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# Spatial Efficiency of Genetically Modified and Organic Crops

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# Spatial Efficiency of Genetically Modified and Organic Crops

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**Abstract**

We analyze the spatial distribution of genetically modified (GM) and organic crops. Because some organic crops will likely be contaminated by GM crops, not all of the non-GM crops can be sold as organic. Therefore, the choice of producing organic crops will depend on the surrounding crops. When producers follow individual strategies, many spatial configurations arise in equilibrium, some being more efficient than others. We examine how coordination among producers has an impact on the spatial distribution of crop varieties. We show that coordination among only a small number of producers can greatly improve efficiency. For instance, an organic producer who has two GM neighbors needs to coordinate only with one of them to reduce spatial externality and improve efficiency.

*Keywords: Genetically Modified crops, externality, spatial localization, coordination*

*JEL classification: D62 (Externalities), L11 (Market Structure)*

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# 1 Introduction

The emergence of Genetically Modified (GM) crops represents a major innovation in modern agricultural production. It is also a controversial one. To understand this controversy a key economic aspect must be considered: the production of GM crops can indirectly raise the cost of producing GM-free crops. Natural contamination phenomena such as cross-pollination or seed contamination prevent producers from obtaining the price premium of GM-free labels in Europe or organic labels in North America. This negative externality is at the core of what is known as the coexistence problem between non-GM and GM crops. When non-GM varieties can be contaminated by neighboring fields, the producer planting decision is no longer based solely on the expected crop price. It becomes a strategic decision in which what other producers are planting matters as well. Thus, whether GM-free crops are produced in equilibrium depends on their relative price but also on existing spatial links between producers. Our objective is to provide a theoretical framework aimed at analyzing strategic planting decisions within a rich set of spatial contexts.

The existence of externalities due to the introduction of GM crops is now well documented. To address this market failure many countries, mostly in Europe, have designed coexistence regulations such as buffer zones, minimal distance requirement or legal liability rules in case of contamination (Beckman et al., 2006). On the contrary, in North America, very few rules and regulations are implemented (Berwald et al., 2006) and, yet, there is coexistence between GM and organic crops (Brookes et al., 2004). For instance, Brookes and Barfoot (2004) report significant increases in areas of organic corn and soybean cultivated in the U.S. between 1995 and 2001. Interestingly perhaps, they also report that states such as Minnesota and Iowa, that have an above average penetration of GM corn, are also those with the biggest areas of organic corn planting. These observations suggest that even in the absence of regulation "natural" coexistence can occur. Clearly, coexistence patterns and the magnitude of inefficiencies depend on the localization of GM and organic varieties in the landscape. Should we see patchworks of organic crops, or more organized clusters of GM and non-GM crops? How do spatial inefficiencies arise in an environment characterized by individual decision makers and in absence of regulation?

To answer these questions, we first analyze the individual decision of producers to grow organic crops in the presence of GM neighbors in a spatial model of variety choices with externalities. We derive the Nash equilibria of this spatial game of crop variety choice. We obtain a multiplicity of equilibria with coexistence with different spatial configurations, some being more efficient than others. The more efficient equilibria are those in which all organic or GM producers are located next to each other in a way that minimizes negative externalities.

Following the analysis of individual decisions, we study what happens when producers can coordinate their planting. In this second part of our analysis, we reexamine the previous questions in a context where producers can form coalitions of different sizes in which they cooperate in their variety choices. Producers need to coordinate their planting strategies with neighbors who might potentially contaminate their crop. Contamination depends on the distance of cross-pollination: the more neighboring producers who can potentially contaminate an organic producer, the higher the coordination costs since a producer has to coordinate with more neighbors. To capture the fact that coordination costs are increasing with the size of the group involved, we assume that coordination is costless within a restricted set of neighboring producers and prohibitively costly above. We consider coalition deviations for coalitions of small size. We show how these deviations can improve the efficiency of the spatial configuration in equilibrium. In the game theory terminology, we apply a variant of a refinement of the Nash equilibrium, the strong Nash equilibrium. This equilibrium concept introduced by Aumann (1959) requires that the equilibrium strategies are robust to the deviation of not only single players but also groups of players.

Surprisingly, we find that in most spatial configurations coordination between two producers is enough to greatly improve efficiency. For instance, if each producer is contaminated by two neighbors, he needs to cooperate with only one of them to eradicate the negative externality and improve efficiency. If each producer is contaminated by four neighbors, cooperating with one of them greatly improves efficiency. Involving also a neighbor of the neighbor would further reduce the externalities. Yet, coordination among four producers fully eliminates externalities.

The underlying issue of our paper is the economic justification of coexistence regulations. Following Coase, producers might be able to coordinate their planting strategies to efficiently localize GM and organic varieties without any regulation (Coase, 1960). However, a premise of the Coasian argument is that the benefits of coordination outweigh the costs. Although in general these coordination costs might be difficult to measure, they are natural (and possibly low) in our spatial framework. Simple coordination processes for crop variety choices are fostered by public authorities in some countries. For instance, in Spain GM producers must inform their neighbors in advance about their intention to grow GM varieties (Brookes et al., 2004). In Portugal, farmers can voluntary associate to create production areas exclusively dedicated to the cultivation of GM or conventional varieties with the agreement of the ministry of agriculture (Carvalho, 2011). As such, coexistence regulations become superfluous in these specific areas simply because GM producers no longer have to comply with them. Following the implementation of this coordination initiative Carvalho (2011) reports that half of GM corns produced in Portugal were planted in GM dedicated areas in 2010. In the same spirit, our model demonstrates that if such coordination is possible, even between a small number of producers, efficiency is restored in most spatial configurations.

Although there exists an abundant economic literature on issues related to GM crops, only a few contributions are aimed at understanding the spatial localization of GM and non-GM crops (Ceddia et al., 2011; Beckmann and Wesseler, 2005; Munro, 2008; Furtan et al., 2007). Because of the spread of crops and their genes and the food labelling thresholds imposed by regulation to prevent non-GM crops to be sold as organic,[1] it is important to determine under what conditions GM and non-GM crops can coexist. In a model of perfect competition with different demands for GM and non-GM food and fixed land size, Munro (2008) shows that an equilibrium in which there is coexistence between GM and organic crops does not necessarily exist. He investigates how public intervention through taxes can help to restore efficiency. In our setting, we show that, on the contrary, under specific conditions coexistence of GM and non-GM crops can happen and that efficiency can be restored in the absence of public government intervention when producers can coordinate. This is in line with recent studies that show that the existence of collaboration

[1] The threshold is such that at least 1% of the crop is contaminated. This threshold is for the European Union, as stated by the Commission Regulation (ER) No 49/2000 (Beckmann and Wesseler, 2005) or EC No. 1830/2003 (Munro, 2008).

between farmers reduces coexistence costs (Skevas et al, 2010). Belcher et al. (2005) develop a model of GM contamination based on cellular automata. In their analysis, fields or “cell” can contaminate others cells with some probability for some limited time and a dynamic study of GM contamination spread is carried out. Unlike in Belcher et al. (2005), we choose to emphasize the importance of coordination in human decisions to determine the extent of contamination.

To study the coexistence of GM and non-GM crops, a buffer zone can be introduced. Furtan, et al. (2007) investigate the feasibility of such a buffer zone as well as the creation of a club of organic producers. They provide historical evidence of social networking ability by Canadian farmers and, by using wheat data from Saskatchewan, they show that only a high premium for organic product makes the organic club feasible. Contrary to our contribution, they do not explicitly analyze the physical localization of producers or their decision to produce organic crops. However, the creation of a group of organic producers and their ability to cooperate is also studied in our contribution. Our findings suggest that there is no longer coexistence when producers can form coalitions.

Government intervention sets the threshold under which an organic crop cannot be considered as organic if contaminated. This intervention has implications for spatial allocation of both crops and their coexistence (Beckmann and Wesseler, 2005; Beckmann et al., 2009). Considering that the coexistence problem is merely a problem of social cost (similar to the logic of Coase, 1960), Beckmann and Wesseler (2005) analyze the impact of different property rights (*ex ante* regulation and *ex post* liability) on the localization choices of producers. Under a set of assumptions, they show that the localization choice does not depend on the government intervention. When GM producers are liable for the negative externalities created on non-GM producers, the introduction of a liability rule for GM producers has an impact on the incentives to collaborate and to organize GM crops areas. Our approach is different as we consider the collaboration of organic producers when they have to incur the cost of the negative externality. Beckmann et al. (2009) introduce uncertainty and dynamic in a model where there is an irreversible effect to adopt GM crops because of specific investment. They provide the example of German regulation (mandatory registration and minimum distance must be respected), where the adoption rate of GM crops is relatively low. They explain this low rate by *ex ante* regulation costs and *ex post* liability costs.

The rest of the paper is organized as follows. In section 2 we present the general model. In section 3 we derive the Nash equilibria with coexistence and we provide two applications: a linear model in which each producer has at most two neighbors and a grid in which each producer has more than two neighbors. In section 4 we introduce coordination problems, and we define conditions under which efficiency is greatly improved. Section 5 concludes.

## 2 The Model

We first consider a general framework in which a set of $N = \{1, ..., n\}$ farmers are localized in a given particular landscape. Each farmer $i \in N$ produces one unit of crops. He chooses whether to produce GM or non-GM crops. The non-GM crop is referred to as "organic crop" even though it could just be labeled GM-free like it is done in the European Union which allows for 1.9% GM content. The two crop varieties differ in costs and revenues. The GM (respectively, organic) crop is sold at price $p_G$ (respectively, $p_O$). Since consumers are willing to pay more for GM-free food, there exists a price premium for organic crops, $p_O - p_G > 0$.[2] The cost of producing one unit of GM crops is normalized to zero. Hence, the profit of a GM producer is simply $p_G$. Producing one unit of organic crops is costlier, and we denote $c > 0$ the organic crop cost. The difference in costs captures the loss of yield due to pest attack or the cost of using more pesticides, for instance. Organic producers are able to sell their crops labeled GM-free if they are not contaminated by their GM neighbors. In order to consider contamination we determine a probability of contamination or, equivalently, the fraction of crops contaminated which depends on the variety choice of neighboring producers. Let $N_i \subset N \backslash \{i\}$ be the set of neighbors of producer $i$.[3] Among these neighbors, we denote by $N_i^G$ the set of GM producers and $N_i^O$ the set of organic producers, with $N_i^G \cup N_i^O = N_i$. Using similar notations, let $n_i$ be the

[2] Consumers perceive GM and non-GM food products as different, and consumers are willing to pay a premium for certified GM free food (Noussair et al., 2004). In a recent paper, Lusk et al. (2005) conduct a meta-analysis of 25 empirical studies on the willingness-to-pay for GM free foods. They find that the simple average premium for purchasing non-GM foods across all valuation studies is 29%.

[3] Neighbors might be more or less far away from a given producer depending on the distance between fields, the wind, the landscape (e.g., if hedges or roads between fields).

total number of neighbors of producer $i$, $n_i^G$ be the number of GM neighbors of $i$ and $n_i^O$ be the number of organic neighbors of $i$. Formally $n_i$ is the cardinal of $N_i$ or $n_i = |N_i|$, $n_i^G = |N_i^G|$ and $n_i^O = |N_i^O|$. We assume that each producer in $N_i^G$ contaminates producer $i$ with probability $\delta$ for every $i \in N$ with $0 < \delta < 1$.[4] Therefore, the probability that producer $i$ is contaminated by his GM neighbors (or, equivalently, the fraction of his crops that is contaminated) is

$$\delta_i = n_i^G \delta. \tag{1}$$

This contamination parameter $\delta_i$ can, equivalently, be interpreted as the fraction of organic crops sold as GM crops. Typically, crops located at the border of the field close to GM crops will be contaminated, whereas crops located in the center of the field, or far away from GM crops will not be contaminated. The more neighbors are producing GM crops, the higher the contaminated surface. An organic producer $i$ will harvest the borders of his field separately and sell the crops (as GM crops) at price $p_G$. He therefore obtains revenues $\delta_i p_G$ on borders and $(1 - \delta_i)p_O$ on the center of his fields. Since he has to incur the cost of producing organic crop $c$, the expected profit of an organic producer who has $n_i^G$ GM neighbors is

$$n_i^G \delta p_G + (1 - n_i^G \delta)p_O - c. \tag{2}$$

We assume that prices $p_O$ and $p_G$ are given. These prices could be determined on the world market, and we study the localization pattern of producers in a small area where their production will not affect world prices. For given prices many spatial configurations can be considered. For instance, it can be the case that only GM crops are produced. This configuration is efficient as there is no loss associated to spatial externalities. Indeed, GM producers do not contaminate their GM neighbors. The situation is similarly efficient if only organic crops are produced: organic producers do not contaminate their organic neighbors. However, situations of coexistence between GM and organic crops will not be efficient as organic producers will always be contaminated by some GM neighbors. By reducing spatial externalities, efficiency will be improved and can even be restored.

[4] For simplicity, we assume that all neighbors have the same impact on an organic producer in terms of probability of contamination. This assumption can be relaxed without altering qualitatively our results.

# 3 Coexistence Equilibrium

We now consider individual variety choices in the spatial model described above. More precisely, we first analyze the Nash equilibrium of the choice between organic and GM crops in the general setting without any assumption on the sets $N_i$ for every $i \in N$. We then compute the Nash equilibria in two particular cases when the spatial model is represented in a line or circle ($n_i = 1$ or 2) and in a grid ($n_i = 3$ or 4).

## 3.1 General setting

A Nash equilibrium of the spatial variety choice model is defined by a set of GM producers $N^G$ and a set of organic producers $N^O$ with $N^O \cup N^G = N$. An equilibrium is a situation from which none of the producers has an incentive to deviate, given the decisions of the other producers. Or, put differently, each producer chooses the variety that maximizes his expected profit given the variety choices of his neighbors. Consider any producer $i \in N$. Given the variety choices $N_i^G$ and $N_i^O$ of his GM and organic neighbors, and given prices $p_O$ and $p_G$, producer $i \in N^O$ prefers to plant organic crops if $n_i^G \delta p_G + (1 - n_i^G \delta) p_O - c \geq p_G$ which is equivalent to

$$(1 - n_i^G \delta)(p_O - p_G) \geq c. \tag{3}$$

The expected revenue premium of the organic crop should exceed its production cost. Similarly, producer $k \in N^G$ chooses the GM variety if $p_G \geq n_k^G \delta p_G + (1 - n_k^G \delta) p_O - c$ which is equivalent to

$$(1 - n_k^G \delta)(p_O - p_G) \leq c. \tag{4}$$

A variety choice $(N^O, N^G)$ is a Nash equilibrium if and only if conditions (3) and (4) hold for every $i \in N^O$ and $k \in N^G$.

Our model of spatial localization exhibits multiple equilibria, some being more efficient than others. Before describing these equilibria in the case of the line and the grid, we analyze some of their properties. First, the equilibrium conditions (3) and (4) imply that $n_k^G \geq n_i^G$, which means that organic producers are surrounded by weakly less GM producers. Second, organic and GM crops might not coexist in the landscape. In particular, only GM crops are planted in equilibrium for parameters (prices, cost, contamination probability, number of neighbors) such that for every $i \in N$

$$p_O - p_G < \frac{c}{1 - n_i^G \delta}.$$

Similarly, there is a Nash equilibrium in which only organic crops are planted if $p_O - p_G > c$. The two varieties coexist in a Nash equilibrium $(N^O, N^G)$ if $N^O \neq \emptyset$ (or, equivalently, if $N^G \neq \emptyset$). Combining (3) and (4), the equilibrium condition with coexistence can be summarized as follows for any $i \in N^O$ and $k \in N^G$

$$\frac{c}{1 - n_k^G \delta} \geq p_O - p_G \geq \frac{c}{1 - n_i^G \delta}. \tag{5}$$

To determine more general equilibrium conditions, we consider the organic and GM producers who have the highest incentive to deviate to another variety. If these producers do not deviate, then none of the producers will have an incentive to deviate. An organic producer who is contaminated by many GM neighbors might have an incentive to become a GM producer as well. Therefore, the organic producer who has the highest number of GM neighbors has the higher incentive to deviate and, thus, we concentrate on this individual. If he does not deviate, none of the other organic producers (with lower incentive to deviate) will do so. Let

$$\overline{n}_o = \max_{i \in N^O} n_i^G, \tag{6}$$

be the maximum number of GM neighbors that an organic producer $i \in N^O$ might have. Along the same lines, a GM producer who has many GM neighbors has little incentive to become an organic producer as he will get a high level of contamination. On the other hand, a GM producer who has few GM neighbors might consider becoming an organic producer. Thus, we consider the incentive to deviate of a GM producer who has only a few GM neighbors and, therefore, a low probability to be contaminated if he decides to produce organic crops. We define

$$\underline{n}_g = \min_{k \in N^G} n_k^G, \tag{7}$$

the lowest number of GM neighbors that a GM producer $k \in N^G$ might have.

By definition of $\overline{n}_o$ and $\underline{n}_g$, the coexistence equilibrium condition (5) holds if and only if it holds for the organic producer with $\underline{n}_g$ GM neighbors and for the GM producer with $\overline{n}_o$ organic neighbors. We thus posit the following Proposition.

**Proposition 1** *A variety choice* $(N^O, N^G)$ *is a Nash equilibrium with coexistence if only if*

$$\frac{c}{1-\underline{n}_g\delta} \geq p_O - p_G \geq \frac{c}{1-\overline{n}_o\delta}, \tag{8}$$

*where* $\underline{n}_g$ *and* $\overline{n}_o$ *are defined by (6) and (7).*

Following directly from Proposition 1, we can provide a necessary condition for a Nash equilibrium with coexistence to exist.

**Corollary 1** *A necessary condition for Proposition 1 to hold is that*

$$\underline{n}_g \geq \overline{n}_o. \tag{9}$$

As long as the maximum number of GM neighbors of an organic producer is smaller than the minimum number of GM neighbors of a GM producer, and prices satisfy inequality (8), an equilibrium exists. Note that there are many candidates to the coexistence equilibrium. Some of them are more efficient than others. The more efficient equilibria are those with the lowest negative externalities. In other words, an equilibrium is more efficient than another one when the organic producers have less GM neighbors (if any), as it reduces the negative externalities.

To illustrate this analysis of the coexistence equilibrium we provide two applications of the general framework. The first application is a linear (or circular) model in which each producer has at most one or two neighbors. The second application is a grid which is more general as a producer can have three or four neighbors.

### 3.2 The linear model: one or two neighbors

We first consider the simplest model of variety choice with a spatial representation by locating producers along a line. Producers are located along the line from 1 to $n$. Each producer $i$ has two neighbors $i-1$ and $i+1$ except for producers located at the extreme 1 and $n$ who have only one neighbor. An alternative linear representation of the spatial model is a circle in which producer 1 is neighbor to producer $n$. In the circular model each farmer has exactly two neighbors. Formally, $n_i \in \{1, 2\}$ for every $i \in N$. In the linear model, $n_1 = n_n = 1$ and $n_i = 2$ for every $i \in N \backslash \{1, n\}$. In the circular model, $n_i = 2$ for every $i \in N$.

We focus on coexistence variety choice Nash equilibria. Clearly, some spatial configurations cannot be sustained in equilibrium. For instance, consider the configuration represented in Figure 1 where $O$ represents an organic producer and $G$ a GM producer.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| O | G | O | G | O | G | O | O |

Figure 1: Not an equilibrium configuration

Since a producer with two GM neighbors chooses to plant organic crops, his expected payoff from doing so should not be lower than if he was a GM producer, i.e., $2\delta p_G + (1-2\delta)p_G - c \geq p_G$. Similarly, since a producer with two organic neighbors plants GM crops, it must be that his expected payoff is weakly higher from doing so, even though his crops would not be contaminated, $p_G \geq p_O - c$. These two conditions cannot be satisfied together. Indeed, the GM producer has an incentive to deviate and produce organic crops as he will face no risk of contamination. On the other hand, the organic producer should produce GM crops since his contamination risk is maximal with all his neighbors producing GM crops. Hence, in equilibrium some spatial configurations of crop variety choices are excluded in the landscape. However, many different configurations might still emerge in a Nash equilibrium even in the simplest spatial model represented by the line.

We now describe some properties of these equilibria by applying Proposition 1 and Corollary 1 before comparing their efficiency. Under coexistence of both varieties in the linear model, at least one organic producer is neighbor to a GM producer which implies $\overline{n}_o \geq 1$. Similarly, at least one GM producer is neighbor to an organic producer which implies that $\underline{n}_g < 2$ since $n_i \leq 2$ for every $i \in N$. Moreover, according to Corollary 1, in a Nash equilibrium with coexistence, the number of GM producers in the neighborhood should not be higher for organic producers than for GM producers. Therefore, $\overline{n}_o \leq \underline{n}_g$. Combining these three last inequalities leads to only one value for $\overline{n}_o$ and $\underline{n}_g$ under coexistence: $\overline{n}_o = \underline{n}_g = 1$, which means that the producers who are more likely to deviate have one GM neighbor. The other neighbor, if any, is an organic producer. This precludes the configuration of Figure 1 in which a producer of one type of crops is located between two producers of the other type of crops. An equilibrium with coexistence exists only if a producer of one type of crops is located next to at least one producer of the same type of crops. Moreover, with $\overline{n}_o = \underline{n}_g = 1$, the equilibrium condition from Proposition 1 becomes

$$p_O - p_G = \frac{c}{1-\delta}. \tag{10}$$

In fact, the producers who are the more likely to deviate have the same payoff with both varieties, $\delta p_G + (1-\delta)p_O - c = p_G$. These producers are indifferent between producing organic and GM crops. Figure 2 below represents several spatial equilibrium configurations in the case of a line of eight producers with the same number of GM and organic producers. It is just an example of comparable configurations as many other equilibria with coexistence exist with 2, 4 or 6 GM (or organic) producers.[5]

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| O | O | G | G | O | O | G | G |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| G | G | O | O | G | G | O | O |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| O | O | O | O | G | G | G | G |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| O | O | G | G | G | G | O | O |

Figure 2: Some equilibrium configurations with the same number of each producer

These four configurations however differ in efficiency. Although as much organic crops are planted in all of these equilibrium configurations ($|N^O| = 4$), the spatial dispersion is better in the last two configurations because less organic crops (or a lower proportion of organic crops) will be contaminated on average. The most efficient configuration is the third one in which all producers of each variety are located in the same area. In this case, the risk or proportion of contamination is minimized to one organic producer.

[5] Note that producers with only one neighbor, i.e., producers located at the extreme of the line, are not always planting organic crops in a Nash equilibrium with coexistence. Indeed, as long as their only neighbor is planting GM crops, producers 1 and $n$ are indifferent between planting organic and GM crops. Therefore, an equilibrium with producers 1 and/or $n$ producing GM crops (e.g., first and third configurations in Figure 2) is consistent with the equilibrium condition (10).

To summarize, in the case of one or two neighbors represented by a line, many spatial configurations with coexistence might emerge, some being more efficient than others. In a line with more than two producers (i.e., if some producers have two neighbors), the equilibrium condition requires that organic producers neighbor to a GM producer are also neighbor to an organic producer (providing that he has two neighbors). The same applies for GM producers: if a GM producer is neighbor to an organic producer, his other neighbor should be a GM producer. These producers are more likely to change their variety choice as they are indeed indifferent between the two varieties.

### 3.3 The grid model: three or four neighbors

The case of the finite grid is arguably richer than the case of the linear model characterized above as producers can be surrounded by more than two neighbors. We consider a finite grid as described in Figures 3 and 4 where each point in the grid represents a producer and both figures contain different configurations.

Insert Figures 3 and 4

In the grid, we represent an organic producer by a black dot, and all the other points in the grid correspond to GM producers. In this setting, a producer is connected to at most four adjacent neighbors (left, right, above and below) but has only two adjacent neighbors in the corners. This richer model allows us to consider more externalities than in the linear case.

We call a *patch* a collection of organic producers who are all connected at least once to each other; a patch is continuous. We distinguish two exclusive types of patch: islands and borders. An island is a patch of connected organic producers fully surrounded by GM producers. On the other hand, a border has at least one producer "touching" the grid limit. In Figures 3 and 4, patterns $B$, $C$, $D$, $F$, $G$, $H$, $I$, and $K$ are islands while $A$, $E$, $J$, and $L$ represent borders.

As shown in Figures 3 and 4, there is potentially a wide variety of patches.[6] However, exactly

[6]Not all possible configurations are represented in Figures 3 and 4. For instance one can think about a ring with one GM producer in the middle of organic producers.

like in the case of the linear model, not all of them are likely to exist for two reasons. First, some patches do not represent equilibrium situations. Second, even though patches are robust to single deviations and represent an equilibrium situation, some of them will be more efficient than others. The more efficient ones will be those with fewer negative externalities.

We first consider equilibrium conditions and efficiency in the case of islands before examining the case of borders. Islands represent spatial configurations in which organic producers are located in the middle of GM producers (configurations $B$, $C$, $D$ in Figure 3 and $F$, $G$, $H$, $I$, $K$ in Figure 4). Not all of the islands will be sustained in equilibrium. Following directly from Corollary 1, we can already rule out islands $C$, $G$ and $K$ in Figures 3 and 4 that are not robust to single deviation. Indeed, for island $C$, $\underline{n}_g = 2$ and $\overline{n}_o = 3$, for island $G$, $\underline{n}_g = 2$ and $\overline{n}_o = 3$ and for island $K$, $\underline{n}_g = 3$ and $\overline{n}_o = 4$. In all these spatial configurations the necessary condition $\underline{n}_g \geq \overline{n}_o$ is violated.

Also, following directly from Proposition 1 we obtain that for spatial configurations in which $\underline{n}_g = \overline{n}_o$ a coexistence equilibrium exist if

$$p_O - p_G = \frac{c}{1 - \overline{n}_o \delta}.$$

This is the case for islands $I$ and $F$ in Figure 4 in which $\underline{n}_g = \overline{n}_o = 3$ and, therefore, it is an equilibrium of coexistence if $p_O - p_G = c/(1 - 3\delta)$.

On the other hand, for patches such that $\underline{n}_g > \overline{n}_o$ a coexistence equilibrium exists if

$$\frac{c}{1 - \underline{n}_g \delta} \geq p_O - p_G > \frac{c}{1 - \overline{n}_o \delta}. \tag{11}$$

This happens with configurations $B$ and $D$ in Figure 3 and $H$ in Figure 4. The left hand side of (11) implies that any GM producer surrounding an island is not connected to another island or to the grid limit. If a GM producer is connected to the grid limit, the necessary condition $\underline{n}_g \geq \overline{n}_o$ is no longer satisfied so it is not an equilibrium configuration.

This leads us to consider borders such as configurations $A$, $E$, $J$ and $L$ in Figures 3 and 4. A set of organic producers belong to a border when every organic producer within the set has at least one GM neighbor and at most three GM neighbors. Because borders have less externalities than islands (at most three GM neighbors versus four in the case of the island), organic producers in a spatial configuration such as a border enjoy a natural advantage compared to islands.

However, not all of the borders represent a Nash equilibrium with coexistence. For instance, configuration $L$ in Figure 4 in which $\underline{n}_g = 0$ and $\overline{n}_o = 2$ cannot be an equilibrium according to Corollary 1 as $\overline{n}_o > \underline{n}_g$. On the other hand, all the other configurations $A$, $E$, $J$ in Figures 3 and 4 are potential candidates for an equilibrium. However, if $p_O - p_G \neq c/(1-2\delta)$, configuration $J$ in Figure 4 cannot be an equilibrium. More generally, there exists no equilibrium in which a border entails one organic producer with two GM neighbors if $p_O - p_G \neq c/(1-2\delta)$.

By applying Proposition 1 we show that the most exposed organic producer has one GM neighbor and will deviate if $p_O - p_G \geq c/(1-\delta)$, while a GM producer will not deviate if $c/(1-2\delta) \geq p_O - p_G$. By putting together these inequalities we obtain that there exists a coexistence equilibrium in the grid in which a border entails organic producers with at most one GM neighbor if

$$\frac{c}{1-\delta} < p_O - p_G \leq \frac{c}{1-2\delta}.$$

A border similar to the spatial configuration $A$ in Figure 3 will therefore be an equilibrium with coexistence. Furthermore, this variety choice Nash equilibrium represents a more efficient configuration as each organic producer has at most one GM neighbor, which reduces the negative externalities due to contamination.

To summarize, in the case of a grid as represented in Figures 3 and 4, configurations $A$, $B$, $D$ in Figure 3 and $E$, $F$, $H$ and $I$ in Figure 4 represent equilibrium situations with coexistence. In all of these configurations an organic producer has at least one organic neighbor and, therefore, at most three GM neighbors. Some of these patches have three GM neighbors which implies many negative externalities. Patches with fewer externalities are the more efficient ones as is the case for configuration $A$ whereas, for the same number of organic producers, island $H$ is strictly more efficient than island $D$.

# 4 Coordination Among Producers

In this section we extent our analysis to coordination problems. We first consider the general case before exploring the two applications developed in the previous section.

## 4.1 General setting

In the general setting we have shown that there exists an equilibrium in which both types of crops coexist if condition (5) is satisfied. In other words, for given prices, as long as an organic producer has less GM neighbors than does a GM producer, it is possible to have coexistence between organic and GM crops. However, an organic producer might try to convince a GM producer (or maybe a few GM producers) to switch to organic crops. The two producers will therefore form a coalition and make their production choice accordingly. To keep our model simple we abstract from any coordination cost.[7] Within this new setting, we investigate whether the coexistence variety choice equilibrium is still robust and what are the implications in terms of efficiency.

To see whether an equilibrium with coexistence is robust to coordination, we consider a situation in which two neighbors (an organic producer and a GM producer) have the same number of GM neighbors, $n = \overline{n}_o = \underline{n}_g$. If the organic producer succeeds in convincing the GM producer to switch to organic crops, the organic producer is left with $(n-1)$ GM neighbors while the former GM producer (who is now an organic producer) still has $n$ GM neighbors. The aggregate payoff for both producers is

$$(n-1)\delta p_G + (1-(n-1)\delta)p_O - c + n\delta p_G + (1-n\delta)p_O - c, \tag{12}$$

when they coordinate their planting decision. In absence of coordination, the aggregate payoff is

$$n\delta p_G + (1-n\delta)p_O - c + p_G. \tag{13}$$

As long as the coordination payoff (12) is greater than the aggregate payoff without coordination (13), the organic producer convinces the GM producer to switch to organic crops. This occurs

[7] In fact, as long as coordination costs are relatively small our findings are robust.

if

$$p_O - p_G > \frac{c}{1-(n-1)\delta}.$$

According to Proposition 1, at the equilibrium, if $n = \underline{n}_g = \overline{n}_o$, the following condition must be satisfied

$$p_O - p_G = \frac{c}{1-n\delta}.$$

Therefore, because the inequality

$$\frac{c}{1-n\delta} > \frac{c}{1-(n-1)\delta}$$

is always satisfied for any $n$, both organic and GM producers gain from coordination. This leads to more efficiency as organic producers will be gathered together, which will reduce the negative externalities due to contamination. Many of the coexistence variety Nash equilibria determined in the previous section are not efficient due to the negative externalities created by contamination. Therefore, coordination, by reducing the number of externalities, leads to more efficiency. We summarize this finding in the following Proposition.

**Proposition 2** *If $\underline{n}_g = \overline{n}_o$ and the organic producer with the maximum number of GM neighbors is next to the GM producer with the minimum number of GM neighbors, the equilibrium is not robust to coordinations of two producers. Therefore coordination among two producers can improve efficiency.*

The result of Proposition 2 still holds when $\underline{n}_g > \overline{n}_o$, but not for all the values of the parameters. Indeed, consider again that the organic producer with the maximum number of GM neighbors is located next to the GM producer with the minimum number of GM neighbors. In this case the aggregate payoff from coordination is

$$(\overline{n}_o - 1)\delta p_G + (1-(\overline{n}_o - 1)\delta)p_O - c + \underline{n}_g\delta p_G + (1-\underline{n}_g\delta)p_O - c,$$

whereas, absent any coordination, the aggregate payoff of the two producers would be

$$\overline{n}_o\delta p_G + (1-\overline{n}_o\delta)p_O - c + p_G.$$

Therefore, both organic and GM producers will be better off if the GM producer becomes an organic producer if

$$p_O - p_G \geq \frac{c}{1-(\underline{n}_g - 1)\delta}.$$

According to Proposition 1, an equilibrium with coexistence exists if condition (8) is satisfied. As

$$\frac{c}{1-(\underline{n}_g - 1)\delta} < \frac{c}{1-\underline{n}_g\delta}$$

is always satisfied, the coexistence equilibrium will not be robust to coordination if

$$\frac{c}{1-\underline{n}_g\delta} \geq p_O - p_G \geq \frac{c}{1-(\underline{n}_g - 1)\delta}.$$

To summarize, even though coordination among GM and organic producers eliminates coexistence variety choice Nash equilibrium, it leads to more efficiency as it reduces the negative externalities.

## 4.2 Linear model

In the linear (or circular) model where each producer has (at most) two neighbors, we have shown that coexistence between crop varieties exists if $\overline{n}_o \leq \underline{n}_g$. We now investigate the impact of a coalition of two producers on the equilibrium with coexistence. To do so, we consider that an equilibrium with coexistence exists with $\overline{n}_o \geq 1$ and $\underline{n}_g \leq 1$. In the case of the circle, the maximum number of GM neighbors that an organic producer can have is two, whereas the minimum number of neighbors that a GM producer can have is zero. However, if $\overline{n}_o = 2$, there is no coexistence equilibrium, therefore we must have $\overline{n}_o = 1$. On the other hand, if $\underline{n}_g = 0$, there is no equilibrium with coexistence either, therefore we must have $\underline{n}_g = 1$. Thus, $\overline{n}_o = \underline{n}_g$. From Proposition 2, because $\overline{n}_o = \underline{n}_g$ there is deviation from the equilibrium with coexistence as a coalition of two producers will always make them better off. Coordination leads to more efficiency as it eliminates the negative externalities.

We summarize these findings in the following Proposition.

**Proposition 3** *In the linear model, efficiency is restored with only a coalition of two producers.*

### 4.3 The grid model

We now consider coordination within the grid model where each producer has at most four neighbors. Because each organic producer can have more than two neighbors, coalitions of more than two producers must be considered as well.

We first consider coordination by coalitions of two producers. It is easy to show that islands are not robust to the deviation of coalitions of two producers. In islands of spatial configuration $B$ or $D$ in Figure 3 an organic producer located in the corner of the island is neighbor to two GM producers and two organic producers. Formally, there exists an organic producer $i$ such that $n_i^G = 2$. Producer $i$ is neighbor to a producer $j$ who is surrounded by three GM producers and therefore $n_j^G = 3$. If the organic producer $i$ convinces the GM producer $j$ to switch to organic crops, both producers could achieve together a total payoff of $p_O - \delta(p_O - p_G) - c + p_O - 3\delta(p_O - p_G) - c$ as producer $i$ will have only one GM neighbor. Both producers will form a coalition if their total payoff from coordination is higher than their aggregate payoff absent any coordination, $p_0 - 2\delta(p_O - p_G) - c + p_G$. Formally, the organic producer can convince the GM producer to switch to organic crops if $p_0 - 2\delta(p_O - p_G) - c > p_G$, which holds by the equilibrium conditions in Proposition 1 (otherwise the organic producer will plant GM seeds in equilibrium). Put differently, if the GM producer $j$ switches to organic crops he loses $p_G - (p_O - 3\delta(p_O - p_G) - c)$ but it increases the organic producer $i$'s payoff by $\delta(p_O - p_G)$. The increase of producer $i$'s payoff is higher than the loss incurred by producer $j$ which leads to the above inequality.

We consider further coordination by excluding islands from spatial configuration equilibrium in the grid. Namely, we consider only "borders" (see configuration $A$ on Figure 3) and "stripes" ($R$ and $S$ in Figure 5 are examples of stripes) of organic producers of any size.[8]

Insert Figure 5

Each GM producer who is the neighbor of an organic producer is also the neighbor of three

[8] We exclude the case of GM producers with two neighbor organic producers (i.e., a stripe of GM producers surrounded by two stripes of organic producers) because it is obviously not robust to the deviation of coalitions of size two.

GM producers, except those who are located at the border of the grid in $R$ who have only three neighbors, two being GM producers. Therefore $\underline{n}_g = 2$. Organic producers who are the more exposed to GM contamination have $\overline{n}_o = 1$ GM neighbors.

We first consider the deviation of the coalition formed by the organic producer $i$ located at the border of the grid and his only GM neighbor producer $j$ (see stripe $R$ in Figure 5). With this spatial configuration $n_j^G = \underline{n}_g = 2$. If the two producers produce organic crops, their total payoff is $p_O - c + p_0 - 2\delta(p_O - p_G) - c$ which is higher than their aggregate payoff absent any cooperation $p_O - \delta(p_O - p_G) - c + p_G$ if $p_O - \delta(p_O - p_G) - c \geq p_G$. This last inequality is also the equilibrium condition (see Proposition 1). Hence, the coexistence equilibrium is not robust to the deviation of coalitions of size two.

Lastly we examine the coordination of size bigger than two in grids *without* border such as stripe $S$ in Figure 5. This more abstract configuration can be thought as one in which stripes are unbounded.[9] In this case where $\overline{n}_o = 1$ and $\underline{n}_g = 3$, Proposition 1's equilibrium condition is

$$\frac{c}{1-3\delta} \geq p_O - p_G \geq \frac{c}{1-\delta}.$$

Graphically, this case corresponds to an organic producer located in the middle of stripe $R$ or $S$. This organic producer can convince his GM neighbor to switch to organic if $p_O - c + p_0 - 3\delta(p_O - p_G) - c > p_0 - \delta(p_O - p_G) - c + p_G$ which is equivalent to $p_O - p_G \geq c/(1-2\delta)$. Therefore, equilibria with coexistence with price difference $p_O - p_G \in [c/(1-2\delta), c/(1-3\delta)]$ are not robust to coordination of size two while those with stripes verifying $p_O - p_G \in [c/(1-\delta), c/(1-2\delta)]$ are. Yet the latter are not robust to coalition deviations of size four. To see this, suppose that the organic producer *and* one of his organic neighbor convince their respective GM neighbors to switch to organic crops. Then the coalition gain that they obtain, $2(p_O - c) + 2(p_O - 2\delta(p_O - p_G) - c)$, is higher than their aggregate payoff, $2(p_O - \delta(p_O - p_G) - c) + 2p_G$, if $p_O - p_G \geq c/(1-\delta)$ which holds in equilibrium. The stripe $R$ is therefore not robust to coordination of size four. This argument holds for any size of the stripe (e.g., with more than two GM producers) because it involves only producers at the border. Hence the negative externalities are eradicated and efficiency is restored when producers in the grid without borders form a coalition of size four.

[9] In a finite setting, such a configuration would be obtained when two concentric circular areas are such that the smaller circle receive organic crop while the outer ring receives GM crops.

Overall, we see that all equilibrium configurations involving coexistence are not robust to deviation of small coalitions of producers. The next result summarizes our findings in the grid case with and without borders.

**Proposition 4** *The coordination of several producers can eliminate spatial externalities (i.e., coexistence) in the following grid cases*

1. *Any island is not robust to coordination by two producers.*
2. *In a grid with borders, stripes and borders are not robust to coordination by two producers. A coordination with two producers eliminates spatial externalities.*
3. *In a grid without borders, coordination of four producers eliminates spatial externalities.*

This result shows that in the grid case with borders – a configuration close to many real spatial configurations – a coordination involving two producers will be enough to eliminate inefficiencies.

## 5 Conclusion

In this paper we have developed a spatial variety choice model in which farmers decide to produce either organic or GM crops. For an individual producer, this decision is strategic since it also depends on the decision of the other producers.

Because of contamination, the decisions to produce GM crops will have negative externalities on an organic producer. In this setting, we characterize the coexistence variety choice Nash equilibrium. Spatial externalities might preclude coexistence in equilibrium, even though we can describe situations in which there is coexistence. However, there exist many coexistence variety choice equilibria, some being more efficient than others. More efficient equilibria represent spatial configurations in which less organic producers are contaminated. By allowing producers to coordinate their production choice, we show that coexistence tends to disappear, which leads to more efficient outcomes. Indeed, less coexistence means that organic producers will suffer less from the negative externality due to contamination. Our findings suggest that whenever coexistence exists, by letting producers coordinate their production choice leads to more efficient situations. In other words, not all the situations will require some external intervention.

In this simple model, we have not been considering any regulation. We show that, even in absence of regulation, coordination can restore efficiency. In our setting, the introduction of regulatory tools favorable to organic producers (e.g., buffer zone) would probably reduce the cost $c$ and reduce the contamination parameter $\delta$. Therefore, following Proposition 1, for low values of the price of organic crops more coexistence will occur, whereas for high values of the organic price, there will be less coexistence. In fact, the constellation of parameters for which there exists an equilibrium as defined by equation (8) will change. Coordination between producers will also happen and restore efficiency as it reduces spatial externalities. Therefore, in our model, the introduction of regulation tools will not affect qualitatively our findings. In the spirit of Coase (1960), it would not affect the size of welfare achieved when producers coordinate their variety choice but rather the distribution of welfare among GM and organic (or conventional) variety producers.

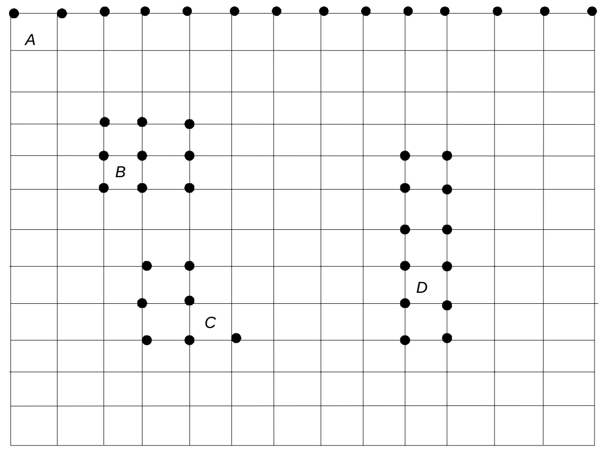


Figure 3: possible configurations in the grid model

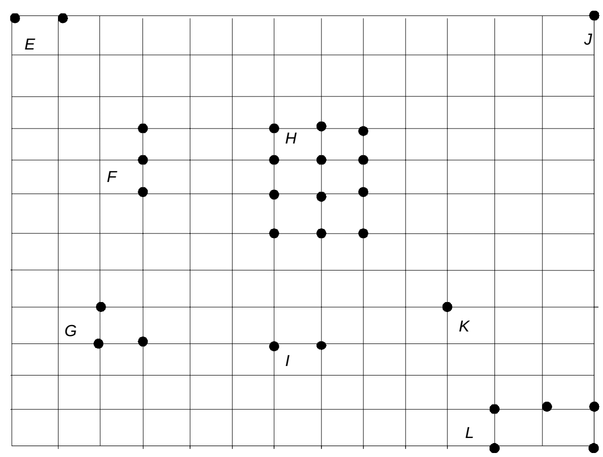


Figure 4: possible configurations in the grid model

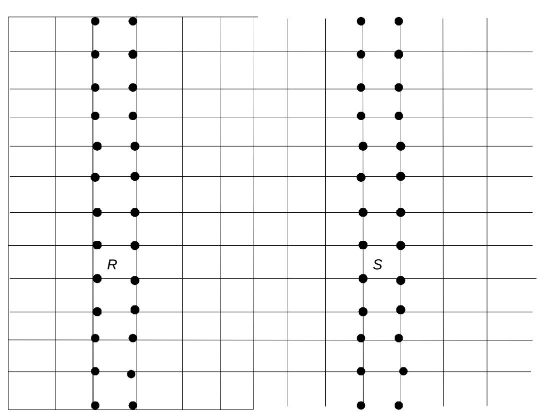


Figure 5: coordination among producers in the grid model

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