N° 2-3/2011 – DECEMBER

RESEARCH IN ECONOMICS AND RURAL SOCIOLOGY

Regulating to manage pesticide resistance development
The question of the sustainability of pest and disease sensitivity to pesticides and resistant varieties

Using pesticides in agriculture and introducing varieties that are resistant to some pests and diseases (insects, fungus, virus and bacteria) exerts selection pressure on the populations of those pests and diseases. In the course of time, the efficiency of this technology may decrease if resistances (to pesticides or resistant varieties) develop. Therefore, the sustainability of pesticides and resistant varieties is largely dependent on their use. The more systemic and intensive the use of the technology, the higher the selective pressure, the quicker the selection of the resistance gene in the population and the faster the technology becomes obsolete. Sustainable management of resistance requires parsimonious use of the preventive means, which is not necessarily compatible with the users' economic interests in the short run. From an economic point of view, the sensitivity of pests or diseases to pesticides or varietal resistances is a natural resource. Sustainable resistance-management strategies aim to extract it in an optimal way in the course of time, that is to say to delay the adaptation of these pest or disease populations[1]. In order to control the development of resistance to pesticides, the "regulator" has various environmental policy tools. Our study helps to understand the determinants in the arbitration between two of these tools: compulsory refuge areas and a tax on pesticides or seeds of resistant varieties. A spatially and temporally explicit bio-economic model was used to compare the performance of the two tools according to various assumptions on pest mobility. This analysis followed on from a previous pluri-disciplinary exercise of bio-economic simulations on the example of European Corn Borers (Vacher et al., 2007).

Although a lot of cases of adaptation to pesticides or resistant varieties have already been identified, the question of sustainable resistance management saw renewed interest with the arrival of "*Bt*" transgenic varieties sold in the Unites States from the mid nineties. These varieties of maize and cotton were obtained by incorporating toxins from *Bacillus Thuringiensis* (*Bt*) bacteria into the plant, making it resistant to crop pests. Sale of these varieties caused a huge reaction from organic farmers and environmentalists worried about the loss of efficacy of *Bt* toxins (which are used in organic spraying), as well as from scientists warning of the high selection pressure exerted by the *Bt* varieties. Following that debate, the United States introduced the first far-ranging compulsory regulation on sustainable resistance management with the refuge area policy. This regulation was implemented by the *Environmental Protection Agency* (EPA).

[1]According to this definition, sustainability aims to preserve the natural resource of pest population sensitivity to control technologies longer, thereby extending the efficacy of the innovation (pesticide or resistant variety). This definition of sustainability does not take account of the potential effects on health or the environment and does not tally with that of sustainable development in the most classical sense of the term (if ever a pesticide has a negative effect on health, a sustainable management policy which prolongs the efficacy of that pesticide causes that negative effect to last.)

It forced *Bt* maize and cotton producers to sow 20% to 50% of the crop with non-*Bt* varieties. These areas provide a "refuge" for pests that are vulnerable to *Bt* toxins, which, by developing and mating with resistant pests, slow down selection of the resistance gene to *Bt* toxins.

The implementation of this large-scale regulation led to research backed up by figures on the biology and economics of these refuge areas for *Bt* crops. In addition to these precise cases, we have seen renewed scientific activity on the more general question of sustainable resistance management. Our study is part of this, looking into the question of the regulations to be implemented, based on the example of *Bt* plants, in order to restrict use of pesticides or resistant varieties and postpone the appearance of resistant pests in an economically acceptable way.

Sensitivity to pesticides, a common resource freely accessible to all

Why do we have to regulate the development of resistance to pesticides? Given that the farmer is the first to suffer from the loss of efficacy of a pesticide, we could expect him to use it carefully to slow down this phenomenon. This is not so, because the farmer is not the only one spraying the pesticide. As pests go from one farm to another, the resistance of pests present on the farm also depends on neighbours' use of the pesticide. This dependency creates an externality between farmers, in the economic sense of the term.

From a conceptual point of view, sensitivity to a pesticide in the genetic inheritance of a pest population has the characteristics of a freely-accessible natural resource. Farmers take some of this resource when spraying a pesticide. The sensitivity to the pesticide varies from one year to another according to the growth of the pest population and its genetic inheritance. Both these variables, the pest population and proportion of resistance genes, are affected by pesticide use. The problem is similar to that of the tragedy of the commons: by ignoring the impact of his own control choice on the pests of the other farmers, each farmer tends to overexploit the resource. This laissez-faire therefore leads to a quicker loss of sensitivity to the pesticide than we would like. That accelerated loss is detrimental to all the farmers.

Compulsory refuge areas or seed taxation: regulation versus economic tool

It is in this spirit that the EPA introduced the compulsory refuge area which obliges each *Bt* producer to sow non-*Bt* varieties on a part of their farm. According to the usual terminology of environmental economics, it is a "command and control" environmental regulation policy because it places an obligation directly on each producer in their technological choice (here, the minimal fraction of crop dedicated to the refuge area) and relies on the regulator's control of compliance with the rule. The advantage of a regulation of this type is the precision for the regulator who directly controls the major parameters of size and location of the refuge area. Its drawback is that it is less flexible than economic tools such as taxes and emissions allowance trading. The latter category of environmental policies allows producers more freedom in the answer they adopt in the face of the environmental constraint.

Another way to maintain areas planted with conventional varieties, for example, would be to discourage the adoption of *Bt* seeds by imposing a tax on such seeds. This economic tool has the advantage of letting farmers choose to adapt to their respective physical, climate and technical conditions. The farmers who are the least affected by the targeted pest will be discouraged from adopting *Bt* varieties, leading them to sow conventional varieties which would then provide natural refuge areas for farmers hit by most severe attacks of the pest. Economic theory favours economic tools for freely-accessible natural resource exploitation because they adapt to the characteristics of the users. However, in this case, the drawback is that the regulator does not control the location of the natural refuges induced by the tax. Poor distribution of these areas in the landscape, far from the areas sowed with *Bt*, will make them ineffective if pests do not migrate between the areas in question. The preference for market tools over regulation tools is challenged again when the spatial distribution of the resource is great, as is the case for sensitivity to pesticides. To be able to delay the selection of resistance genes, the refuge areas which concentrate the pesticide-sensitive genes must be scattered around the landscape. This characteristic makes the problem we are studying here different from the examples studied hitherto in the literature on natural resource management in which location is important. For example, for the protection of animal species (elephants, apes …), a concentration of protection areas into sizeable natural reserves is more adequate (contrary to the scattered refuge areas required here).

Our study (Ambec and Desquilbet, 2011) helps provide a better understanding of the determinants in the arbitrations between these two environmental policy tools, compulsory refuge areas and a tax on GMO seeds, in the sustainability of resistance to GMO pesticides. A bio-economic model with a double spatial and temporal dimension was used to compare the performance of the two tools according to various pest mobility hypotheses (see framework).

A model centred on the spatial location of refuge areas and pest mobility

Our economic model describes the individual farmers' choice of crops, Bt GMO or conventional, in the light of the yield losses caused by pests on each farm. The biological model must be rich enough to describe these yield losses which depend on pest population and the proportion of resistance genes within that population. These two variables are the state variables of our dynamic system. To remain comprehensible, the model is kept as simple as possible in its economic, temporal and spatial aspects. Time is limited to two periods and space to one dimension: farmers are located on a line or a circle. At each period, the pest biological cycle is divided into three phases. During the first phase, pest larvae are born and feed on crops. Their survival depends on each type of plant, conventional or *Bt*. In the fields sowed with *Bt*, only the larvae with two resistance genes ("rr" genotype) survive. During the second phase, the larvae metamorphose into butterflies and migrate. The scale of butterfly migration lessens with the distance between two farms. Finally, the third phase is a reproduction phase with gene transmission and population growth. These three biological phases give rise to two dynamic equations for each farm: one for the number of pests and another for the number of resistant pests. At the second period, these two state variables depend on the initial characteristics from the first period, meaning on the number of pests and proportion of resistant pests, as well as on the farmer's choice of variety and all on that of his neighbours. This is therefore an economic model with an externality: each farmer's profit on his own farm depends on the number of pests and proportion of resistant pests which are themselves affected by the other farmers' choices of variety.

This paper centred on the spatial aspects has been voluntarily simplified regarding the time aspects. In another study (Desquilbet and Hermann, 2011), we looked into the time aspect of the refuge area policy in the case of pest perfect migration between *Bt* area and refuge area. This paper takes an interest in the optimal evolution of the compulsory refuge area over time, or in other words, in the development of the optimal extraction rate of pest population sensitivity to *Bt*. A key result is that the optimal path of refuge policy depends largely on whether there is a *Bt* seed additional cost or not, a variable of which the effects have not been studied systematically in previous literature. We also show the importance of consistent modelling of *Bt* plant effects on pest populations. The inconsistency between some results in the literature may be attributed to inadequate hypotheses in the biological models used.

Two Bt crop externalities, negative on resistance development, positive on population size

With the model, we compared production efficiency under three systems: laissez-faire (no regulation), a compulsory refuge area and tax on *Bt* maize. This comparison was made under various hypotheses of pest mobility and spatial dispersal of the pest population. The model helps clarify the effect of externalities on the use of seed pesticides. In the absence of pest mobility from one farm to another, laissez-faire production is optimal. If it is effective, the farmer will himself sow a part of his farm as a refuge area to delay resistance gene selection. Regulator intervention is only justified when pests move from one farm to another. In that case, the farmer's decision to sow a refuge area to slow down resistance development will also be of benefit to his neighbours. Yet, the farmer will be the only one to bear the necessary investment.

When pests are mobile from one farm to another, the farmer's choice of pesticide variety generates two externalities on his neighbours, each one affecting one of the state variables. The first externality is negative and is due to the selection of resistance genes: the more *Bt* seeds the farmer sows, the higher the proportion of resistant pests on his neighbours' farms. The second externality is linked to the pest population: by using more of the *Bt* variety, a farmer reduces the number of pests on his farm and therefore the population migrating into his neighbours' fields. Both externalities imply that the laissez-faire situation is ineffective (unless the two externalities cancel each other out) and may be improved by a public policy.

Tax the optimal response if pests migrate over long distances

We first considered the case of pests migrating over long distances. It was translated into the model by two hypotheses. First, the dispersal of pests does not depend on the distance between farms. Second, pests migrate over a territory with various climate and biological characteristics and with an initial population of different pests. In that case, the tax (or subsidy) on *Bt* seeds allows optimal management of resistance. While the negative externality on resistance development requires a tax on *Bt* seeds in order to be corrected, the positive externality on the reduction of the pest population justifies a subsidy on *Bt* seeds. The choice of a tax or a subsidy depends on the relative importance of each externality. This result is consistent with the economic theory. Here, the spatial location of the externalities is uniform and the producers' opportunity costs for the reduction of externalities are heterogeneous. The tax is therefore a more effective tool to reduce the externalities than an imposed production technology like the compulsory refuge area.

Preference for compulsory refuge area if pests migrate over short distances and if all farmers act identically

When they migrate over short distances, the pests which leave a farm mainly go to immediately neighbouring farms. In the model, we suppose that the proportion of pests which migrate from one farm to another decreases as distance increases. To simplify, we suppose that farmers face similar climate and biological characteristics, and therefore the same pest population within the migration distance. In this case, when the negative externality linked to resistance development dominates, the refuge area is an effective regulation. A tax also enables effective production if each producer anticipates the impact of his choice of variety on resistance development on his farm. Under this behavioural hypothesis, each farmer dedicates a part of his farm to the conventional variety to slow down resistance development. The tax therefore determines the size of that refuge area set aside by the farmer. If farmers neglect the impact they have on resistance gene development, the tax does not allow the creation of such voluntary refuges. They must therefore be compulsory.

Heterogeneous farmers and imperfect pest mobility: no clear-cut result in favour of any approach

Finally, we studied the most usual model case when farmers face heterogeneous pests and when pest mobility is imperfect. The simulations carried out under various heterogeneousness hypotheses between farmers do not clearly suggest the dominance of either of the tools according to the hypotheses on these two variables. These simulations suggest that it is usually difficult to infer among heterogeneous producers which type of producers should plant more pesticide varieties than others and which type of producers should plant less. They also indicate that the best public policy for a given degree of producer heterogeneousness and pest dispersal may be differ according to whether farmers are short-sighted or not, meaning whether each farmer is aware or not of the impact of his crop choices on future development of the pest population and resistance on his own farm.

Lessons for the regulator

What can be learned from this modelling exercise of regulation tools aiming to manage use of pesticides sustainably? First, we must remember that the development of pesticide resistance is not the only externality due to pest mobility. It must not be forgetten that spraying pesticide over a farm is of benefit to neighbours because it reduces the pest population on the neighbouring farms. This positive externality has an opposite effect to the negative externality linked to the loss of pesticide sensitivity in the pest genetic inheritance. It encourages each farmer to underuse pesticides. The regulation must take this into account by reducing the tax or refuge area. Second, the choice between tax and compulsory refuge area depends on pest mobility. When pests migrate over long distances, a tax is better. In the opposite case of low mobility, such as with the corn borer, for instance, the refuge area is preferable.

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This research was granted financing within the project CEDRE (Sustainable management of disease resistance in plants) from the 2005 ADD call for project (agriculture and sustainability).

For Further information

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Published by the INRA Department of Social Sciences, Agriculture and Food, Rural Development and Environment
Publishing unit: Editorial Director: Bertrand Schmitt– Editor: Sophie Drogué (Chief Editor),
Translation and composition: Ariel Gille