogeneous pest attacks, the resistance level at any location is independent of the pest population level. The marginal impact of the planting strategy in period 1 on

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the pest population and resistance in the second period is:

$$\begin{aligned}\frac{dn_{j2}}{dx_{i1}} &= -\gamma\delta_{j-i}n_1(1-w^2),\\ \frac{dw_{j2}}{dx_{i1}} &= \frac{\delta_{j-i}(1-w)w^2}{\left(\sum_{k\in\Omega}\delta_{j-k}(1-x_{k1}(1-w^2))\right)^2}.\end{aligned}$$

Since all producers face the same pest population, the two marginal impacts differ only by the distance among producers through the dispersion parameter δ_{j-i} between producer i and j.

6.1 Optimum and equilibrium planting strategies

The second-order conditions which ensure that the optimal planting strategy is unique imply that x_{it}^* must be the same around the circle for $t = 1, 2$.[9] From the dynamic laws of motion, it implies that the pest population and resistance in the second period are the same in every field along the circle ($n_{i2} = n_2$ and $w_{i2} = w_2$ for every $i \in \Omega$). The first-order conditions (6) and (7) become:

$$\begin{aligned}n_1(1-w^2)[1+\rho\gamma(1-x_2(1-w_2{}^2))] + \underline{\lambda}_{i1}^* &= c + \rho\frac{2w^2(1-w)w_2n_2x_2}{(1-x_1(1-w^2))^2} + \bar{\lambda}_{i1}^* \qquad (20)\\ \rho n_2(1-w_2{}^2) + \underline{\lambda}_{i2}^* &= \rho c + \bar{\lambda}_{i2}^*, \qquad (21)\end{aligned}$$

with the dynamics of the pest population and resistance levels simply given by:

$$\begin{aligned}n_2 &= \gamma n_1(1-x_1(1-w^2)), \qquad (22)\\ w_2 &= w\frac{1-x_1(1-w)}{1-x_1(1-w^2)}. \qquad (23)\end{aligned}$$

In the second period, the efficient strategy requires that all farmers either use only the conventional variety, or else the pesticide variety. The first case occurs when pest resistance w_2 is high enough, and the pest population is low enough, so that the benefit $n_2(1-w_2{}^2)$ of the pesticide variety is offset by its cost c. Formally, if $n_2(1-w_2{}^2) < c$, then $\underline{\lambda}_{i2}^* > 0$ and $\bar{\lambda}_{i2}^* = 0$ for every $i \in \Omega$ in (21) and $x_2^* = 0$. In this case, the first-period efficient planting strategy is defined by:

$$n_1(1+\rho\gamma)(1-w^2) + \underline{\lambda}_{i1}^* = c + \bar{\lambda}_{i1}^*.$$

Since only conventional varieties are planted in the second period, pest resistance that arises from the use of the pesticide seed in the first period is not an issue. Therefore,

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

the cost associated with the increase in pest resistance disappears in the first-order conditions. The benefit of the pesticide variety in period 1 is the reduction of the current and future pest population. Two different cases may then arise:

- Only the conventional variety should be planted in both periods if the benefit of the pesticide variety is lower than its over-cost, formally if $n_1(1+\rho\gamma)(1-w^2) < c$. Substituting the state variable $n_2 = \gamma n_1$ and $w_2 = w$ in the second-period first-order condition shows that $\gamma n_1(1-w^2) < c$ must also hold for this case to occur.

- Only the pesticide variety should be planted in the first period, and the conventional variety in the second period, in the reverse case where $c < n_1(1+\rho\gamma)(1-w^2)$. The dynamic equation then leads to a fully resistant population of pests $w_2 = 1$ and the second-period second-order condition boils down to $c > 0$.

The second possible efficient planting strategy in the second period is to use only pesticide seeds. It is efficient if pest resistance w_2 is low enough, and the pest population n_2 is high enough, so that $n_2(1-{w_2}^2) > c$. This implies $\underline{\lambda}^*_{i2} = 0$ and $\bar{\lambda}^*_{i2} > 0$ for every $i \in \Omega$ and therefore $x^*_2 = 1$. In this case, the first-period first-order conditions become:

$$n_1(1-w^2)(1+\rho\gamma {w_2}^2) + \underline{\lambda}^*_{i1} = c + \rho \frac{2w^2(1-w)w_2 n_2}{(1-x^*_1(1-w^2))^2} + \bar{\lambda}^*_{i1}.$$

Note that we can easily exclude planting only pesticide seeds in the first and second periods as an efficient strategy. If only pesticide seeds are planted in the first period, then all pests become resistant in period 2, and pesticide seeds are ineffective although more costly than conventional seeds. Therefore, we can distinguish two possible cases:

- Only the conventional variety should be planted in the first period, and the pesticide variety in the second period, if $\underline{\lambda}^*_{i1} > 0$ and $\bar{\lambda}^*_{i1} = 0$. From (22) and (23), given $x^*_1 = 0$, the dynamics of the state variables simplify to $n_2 = \gamma n_1$ and $w_2 = w$. Using these definitions in the above first-order conditions and using $x_1 = 0$, this case arises if $n_1[1-w^2+\rho\gamma(1-w)^2 w^2] < c$ and $c < \gamma n_1(1-w^2)$.

- The optimal planting strategy prescribes that part of the fields should be devoted to the conventional variety in the first period, and that only the pesticide variety should be planted in the second period. In this case, the efficient proportion of the pesticide variety is implicitly defined by the first-order condition with $\underline{\lambda}^*_{i1} = \bar{\lambda}^*_{i1} = 0$, that is:

$$n_1(1-w^2)(1+\rho\gamma {w^*_2}^2) = c + \rho \frac{2w^2(1-w)w^*_2 n^*_2}{(1-x^*_1(1-w^2))^2}, \tag{24}$$

  in which n^*_2 and w^*_2 are functions of x^*_1 as defined by equations (22) and (23).

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We now examine the equilibrium strategy, still assuming that farmers are homogeneous and that pests are imperfectly mobile. As for the optimal planting strategy, the equilibrium planting strategy is the same for every farmer since farmers are identical along the circle: $x_{it} = x_t^e$ for every $i \in \Omega$ and for $t = 1, 2$. This implies that the pest population and resistance in period 2 are the same along the circle, that is, $w_{i2} = w_2^e$ and $n_{i2} = n_2^e$ for every $i \in \Omega$. The first-order equilibrium conditions (8) and (9) simplify to:

$$n_1(1-w^2)[1+\rho\gamma\delta_0(1-x_2(1-w_2^{e2}))] + \underline{\lambda}_{i1}^e = c + \rho\frac{\delta_0 2w^2(1-w)w_2^e n_2^e x_2}{(1-x_1(1-w^2))^2} + \bar{\lambda}_{i1}^e, \quad (25)$$

$$\rho n_2(1-w_2^{e2}) + \underline{\lambda}_{i2}^e = \rho c + \bar{\lambda}_{i2}^e, \quad (26)$$

in which n_2^e and w_2^e are functions of x_1^e as defined by equations (22) and (23). The equilibrium first-order condition (25) differs from the efficiency first-order condition (20) by the dispersion parameter, which is δ_0 rather than $\sum_{j\in\Omega}\delta_{i-j} = 1$. This reflects the fact that every farmer takes into account the impact of his planting strategy only on his own pest population and resistance, which is of magnitude δ_0, and not on other farmers $j \neq i$, each of whom is affected by a magnitude δ_{i-j}. The above results are summarized in the following proposition.

Proposition 4 *With imperfectly mobile pests and homogeneous farmers, depending on the parameters of the model, the efficient planting strategy prescribes that either only the conventional variety should be planted in both periods; or only the pesticide variety in the first period, and then only the conventional one in the second period; or vice-versa; or else a share* x_1^* *of the pesticide variety in the first period, as defined in (24) with* $0 < x_1^* < 1$*, and then only the pesticide variety in second period. The equilibrium planting strategy is not efficient because each producer takes into account the impact of his planting strategy on the second-period pest population and resistance levels only on his own field.*

We focus on the most interesting case in which the conventional variety is planted in some but not all areas in the first period to reduce second-period resistance to pesticides, i.e., $0 < x_1^* < 1$, where x_1^* is implicitly defined by (24).

6.2 Optimal regulation

We again consider two regulatory instruments to improve efficiency: a tax or subsidy on pesticide seeds, τ; and a mandatory refuge area, $\overline{x}$. Neither of these two instruments depends on farmers' localization. Let us denote by $x_1^e(\tau)$ the first-period planting strategy

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with a tax τ. The efficient tax τ^* is such that $x_1^e(\tau^*) = x_1^*$. Since the second-period first-order conditions are the same in optimum (equation (21)) and in equilibrium (equation (26)), the second-period equilibrium planting strategies $\boldsymbol{x}_2^*$ are first-best as long as the pest population and resistance are also efficient, i.e. as long as $w_2^e = w_2^*$ and $n_2^e = n_2^*$, if the first-period equilibrium planting strategies are also first-best. Therefore, regulation is needed only in the first period to restore efficiency. We consider here the case where the optimum requires to plant a share of pesticide variety in the first period, and then all the fields with the pesticide variety in the second period. The second-period equilibrium planting strategy $x_{i2}^e = x_2^* = 1$ is efficient for every $i \in \Omega$. With a tax τ on pesticide seeds, the first-period equilibrium conditions (25) for an interior solution $0 < x^e(\tau) < 1$ become:

$$n_1[1 - w^2 + \rho\gamma\delta_0(B^\tau - A^\tau)] = c + \tau, \tag{27}$$

where $A^\tau \equiv \dfrac{\delta_0 2w^2(1-w)w_2^e(\tau)}{(1 - x_1^e(\tau)(1-w^2))^2}$ and $B^\tau = (1-w^2)(w_2^e(\tau))^2$ capture respectively the impact of pesticide seeds on second-period pest resistance and population levels, $w_2^e(\tau)$ being defined by the dynamic motion equation (23) with $x_1 = x_1^e(\tau)$. Using a similar notation with x_1^* and w_2^* instead of $x_1^e(\tau)$ and $w_2^e(\tau)$ to define A^* and B^*, the efficient first-order conditions write

$$n_1[1 - w^2 + \rho\gamma(B^* - A^*)] = c. \tag{28}$$

The two above first-order conditions differ in the weight assigned to the net impact of the first-period planting strategy x_1 on the second-period pest resistance and population levels, namely $\gamma(B^\tau - A^\tau)$ and $\gamma(B^* - A^*)$. In equilibrium, each producer considers only his impact on his own field δ_0, whereas the total impact on all producers is $\sum_{i\in\Omega}\delta_{j-i} = 1 > \delta_0$. Efficiency can be restored by a Pigouvian tax that make each producer pay (or receive) the net impact of his own strategy on all others producers at the first-best, formally:

$$\tau^* = (1 - \delta_0)(A^* - B^*).$$

As before, the tax is positive if $A^* - B^* > 0$. Then, the negative impact on pest resistance will then be greater than the positive impact on the pest population: the pesticide variety has an overall negative impact on other farmers' second-period profits, and should therefore be taxed to induce a smaller share of pesticide plantings. If $A^* - B^* < 0$, the impact is positive and, therefore, a subsidy restores efficiency.

Since the efficient first-period planting strategy x_1^* is the same for all producers, it can be implemented with a mandatory refuge $\bar{x}_1 = x_1^*$ when the negative impact on pest resistance is greater than the positive impact on pest population, formally when

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$A^* > B^*$. In this case, without a tax, all producers tend to plant too much pesticide seeds. If an upper bound $\bar{x}_1 = x_1^*$ is imposed on the share of pesticide seed per field, each producer is bounded by this constraint and thus selects the efficient planting strategy.

We conclude the section by examining the case of myopic or atomistic producers. When each producer ignores the impact of his planting strategy on the second-period pest resistance and population in his own field, δ_0 is nil in the equilibrium first-order conditions (25) and (26). It immediately follows that all producers will pick the same extreme planting strategy with any tax τ: only the pesticide or only the conventional variety. Hence the tax or subsidy does not restore efficiency. In contrast, a mandatory refuge still restores efficiency when the net impact of pesticide variety is negative, that is when $A^* > B^*$. If all producers are willing to plant only pesticide seeds in the first period in equilibrium, they are bound with the constraint to plant at least share $1 - x_1^*$ of their field with the conventional variety and thus implement the first-best. The above results are summarized in the following last proposition.

Proposition 5 *Assume that pests are imperfectly mobile, that farmers are homogenous, and that the efficient planting strategy requires a share of each field to be devoted to the conventional variety. When the negative externality of pesticide plantings on future pest resistance is greater than its positive externality on the future pest population, a tax on pesticide seeds and a mandatory refuge both implement the first-best. In the opposite case, only a subsidy of pesticide seeds restores efficiency. However, the tax or subsidy instrument is not efficient if producers are myopic or atomistic, while the mandatory refuge remains efficient in this case as long as the net effect of externalities is negative.*

7 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. To reduce the dimension of the simulations, we assume that $c = 0$, that is, pesticide seeds and conventional seeds have the same cost. In this case, it is always optimal, both individually and collectively, to use only pesticide seeds in the second period, which makes the problem simpler because only the first-period planting strategies have to be determined in the simulations. We set $\rho = 0.97$ and $w = 0.25$. We assume that $I = 3$: four producers are located equidistantly on a circle, face initial pest attacks n_{i1} with $n_{11} \leq n_{21} \leq n_{31}$ and $n_{21} = n_{41}$, and are characterized by pest population growth rates $\gamma_1 \leq \gamma_2 \leq \gamma_3$ and $\gamma_2 = \gamma_4$. We model pest dispersal by

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$\delta_1 = h_\delta$ and $\delta_2 = (h_\delta)^2$. We assume that the average initial pest attack is equal to 0.5 and that heterogeneity in pest attacks takes the form $n_1 = 0.5(1 - h_n)$, $n_2 = n_4 = 0.5$ and $n_3 = 0.5(1 + h_n)$. We model the pest population growth rate at location i as $\gamma_i = 10n_{i1}$. We let 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 ($h_n = 0$, in which case all producers face pest attacks 0.5) and maximum heterogeneity ($h_n = 1$, in which case pest attacks vary linearly between $n_1 = 0$ and $n_3 = 1$). 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.[10]

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 or subsidy level and with the optimal uniform refuge.[11]

Table 1 below indicates which of the two instruments, tax/subsidy 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.[12]

[Insert Table 1]

Consistent with our theoretical results, we find that no regulation is needed when pests are not mobile ($h_\delta = 0$) and that both the tax and the refuge allow the optimum to be implemented if producers are homogeneous ($h_n = 0$) (since in our simulations farmers are not atomistic). We also find that both the tax and the refuge allow for efficiency to be restored when pests are perfectly mobile. This warrants further analysis.

Our Proposition (3), which indicates that only the tax or subsidy on pesticide seeds is expected to restore efficiency with perfect pest mobility, holds only when pesticide seeds are more costly than conventional seeds. This is not the case in our simulations, in which $c = 0$. Then, in optimum, equation (13) implies that only pesticide seeds are planted in the second period. In the first period, in all our simulations, we find that the

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[10] Our multiplicative 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 finding that pest dispersal decreases more than linearly with distance. Our additive formulation of heterogeneity in initial 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 in initial 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).

[11] We perform the simulations with the Mathematica software, using the function NMaximize.

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

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optimum with perfect pest mobility always requires only interior strategies x_{i1}. From (12), such interior strategies must satisfy $1 - w^2 + \rho(A - B) = 0$. In this particular case where $x_{j2} = 1$ for every $j \in \Omega$, the terms A and B (defined in (14) and (15)) are functions of individual planting strategies x_{i1} only through two terms ($\sum_{j\in\Omega}\left[n_{j1}\left(1 - x_{j1}(1-w)\right)\right]$ and $\sum_{j\in\Omega}\left[n_{j1}\left(1 - x_{j1}(1-w^2)\right)\right]$), which in our simulations induce only two constraints on three different types of producers. Our simulations indicate that there is always some mandatory refuge level that induces the three different types of farmers to plant pesticide seeds in the first period on proportions of their fields that allow for these two constraints to be met. Therefore, in this particular case where $c = 0$, the mandatory refuge strategy appears as a possible alternative to the tax strategy in the case of perfect pest mobility.

There is no other simulation in which either the tax/subsidy or the refuge implements the optimum. The subsidy is warranted in none of the simulations. Table 1 illustrates the relative performance of the other two instruments: tax or refuge. As long as the degree of pest dispersal and/or heterogeneity between farms remain very small, 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 little heterogeneity between farms, the tax and the refuge perform fairly similarly since they are equivalent with homogeneous farmers. When the level of either pest dispersal h_δ or heterogeneity between farms h_n, or both, becomes high, the gap in the performance between the two instruments becomes significant.

The literature on common-pool resources and the environment usually suggests that market-based instruments dominate command-and-control instruments, especially when producers are heterogeneous. The theoretical results of this paper show that in our framework the tax dominates the refuge when pest mobility is perfect. In the light of this, it could seem intuitive that an increase either in pest mobility or in farm heterogeneity would reinforce the superiority of the tax over the refuge. This is not however what happens in these simulations. With high levels of pest mobility, the refuge actually dominates the tax in our simulations. The results are not clear-cut for a high level of farm heterogeneity, with which either the tax or the refuge may be the best strategy depending on the pest dispersal level.

The clue of these results is that, compared with equilibrium values, the tax regulation induces producers facing lower pest attacks n_i to plant even less of the pesticide variety. This result is consistent with the general idea that taxes assign the cost of reducing externalities to the agents who have the lowest opportunity costs. Allocating the costs of reducing externalities in this way is efficient under perfect pest mobility, as posited in Proposition 1; however, it turns out that this is not the general case under imperfect pest

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mobility. In almost all our simulations in which neither the tax nor the refuge allow us to restore efficiency, the first-best requires that the proportion of pesticide variety that farmers should plant will increase as the initial level of pest attacks decreases. That is, in most simulations, the less vulnerable producer 1 should plant more of the pesticide variety than the producers with intermediate levels of pest attacks (producers 2 and 4), who should in turn plant more of the pesticide variety than the producer with the highest levels of pest attacks (the more vulnerable producer 3). The tax instrument will then not necessarily improve the equilibrium outcome in the right direction. On the other hand, although the refuge is a command-and-control instrument, it leaves some flexibility to producers since they can plant more than the minimal requirement with conventional varieties. This flexibility is used in 19 simulations: the producer with high levels of pest attacks (producer 3), and potentially the producers with intermediate levels of pest attacks, choose to plant less of the pesticide variety than the maximum authorized planting. Which of the two, the tax or the refuge, is closer to the optimum, -given that this optimum is non-monotonic in pest attacks in most simulations and that the refuge strategy does not constrain all producers in 19 simulations- then depends on the parameters of each simulation.

For further insight on this situation, we take a closer look at a simulation in which pesticide plantings are not ranked according to pest attacks in the first-best. Table 2 describes simulation results when the heterogeneity of pest attacks is maximum, equal to $h_n = 1$, and the pest mobility parameter is low and equal to $h_\delta = 0.2$. In this simulation, pest attacks are $n_1 = 0$, $n_2 = n_4 = 0.5$ and $n_3 = 1$. Producer 1, who faces no pest attacks, plants no pesticide variety: he is not influenced by the decisions of other producers and does not influence their decisions. Producers with intermediate levels of pest attacks plant the highest proportion of pesticide variety both in the first-best (where $x_2 = x_4 = 0.989$ and $x_3 = 0.910$) and in the unregulated equilibrium (where $x_2 = x_4 = 0.990$ and $x_3 = 0.934$). The best tax strategy (where $x_2 = x_4 = 0.975$ and $x_3 = 0.929$) dominates the optimal refuge strategy (where $x_2 = x_4 = \overline{x} = 0.979$ and $x_3 = 0.937$).

[Insert Table 2]

Producer 3 faces half of the total initial pest attacks, and a pest growth rate of $\gamma_3 = 10$, and has producers 2 and 4 both as direct neighbors. Producers 2 and 4 combined face the other half of initial pest attacks, each with a pest growth rate $\gamma_2 = \gamma_4 = 5$, and each of them has only producer 3 as a direct neighbor. The pest mobility parameter is $\delta_1 = 0.2$ for a neighboring producer $\delta_2 = 0.04$ for a producer located on the opposite side of the circle. Therefore, while planting decisions of producer 3 have an important impact at locations 2 and 4, producers 2 and 4 each influence only producer 3 at a significant scale, while producer 2 does not influence much the resistance for producer 4, and vice versa. Taking into account the impact of each producer on future pest population and resistance at all locations, it is then optimal that producer 3 plants less pesticide variety than producers 2 and 4. The main difference in the equilibrium is that producer 3, who does not account for how he affects producers 2 and 4, plants a significantly higher proportion of the pesticide variety (0.934 instead of 0.910). In equilibrium producer 3 still plants less pesticide variety than producers 2 and 4, because given the higher pest growth rate he faces, it is more important for him to keep the ability to control pests in period 2. The tax instrument is an incentive for both types of producers to decrease their pesticide plantings compared with the equilibrium, although it puts more constraint on producers 2 and 4 than on producer 3, which is suboptimal. The refuge strategy constrains producers 2 and 4, but not producer 3, who increases his pesticide plantings compared with the unregulated equilibrium, because he anticipates less pesticide plantings from his neighbors and therefore a smaller externality on his future resistance level. All in all, the tax therefore makes possible to get closer to the first-best in this case.

Note that there are only four producers and three different levels of pest attacks in these simulations. This causes pest attacks to vary substantially from one producer to his neighbor when producers are heterogenous. This uneven characteristic of our producers' set is one reason why the best regulatory instrument may change non-monotonically as heterogeneity or dispersal increase.

It is also interesting to investigate how the results change if we assume that farmers are "myopic" in the sense that they do not take into account for their own effect on future pest population and resistance development. This assumption is often retained in simulation models of pest resistance management (e.g. Vacher et al., 2006). When farmers are myopic, we find that both the tax and the refuge make it possible to restore efficiency when the farmers are homogeneous or when pest dispersal is perfect. In all other simulations, the refuge always performs better than the tax (detailed results not shown). Myopic farmers all use only the pesticide variety in the first period, because they take into account only for its immediate effect on pest population reduction at the end of period 1. The tax induces myopic farmers with the lower level of pest attacks to reduce their pesticide plantings the most, while in optimum, as described above, they should be planting the highest proportion of the pesticide variety. The refuge is constraining for all myopic farmers in all simulations, and therefore induces all producers to reduce equally their proportion of pesticide plantings, yielding a result closer to the optimum.

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Many of the results obtained here may be very specific to our assumption of only four producers, and to our specific parametrization of this set of simulations. Therefore, we cannot infer too much from them about the conditions under which one instrument dominates the other in general. We nevertheless believe that these simulations are useful for two reasons. First, they illustrate that the optimal, equilibrium and regulated planting strategies may be far from self-evident: it cannot be taken for granted that any specific types of producers should optimally -and actually do in equilibrium- plant the smallest or the highest proportion of pesticide varieties, cannot be taken for given in general. Second, these simulations highlight the crucial importance of the assumption of myopic *versus* non-myopic farmers, that may cause a major change in public policy prescriptions. As long as farmers have a non-infinitesimal impact on resistance and population at their own location − either because they are not too numerous, or because pest mobility is limited − they are not ”population and resistance takers”. But it is not clear to what extent producers are actually aware of how their current actions affect their future pest damages.

8 Conclusion

How should pest resistance to pesticide seeds be regulated? This 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 these features are two parameters. We find that the first-best pest resistance management can be achieved (i) with a tax or a subsidy on pesticide seeds if pests move uniformly across fields; (ii) with a mandatory refuge or a tax or subsidy on pesticide seeds if farmers are homogeneous, provided that the net externality of pesticide plantings on future pest resistance and population is negative for the refuge, and provided that each farmer has a non-negligible impact on resistance in his own field for the tax or subsidy. 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 the level of either pest mobility or farmers’ heterogeneity is high. The simulations suggest that the policy prescription for a given level of producers’ heterogeneity and pest dispersal may change, depending on whether farmers are assumed to be myopic or not.

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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. Market-based instruments therefore tend to minimize the costs to reduce resource use or pollution. 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/subsidy 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.

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A Proof of Proposition 2

In this section, we describe the equilibrium planting strategies with perfectly mobile pests and non-myopic producers. Define $C = \sum_{j\in\Omega}[n_{j1}(1 - x_{j1}(1 - w))]$. Using (10) and (11), the second-period first-order equilibrium condition (18) may be written:

$$\rho\frac{\gamma_i}{(2I-2)D}(D^2 - w^2C^2) + \underline{\lambda}^e_{i2} = \rho c + \bar{\lambda}^e_{i2}. \tag{29}$$

where $D = \sum_{k\in\Omega} n_{k1}(1 - x_{k1}(1 - w^2))$. In equation (29), in addition to the multipliers, only γ_i in the left-hand side term varies with i . Since γ_i is increasing in i on the first half of the circle ($i \in [1, ..., I]$), it must be that $\underline{\lambda}^e_{i2} > 0$ and $\bar{\lambda}^e_{i2} = 0$ for producers i such that $\gamma_i < \gamma^{ea}$ and $\underline{\lambda}^e_{i2} = 0$ and $\bar{\lambda}^e_{i2} > 0$ for producers i such that $\gamma_i > \gamma^{ea}$, where the threshold γ^{ea} is defined by (29) with $\underline{\lambda}^e_{i2} = \bar{\lambda}^e_{i2} = 0$:

$$\gamma^{ea}(D^2 - w^2C^2)/((2I - 2)D) = c. \tag{30}$$

Therefore, equations (29) and (30) imply the following equilibrium strategy at the second period. Along the first half of the circle $i \in [1, ..., I]$, $x^e_{i2} = 0$ for every producer i with $\gamma_i < \gamma^{ea}$ and $x^e_{i2} = 1$ for every producer i with $\gamma_i > \gamma^{ea}$. The second half of the circle is the mirror image of the first one.

Let us denote by n^{ea} the first-period pest attack of the threshold producer with growth rate γ^{ea}. For any producer i with $n_{i2} < n^{ea}$, the first-period first-order equilibrium condition (17) with $x^e_{i2} = 0$ simplifies to:

$$n_{i1}\left(1 - w^2\right)\left[1 + \gamma_i\frac{\rho}{2I-2}\right] + \underline{\lambda}^e_{i1} = c + \bar{\lambda}^e_{i1}. \tag{31}$$

Since γ_i and n_{i1} are both increasing in i on the first half of the circle , it must be that $\underline{\lambda}^e_{i1} > 0$ and $\bar{\lambda}^e_{i1} = 0$ for producers i such that $n_{i1} < n^{eb}$, and, $\underline{\lambda}^e_{i1} = 0$ and $\bar{\lambda}^e_{i1} > 0$ for producers i such that $n_{i1} > n^{ea}$, where n^{eb} and γ^{eb} are defined by (31) with $\underline{\lambda}^e_{i2} = \bar{\lambda}^e_{i2} = 0$, that is:

$$n^{eb}(1 - w^2)(1 + \gamma^{eb}\rho/(2I - 2)) = c. \tag{32}$$

The above conditions on the multipliers imply that $x^e_{i1} = 0$ for any producer i such that $n_{i1} < \min\{n^{ea}, n^{eb}\}$ and that $x^e_{i1} = 1$ for any producer i such that $n_{i1} \in (n^{eb}, n^{ea})$.

For any producer i with $n_{i2} > n^{ea}$, the first-period first-order equilibrium condition (17) with $x^e_{i2} = 1$ simplifies to:

$$n_{i1}\left(1 - w^2\right)\left[1 + \gamma_i\frac{\rho w^2 C\sum\limits_{j\in\Omega}[n_{j1}(1 - x_{j1})]}{(2I-2)D^2}\right] + \underline{\lambda}^e_{i1} = c + \bar{\lambda}^e_{i1}. \tag{33}$$

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As before, since n_{i1} and γ_i are both increasing in i on the first half of the circle ($i \in [1, ..., I]$), for (33) to hold, it must be that $\underline{\lambda}_{i1}^e > 0$ and $\bar{\lambda}_{i1}^e = 0$ for producers i with $n_{i1} < n^{ec}$, and, $\underline{\lambda}_{i1}^e = 0$ and $\bar{\lambda}_{i1}^e > 0$ for producers i such that $n_{i1} > n^{ea}$. The threshold pest attack n^{ec} and the corresponding pest population growth γ^{ec} are defined by (33) with $\underline{\lambda}_{i2}^e = \bar{\lambda}_{i2}^e = 0$:

$$n^{ec}\left(1 - w^2\right)\left[1 + \gamma^{ec}\rho w^2 C \times F/((2I-2)D^2)\right] = c, \tag{34}$$

with $F = \sum_{j\in\Omega}\left[n_{j1}(1 - x_{j1})\right]$. We have established that $x_{i1}^e = 0$ for any producer i with $n_{i1} \in (n^{ea}, n^{ec})$ and $x_{i2}^e = 1$ for any producer i with $n_{i1} > \max(n^{ea}, n^{ec})$. It is easily shown that $w^2CE/D^2 < 1$, and therefore $n^{ec} < n^{eb}$.

Hence, three possible equilibrium configurations may emerge in period 1 with perfectly mobile pests, depending on parameters. In these configurations, crop allocations on the first half of the circle are determined as follows. If $n^{ea} < n^{ec} < n^{eb}$, then producers with $n_{i1} < n^{ec}$ grow only the conventional crop while producers with $n_{i1} > n^{ec}$ grow only the pesticide crop. If $n^{ec} < n^{ea} < n^{eb}$, then producers with $n_{i1} < n^{ea}$ grow only the conventional crop while producers with $n_{i1} > n^{ea}$ grow only the pesticide crop. If $n^{ec} < n^{eb} < n^{ea}$, then producers with $n_{i1} < n^{eb}$ grow only the conventional crop while producers with $n_{i1} > n^{eb}$ grow only the pesticide crop. In each case, crop allocations on the second half of the circle are the mirrors of those of the first half.

In each half-circle, during the first period, producers with low pest attack up to a threshold n_1^e plant conventional variety and those with pest attack above n_1^e plant pesticide varieties. The threshold n_1^e is implicitly defined either by $n_1^e = n^{ea}$ (equation (30)), or by $n_1^e = n^{eb}$ (equation (32)), or by $n_1^e = n^{ec}$ (equation (34)), depending on the equilibrium configuration that emerges.

B Proof of Proposition 3

We show that efficiency can be restored with a tax or subsidy on pesticide seeds when pests are perfectly mobile and producers are non-myopic (that is, take into account the impact of their first-period variety choice on future pest resistance and population). A tax τ increases the cost of pesticide seeds from c to $c+\tau$. Therefore, with a tax regulation, the three equations (30)), (32)), and, (34)), which implicitly define the threshold pest attacks in each of the three equilibrium configurations, become respectively:

$$\begin{aligned}
\gamma^{ea}(D^2 - w^2C^2)/((2I-2)D) &= c + \tau, && (35)\\
n^{eb}(1 - w^2)(1 + \gamma^{eb}\rho/(2I-2)) &= c + \tau, && (36)\\
n^{ec}\left(1 - w^2\right)\left[1 + \gamma^{ec}\rho w^2 C \times F/((2I-2)D^2)\right] &= c + \tau. && (37)
\end{aligned}$$

Each of the above equation defines an equilibrium threshold pest attack $n_1^e(\tau)$ for a tax level τ. In each configuration, there exists a tax level such that the threshold equilibrium pest attack equals the efficient one, i.e. τ^* is such that $n_1^e(\tau^*) = n_1^*$ where n_1^* is defined in (16). For instance, in the simplest configuration described in equation (36), the tax level is explicitly defined by $\tau^* = n_1^*(1 - w^2)(1 + \gamma^* \rho/(2I - 2)) - c$, where γ^* is the growth rate for producer with pest attack n_1^*.

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