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Addressing Genetic Pollution from Pollen Drift on a Heterogeneous Landscape

Addressing Genetic Pollution from Pollen Drift on a Heterogeneous Landscape

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Agriculture Economics

by

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Bachelor degree in Agriculture, 2008

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This thesis is approved for recommendation to the Graduate Council.

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Abstract

Genetically modified (GM) crops are crops in which single or multiple genes have been introduced artificially in order to obtain certain characteristics that are difficult to obtain through conventional breeding. Even though farmers have the right to freely choose what types of crops to grow, pollen mediated gene flow from GM crops to non-GM crops can limit the possibility for crops to coexist on a same landscape, resulting in economic losses that depend on the institutional arrangements and the type of property rights in place. Although it is well known that spatial variability affects the degree of cross-contamination between GM and non-GM crops, no spatial analysis has been carried out to investigate how heterogeneity of landscapes influences the possibility for GM and non-GM crops to coexist. We aim with this research to analyze how spatial variability affects land allocation between GM and non-GM corn crops through a model composed of two parts: the first one simulates spatial units based on landscape criteria through Voronoi diagrams, and the second one reallocates the land between buffers, the GM and the non-GM crop based on cross-contamination and initial assignment of property rights. The model identifies coexistence clusters based on the deviation from an initial land allocation. We show that increasing spatial variability reduces the possibility of acceptable coexistence of crops and increases the economic losses. The economic impact from the assignment of property rights depends on the parameters that drive profitability differences (average market prices, yields and production costs). We show that buffer zones enforced to reduce cross-contamination result in less coexistence in heterogeneous spatial situations. We also elicit the economic value of unobserved factors that create a competitive advantage for certain farmers necessary for alternative crops to coexist on the same landscape.

Keywords: coexistence, GMOs, spatial heterogeneity, simulation, spatial optimization.

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1 Introduction.

Genetically modified (GM) crops are crops in which single or multiple genes have been introduced artificially in order to obtain certain characteristics that are difficult to reach through conventional breeding techniques. Even though farmers have the right to freely choose what types of crops to grow, pollen drift from one crop to another and post-harvest lack of segregation could result in adventitious presence of modified genes into conventional crops, affecting the ability of producers to freely choose the products that optimize their profitability. The purpose of this study is to analyze coexistence from pollen dispersal from an economic standpoint, with particular reference to the role that heterogeneous landscapes with regard to field size, shape and aggregation of the same field types have in determining the economic possibility for crops to coexist. Moreover, the study will focus on two alternative property right assignments (right for non-GM farmers to not be polluted and right for GM farmers to not prevent contamination). In particular, the main assumption of the study is that absolute and relative size and shape of fields affects the size of buffers needed to prevent cross-contamination to threshold levels[1]. Due to the fact that the creation of buffers represents an economic loss, the profitability of farmers varies across fields because buffers are made to meet the contamination thresholds. This profit variability depends on the amount of buffers needed, which is affected by space (position of fields, position of the source of contamination, size and shape of fields). The study aims to answer the following questions:

- What is the degree of heterogeneity in profitability of crops for the farmers that need to prevent contamination through creation of buffers in the case of homogeneous space?

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[1] The definition of threshold levels can vary on a country basis and is object of strong political more than technical debate due to the fact that it determines the types of measures required to prevent cross contamination and their resulting enforcement costs.

- How much does heterogeneity of space affect the heterogeneity in profitability of crops for the farmers that need to prevent cross-contamination when compared to a situation characterized by spatial homogeneity?
- Does the property right assignment have an impact on the overall effectiveness of the creation of buffers in terms of landscape net returns and profitability of crops?
- What is the effect of different dispersal functions and thresholds of contamination on buffer size??

The model to address this problem is composed of two parts: the first one generates spatial units through simulation, and the second one allocates the land to each spatial unit based on profitability of crops, the degree of contamination that occurs from GM to non-GM crops, and the maximum threshold of contamination allowed.

2 Background: GM crops, non-GM crops and coexistence.

2.1 Benefits and costs of GM crops.

The benefits of external genes introduced into crops include resistance to pests, insects, and herbicides (Mandel, 2003), lower environmental impacts because pesticide and herbicide application is reduced (Winston, 2009), improved shelf-life for products obtained from some GM crops, and enhanced nutritional characteristics (Frompovicz, 2006).

On the other hand, there are a number of concerns related to the introduction and use of GM crops. Among them are the risk of cross contamination between food and feed supply chains (Frompovicz, 2006), the lack of studies on the long-term effects of GM consumption for humans (Strauss, 2006), and the possibility that allergens could be transferred through pollen dispersal from the genetically modified plants to the conventional ones (Pusztai, 2001). Other concerns relate to the general loss of biodiversity (Repp, 1999) the creation of natural resistance among insects, weeds, and other pests (Frompovicz, 2006; Strauss, 2006), the possibility of cultural and social losses in terms of traditional systems of knowledge and cultural values and practices (Altieri & Nicholls, 2001), the monopolization of the seed market (Sharma, 2004), and the negative economic impacts of intellectual property rights that seed companies hold and that require pollutees to pay for being polluted in case of unintended cross-contamination (Heald & Smith, 2006).

2.2 Pollen drift.

Pollen drift in terms of agricultural crops can be defined as the unintentional transfer of pollen from one crop to another resulting in cross-contamination, i.e. the unintended presence of an external genome into the recipient (Cox, 2008). This is a major concern because it affects whether or not genetically modified and non-GM crops can coexist on the same landscape in terms of the economic harm that results from the unintended cross-contamination.

2.3 The problem of GM contamination.

Cross contamination between crops can happen both before and after harvest. In the first case cross-contamination is the result of pollen dispersal, whereas in the second case it arises from failure to segregate during or after harvesting. Since the introduction of biotechnological engineering techniques into crops and animals (1994 in the U.S. and in 1997 in Europe), more than 390 cases of contamination have been recorded around the world. Among them, 43 occurred in North America (USA and Canada), and 247 in Europe, ranging from imports of unauthorized GM products, to adventitious presence of non-authorized[1] GM seeds into either non-GM or authorized GM seeds or presence of authorized GM seeds into non-GM seeds, to cross contamination from authorized or non-authorized hybrids into non-GM or organic crops (GeneWatch UK & Greenpeace, 2014).

2.3.1 GM contamination in Europe.

As of today there are in Europe 49 GM organisms authorized and currently utilized for food and feed consumption. Two of them are allowed to be grown within the EU borders (corn hybrid MON 810® and GM starch potato Amflora®), and another variety of maize, Pioneer® 1507, is in

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[1] In order to be sold commercially, GM varieties in the US need to receive authorization from the Animal and Plant Inspection Service (APHIS), the US Department of Agriculture (USDA), the Food and Drug Administration (FDA) and the Environmental Protection Agency (EPA) based on the intended use. In the EU GM varieties need to be evaluated by the European Food Safety Authority (EFSA). Based on the evaluation, the European Commission issues a draft proposal for authorization or non-authorization. The Standing Committee on the Food Chain and Animal Health can either accept or pass the draft of proposal to the Council of Agricultural Ministers, which has three months to either accept or refuse the proposal with a qualified majority of votes. If no qualified majority is reached, the proposal is passed back to the European Commission that is required to adopt it.

the process of being authorized. Eight member states have prohibited GM cultivation in their territories (Austria, Bulgaria, Greece, Germany, Hungary, Italy, Luxembourg, and Poland). In 2012 MON 810® was mainly cultivated in Spain, Portugal, Czech Republic, Romania, and Slovakia, representing no more than 1.25% of the total maize grown in Europe (ISAA, 2012).

The Rapid Alert System for Food and Feed (RASFF) is the tool utilized by the national food and feed safety authorities together with the European Commission, EFSA (European Food Safety Authority), Norway, Liechtenstein, Iceland and Switzerland to report potential risks and share information and cross-border strategies (European Commission, 2015). Since 2002 the RASFF database reports that there have been 616 cases of introduction or attempt to introduce unauthorized GMOs into the European common market (RASFF, 2015), mostly from China and the United States. As far as cross-contamination of crops, unauthorized GM trials, and cultivation of unauthorized GM varieties, there is no global source of information. Most of the information on the subject comes from press releases of non-governmental organizations or from the media. According to these sources, the recorded cases of cross-contamination of crops in Europe since 1997 have been at least 37. In some of the cases the adventitious presence of GMOs was caused directly from cross-pollination, and was found either in the crops, food or feed, whereas in other cases the contamination resulted from impure seeds due to cross-contamination; some recorded cases of contamination were the result of non-authorized or incorrectly managed research trials, and others (feral population on the table) were the result of some GM plants which remained in the environment and become wild. There is no available research on the overall economic impact of the recorded cases. (Figure 1).

Figure 1 – Genetic modification contamination in Europe.

Year	Country	Recipient	Organism
1998	Germany	Crop	Corn
1999	Switzerland	Seed	Corn
2000	France	Seed	Oilseed rape - Canola
2000	France	Seed	Sugar beet
2000	Germany	Seed	Oilseed rape - Canola
2000	Germany	Seed	Sugar beet
2000	The Netherlands	Seed	Sugar beet
2000	UK	Seed	Oilseed rape - Canola
2000	UK	Seed	Sugar beet
2001	Austria	Seed	Corn
2001	France	Seed	Corn
2001	France	Seed	Oilseed rape - Canola
2001	France	Seed	Soybean
2002	France	Seed	Oilseed rape - Canola
2002	UK	Seed	Oilseed rape - Canola
2003	Italy	Seed	Corn
2003	Spain	Crop	Corn
2004	Croatia	Seed	Corn
2004	Greece	Seed	Corn
2005	Romania	Crop	Potatoes
2005	Romania	Seed	Soybean
2005	Romania	Crop	Plum
2005	Serbia	Seed	Soybean
2005	Spain	Crop	Corn
2005	Spain	Crop	Corn
2006	France	Seed	Corn
2006	Romania	Seed	Soybean
2006	Slovenia	Seed	Corn
2007	Germany	Seed	Oilseed rape - Canola
2007	Romania	Seed	Soybean
2008	UK	Seed	Oilseed rape - Canola
2010	Germany	Seed	Corn
2010	Ireland	Seed	Corn
2010	Sweden	Seed	Potatoes
2011	Hungary	Seed	Corn
2011	Switzerland	Feral population	Thale Cree
2012	Czech Republic	Food	Corn

Source: (GeneWatch UK & Greenpeace, 2014; RASFF, 2015)

2.3.2 GM Contamination in the US.

Unlike the European Union, the policy environment in the United States assumes positive property rights (right to...) for GM farmers instead of negative ones (freedom from…) for consumers, based on the rationale that GM crops have been determined to be “substantially equivalent” to non-GM crops (Conner, 2003). This has resulted in the absence of regulation for GM producers with regard to ways to prevent pollen spread, and in mandatory measures developed by the United States Department of Agriculture’s (USDA) National Organic Program (NOP) for organic farmers to self-protect against pollen spread from neighboring GM fields (GOP, 2015). Due to the institutionalized equivalence of GM and non-GM crops most of the recorded cases of cross-contamination in the US relate to either contamination of organic crops due to ineffective or inadequate enforcement of technical and spatial segregation measures, or to cross-contamination originating from illegal planting of varieties not yet approved by the USDA for growing. Since the introduction of GM crops at least 27 cases of cross-contamination have been recorded (Figure 2).

Figure 2 – List of recorded genetic modification contamination cases in the US.

Year	State	Recipient (7)	Organism	Source
1995	California	Seed - Feed	Cotton	(1)
1997	Various locations	Seed - Crop	Canola	(1)
1998	Hawaii	Food	Papaya	(1)
1998	Illinois	Seed - Crop	Corn	(1)
2001	North Carolina	Crop	Tobacco	(1)
2001	Various locations	Seed - Crop	Corn	(1)
2001	Various locations	Crop	Cotton	(1)
2002	Various locations	Crop	Corn - Soybeans	(1)
2003	n.d.	Field test	Corn	(1)
2004	Hawaii	Food	Papaya	(2)
2004	Ohio	Seed	Creeping Bentgrass	(1)
2004	California	Seed	Tomato	(1)
2005	North Carolina	Seed	Corn	(1)
2006	North Carolina	Field test	Corn	(1)
2006	South Carolina	Field test	Trees	(1)
2006	Hawaii	Experimental trials	Corn - Sugar cane	(3)
2007	Various locations	Field test	Creeping Bentgrass	(1)
2007	n.d.	n.d.	rice	(1)
2007	n.d.	Field test	Corn	(1)
2008	n.d.	Seed	Corn	(1)
2010	n.d.	Crop	Cotton	(1)
2010	North Dakota	Green spaces	Canola	(4)
2011	n.d.	Equipment	Rice	(1)
2011	n.d.	Seed	Corn	(1)
2013	Washington	Crop	Alfalfa	(5)
2013	Oregon	Crop	Wheat	(6)
2014	Washington	Field test	Apple trees	(1)

Sources: (1) APHIS - USDA, 2015; (2) Gonsalves, Lee, & Gonsalves, 2004; (3) Weiss, 2006; (4) Gillam, 2006; (5) USDA, 2013; (6) Black, 2010; (7) Seed: contamination originates from accidental seed mix; Crop, feed, food, field test, equipment: contamination found in the crop; feed, food, field test, and equipment. Experimental trials: contamination has been found in laboratory trials; Green spaces: contamination found in non-cultivated green spaces, such as roadsides; n.d.: no information.

2.3.3 The economics of GMOs versus non-GMOs: preferences, attitudes and acceptance.

Consumer acceptance of biogenetic engineering is controversial. Even though science seeks a global consensus (Collingridge & Reeve, 1986), the political acceptance of the science determines not only the perceived credibility of scientific knowledge but also the degree of consensus in the scientific world on risks and benefits of technology, in this case biotechnology (Montpetit, 2011). When there is no scientific consensus the political processes need to deal with uncertain risks, that is situations that are associated with a certain degree of risk that is difficult to quantify due to limited experience, complexity of causalities, and the heterogeneity of short and long term effects (van Asselt & Vos, 2008). An uncertain risk, as opposed to a quantifiable hazard, lacks the proof of a negative outcome, but this cannot dismantle the possibility that one might occur (Lang & Hallman, 2005). Lack of political acceptance and scientific consensus, uncertain risks related to biotechnologies, and the lack of knowledge force consumers to make economic decisions based on trust instead of knowledge (Lang & Hallman, 2005; Luhmann *et al.*, 1979).

The debate on the reasons underlying public acceptance or aversion towards GMOs is far from being over, and many of the scholars attribute negative attitudes to irrationality or low understanding (Marchant, 2001), whereas others claim that the degree of irrationality among the public toward biotechnological engineering is low (Marris, 2001). Regardless of the rationality or not of consumers' choice, the findings of a great number of economic studies on the demand for GM and non-GM crops summarized by a meta-analysis performed by Lusk *et al.* (2005) indicate that globally consumers value non-GM food on average 23% more than GM food. European consumers' willingness to pay (WTP) for non-GM food is 29% higher than the WTP of consumers in the United States. For both the EU and the U.S. general acceptance for GM meat products is lower than any other GM product, whereas oil obtained from GM vegetables is the most accepted type of GM-derived product (even though it does not contain GM genes). Second-generation GMOs, providing direct benefits for producers and consumers in terms of improved nutritional content or improved resistance to environmental threats, result in WTP values higher than any other GMOs for all study locations. The premium of non-GM food over GM food is half for the second generation GMOs compared to the first generation. The findings support the general reluctance of consumers toward the introduction of genetically modified organisms (see for a review on worldwide consumer acceptance of GMOs, Costa-Font *et al.* (2008). The acceptance for organic products is higher, and limited only by availability and price issues (Fotopoulos & Krystallis, 2002; Magnusson *et al.*, 2003).

From the GMO producer side, there is extensive literature investigating the socio-economic impact of GMOs in terms of costs and benefits for individual adopters. The meta-analysis carried out by Finger *et al.* (2011) focusing on 203 studies of insect resistant *bt*-corn and *bt*-cotton show that on average the adoption of GM technology can lead to higher yields, lower costs for insect control, and higher seed costs. There is a total increase of net benefits compared to the non-GM technology, even though on a global level no large yield effect is observed. Another important finding of the study on the specific case of insect-resistant crops is that the magnitude of the increased benefits depends greatly on the existing insect management practices in place in the countries of analysis. Greater benefits result from the adoption of the *bt* technology where less advanced pest management systems are in place. In countries characterized by well-established insect management systems, the benefits of GM adoption arise mostly from cost savings in chemicals, whereas for countries with less advanced agricultural practices the main driver for increased benefits is the reduced loss of yield from the GM adoption. Long term shifts of the supply and demand curves for seeds and chemicals, induced insect and weed resistances, increasing land rents, reduced output prices due to increasing adoption of the GM technology, and higher costs due to regulation were not part of the analysis by Finger *et al.* (2011).

Widespread adoption of GM crops could increase the global supply of the crops and lead to a reduction of commodity prices in a range varying from 2% to 4% (Zilberman, 2014), and even up to 10% in case of cotton (Zilberman *et al.*, 2010). Distributional effects are also a subject of research. Zilbermann (2014) reviews different studies that measure gains from the GM adoption for farmers ranging from 4% to 40%, for innovators from 10% to 70% (40% on average), and for consumers in the US from 6% to 60% while from 6% to 30% for the rest of the world. Quaim (2009) reviews a series of studies that through general equilibrium models calculate annual worldwide welfare gains from the introduction of GMOs ranging from 0.7 to 1.8 billion US $ for cotton, from 7 to 9.9 billion US $ for oilseed and corn, and from 2.0 to 2.5 billion US $ for rice.

There are many controversies that regard the economic impact of regulation on the adoption of GM technology. For this reason, limited consensus has been reached on the appropriate level of regulation to address cross-contamination and all other possible negative externalities. The regulatory system involves costs to test the potential bio-safety and food safety of GM crops, costs to prevent the commercialization of GMOs potentially harmful for people, for animals, or for the environment, and the costs of voluntary or mandatory information through labeling. Other regulatory costs are the result of regulation on agricultural practices and segregation mechanisms throughout the whole supply chain. Regulatory costs can also reduce the level of investments in innovation (Qaim, 2009). A review of the studies on the regulatory costs for biosafety performed by Bayer *et al.* (2010) shows that compliance costs range from US $100K to US $4M based on the country, trait, and the developer of the GM trait. Costs of approval in the US can range from $318K up to $12.5M[1]. The impact of identity preservation (IP) compliance rules can also be significant, with distributional impact depending on the assignment of property rights. Studies on IP costs show that costs are based on the regulated level of thresholds allowed in terms of prevention of excessive cross-contamination for meeting labeling standards (Bullock & Desquilbet, 2002). Desquilbet and Bullock (2009) analyze the economic consequences of IP in terms of who benefits and who loses from the maintenance of a dual market for GM and non-GM crops. Their findings are that in a bifurcated market there might be multiple equilibria in which those indifferent to GM might lose more than those averse to GM due to the introduction of GMOs in the market. The presence of those averse to GMOs does not necessarily result in a segregated market, and the presence of efficient GM suppliers does not necessarily result in the emergence of a GM market.

Identifying the size of the demand for non-GM food is complicated by the lack of official statistics, and data for the organic food market are often used as a proxy, even though that is likely to be an underestimation (Heald & Smith, 2006). An example of a segregated international non-GM market is the non-GM soybean contract offered by the Tokyo Grain Exchange[2]. However, there is an increasing demand for non-GM products in the food industry, in addition to consumers lobbying for legislators to introduce labeling to track the presence of GMOs in food.

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[1] Nominal values. There is no reference on the year the mentioned values are referring to.

[2] For a detailed analysis of the contract see e.g. Parcell (2001).

2.3.4 The economics of cross-contamination and genetic pollution.

Cross contamination is not an externality problem unless economic harm occurs as defined by a social institution[1] (Wesseler *et al.*, 2012). Institutional and social factors affecting the economics of co-existence include the definitions of GM, non-GM, and organic, what type of property rights are in place, who is entitled with property rights, what the collective-choice rules[2] are, and what type of governance structures[3] are in place. Freedom of action is a common principle in both the United States and Europe, whereas the precautionary principle is part of the European legislation only; this translates from the "how much harm is allowable?" approach in the US to the "how little harm is possible?" approach adopted by the European legislator (Evans-Agnew, 2004).

Pollen-mediated gene flow is an example of an externality where the assignment of property rights, transaction costs, and initial spatial configuration of GM and non-GM crops affect the adoption of pollen abatement strategies, the final spatial configuration of crops, and firm profits (Beckmann *et al.*, 2006). According to the precautionary principle, the property right system

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[1] Cross-contamination is a human-made definition and, as a biological phenomenon, it guarantees the very same existence of crops that are not self-pollinating, such as corn. As an example of the human nature of the definition of cross-contamination, contamination that occurs from a non-GM non organic crop to an organic crop does not, as of today, result in an economic harm.

[2] Collective choice rules are defined as "rules that are used by appropriators, their officials, or external authorities in making [operational] rules" (Ostrom, 1990). They are collocated between *operational rules,* which are daily decisions made by appropriators, and *constitutional rules,* which are the superior set of rules that affect who is entitled and creates the sets of rules under which the collective choice rules are established.

[3] A governance structure is defined as "a system of rules plus the instruments that serve to enforce the rules" (Furubotn & Richter, 1997). Governance structures at the collective-choice level include not only the sets of collective choice rules, but also the mechanisms of enforcement.

adopted in the European Union grants the right not to be polluted to non-GM farmers, whereas in the US the legal framework is not as well defined, and cross-contamination can be considered a case of trespass in some jurisdictions, but it can also result in strict liability due to a series of heterogeneous causes in other jurisdictions[1] (Flood, 2002). As stated by Coase (1960), regardless of the initial assignment of property rights, the final outcome (in this case the final allocation of land between GM and non-GM crops) will be efficient if there are no obstacles limiting the possibility for the parties to bargain and if perfect information is assumed. Assuming all Coasean obstacles are removed, there is no loss of economic welfare, but there are costs to reach this efficient outcome. The costs include the regulatory framework developed for hosting two existing markets of GM and non-GM crops, costs of "fencing", that is costs for implementing measures aimed at reducing the magnitude of pollen flow, and the costs of choosing one production system as opposed to the other. The extremely simplified system commonly assumed allows for a costless switch from one production system to another.

The value of coexistence on a specific landscape is the sum of the profits of GM and non-GM crops minus damages and the costs for preventing the damage. GM and non-GM rents are highly heterogeneous and their variability arises from the heterogeneity of the environment in which crops are grown. Even though premiums for GM and non-GM crops are substantially homogeneous, local variability in yield explains the relative competitive advantage on the same landscape that some groups of farmers can have in the production of respectively non-GM or

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[1] Possible liability factors are: the activity involves a high degree of risk, the harm will be great, reasonable care can eliminate the risk, the activity is matter of common usage, the activity is inappropriate to the place where it is carried on, the value of the activity for the community. The judiciary literature has identified the aforementioned factors on a jurisdiction and case-by-case basis.

GM crops (Demont *et al*., 2009); as an example, local variability in soil fertility could advantage a farmer that grows a non-GM crop because her farm is part of an area with higher content of organic matter than another in which the neighboring farmer grows the isogenic GM crop. For this reason the global value of coexistence on a landscape is higher than the value of uniform adoption of either GM or non-GM crops on the landscape (Beckmann & Wesseler, 2007). The damages that occur from pollen contamination depend on the social and bio-physical aspects of the landscape, e.g. the number of GM and non-GM farms on the landscape, type of crop, wind direction, form and size of fields. The institutional arrangements include property rights assignment, regulatory thresholds for allowed cross-contamination, ex-ante regulations and ex-post liabilities that affect the prevention efforts, and the costs of segregation occurring for the whole storage and processing chain (Wesseler *et al*., 2012). Benefits and costs of governance structures depend strongly on the definition of the thresholds for contamination that are the result of strong political debate. Lower threshold mean the likelihood of cross-contamination increases the gap between the private and the socially best outcomes (Beckmann & Wesseler, 2007). Other economic consequences arise from institutional arrangements concerning trade between countries and regulation of trade in terms of labeling, thresholds of GM contamination, varieties approved for consumption can have a significant impact on welfare (for a political-economic analysis of the impact and outcomes of the GMO Trade Agreement (GTA) part of the Transatlantic Trade and Investment Partnership (TTIP) see e.g. Shao *et al.* (2014).

Although it is well known that the initial spatial configuration of land affects the degree of cross-contamination between GM and non-GM crops (Weekes et al., 2007), no spatial analysis has been carried out to investigate how variability in field size, shape and aggregation of fields within farms influences the possibility for GM and non-GM crops to coexist. The purpose of this study is to elicit the economic consequences that farmers have to bear in order to avoid cross-contamination between GM and non-GM crops taking into account alternative property rights. To do so, we create through simulation a heterogeneous landscape in terms of sizes and shapes of fields and we reallocate land from an initial random allocation between a GM and a non-GM crop using an optimization model that simulates pollen dispersal dynamics. We can therefore elicit patterns of coexistence and economic losses that arise from spatial variability.

3 Literature review.

Since the introduction of GM crops on the market, pollen dispersal has been a main obstacle to guarantee the possibility for preventing farmers from freely choosing what type of crop to grow. The adventitious presence of genetic material from one crop in another is an externality problem because of the financial harm to producers that can no longer sell their crop in the desired market. Pollen drift is a spatial phenomenon, and therefore the economic consequences arising from cross-contamination of crops depend on the spatial configuration of the land used for agricultural purposes. Over the years the research on coexistence with a focus on spatial analysis has grown significantly. Munro (2008) creates a spatial optimization model in order to identify potential external effects based on patterns of planting, welfare losses in case of unregulated transgenic technology, and policy implications of coexistence regulations. The spatial analysis focuses on a rectangular-shaped spatial economy where only the non-GM and GM varieties of the same crop can be grown, and whose area is normalized to 1. Cross contamination between the GM variety and the non-GM one results in a shadow area representing the portion of space where cross-contamination occurs. Based on the value of the distance, different spatial configurations can be identified, and the paper focuses on the situation where the two varieties are separated by a single linear boundary across the width of the rectangular area. The spatial model solves for quantities of each variety. The main findings of the research are that the area planted with the GM variety determines a spatial externality that is not linear and whose magnitude is proportional to the square of the GM area. Moreover, the initial spatial configuration of the relative position between non-GM and GM can result in suboptimal outcomes that, due to excessive cross contamination, are not suitable for non-GM planting that are up to 3.7 times larger than the area not suitable in case of the spatially optimal distribution of

GM and non-GM crops. From a policy standpoint the study shows that market based tools for solving the externality can result in multiple unstable equilibria whose outcome is consumption efficiency, but not necessarily production efficiency. The study does not focus on alternative assignment of property rights and does not model the economics of mechanisms for self-protection for farmers.

Belcher *et al.* (2005) develop an agent based model in which macro-level characteristics such as speed or stability of GM crop expansion are simulated over a 50 year time frame using a cellular automaton assuming the institutional arrangement in which property rights are assigned to polluters. The agents are 100 square fields in a 10 by 10 grid with a field size that characterizes the average western Canadian landscape. The model aims at simulating the rate at which contamination expands over time and the final spatial outcomes, and it takes into account probabilities of cross-contamination as instrument for modeling the magnitude of the externality. The main finding is that the probability of cross-contamination affects the time in which the whole landscape becomes eventually contaminated in case of irreversibility of the contamination. In case of reversibility, spatial configurations that result in an uncontaminated landscape for over 50 years exist. From a policy standpoint the focus on the inter-temporal coexistence should be given to all elements positively influencing decontamination rates, such as agricultural practices. Perry (2002) develops a model focusing on separation distances (distances between fields used to create buffer zones) that represent the landscape as a square grid of 70 by 70 3 ha fields where only two crops can be grown (GM and non-GM). The purpose of the study is to identify the relative maximum proportion of the two types of crop that can coexist on the landscape based on varying separation distances and property rights assigned to pollutees. Among all scenarios simulated, the only one where coexistence is possible is one where the proportion of the non-GM land is 0.03% and separation distances are up to 3000m. In a scenario where 14% of fields are non-GM and in which separation distances currently applied in the United Kingdom are in place there would be very little coexistence reachable.

Ceddia *et al.* (2011) create a spatial profit maximization model in which the land is allocated between conventional oilseed rape, GM oilseed rape, wheat and buffer zones; pollen drift is simulated by using an empirical function and the spatial analysis focuses on a 100 ha landscape consisting of a 1000 by 1000 grid of 1 m^2 cells constituting 100 identical 1 ha fields. An aggregation index is defined to take into account spatial aggregation (neighboring cells that are part of the same field, and aggregation of fields by type) of crops of the same type, and alternative assignments of property rights are investigated. Through Monte Carlo simulation, the authors find that in the case of property rights assigned to GM farmers, non-GM growers will protect themselves creating buffers and will tend to create clusters of non-GM fields away from the GM ones. When property rights are assigned to non-GM farmers, there are mutual interdependences due to the GM land allocation and coordination decisions. The model identifies the first best option as the spatial aggregation of fields of the same type, and as second best option the creation of buffers. Höltl and Wurbs (2008) analyze GIS based field patterns in two rural districts in Brandenburg (Germany) in order to simulate coexistence scenarios based on different isolation distance regulations for three initial proportions of *bt*-corn cultivation relative to the overall agricultural land and property rights assigned to pollutees. The findings confirm that the variability in the feasible degree of coexistence on a landscape depends on size and number of fields, as well as the distribution patterns of non-GM fields and separation distances required for creating buffers.

Demont *et al.* (2009) use GIS analysis on an actual 100 km^2 landscape in the region of Selommes (France) to identify potential *shadows*, which are a measure of the opportunity costs that GM farmers need to bear in order to comply with ex-ante regulations to prevent cross-contamination of neighboring non-GM fields in the case where property rights are assigned to non-GM producers. Due to the relative heterogeneity of rents for GM and non-GM crops at the regional level as a consequence of regional differences in yields, the loss of rent for GM producers due to ex-ante regulation cannot be compensated by the rent resulting from the creation of buffer areas. That leads GM farmers to tend to convert the entire field into the second best option in terms of rent, and to the emergence of a potential domino effect that arises from the consecutive decision for the second best option adopted stepwise by all neighboring GM farmers. In their spatial simulation of the impact of communication between farmers and legal information requirements on coexistence, Breustedt *et al.* (2013) consider a landscape model composed of two 1600 ha areas in which the units are 1 ha squared cells that aggregate to create fields. The landscape model connects with a biophysical model that simulates cross-pollination and an economic model that maximizes net producer benefits based on three policy scenarios (first best potential solution, unilateral information requirements for GM producers and bilateral information requirements for both types of farmers). Due to cross contamination damages, the study shows that GM benefits do not necessarily increase linearly with increasing shares of GM crops on the landscape. It is also possible, in case of optimal and costless coordination, to almost entirely prevent cross contamination damages in spatial situations characterized by large plot sizes: this is because, when fields are harvested as units, there is a dilution effect due to the fact that more contaminated parts of the crop mix with less contaminated parts. In case of suboptimal coordination, unilateral information results in higher cross- contamination damages than when bilateral information requirements exist. Moreover, damages are always higher in case of smaller plot sizes for both types of information scenarios.

Cross-contamination damages are affected as shown by Weekes *et al.* (2007) by size of fields. In their study they find for example that to guarantee a cross-contamination not exceeding 0.5% in a situation of two squared fields sharing one edge, a separation distance of 11m is needed when the fields area is 50 by 50 m, whereas only 2 meters are required if the field size is 500 by 500 m.

As illustrated above, the size of fields, the share of arable land, and more generally, landscape structure, affect cross-pollination.

A disadvantage of most of the simulation models discussed above is that landscapes are assumed to be homogeneous, whereas the models based on actual landscapes are difficult to apply in their results to different geographical areas. None of the studies analyzes the impact of aggregation of fields within farms: although Ceddia *et al.* (2011) introduce an aggregation index for fields of the same type, the constraints in the allocation of land that come from spatial distribution and aggregation of plots within single farms operating on the landscape have not been modeled so far. The purpose of this research is to include into a simulation model some of the relevant criteria that characterize heterogeneity in landscapes in order to identify how much spatial variability of field size and shape across a landscape affects the possibility for GM and non-GM crops to coexist. Such a simulation model also allows for scenario analyses by modifying the degree of heterogeneity on the simulated landscape.

4 Methods.

The model is composed of two parts: the first one generates spatially variable fields shapes and sizes through simulations, and the second one allocates land among GM and non-GM corn, and a buffer crop of non-GM corn that separates the GM and non-GM corn for each field based on profit maximization.

4.1 Voronoi segmentation.

In order to simulate spatial variability, a two-dimensional Voronoi-based segmentation has been applied on a square 49 hectare area. A Voronoi diagram (Figure 3) is a geometrical construct defined by a set of randomly scattered points (seeds) on a landscape, each one of which generates a polygon based on the *nearest-neighbor* rule: each point is associated with a set of points identified as closer to the generating point than to any other point on the landscape (Aurenhammer, 1991). Each point on any edge between two polygons is equidistant to two points, each vertex is equidistant to at least three of the discrete points.

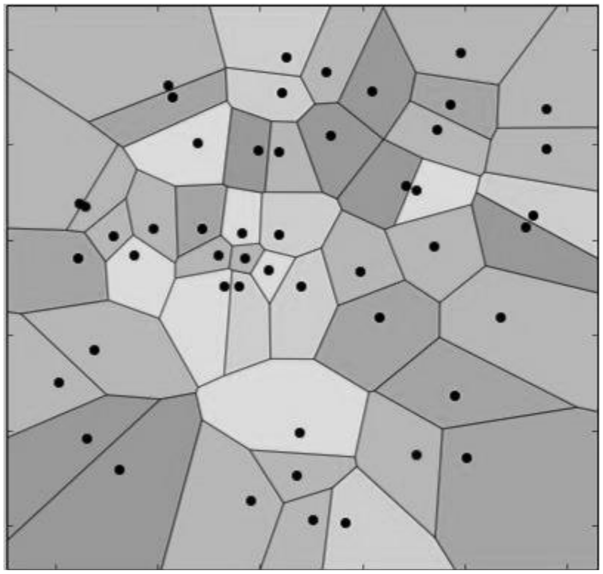

Figure 3 – Voronoi segmentation created from 50 seeds.

Each polygon created through the Voronoi segmentation represents an agricultural field in the simulated landscape. A repeated random assignment of spatial coordinates of the seeds on the landscape generates polygons that differ in size and shape (Figure 4).

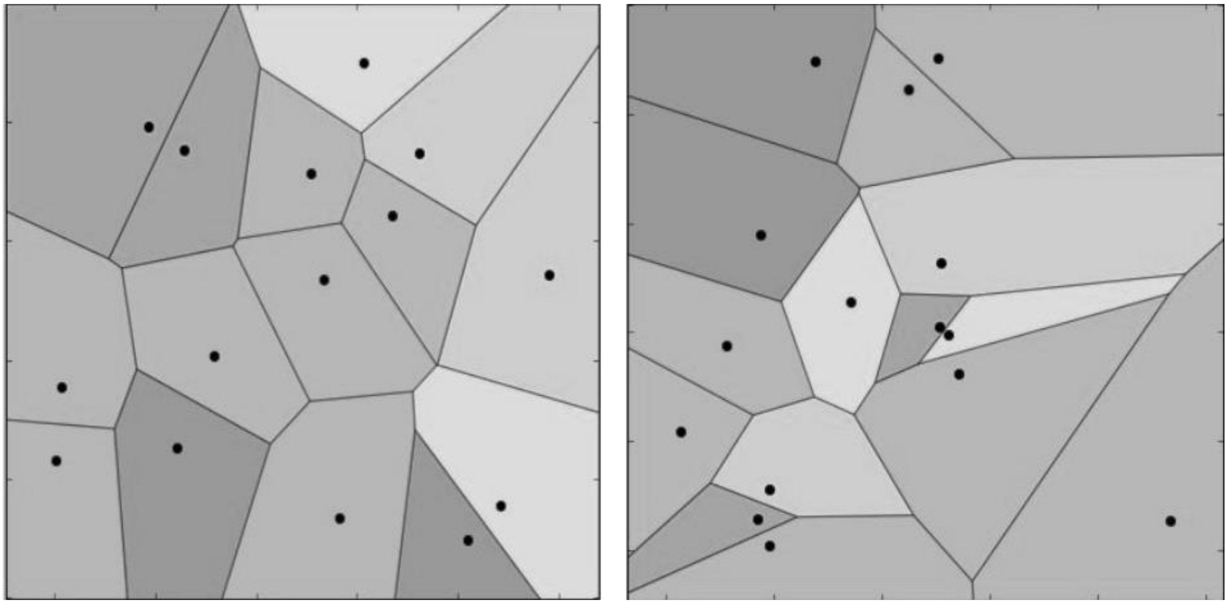

Figure 4 – Two landscapes originated from 15 randomly allocated seeds.

4.2 Spatial dynamic modeling.

The dynamics of cross-contamination and the transition of land types are modeled using a grid of equally sized square cells *i* that overlap the polygons simulated through from the chosen Voronoi configuration. Each polygon is composed of a subset of the grid of cells based on the amount of surface that the polygon and the square cells share (Figure 5). The polygons constrain the choice of whether GM or non-GM crop are grown within the cells.

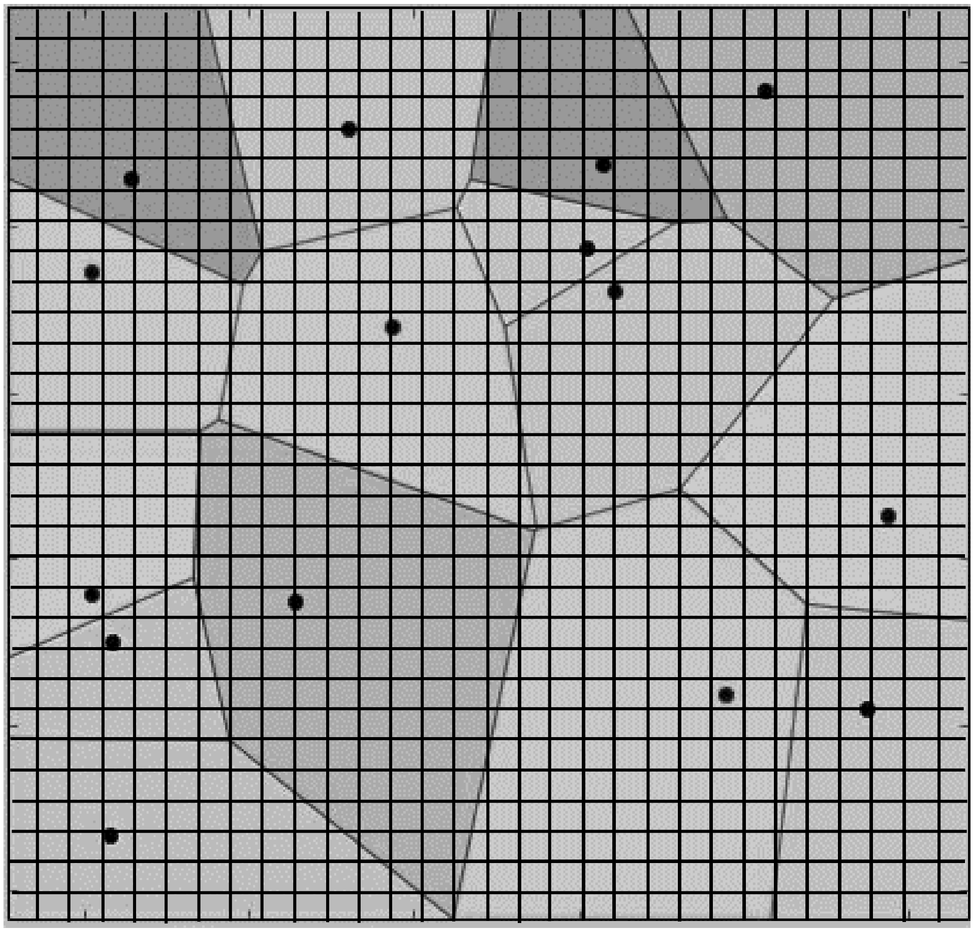

Figure 5 – Grid of square cells overlapping a Voronoi segmentation.

The model keeps track of the total amount of land in three alternative possible states *l* (GM corn, non-GM corn and buffer) for each cell *i*. Only one possible state is allowed for any cell *i*, and each of the three states is indicated through a binary variable (presence = 1, absence = 0). Buffer zones are created in order to prevent cross-contamination from GM corn to non-GM corn, and the buffers are non-GM corn, with higher production cost, that can only be sold in the lower price GM market due to cross-contamination.

Any land use *l* can be chosen so long as the cumulative amount of land L_{li} for each cell *i* at the end of the optimization equals the original amount of land L_{li0} for each cell i_0 (1).

$$\sum_{l=1}^{m}\sum_{i=1}^{n} L_{li} = \sum_{l=1}^{m}\sum_{i0=1}^{n} L_{li0} \qquad (1)$$

Cross contamination between GM-corn and non-GM corn for each cell *i* from all the surrounding cells *j* is modeled using a negative exponential function based on distance δ_{ij} between cells defined by Lavigne *et al*., (1998)

$$g_i(\delta) = \sum_{j=1}^{n} GM_j * K\frac{\alpha^2}{2\pi}e^{-\alpha\delta_{ij}} * NGM_i \qquad (2)$$

where $g_i(\delta)$ is the percentage of contamination in cell *i* from source cell *j*, GM_i, NGM_i, GM_j, and NGM_j are respectively the binary variables defining the land state (GM and non-GM) in cell *i* and *j*, and α and *K* are constants that modify the position and steepness of the negative exponential function. The first term of the multiplication accounts for the presence of the GM crop for all cells *j* surrounding cell *i*, the second term indicates the effect of distance from each cell *j* to cell *i* on the degree of contamination, and the third term accounts for the land state in cell *i*. If cell *i* is buffer or GM, the term will be 0, indicating that contamination only affects non-GM cells. This empirical model does not take into account factors such as weather patterns that could result in spatially variable magnitude of pollen dispersal.

Two alternative property right arrangements are considered: in the first case (property rights to GM producers), buffers can only be created on non-GM land. This simulates the case in which non-GM farmers need to protect themselves from contamination by GM pollen coming from neighboring farms. In the alternative case, buffers can only be created into GM land to simulate the case in which non-GM producers have the right not to be polluted, and therefore the responsibility for preventing cross-contamination lies with GM farmers (e.g. Europe).

Land is therefore constrained as in Equations (3) and (4):

1) Property rights to GM producers:

$$\sum_{i=1}^{n} GM_i = \sum_{i0=1}^{n} GM_{i0}$$

$$\sum_{i=1}^{n} NGM_i = \sum_{i0=1}^{n} NGM_{i0} - \sum_{i=1}^{n} B_i \qquad (3)$$

2) Property rights to non-GM producers:

$$\sum_{i=1}^{n} GM_i = \sum_{i0=1}^{n} GM_{i0} - \sum_{i=1}^{n} B_i$$

$$\sum_{i=1}^{n} NGM_i = \sum_{i0=1}^{n} NGM_{i0} \qquad (4)$$

Equation (3) indicates that the overall amount of GM land GM_i for each cell i at the end of the optimization has to be equal to the amount of GM land GM_{i0} for each cell i_0 at the beginning of the optimization. The final amount of non-GM land NGM_i for each cell i at the end of the optimization process is equal to the initial amount of non-GM land NGM_{i0} for each cell $_{i0}$ minus the amount of land reallocated into buffers B_i for avoiding cross-contamination to exceed the set threshold.

Equation (4) indicates that the overall amount of non-GM land NGM_i for each cell i at the end of the optimization has to be equal to the amount of non-GM land NGM_{i0} for each cell i_0 at the beginning of the optimization. The final amount of GM land GM_i for each cell i at the end of the optimization process is equal to the initial amount of GM land GM_{i0} for each cell $_{i0}$ minus the amount of land reallocated into buffers B_i for avoiding cross-contamination to exceed the set threshold.

Due to potential of cross-contamination, farmers will switch to buffer or GM based on whether or not the projected level of contamination g_i as a proportion of the entire field will exceed the regulatory threshold h_f of contamination defined as a proportion of each field f composed of subsets of cell fi based on the following rule (5):

$$\frac{\sum_{fi=1}^{m}\sum_{j=1}^{n} GM_j * K\frac{\alpha^2}{2\pi}e^{-\alpha\delta_{fij}} * NGM_{fi}}{\sum_{fi=1}^{m} NGM_{f1}} \leq h_f \qquad (5)$$

This means that the overall proportion of any non-GM field f contaminated cannot be higher than the threshold h_f. The overall proportion of a non-GM field contaminated is the arithmetic average of the proportion of the subset of cells f_i contaminated. In other words, all non-GM cells in each field f are harvested together. Buffers will be created on the edges between non-GM and GM fields for two reasons: to increase the distance between subsets of non-GM cells in one field and subsets of GM cells in the neighboring fields, and to reduce the overall contamination in a non-GM field by taking out non-GM harvest cells that are too contaminated for the non-GM field to meet the regulatory contamination threshold.

The producer profit motive guides the transitions that occur among land states. Farm profits of the crop production are maximized subject to the regulatory threshold of contamination, potentially allowing coexistence of genetically modified and conventional crops on the same landscape. The economic parameters needed to describe the profit objective are the price per ton of corn crop p_l, assuming that different markets for GM and non-GM corn exist, and that corn produced in buffer areas can only be sold in the GM corn market. The cost for producing one hectare of crop l is expressed by c_l. The yield for each crop is expressed with the parameter y_l in tons per hectare, and is assumed to depend on the production system l, where for simplicity buffers have the same yield as non-GM corn. The resulting objective function is shown in Equation (6)

$$\max_{GM_{fi},NGM_{fi},B_{fi}} := \sum_{i=1}^{m}\sum_{l=1}^{n}(p_l y_l - c_l) \text{ for all types of land} \qquad (6)$$

subject to the cross-contamination

(5), dynamics of land use (3), and the non-negativity constraints for areas of each land use and the initial condition of the variables defined as (7):

$$L_{li0} \geq 0;\ L_{li0} = 0 \qquad (7)$$

The optimization problem has a mixed integer non-linear form solved using the SCIP (Solving Constraint Integer Programs) algorithm. The non-linear constraints are present in Equation

(5) for the threshold of contamination in terms of the negative exponential dispersal function. Linear constraints are those associated with the land transitions. The SCIP algorithm is set to stop when the relative gap between the best estimate for the optimal solution and the best integer solution found is lower than 0.1%. This compromise to balance computational speed and precision of the solution explains slight deviations in terms of overall area from the initial to the final allocation of land states. The computational complexity encountered arises from the number of cells and the number of combination of distances between cells that the model needs to

account for in the solving process. Constraints in the position of specific cells (e.g. fields) simplify and speed the computational process, even though it has not been possible to simulate the switch of entire fields from one state to another due to the fact that the process would consequentially affect all other neighboring fields, resulting in the impossibility to solve the model in reasonable times. The optimizations have been performed with the Generalized Algebraic Modeling System (GAMS) 23.5.1.

4.3 Sensitivity analysis.

4.3.1 Sensitivity on unconstrained and homogeneous landscape.

Sensitivities on profitability track economic losses associated with the creation of buffers for either GM or non-GM farmers depending on the assignment of property rights. The first set of sensitivity analyses is performed on landscape characterized by size *s* and by the presence of only two fields (one GM and one non-GM) that vary in their relative size in *t* hectare steps. No constraints on the position and shape of the two fields are set, so to allow for the identification of the most efficient relative positions of the fields in terms of reduction of cross-contamination. For the GM and no-GM property right arrangements two profitability levels are analyzed at the baseline threshold of contamination and with the baseline dispersal function.

4.3.2 Sensitivity on relative profitability between GM, non-GM and buffers on a heterogeneous landscape.

For this set of sensitivities a spatial unit randomly selected and composed of 15 heterogeneous fields is considered and the profitability of each field is computed to study how the final the ratio between buffer and the planted GM or non-GM crop in each field depends on the position of the field on the landscape, land use for the neighboring fields, and size of each field.

Two sets of sensitivities have been conducted with regard to the farmers with the property rights:

1) Property rights to GM farmers: GM land is fixed, non-GM land can switch into buffers, and non-GM is more or less profitable in comparison to GM land in 5% steps (-15%, -10%, -5%, 0%, +5%, +10%, +15%, +20%, +25%, +30%).

2) Property rights to non-GM farmers: non-GM land is fixed, GM land can switch into buffers, and GM is more or less profitable in comparison to non-GM land in 5% steps (-15%, -10%, -5%, 0%, +5%, +10%, +15%, +20%, +25%, +30%).

Profitability of buffers depends on both GM prices and non-GM costs and yields, due to the fact that buffers are constructed with the characteristics of the non-GM crop in terms of agricultural production practices yields and production costs, but need to be sold into the GM market as consequence of cross contamination.

In the case in which non-GM producers have the right not to be polluted, the variation in relative profitability for the GM to the non-GM crop also results in a variation in profitability for buffers because of the increase in the market price for buffers. The model has been set up so that the maximum profitability for buffers cannot exceed the profitability for the non-GM crop. In the opposite property right scenario, what varies is the non-GM net returns, meaning that the relative profitability between GM and the buffer also changes. The model has been set up so that the relative profitability between non-GM and the buffer remains constant (buffer randomly selected to be 30% less profitable than non-GM, so to result in a significant economic loss[9]). Due to the way in which buffers are constructed and the fact that the buffer profitability varies based on which crop varies its profitability for the sensitivity analyses, the comparison between the

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[9] For simulation purposes we fix the gap in profitability between the buffer and the non-GM crop. By doing so, we allow to identify only the spatial components that determine the variation in buffer enforcement costs. We therefore reason in terms of flexible coexistence as defined by Demont *et al.* (2009). The random selection of a 30% gap is only for sake of the simulation, and does not represent any real case scenario, given the fact that segregated institutionalized markets for a GM or the alternative non-GM non-organic crop do not exist yet. Since enforcing buffers represents an economic loss, the profit maximizing model will minimize the amount of buffer subject to the specified threshold of contamination.

sensitivities performed under alternative property right assignments cannot be done. A further sensitivity analysis will allow for directly comparing alternative property rights.

4.3.3 Sensitivity on regulatory thresholds of contamination on a heterogeneous landscape.

Thresholds of contamination directly affect the amount of land that is needed to create effective buffers. Less stringent thresholds result in less land allocated for buffers, and therefore different levels for thresholds of contamination also directly affect returns for each field on the landscape. Along with the scenarios of relative profitability between GM and non-GM as indicated in Figure 11 and Figure 12, sensitivities have been performed with the following threshold levels: 5%, 2%, 1%, 0.9%, 0.5%, 0.25%, 0.1% of maximum contamination permitted to still classify a crop for the market as non-GM. The value of 0.9% is the baseline since it is the current legislative threshold of contamination in the European Union, the other values have been randomly selected to represent a possible range of contamination thresholds both more and less stringent than the current European framework, in order to have an indication on the effect of a possible relaxation or tightening of the current regulation under alternative property rights. Due to the fact that the study specifically aims at analyzing the coexistence between GM and non-GM non-organic crops, the threshold of 0% contamination has not been considered in the sensitivity sets. The threshold values higher than 0.9% have been selected as in Everson and Santaniello (2006).

4.3.4 Sensitivity on dispersal functions on a heterogeneous landscape.

The magnitude of pollen dispersal directly affects the size of buffers and economic returns. A sensitivity analysis has been carried out modifying the parameter K of the dispersal function along with the relative profitability between GM and non-GM as indicated in Figure 11 and Figure 12. The values randomly selected and used for K are 150, 300, 455, 600, 750 and 900, to represent a range that could represent crops characterized by having pollen with lower or higher mobility.

4.3.5 Sensitivity on prices, yields and production costs.

The dependence of buffers on non-GM production costs and yields and GM market prices makes the comparison of different profitability scenarios under alternative property rights impossible. For this reason an additional set of sensitivities has been conducted. Two profitability scenarios have been analyzed (respectively GM and non-GM net returns 10% higher than the baseline), as result of the individual variation in, respectively, GM and non-GM prices, yields and production costs. Although some of the assumptions might not likely happen in reality (for instance GM farmers adopting the same agricultural non-GM technique for buffers, from pest and weed control to varietal choice), the importance of this group of sensitivities lies in the fact that alternative property right assignments might result in differential economic losses for the creation of buffers based on the specific parameter (yield, price or production cost) that might vary to determine a difference in GM and non-GM profitability.

5 Data.

Two different sets of data have been created and used in order to perform the different sensitivity analyses indicated above. The common elements of the baselines for both sets of sensitivities are described in Figure 6.

Figure 6 - Parameters defining the spatial baseline of analysis.

Parameter	Data
Cell side length [m]	25
Cell size [m^2]	625
Dispersal parameter K	455
Dispersal parameter α	0.125
Treshold of contamination [%]	0.9

A cell side of 25 meters has been chosen to balance computational complexity and landscape resolution. Given that most of the regulation adopted to guarantee coexistence in the EU requires buffers that are 50 meters wide, a 25 meter landscape resolution allows representation of the magnitude of cross-pollination and the creation of buffers in an adequate way keeping manageable the number of iterations needed for the optimization. The functional form of the dispersal curve has been taken from Lavigne *et al*. (1998) and its parameter *K* has been modified so to have unobserved contamination at a distance of 100m from the contamination source, 100% in the first meter from the source, and a drop from 100% to 3% contamination in the first 30 meters. This modified dispersal function describes a type of pollen dispersal that could be attributed to a cross-pollinating crop such as corn[10]. The threshold of contamination used in the baseline reflects the legislation currently adopted by the European Union.

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[10] The dispersal function described by a coefficient $K = 1$ and $\alpha = 0.375$ has been used by Lavigne (1998) to model pollen dispersal of oilseed rape.

The profitability baseline for the GM, non-GM and buffer crops and for both sets of sensitivity analyses is shown in Figure 7.

Figure 7. Prices, yields and costs for each crop in the baseline.

	Price [$/t]	Yield [t/ha]	Cost [$/ha]	Profits [$/ha]
gm	271.25	11	1498.78	1484.97
nogm	271.25	11	1498.78	1484.97
buff	271.25	11	1498.78	1484.97

The values for prices, yields and costs were obtained from the 2014 Crop Production Budgets for Farm Planning (University of Arkansas Division Of Agriculture Research and Extension, 2013)[11]. The baseline for profitability considers all types of the crop equally profitable, meaning there is no economic incentive to switch from one production system to another, and that cross-contamination does not result in any economic damage. This is a starting point to compare economic outcomes for the alternative property right arrangements when the relative profitability between production systems varies.

5.1 Homogeneous and unconstrained landscape.

The baseline for the unconstrained type of landscape (Figure 8) is a square grid of 225 cells that constitute only 2 fields, one GM and the other non-GM. The shape and the position of the two fields is not constrained in space, which means that the model will create the two fields based on the two subsets of cells that minimize cross-contamination changing their position in space and their shapes. Due to the high computational complexity (the optimization process has no

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[11] The average market prices for corn vary on a state-by-state level in the U.S. and on a national level in the E.U. As of today, there is no aggregation of corn market prices at the EU 28, EU 27, EU 18 or EU 17 as it happens for other commodities. For the sake of the modeling exercise, it is important to have a uniform baseline. The Arkansas Crop Production Budget 2014 has been used as data source in this study for its thoroughness in eliciting all production costs.

constraints regarding the initial position of cells with the alternative land states) the landscape size has been limited to only 14.06 hectares. There is still the possibility to have economic losses for the landscape arrangement that maximizes economic efficiency where there is perfect mobility of the source and the recipient of contamination. This first unconstrained model does not represent a realistic situation, but its importance lies in the fact that it allows to identify a reference in terms of the magnitude of the economic losses and the percentage of land allocated into buffers when the most efficient spatial allocation of land is reached.

Figure 8. Parameters defining the homogeneous and unconstrained landscape

Parameter	Data
Number of cells *s*	225
Total surface *t* (ha)	14.06
Number of fields	2
Number of GM fields	1
Number of no-GM fields	1

5.2 Heterogeneous landscape analysis.

The analysis of coexistence in the case of spatial heterogeneity has been carried out on a square 900 cell grid whose area is 56.25 hectares[12]. The size has been selected in order to balance computational complexity while still being able to represent basic spatial features. The particular landscape chosen for the analysis as well as the position of GM versus non-GM fields comes

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[12] The average farm size in the European Union is about 15 hectares (European Commission, 26 June 2013). In comparison, the average U.S. farm size is about 180 hectares. A size of 56 hectares allow to represent a spatial situation in which 3 average E.U. farms coexist. A larger landscape would increase computational complexity significantly. Although information on the average size of fields is not available in public databases, a landscape structure with fields smaller than 10 hectares as the one introduced through the particular Voronoi diagram analyzed could represent for instance the Italian landscape patterns (JRC - European Commission, 2008).

from a randomly selected Voronoi diagram. Figure 9 shows the parameters that define the initial spatial configuration used as the baseline of the analysis.

Figure 9. Parameters defining the heterogeneous landscape.

Parameter	Data
Number of cells	900
Total surface (ha)	56.25
Number of fields	15
Number of GM fields	8
GM area [%]	55.1%
Number of no-GM fields	7
no-GM area [%]	44.9%

Figure 10 shows the geometric representation of the baseline landscape and the spatial allocation of GM fields and non-GM fields (white and dotted polygons respectively). Fields are numbered and area ranges from 1.00 hectare (field 7) to 7.56 hectares (field 14). The average size of fields is 3.75 hectares. Each field is cultivated by a different farmer.

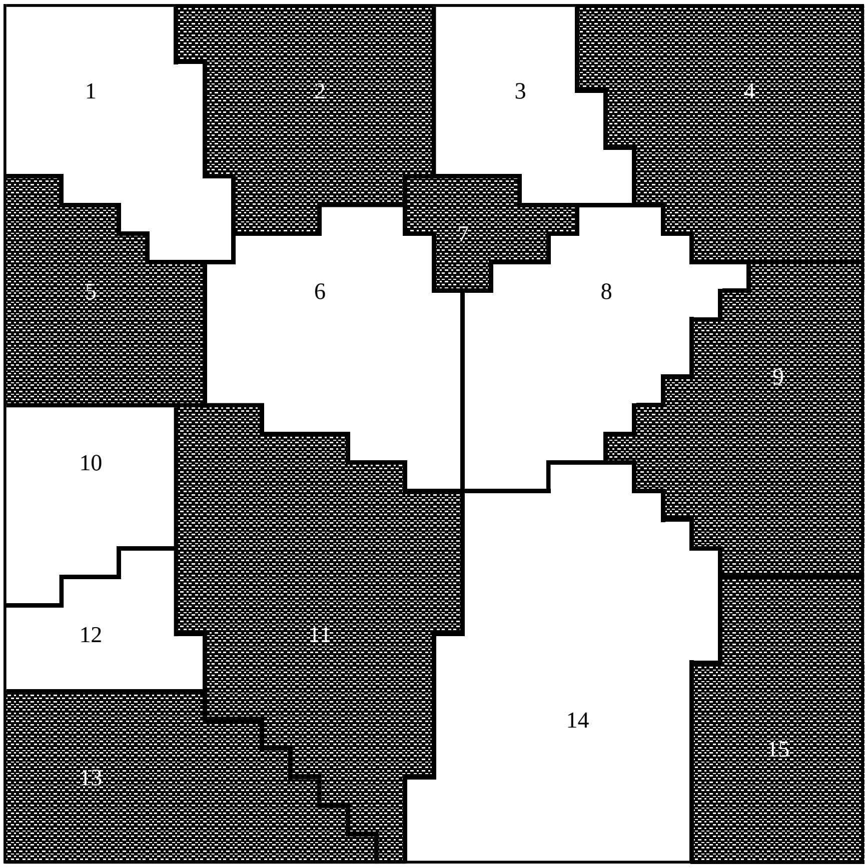

Figure 10. Spatial representation of fields originated from the Voronoi segmentation for the baseline landscape.

Figure 11 and Figure 12 show the datasets for the sensitivities on relative net returns among GM, non-GM, and buffers for both property right assignments. Buffers are constructed to have GM market prices and non-GM production costs and yields. As a result of changing GM or non-GM profitability, buffer net returns vary as well. For the situation in which GM producers are entitled with property rights buffers are set to be always 30% less profitable than non-GM, whereas for the alternative property right assignment profitability for buffers is constrained to be always lower than non-GM profitability[13].

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[13] Due to the fact that the increase in GM market prices also results in an increase in the buffer market prices, it is not realistic to set the profitability of buffers to be always 30% lower than the non-GM profitability, and it is expected that increasing profitability for the GM crop will also

Figure 11. Net returns for GM, non-GM and buffers. Property rights to GM farmers.

	non-GM and buffer net returns as compared to fixed GM net returns. [$/ha]									
	-15%	-10%	-5%	0%	5%	10%	15%	20%	25%	30%
gm	1485.0	1485.0	1485.0	1485.0	1485.0	1485.0	1485.0	1485.0	1485.0	1485.0
nogm	1262.2	1336.5	1410.7	1485.0	1559.2	1633.5	1707.7	1782.0	1856.2	1930.5
buff	883.6	935.5	987.5	1485.0	1091.5	1143.4	1195.4	1247.4	1299.3	1351.3

Figure 12. Net returns for GM, non-GM and buffers. Property rights to non-GM farmers.

	GM and buffer net returns as compared to fixed non-GM net returns. [$/ha]									
	-15%	-10%	-5%	0%	5%	10%	15%	20%	25%	30%
gm	1262.2	1336.5	1410.7	1485.0	1559.2	1633.5	1707.7	1782.0	1856.2	1930.5
nogm	1485.0	1485.0	1485.0	1485.0	1485.0	1485.0	1485.0	1485.0	1485.0	1485.0
buff	1039.5	1070.4	994.6	1485.0	1053.3	1082.4	1111.4	1140.2	1168.8	1197.3

5.3 Heterogeneous yields, prices and production costs.

The dataset for the two profitability scenarios analyzed in the last set of sensitivity analyses is shown in Figure 13 (both in terms of prices, yields and production costs, and landscape configuration). All combinations of prices, yields and production costs result in GM 10% more profitable than non-GM, or non-GM 10% more profitable than GM, with reference to the baseline for the heterogeneous landscape both in terms of prices, yields and production costs, and landscape configuration.

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result in an increased profitability for buffers. However, to prevent incentives to switch production systems from non-GM to buffers, the values for the buffer profitability have been constrained to be always lower than the non-GM ones.

Figure 13. Prices, yields and production costs for GM, non-GM and buffers for the two profitability scenarios analyzed.

Scenario		Price [$/t]	Yield [t/ha]	Cost [$/ha]	Profits [$/ha]
no-GM +10%	gm	271.25	11.00	1498.78	1484.97
	nogm	271.25	11.60	1498.78	1648.66
	buff	271.25	11.60	1498.78	1648.66
	gm	271.25	11.00	1498.78	1484.97
	nogm	271.25	11.00	1335.09	1648.66
	buff	271.25	11.00	1335.09	1648.66
	gm	271.25	11.00	1498.78	1484.97
	nogm	286.13	11.00	1498.78	1648.66
	buff	271.25	11.00	1498.78	1484.97
GM +10%	gm	271.25	11.60	1498.78	1648.66
	nogm	271.25	11.00	1498.78	1484.97
	buff	271.25	11.00	1498.78	1484.97
	gm	271.25	11.00	1335.09	1648.66
	nogm	271.25	11.00	1498.78	1484.97
	buff	271.25	11.00	1498.78	1484.97
	gm	286.13	11.00	1498.78	1648.66
	nogm	271.25	11.00	1498.78	1484.97
	buff	286.13	11.00	1498.78	1648.66

6 Results.

A central assumption of this study is that the value of coexistence on a landscape is higher than the value of the uniform adoption of the GM or the non-GM crop (Beckmann & Wesseler, 2007). There are a number of unobservable elements that contribute to spatial heterogeneity. Among them the following can be listed: variability in soil fertility, depth and permeability, land exposure, availability of water, amount of organic matter, carbon to nitrogen ratio, variability in soil acidity, types of crops that have been grown previously and agricultural practices. The effect of all these variables is a high degree of heterogeneity in the profitability of crops that could result in farmers having a local competitive advantage in comparison to their neighbors even in case they grow the crop that is less profitable on average terms. To observe the less profitable crop grown, and thus have coexistence on the landscape, the unobserved competitive advantage must be at least equal to the gap between the most profitable and the least profitable crop. The required magnitude of this unobserved competitive advantage can be inferred from the optimization model by forcing crops to coexist.

6.1 Sensitivity on unconstrained and homogeneous landscape.

6.1.1 Property rights to GM producers.

Figure 14 shows the amount of the net economic returns at the landscape level and the amounts of buffer needed for the non-GM portion of the landscape to be contaminated below the 0.9% threshold. Represented in the graph are all the intermediate situations between a landscape grown with only the GM crop, or only the non-GM crop. It can be observed that the percentage of buffer varies from a minimum of 0% (in case of no coexistence in place) to a maximum of 7.8% of the entire landscape. The situation in which the amount of GM crop equals the amount of non-GM crop (maximum coexistence), the buffer needed to prevent cross-contamination to the threshold level is around 6% of the whole landscape surface. The amount of buffers starts to decline when the GM crop covers around 75% of the landscape due to increasing saturation: The reduction in the surface of the non-GM crop results also in a reduction on the length of the edge delimiting the two crops, which translates into a decrease in the surface needed to reduce contamination. The non-GM crop cannot be grown on the landscape when the GM crop covers about 93% of the available surface. The amount of buffer needed to prevent contamination is unrelated to the profitability levels of the crops, as expected, and only depends on the specific maximum level of contamination allowed.

With regard to landscape net returns, it can be seen that when non-GM profitability is 10% higher than GM an increase in the GM surface, as expected, determines a reduction in net returns whose maximum value is little above $3000. When the maximum degree of coexistence is observed, net returns for the landscape are about $2000 below the net returns in the case of full adoption of the non-GM crop.

When non-GM profitability is 10% lower than GM profitability, the economic value of the crops on the landscape varies from about $27k to about $30k; when the maximum degree of coexistence is observed, the value of both crops on the landscape is about $1900 lower than in the case of full adoption of the GM crop on the entire landscape.

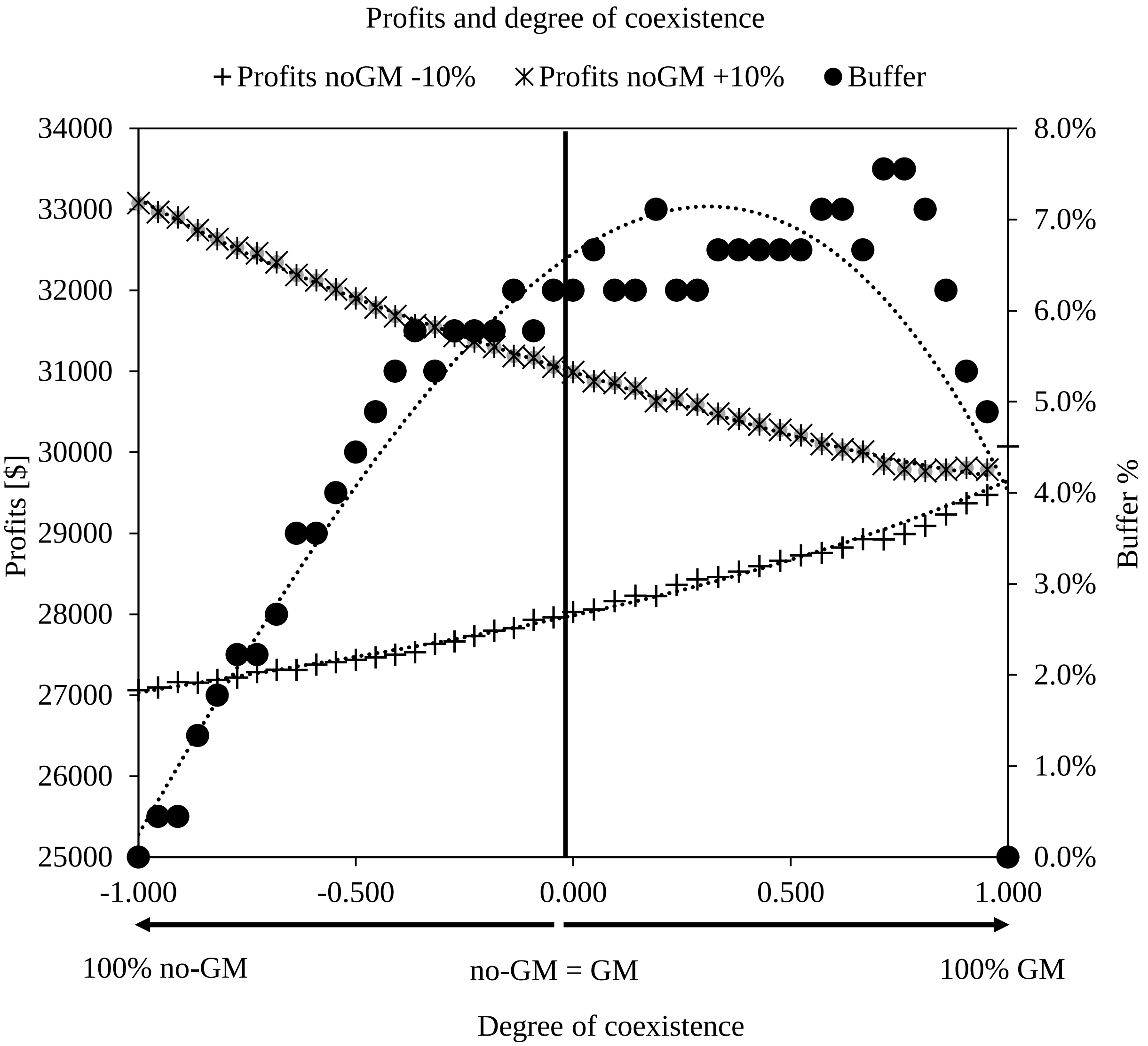

Figure 14. Amount of buffer and landscape economic returns for +10% and -10% non-GM profitability compared to GM.

With respect to profitability of the two crops, it can be seen in Figure 15 that the cost per hectare that non-GM producers need to bear in order to create buffers is variable depending on the GM area on the landscape and the relative position of the GM and non-GM sets of cells, and its maximum value is about $340/hectare. When the non-GM crop is 10% more profitable than the GM crop, there is an economic incentive to grow the non-GM crop up until the GM area equals around 11 hectares. For bigger GM areas the higher non-GM profitability does not allow for covering the costs of creating buffers. In the -10% profitability scenario for the non-GM crop, when coexistence is observed the unobserved variability that gives non-GM producers a competitive advantage in case coexistence should vary from around 150$/ha to about 360$/ha depending on the amount of GM land on the landscape.

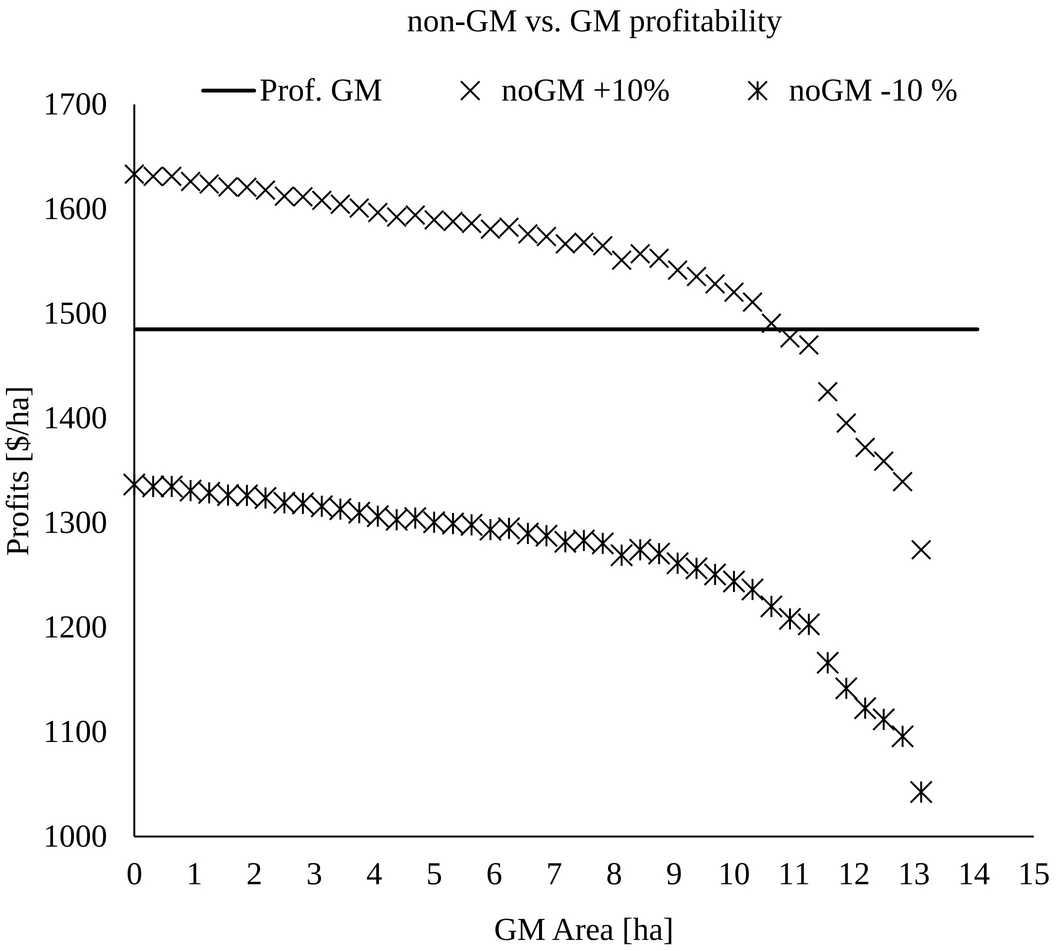

Figure 15. +10% and -10% non-GM profitability compared to GM.

6.1.2 Property rights to non-GM producers.

Figure 16 illustrates buffer areas in relation to the amount of coexistence between the GM and the non-GM crop on the landscape, and the net returns at the landscape level when the GM crop is 10% less or more profitable than the non-GM crop. The amount of buffer needed for avoiding contamination in measurements greater than the 0.9% threshold is not influenced by either the property right assignment or the profitability levels of GM and non-GM crops. The model minimizes the amount of buffers by reason of minimizing the economic losses that buffers entail. Since the profitability of buffers is always modeled as lower than both the GM and the non-GM crop, buffers will always be minimized.

As for the economic returns at the landscape level, it can be observed that they vary from a value of around 30k$ (100% no-GM) to a maximum of a little under 33k$ (100% GM in case of GM 10% more profitable than non-GM), and to a minimum of about 26.9k$ (100% GM in case of GM 10% less profitable than non-GM). AS for the alternative assignment of property rights, a 6% buffer is needed for guaranteeing the maximum degree of coexistence. The landscape net returns when the maximum degree of coexistence is observed (GM area = non-GM area) vary from a little above 28k$ to a little below 31k$ based on the relative profitability between the GM and the non-GM crop.

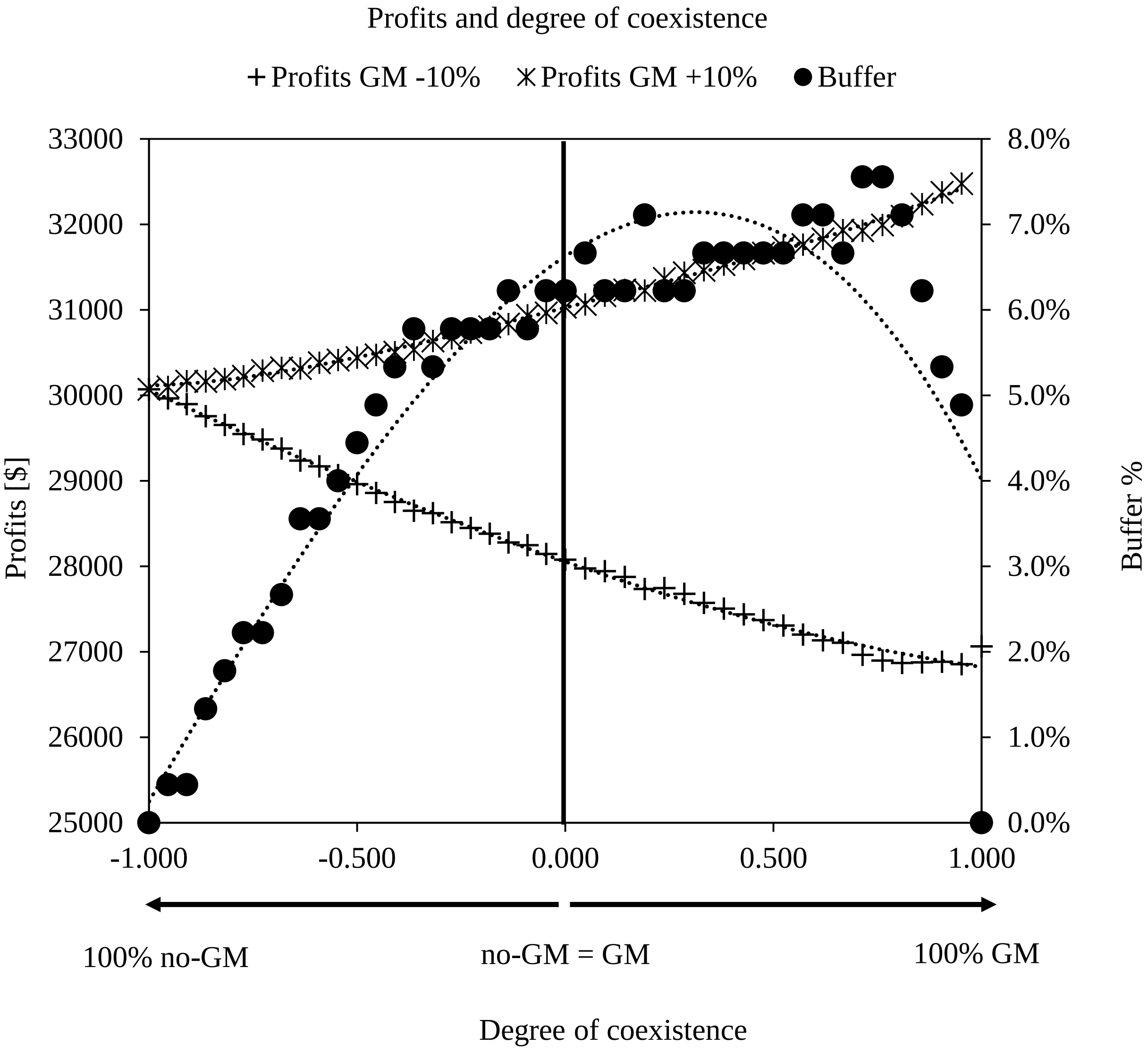

Figure 16. Amount of buffer and landscape economic returns for +10% and -10% GM profitability compared to non-GM.

Figure 17 shows per hectare net returns of the GM crop in comparison to the non-GM crop taking into account the costs for meeting the 0.9% contamination threshold and as a function of the GM area on the landscape. Since GM producers have to bear the costs of preventing contamination and buffers vary as the GM area varies, GM profitability also changes, whereas the non-GM profitability remains constant. It can be observed that GM profitability increases as the GM area increases, and the magnitude of the increase is about $60/ha in the case where GM is 10% more profitable than non-GM, and about $30/ha in the case where GM is 10% less profitable than non-GM. In the case where coexistence is observed and GM is 10% more profitable than non-GM, non-GM producers have a competitive unobserved advantage that varies from $20/ha to about $110/ha based on the amount of the GM crop on the landscape. On the other hand, when GM is 10% less profitable than non-GM and coexistence is observed, GM farmers have a competitive advantage that varies from $180 to $200/ha based on the amount of GM land, the more GM land on the landscape the less the competitive advantage.

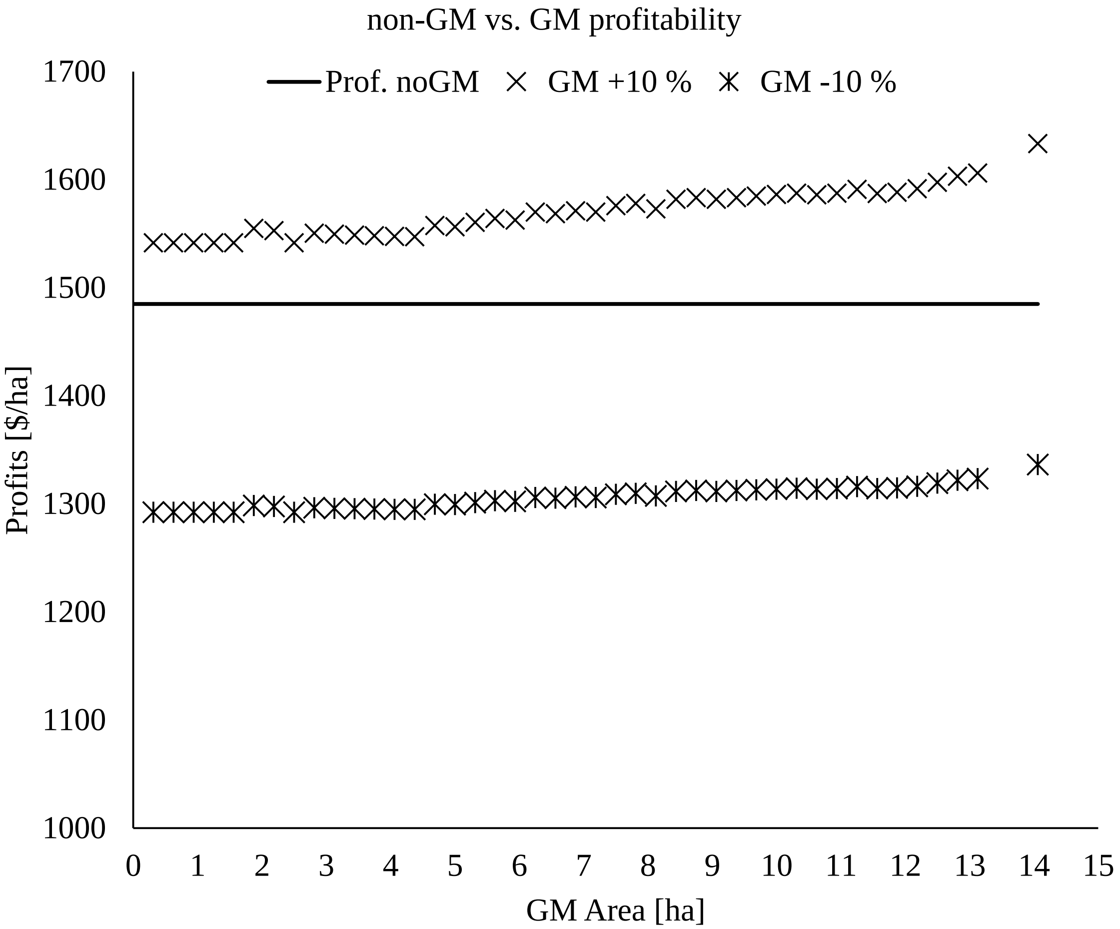

Figure 17. +10% and -10% GM profitability compared to non-GM.

6.2 Sensitivity on profitability and thresholds of contamination.

6.2.1 Property rights to GM producers.

Figure 18 shows the economic losses and gains at the landscape level as a function of increasing profitability for the non-GM crop in comparison to the GM crop, and thresholds of contamination. GM land is constrained so that fields do not switch into a more profitable non-GM crop. One explanation for the constraint that the GM crop is grown despite lower net returns may be unobserved factors[14] for those fields to switch to non-GM. Stricter thresholds result in greater economic losses. A threshold of 0.1% implies that there is no economic incentive for growing the non-GM crop even in case it is 25% more profitable than the non-GM. For the legislative threshold adopted in the European Union, coexistence becomes profitable when the non-GM crop is between 15% and 20% more profitable than the GM one. When non-GM is 5% more profitable than the GM crop, a threshold of 5% still results in coexistence on the landscape less profitable than the baseline.

At the landscape level through Figure 18, it is possible to quantify what competitive advantage non-GM farms need to have in order to keep growing the non-GM crop. In the case where the non-GM crop is 15% less profitable than the GM one and a 0.10% threshold is in place, coexistence is only possible if non-GM farms have a competitive advantage that is at least sufficient to balance the 14.7% loss. If coexistence is observed on the landscape for all positive values in Figure 18, GM farmers have an overall competitive advantage in relation to non-GM farmers.

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[14] E.g. higher soil fertility in the GM area, better irrigation management and so on.

Figure 18. Percentage variation in overall economic returns relative to the baseline.

Profitability	Thresholds of contamination (%)							
noGM	5.00%	2.00%	1.50%	1.00%	0.90%	0.50%	0.25%	0.10%
-15%	-10.1%	-11.3%	-11.6%	-12.3%	-12.5%	-13.2%	-13.9%	-14.7%
-10.0%	-8.0%	-9.3%	-9.7%	-10.4%	-10.5%	-11.3%	-12.0%	-12.9%
-5.0%	-5.9%	-7.2%	-7.7%	-8.4%	-8.6%	-9.4%	-10.2%	-11.1%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5.0%	-1.9%	-3.3%	-3.8%	-4.6%	-4.8%	-5.7%	-6.5%	-7.6%
10.0%	0.2%	-1.3%	-1.8%	-2.7%	-2.9%	-3.8%	-4.7%	-5.8%
15.0%	2.2%	0.6%	0.1%	-0.8%	-1.0%	-2.0%	-2.9%	-4.1%
20.0%	4.3%	2.6%	2.1%	1.2%	1.0%	0.0%	-1.0%	-2.2%
25.0%	6.3%	4.6%	4.0%	3.0%	2.8%	1.8%	0.7%	-0.5%
30.0%	8.4%	6.6%	6.0%	5.0%	4.8%	3.7%	2.6%	1.3%

Figure 19 shows economic losses or gains as a function of thresholds of contamination and relative profitability between the GM and the non-GM crop at the field level. This allows for the identification of spatial differences in economic returns from heterogeneity of the fields on the landscape based on field shape, size and position in space. Due to the property right arrangements, it is assumed that GM fields have homogeneous profitability that is not affected by space, whereas heterogeneity is expected for non-GM fields.

The results show that fields 14 and 10 are the most suitable for coexistence, whereas field 3 is the least suitable. In particular, fields 14 is the largest among the non-GM fields, whereas field 10 borders with one GM field and with the edge of the area created: it therefore receives contamination only from two edges. For field 3, the costs of creating buffers can be compensated only in case profitability for non-GM is 20% higher than profitability for GM, and with a contamination threshold higher than 5%. A threshold of 5% is not high enough to make coexistence profitable for any of the fields when non-GM is 5% more profitable than GM. The legal threshold of 0.9% can be economically sustainable when non-GM is 15% more profitable than GM only for fields 10 and 14, and six out of the seven non-GM fields are economically sustainable at the 0.9% threshold when the non-GM crop is 30% more profitable than the GM crop.

Due to computational complexity of the model, it is only possible to elicit when a field is suitable or not for non-GM crops, and all the negative values (represented with dashes in the table) only indicate the spatial economic unsuitability for the non-GM crop. In fact, due to spatial inter-relations of pollen dispersal between fields, it is impossible to derive that whenever a field is not suitable for the non-GM crop that it is economically better for the GM alternative. This is because switching a field from non-GM to GM will affect the profitability of all neighboring non-GM fields that will require additional buffers that were not required before. A switch of one field from non-GM to GM could even result in the consequential disappearance of all non-GM fields on the landscape.

The degree of heterogeneity in field profitability that arises from spatial configuration, thresholds of contamination and relative profitability between the alternative crops can be expressed in terms of minimum and maximum values of net returns at the field level: a -15% profitability for non-GM results in lower non-GM field net return with respect to the baseline ranging from -41% to -20%, whereas a +30% profitability for non-GM results in varying net returns for non-GM fields in a range that varies form -9% to +22%. Compared to a hypothetical situation with no economic damage resulting from cross-pollination, the cost for creating buffers into non-GM fields varies from 6% to 30%.

In Figure 20 and Figure 21 are shown the spatial configurations of GM, non-GM and buffer areas as resulting from the model runs for the 5%, 2%, 1.5%, 1%, 0.9%, 0.5%, 0.25% and 0.1%. Buffers are created inside the non-GM fields, and increasing buffers result from stricter thresholds of contamination. It is worth noting that buffers do not represent uniformly wide areas that separate GM from non-GM fields, but they are areas that, due to their particular position, and degree of reduced contamination as a function of their position, determine an overall contamination in all the remaining non-GM area lower than the set thresholds of contamination. This explains why there are some non-GM cells adjacent to GM fields that do not need to be turned into buffer, as well as a degree of variation it the width of buffers for same edges between GM and non-GM fields.

Figure 19. Percentage variation in returns for non-GM fields in relation to GM profitability.

no-GM profitability	Threshold of contamination	Field						
		1	3	6	8	10	12	14
5.0%	5.00%	--	--	--	--	--	--	--
	2.00%	--	--	--	--	--	--	--
	1.50%	--	--	--	--	--	--	--
	1.00%	--	--	--	--	--	--	--
	0.90%	--	--	--	--	--	--	--
	0.50%	--	--	--	--	--	--	--
	0.25%	--	--	--	--	--	--	--
	0.10%	--	--	--	--	--	--	--
10.0%	5.00%	0.7%	--	--	1.6%	1.8%	--	3.5%
	2.00%	--	--	--	--	1.2%	--	1.7%
	1.50%	--	--	--	--	--	--	1.0%
	1.00%	--	--	--	--	--	--	1.0%
	0.90%	--	--	--	--	--	--	--
	0.50%	--	--	--	--	--	--	--
	0.25%	--	--	--	--	--	--	--
	0.10%	--	--	--	--	--	--	--
15.0%	5.00%	5.2%	--	3.6%	6.2%	6.4%	0.4%	8.2%
	2.00%	1.0%	--	0.1%	1.9%	5.9%	--	6.3%
	1.50%	0.7%	--	--	0.7%	4.4%	--	5.6%
	1.00%	0.7%	--	--	0.7%	4.4%	--	5.6%
	0.90%	--	--	--	--	0.6%	--	3.2%
	0.50%	--	--	--	--	--	--	0.9%
	0.25%	--	--	--	--	--	--	--
	0.10%	--	--	--	--	--	--	--
20.0%	5.00%	9.8%	1.1%	8.1%	10.9%	11.0%	4.8%	12.9%
	2.00%	5.4%	--	4.4%	6.3%	10.5%	--	10.9%
	1.50%	5.0%	--	2.8%	5.1%	9.0%	--	10.2%
	1.00%	5.0%	--	2.8%	5.1%	9.0%	--	10.2%
	0.90%	2.3%	--	--	3.5%	5.0%	--	7.6%
	0.50%	--	--	--	0.5%	3.0%	--	5.3%
	0.25%	--	--	--	--	2.5%	--	3.3%
	0.10%	--	--	--	--	1.0%	--	1.0%
25.0%	5.00%	14.4%	5.3%	12.6%	15.5%	15.7%	9.1%	17.6%
	2.00%	9.8%	--	8.8%	10.7%	15.1%	2.0%	15.5%
	1.50%	9.4%	--	7.1%	9.5%	13.5%	--	14.8%
	1.00%	9.4%	--	7.1%	9.5%	13.5%	--	14.8%
	0.90%	6.6%	--	3.7%	7.8%	9.3%	--	12.1%
	0.50%	3.8%	--	2.1%	4.7%	7.3%	--	9.6%
	0.25%	2.0%	--	--	1.2%	6.7%	--	7.6%
	0.10%	0.3%	--	--	--	5.2%	--	5.2%
30.0%	5.00%	19.0%	9.5%	17.2%	20.1%	20.3%	13.5%	22.3%
	2.00%	14.2%	1.3%	13.2%	15.2%	19.7%	6.1%	20.2%
	1.50%	13.8%	--	11.4%	13.9%	18.0%	3.8%	19.4%
	1.00%	13.8%	--	11.4%	13.9%	18.0%	3.8%	19.4%
	0.90%	10.9%	--	7.8%	12.1%	13.7%	1.5%	16.6%
	0.50%	7.9%	--	6.2%	8.9%	11.6%	0.1%	14.0%
	0.25%	6.1%	--	2.6%	5.3%	11.0%	0.1%	11.9%
	0.10%	4.3%	--	--	1.5%	9.4%	--	9.4%

Figure 20. GM, non-GM fields and buffers. From top to bottom and from left to right are the 5%, 2%, 1.5% and 1% thresholds. GM fields are represented with the light grey patterns, buffers are the dark-grey patterned areas, and white areas are the non-GM fields.

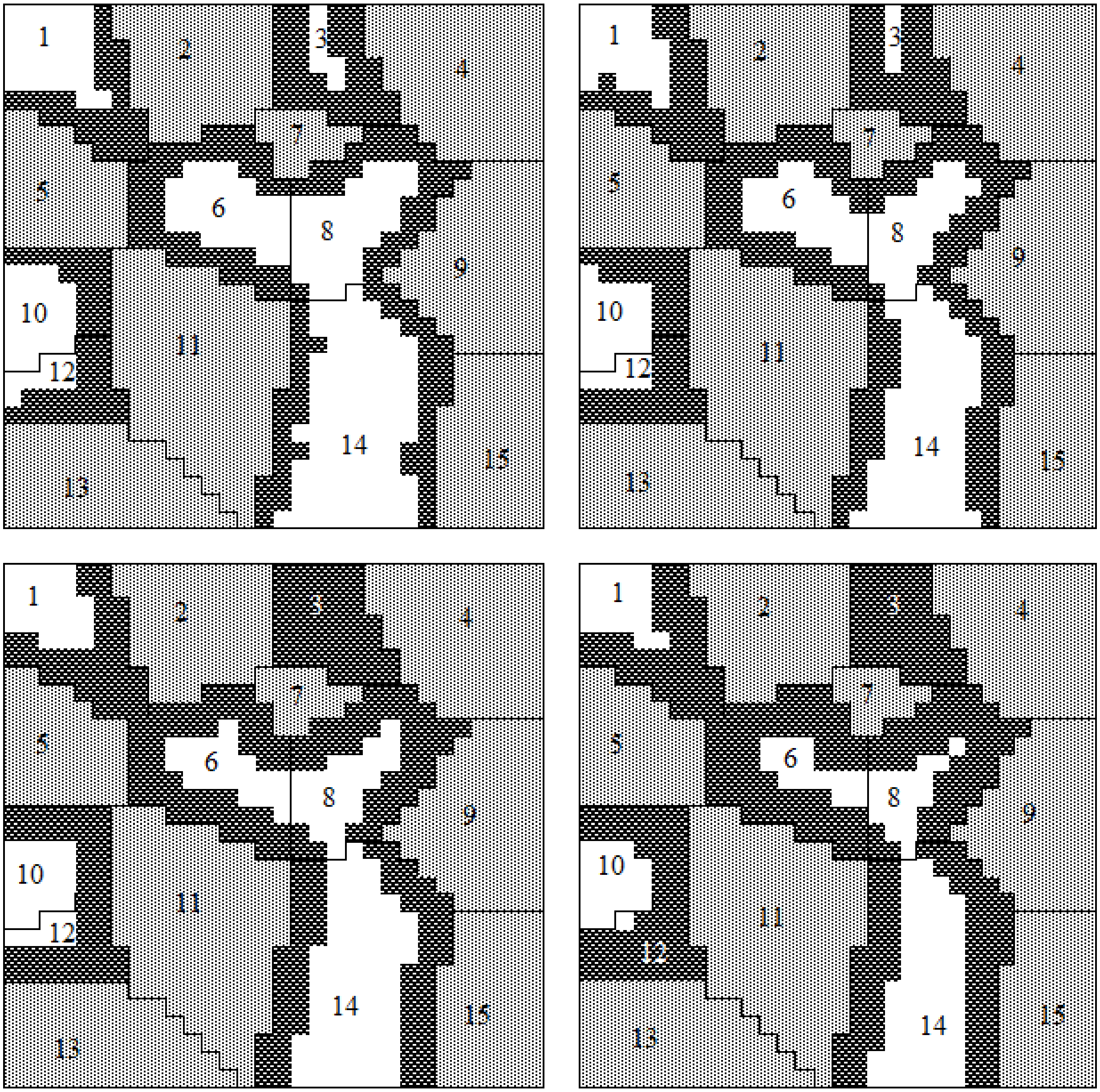

Figure 21. GM, non-GM fields and buffers. From top to bottom and from left to right are the 0.9%, 0.5%, 0.25% and 0.1% thresholds. GM fields are represented with the light grey patterns, buffers are the dark-grey patterned areas, and white areas are the non-GM fields.

6.2.2 Property rights to non-GM producers.

Figure 22 shows the percentage deviation from the baseline of overall economic returns on the landscape in the case where property rights are assigned to non-GM producers, and buffers are created into GM fields. As in the alternative property right scenario, tighter thresholds result in increasing economic losses. At the 0.9% threshold coexistence becomes profitable when the GM crop is between 10% and 15% more profitable than non-GM, and at the 0.1% threshold coexistence becomes profitable when the GM crop is between 20% and 25% more profitable than the non-GM crop. For allowing economic coexistence, a threshold higher than 5% should be in place when the non-GM crop is 5% more profitable than the alternative non-GM crop. For all combinations characterized by negative values, a competitive advantage for GM farms is assumed to be in place if coexistence exists on the landscape. For all positive values non-GM farmers have some degree of competitive advantage in comparison to GM farmers when coexistence is in place in order to balance the losses that would result in the switch of production system.

Figure 22. Percentage variation in overall economic returns relative to the baseline.

Profitability	Thresholds of contamination (%)							
GM	5.00%	2.00%	1.50%	1.00%	0.90%	0.50%	0.25%	0.10%
-15%	-10.0%	-10.4%	-10.6%	-10.9%	-11.0%	-11.4%	-11.8%	-12.2%
-10.0%	-7.6%	-8.1%	-8.4%	-8.7%	-8.7%	-9.3%	-9.7%	-10.2%
-5.0%	-6.1%	-6.9%	-7.2%	-7.7%	-7.8%	-8.6%	-9.3%	-10.2%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5.0%	-1.3%	-2.2%	-2.7%	-3.3%	-3.4%	-4.4%	-5.3%	-6.2%
10.0%	1.2%	0.2%	-0.4%	-1.0%	-1.1%	-2.2%	-3.2%	-4.3%
15.0%	3.5%	2.5%	1.9%	1.2%	1.1%	-0.1%	-1.1%	-2.3%
20.0%	5.9%	4.8%	4.1%	3.4%	3.3%	2.0%	0.9%	-0.4%
25.0%	8.3%	7.1%	6.4%	5.6%	5.5%	4.1%	2.9%	1.6%
30.0%	10.7%	9.4%	8.7%	7.8%	7.7%	6.2%	4.9%	3.5%

Figure 23 shows the deviation from the baseline in terms of profitability at the field level. Fields 13, 9 and 4 are the most suitable for growing GM crop and for preventing GM pollen dispersal through buffers. When GM profitability is 5% higher than non-GM, growing the GM crop in fields 13, 9 and 4 is from 0.2% to 1.5% more profitable than growing the non-GM crop. Field 7 is never profitable for growing the GM crop at the profitability levels analyzed. With the exclusion of field 7, all fields allow for coexistence on the landscape at the 0.9% threshold when GM profitability is 20% higher than the non-GM profitability.

As for the alternative assignment of property rights, computational complexity does not allow for the switching of entire fields from a land state to the alternative one. For this reason the unsuitability for one field in terms of coexistence does not imply the entire field would switch into the alternative crop at the given profitability level, because that would affect the relative profitability for all neighboring fields.

At the -15% profitability level for GM compared to non-GM, GM fields are from 17% to 30% less profitable than the baseline, whereas at the +30% level the relative profitability for GM fields varies from -19% to +25%. The cost for creating buffers into the GM fields reduces the profits by 5 to 28% compared to the profits of the field without buffer, with an average loss of 9.8%.

In Figure 24 and Figure 25 are shown the spatial configurations of GM, non-GM and buffer areas as resulting from the model runs for the 5%, 2%, 1.5%, 1%, 0.9%, 0.5%, 0.25% and 0.1%. Buffers are in this case created into GM fields. As in the previous case, the most efficient configurations result in buffers that are not homogeneous in their width. The overall amount of buffer areas increases as consequence of increasingly strict thresholds of contamination.

Figure 23. Percentage variation in returns for GM fields in relation to non-GM profitability.

no-GM profitability	Threshold of contamination	Field							
		2	4	5	7	9	11	13	15
5.0%	5.00%	--	1.5%	--	--	0.2%	--	1.1%	--
	2.00%	--	--	--	--	--	--	1.1%	--
	1.50%	--	--	--	--	--	--	--	--
	1.00%	--	--	--	--	--	--	--	--
	0.90%	--	--	--	--	--	--	--	--
	0.50%	--	--	--	--	--	--	--	--
	0.25%	--	--	--	--	--	--	--	--
	0.10%	--	--	--	--	--	--	--	--
10.0%	5.00%	--	6.1%	--	--	4.7%	0.7%	5.8%	4.2%
	2.00%	--	3.8%	--	--	3.7%	--	5.8%	3.7%
	1.50%	--	3.4%	--	--	1.6%	--	4.0%	3.7%
	1.00%	--	3.4%	--	--	1.6%	--	4.0%	3.7%
	0.90%	--	3.0%	--	--	0.1%	--	2.8%	3.1%
	0.50%	--	1.8%	--	--	0.1%	--	1.6%	--
	0.25%	--	--	--	--	--	--	1.6%	--
	0.10%	--	--	--	--	--	--	--	--
15.0%	5.00%	2.7%	10.8%	1.9%	--	9.3%	4.9%	10.4%	8.7%
	2.00%	0.7%	8.2%	--	--	8.2%	2.5%	10.4%	8.2%
	1.50%	--	7.9%	--	--	6.0%	1.3%	8.5%	8.2%
	1.00%	--	7.9%	--	--	6.0%	1.3%	8.5%	8.2%
	0.90%	--	7.4%	--	--	4.2%	--	7.2%	7.5%
	0.50%	--	6.2%	--	--	4.2%	--	5.9%	3.7%
	0.25%	--	4.1%	--	--	2.5%	--	5.9%	1.9%
	0.10%	--	2.5%	--	--	--	--	3.7%	0.9%
20.0%	5.00%	6.8%	15.5%	5.9%	--	13.9%	9.2%	15.1%	13.2%
	2.00%	4.7%	12.7%	3.0%	--	12.7%	6.5%	15.1%	12.7%
	1.50%	3.8%	12.3%	2.1%	--	10.3%	5.2%	13.0%	12.7%
	1.00%	3.8%	12.3%	2.1%	--	10.3%	5.2%	13.0%	12.7%
	0.90%	2.4%	11.8%	1.2%	--	8.4%	2.4%	11.6%	12.0%
	0.50%	--	10.5%	--	--	8.4%	--	10.2%	7.9%
	0.25%	--	8.2%	--	--	6.6%	--	10.2%	5.9%
	0.10%	--	6.5%	--	--	3.0%	--	7.9%	4.8%
25.0%	5.00%	10.8%	20.2%	9.9%	--	18.4%	13.4%	19.8%	17.7%
	2.00%	8.6%	17.2%	6.8%	--	17.2%	10.6%	19.8%	17.2%
	1.50%	7.7%	16.8%	5.9%	--	14.6%	9.2%	17.5%	17.2%
	1.00%	7.7%	16.8%	5.9%	--	14.6%	9.2%	17.5%	17.2%
	0.90%	6.2%	16.2%	4.9%	--	12.6%	6.1%	16.1%	16.4%
	0.50%	1.4%	14.8%	--	--	12.6%	3.1%	14.5%	12.0%
	0.25%	--	12.4%	--	--	10.6%	0.6%	14.5%	9.9%
	0.10%	--	10.6%	--	--	6.8%	--	12.0%	8.7%
30.0%	5.00%	14.9%	24.9%	13.9%	--	23.0%	17.6%	24.4%	22.2%
	2.00%	12.5%	21.7%	10.6%	--	21.7%	14.6%	24.4%	21.6%
	1.50%	11.5%	21.2%	9.6%	--	18.9%	13.1%	22.0%	21.6%
	1.00%	11.5%	21.2%	9.6%	--	18.9%	13.1%	22.0%	21.6%
	0.90%	9.9%	20.6%	8.6%	--	16.8%	9.9%	20.5%	20.8%
	0.50%	4.8%	19.1%	2.8%	--	16.8%	6.7%	18.8%	16.1%
	0.25%	2.4%	16.6%	--	--	14.7%	4.0%	18.8%	13.9%
	0.10%	--	14.6%	--	--	10.5%	1.2%	16.2%	12.7%

Figure 24 GM, non-GM fields and buffers. From top to bottom and from left to right are the 5%, 2%, 1.5% and 1% thresholds. GM fields are represented with the light grey patterns, buffers are the dark-grey patterned areas, and white areas are the non-GM fields.

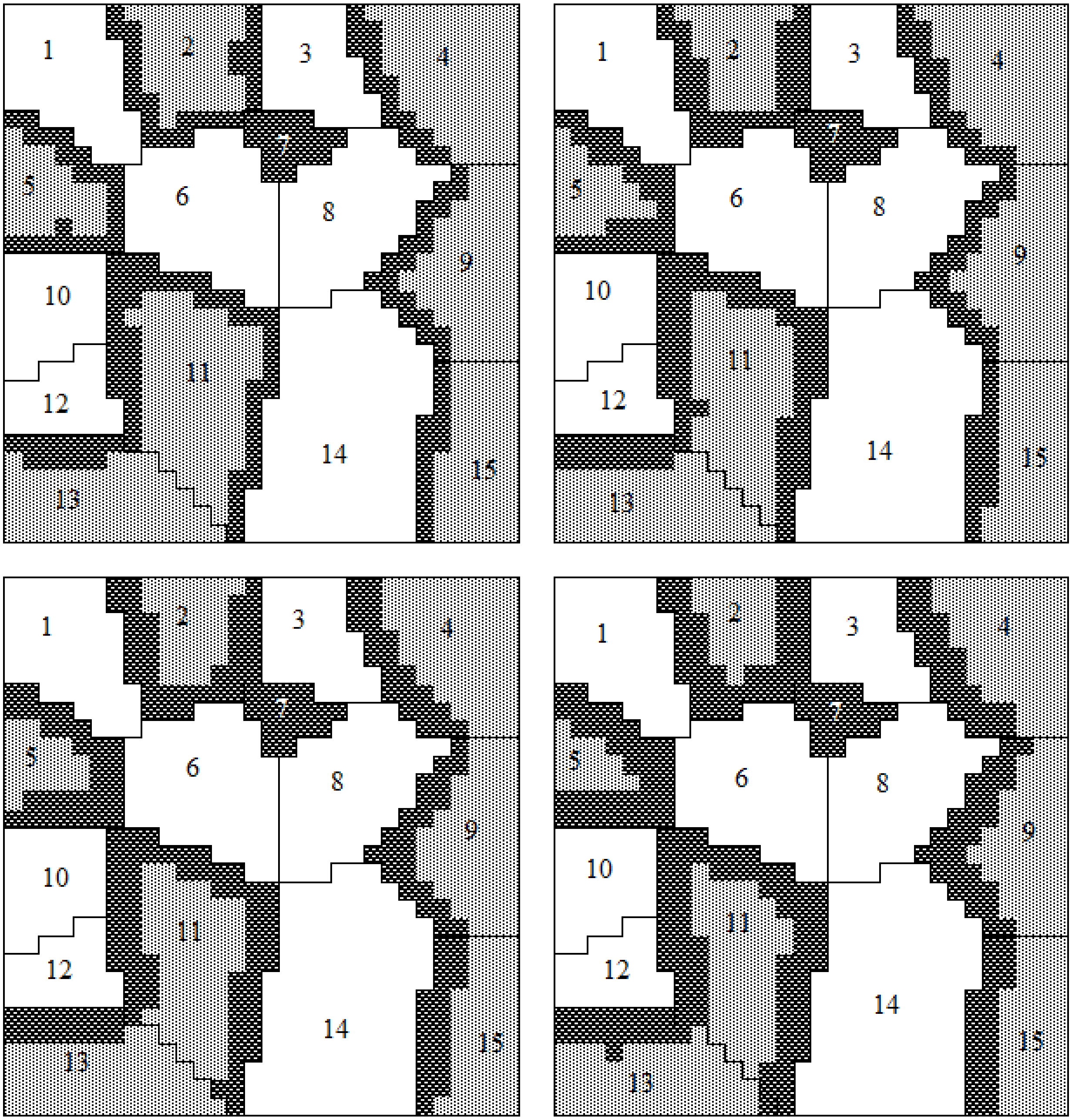

Figure 25. GM, non-GM fields and buffers. From top to bottom and from left to right are the 0.9%, 0.5%, 0.25% and 0.1% thresholds. GM fields are represented with the light grey patterns, buffers are the dark-grey patterned areas, and white areas are the non-GM fields.

6.3 Sensitivity on the dispersal function.

6.3.1 Property rights to GM producers.

The effect of varying pollen dispersal on profitability (Figure 26) is comparable to the effect of varying thresholds, due to the fact that a larger dispersal implies bigger buffers to prevent cross-contamination as a more stringent threshold implies bigger buffers. It can be seen that the average contamination at 25m distance (the length size of each cell *i*) varies from 1.6% to 9.8%, and that at 50m (2 adjacent cells), the average contamination varies from 0.4% to 0.07%. At 75m the maximum contamination observed is 0.02%. Lower values for the parameter *K* result in lower final values of contamination.

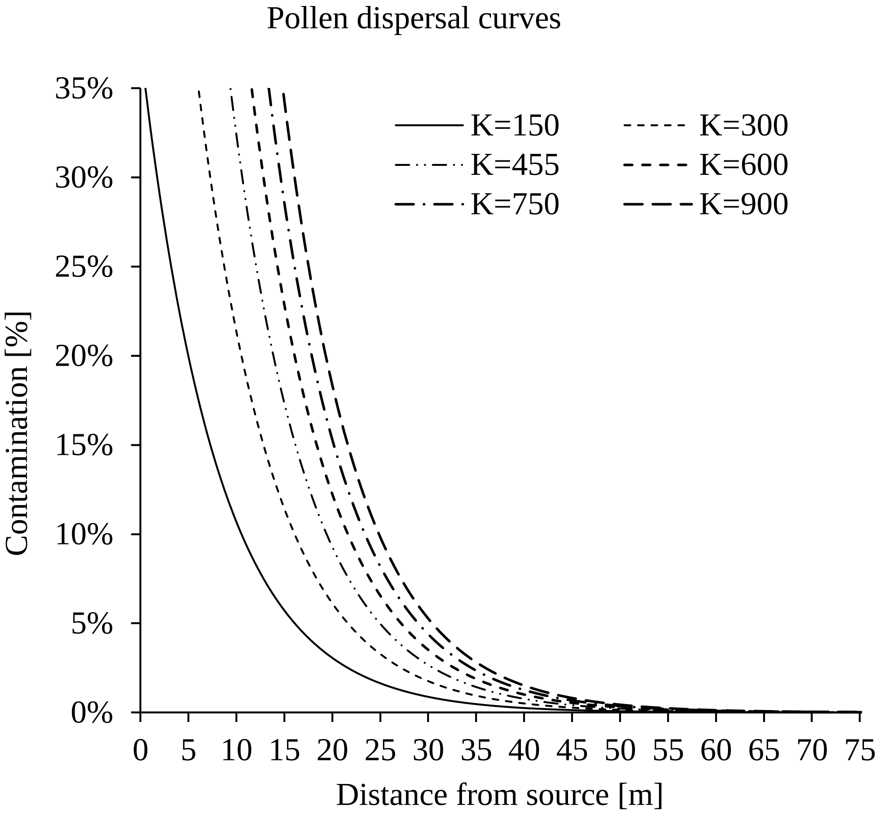

Figure 26. Pollen dispersal curves based on different values for the parameter K.

Figure 27 shows the effect of different dispersal functions on overall landscape profits. Larger values for the parameter *K* mean larger dispersal curves. In the baseline, *K* assumes a value of 455, and the threshold of contamination for all dispersal curves is set at 0.9%. The results show that coexistence on the landscape is economically viable when non-GM net returns are between 15% and 20% higher than GM net returns (between 10% and 15% for *K* = 150). A 10% difference in profits between the non-GM and the GM crop is not enough at the 0.9% threshold to balance the overall cost of implementing. The maximum economic loss is 13.3%, indicating the minimum economic value of the competitive advantage that non-GM farmers need to have in case coexistence is in place when the 0.9% threshold and a dispersal function described by *K* = 900.

Figure 27. Percentage variation in overall economic returns relative to the baseline with different dispersal functions.

Profitability			*K*			
noGM	150	300	455	600	750	900
-15%	-10.8%	-11.8%	-12.5%	-12.8%	-13.1%	-13.3%
-10.0%	-8.8%	-9.8%	-10.5%	-10.9%	-11.2%	-11.4%
-5.0%	-6.7%	-7.9%	-8.6%	-9.0%	-9.3%	-9.5%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5.0%	-2.8%	-4.0%	-4.8%	-5.3%	-5.6%	-5.8%
10.0%	-0.8%	-2.0%	-2.9%	-3.4%	-3.7%	-3.9%
15.0%	1.2%	-0.1%	-1.0%	-1.5%	-1.9%	-2.1%
20.0%	3.3%	1.9%	1.0%	0.4%	0.0%	-0.2%
25.0%	5.2%	3.8%	2.8%	2.3%	1.9%	1.7%
30.0%	6.0%	6.0%	6.0%	4.2%	3.8%	3.6%

Figure 28 reports the percentage deviation of field profitability at the 0.9% threshold of contamination and with varying relative profitability between non-GM and GM. It can be seen that when non-GM profitability is 5% higher than the GM one, no field is big enough to allow for balancing the economic loss determined by the creation of buffers. Fields 14 and 10 are the most suitable for growing non-GM crops, whereas field 3 is the less suitable. Field 14 is the biggest non-GM field in the area, whereas Field 3 owes its economic suitability for growing non-GM due to its position and the fact that contamination only comes from two of its four edges. With a 30% differential in profitability between the non-GM and the GM crop all fields are suitable for coexistence except field 3 which is only adequate in case the dispersal function is defined by *K*=150. At the -15% level for non-GM profitability, the cost for creating buffers ranges from 7% to 27% of the net returns achieved in case of no buffer needed, and the average buffer cost for creating buffers is about 15% of non-GM field profits. A -15% profitability for the non-GM crop results in lower non-GM field net return with respect to the baseline ranging from -38% to -21%, whereas a +30% profitability for non-GM results in varying net returns for non-GM fields in a range from 0.7% to +21%.

As indicated previously, the results only give an indication of the suitability for growing the non-GM crop for each field based on an economic analysis. Unsuitability does not imply that the field would switch into the alternative land use, because that would affect the relative profitability of all neighboring fields as a consequence of changes in the surface needed for buffers.

In Figure 29 and Figure 30 are shown the spatial configurations of GM, non-GM and buffer areas as resulting from the model runs for *K* values of 150, 300, 455, 600, 750 and 900. Buffers are created into GM crops and they increase with the increasing magnitude of cross-contamination due to distance. As in the previous cases, buffers are heterogeneous in its width and are the result of the most economically efficient allocation of cells. A homogeneous and adequately sixed buffer would result suboptimal economic returns while guaranteeing the meeting of the established maximum thresholds of contamination.

Figure 28. Percentage variation in returns for non-GM fields in relation to GM profitability with different dispersal functions.

no-GM profitability	*K*	Field						
		1	3	6	8	10	12	14
5.0%	150	--	--	--	--	--	--	--
	300	--	--	--	--	--	--	--
	455	--	--	--	--	--	--	--
	600	--	--	--	--	--	--	--
	750	--	--	--	--	--	--	--
	900	--	--	--	--	--	--	--
10.0%	150	--	--	--	--	0.8%	--	2.6%
	300	--	--	--	--	--	--	0.7%
	455	--	--	--	--	--	--	--
	600	--	--	--	--	--	--	--
	750	--	--	--	--	--	--	--
	900	--	--	--	--	--	--	--
15.0%	150	2.6%	--	1.1%	2.9%	5.4%	--	7.3%
	300	0.0%	--	--	0.7%	3.0%	--	5.3%
	455	--	--	--	--	0.1%	--	3.0%
	600	--	--	--	--	0.1%	--	3.0%
	750	--	--	--	--	--	--	0.9%
	900	--	--	--	--	--	--	0.5%
20.0%	150	7.1%	--	5.5%	7.4%	10.0%	2.0%	12.0%
	300	4.4%	--	1.7%	5.1%	7.5%	--	9.9%
	455	2.3%	--	--	3.5%	4.5%	--	7.5%
	600	2.3%	--	--	3.5%	4.5%	--	7.5%
	750	--	--	--	0.5%	3.5%	--	5.3%
	900	--	--	--	--	2.6%	--	4.8%
25.0%	150	11.6%	0.3%	9.9%	11.9%	14.5%	6.3%	16.6%
	300	8.7%	--	5.9%	9.5%	12.0%	--	14.4%
	455	6.6%	--	3.7%	7.8%	8.8%	--	12.0%
	600	6.6%	--	3.7%	7.8%	8.8%	--	12.0%
	750	3.8%	--	2.1%	4.7%	7.9%	--	9.7%
	900	3.8%	--	1.5%	4.2%	6.9%	--	9.2%
30.0%	150	16.0%	4.3%	14.3%	16.3%	19.1%	10.5%	21.3%
	300	13.1%	--	10.2%	13.9%	16.5%	3.6%	19.0%
	455	10.9%	--	7.8%	12.1%	13.2%	2.2%	16.5%
	600	10.9%	--	7.8%	12.1%	13.2%	2.2%	16.5%
	750	7.9%	--	6.2%	8.9%	12.2%	0.7%	14.1%
	900	7.9%	--	5.5%	8.3%	11.1%	0.7%	13.6%

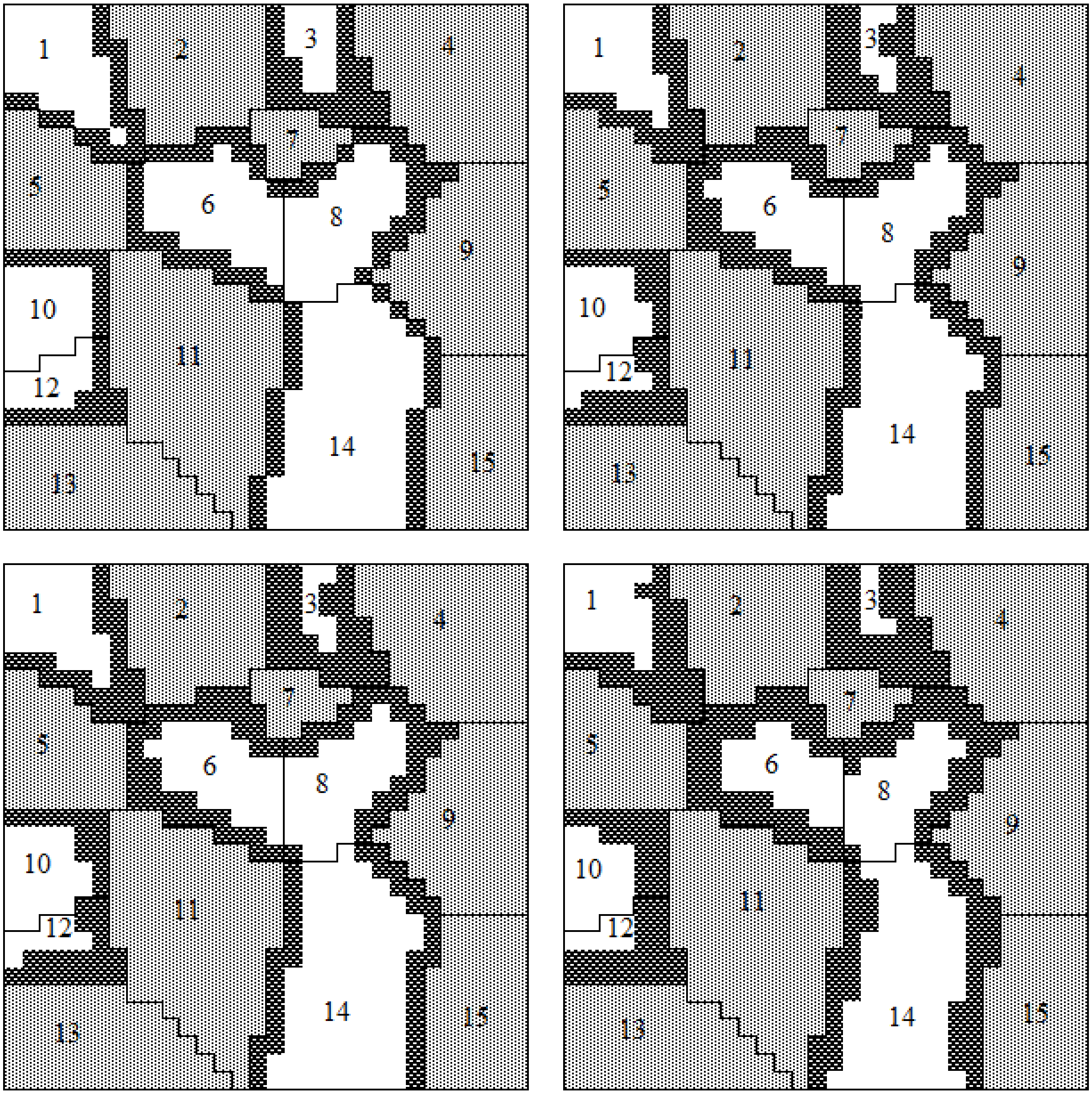

Figure 29. GM, non-GM fields and buffers. From top to bottom and from left to right are the dispersal functions with K=150, 300, 455 and 600. GM fields are represented with light grey patterns, buffers are the dark-grey patterned areas, and white areas are the non-GM fields.

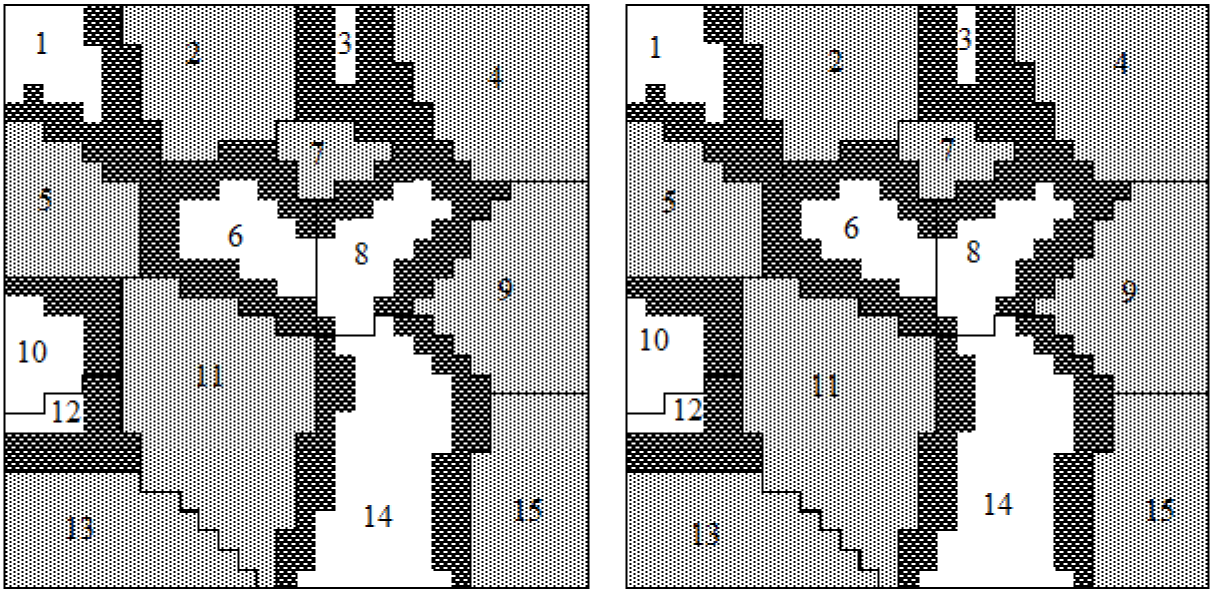

Figure 30. GM, non-GM fields and buffers. From left to right are the dispersal functions with K=750 and 900. GM fields are represented with light grey patterns, buffers are the dark-grey patterned areas, and white areas are the non-GM fields.

6.3.2 Property rights to non-GM producers.

When property rights are assigned to non-GM producers, buffers are created into GM fields in order to prevent contamination into the neighboring non-GM fields. Figure 31 illustrates the economic losses and gains at the landscape level determined by variation in the pollen dispersal function. It can be seen that at the 0.9% threshold a minimum 15% difference in profitability between the non-GM and the GM crop is required for the coexistence to be economically viable for all values of *K* (10% for *K*=150). The maximum economic loss is equal to 11.4%, meaning that non-GM farmers should have a competitive advantage not described by market prices resulting in at least 11.4% of the non-GM profitability if coexistence is in place. A 30% higher profitability for the GM crop translates on the specific landscape considered into a 9.9% increase in the overall economic value of the production.

Figure 31. Percentage variation in overall economic returns relative to the baseline.

Profitability				*K*		
noGM	150	300	455	600	750	900
-15%	-10.3%	-10.7%	-11.0%	-11.2%	-11.3%	-11.4%
-10.0%	-7.9%	-8.4%	-8.7%	-9.0%	-9.2%	-9.3%
-5.0%	-6.6%	-7.3%	-7.8%	-8.2%	-8.5%	-8.7%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
5.0%	-1.9%	-2.8%	-3.4%	-3.9%	-4.2%	-4.5%
10.0%	0.5%	-0.5%	-1.1%	-1.7%	-2.1%	-2.4%
15.0%	2.9%	1.8%	1.1%	0.5%	0.1%	-0.3%
20.0%	5.2%	4.0%	3.3%	2.6%	2.2%	1.8%
25.0%	7.5%	6.3%	5.5%	4.8%	4.3%	3.9%
30.0%	9.9%	8.6%	7.7%	7.0%	6.5%	6.0%

Figure 32 shows the economic losses and gains for each field compared to the baseline. All percentage values express the percentage deviation due to the presence into GM fields of heterogeneous buffers that reduce the overall field profitability.

It can be seen that at the 0.9% threshold fields 13, 4, 9 and 15 are the most suitable for creating buffers, whereas field 3 is the less suitable. The economic loss due to the presence of buffers in field 3 cannot be balanced even in the case in which pollen dispersal is low (*K*=150), and GM profitability is 30% higher than the non-GM alternative.

Heterogeneity in profitability can be expressed in terms of costs for creating buffers: they vary from a minimum of 4% to a maximum of 28% of the overall profits for each field, with an average of 10%. In Figure 33 and Figure 34 are shown the spatial configurations of GM, non-GM and buffer areas as resulting from the model runs for *K* values of 150, 300, 455, 600, 750 and 900. As previously, buffer areas increase with the increasing magnitude of cross-contamination due to distance expressed by the increase of the parameter *K* of the dispersal function.

Figure 32. Percentage variation in returns for GM fields in relation to non-GM profitability with different dispersal functions.

no-GM profitability	*K*	Field							
		2	4	5	7	9	11	13	15
5.0%	150	--	--	--	--	--	--	1.1%	--
	300	--	--	--	--	--	--	--	--
	455	--	--	--	--	--	--	--	--
	600	--	--	--	--	--	--	--	--
	750	--	--	--	--	--	--	--	--
	900	--	--	--	--	--	--	--	--
10.0%	150	--	4.2%	--	--	3.7%	--	5.8%	3.5%
	300	--	3.4%	--	--	1.6%	--	4.0%	2.8%
	455	--	3.0%	--	--	0.1%	--	2.8%	1.9%
	600	--	3.0%	--	--	0.1%	--	2.8%	1.9%
	750	--	1.8%	--	--	0.1%	--	1.6%	0.2%
	900	--	1.8%	--	--	--	--	1.6%	--
15.0%	150	2.0%	8.7%	0.2%	--	8.2%	2.7%	10.4%	7.9%
	300	--	7.9%	--	--	6.0%	1.3%	8.5%	7.2%
	455	--	7.4%	--	--	4.2%	--	7.2%	6.2%
	600	--	7.4%	--	--	4.2%	--	7.2%	6.2%
	750	--	6.2%	--	--	4.2%	--	5.9%	4.4%
	900	--	6.2%	--	--	3.7%	--	5.9%	3.4%
20.0%	150	6.1%	13.3%	4.0%	--	12.7%	6.8%	15.1%	12.4%
	300	3.8%	12.3%	2.5%	--	10.3%	5.2%	13.0%	11.6%
	455	2.4%	11.8%	0.3%	--	8.4%	2.8%	11.6%	10.6%
	600	2.4%	11.8%	0.3%	--	8.4%	2.8%	11.6%	10.6%
	750	--	10.5%	--	--	8.4%	0.4%	10.2%	8.6%
	900	--	10.5%	--	--	7.8%	--	10.2%	7.6%
25.0%	150	10.1%	17.8%	7.9%	--	17.2%	10.9%	19.8%	16.8%
	300	7.7%	16.8%	6.2%	--	14.6%	9.2%	17.5%	16.1%
	455	6.2%	16.2%	3.9%	--	12.6%	6.6%	16.1%	14.9%
	600	6.2%	16.2%	3.9%	--	12.6%	6.6%	16.1%	14.9%
	750	2.3%	14.8%	--	--	12.6%	4.0%	14.5%	12.8%
	900	1.4%	14.8%	--	--	12.0%	2.7%	14.5%	11.7%
30.0%	150	14.1%	22.3%	11.8%	--	21.7%	14.9%	24.4%	21.3%
	300	11.5%	21.2%	10.0%	--	18.9%	13.1%	22.0%	20.5%
	455	9.9%	20.6%	7.5%	--	16.8%	10.3%	20.5%	19.3%
	600	9.9%	20.6%	7.5%	--	16.8%	10.3%	20.5%	19.3%
	750	5.8%	19.1%	3.2%	--	16.8%	7.6%	18.8%	17.0%
	900	4.8%	19.1%	2.4%	--	16.1%	6.2%	18.8%	15.8%

Figure 33. GM, non-GM fields and buffers. From top to bottom and from left to right are the dispersal functions with K=150, 300, 455 and 600. GM fields are represented with light grey patterns, buffers are the dark-grey patterned areas, and white areas are the non-GM fields.

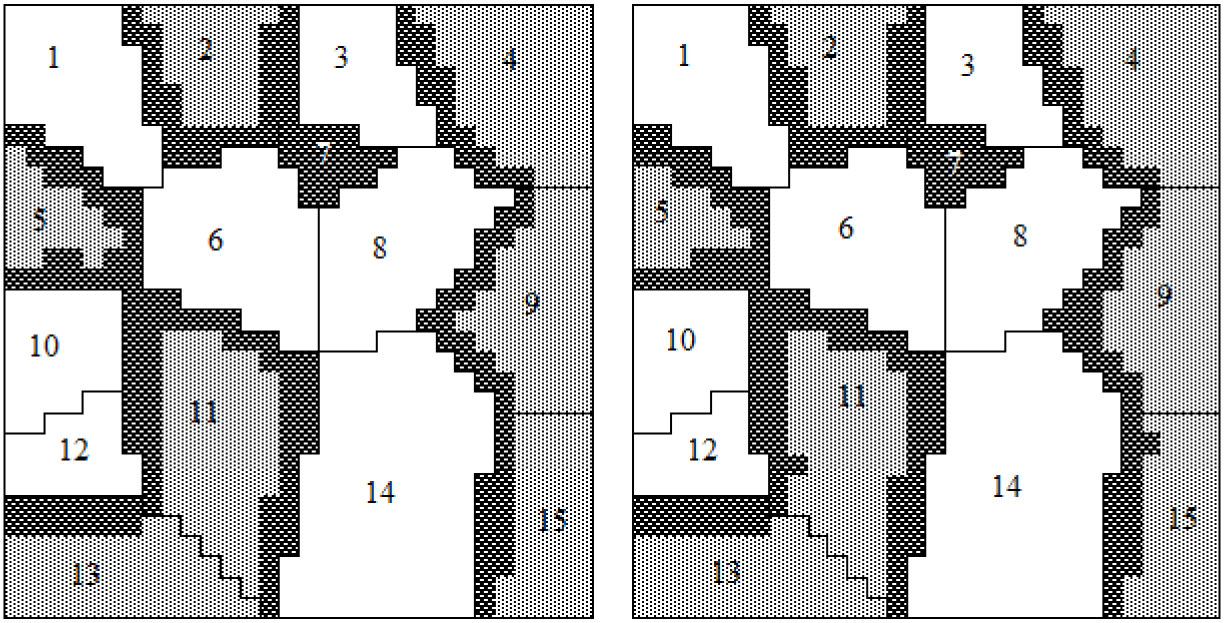

Figure 34. GM, non-GM fields and buffers. From left to right are the dispersal functions with K=750 and 900. GM fields are represented with light grey patterns, buffers are the dark-grey patterned areas, and white areas are the non-GM fields.

6.4 Sensitivity on prices, yields and production costs.

Figure 35 and Figure 36 show respectively net returns and buffer enforcement costs or gains per hectare at the landscape level for both GM and non-GM farmers if GM or non-GM become 10% more profitable than the other crop. The 10% rise in profitability is either from an increase in yields, an increase in the market price, or a decrease in production costs. These are compared to the baseline profitability augmented by 10%, which represents a hypothetical situation for which there are no economic losses resulting from creating buffers: this allows the identification of the magnitude of buffer enforcement losses. In Figure 36, positive values represent economic gains, whereas negative values represent economic losses in dollars per hectare; they are calculated by subtracting the +10% augmented crop profitability (no buffer enforcement) from the crop profitability that takes into account the amount of buffers needed to prevent contamination at the landscape level. The results in the tables come from the spatially heterogeneous landscape obtained through the Voronoi method.

An increase in the non-GM price that should result in non-GM 10% more profitable than the baseline will actually reduce the overall profitability for non-GM by $81.5 per hectare due to the economic loss incurred to enforce buffers. This arises from the fact that the selling price for the non-GM crop increases, whereas the market price at which the buffer crop is sold remains constant. The more the non-GM market price increases, the more the loss of net returns due to the creation of buffers increases. On the other hand, when an increase in non-GM yield or a reduction in non-GM production costs makes non-GM profitability increases by 10%, no economic losses are observed in comparison to the baseline for the non-GM producers, and therefore the final profitability values are 10% higher than the baseline. This is because an increase in non-GM yields also results in an equal increase in buffer yields. The same can be said for production costs.

In the alternative property right scenario (GM producers need to create buffers) market prices have no positive nor negative effect; however, an increase in non-GM yields or a reduction of non-GM production costs have a positive economic impact for GM producers due to the increased economic returns of buffers. This gain for GM producers is equal to around $53 per hectare.

When the GM crop is more profitable by 10%, price is again the only element that impacts non-GM producers in case they are required to create buffers to prevent cross-contamination in their crops. The magnitude (Figure 36) of the resulting economic gain is about $81.5 per hectare, and it derives from the increased market price at which the buffer crop is sold. On the other hand, the creation of buffers means an economic loss for GM producers equal to around $52 per hectare that result from the fact that an increase in yields or decrease production costs for the GM crop does not correspond to an increase in yields or decrease in production costs for the buffer crop. This is because the buffer crop is planted as a non-GM crop while later sold as a GM crop because of contamination.

Figure 35. Crop profitability on the basis of the property right assignment and the profitability scenario with respect to the baseline.

		GM prop. rights		no-GM prop. rights	
		GM [$/ha]	no-GM [$/ha]	GM [$/ha]	no-GM [$/ha]
no-GM +10%	Yield	1484.97	1648.66	1538.09	1648.66
	Cost	1484.97	1648.66	1538.09	1648.66
	Price	1484.97	1567.20	1484.97	1648.66
GM +10%	Yield	1648.66	1484.97	1595.54	1484.97
	Cost	1648.66	1484.97	1595.54	1484.97
	Price	1648.66	1566.43	1648.66	1484.97

Figure 36. Buffer enforcement costs (negative values) or gains (positive values) on the basis of the property right assignment and the profitability scenario with respect to the baseline

		Buffer enforcement costs or gains			
		GM prop. rights		no-GM prop. rights	
		GM [$/ha]	no-GM [$/ha]	GM [$/ha]	no-GM [$/ha]
no-GM +10%	Yield	--	0.00	53.12	--
	Cost	--	0.00	53.12	--
	Price	--	-81.46	0.00	--
GM +10%	Yield	--	0.00	-53.12	--
	Cost	--	0.00	-53.12	--
	Price	--	81.46	0.00	--

7 Discussion.

Figure 37 recaps and combines the sensitivities performed on the constrained landscape and shows the amount of GM crop, buffer crop and non-GM crop on the landscape as consequence as three different degrees of pollen dispersal, three different contamination thresholds, and alternative property right assignments. It can be observed that the farther the pollen moves (higher values of the dispersal parameter *K*), the greater the buffer area needed to prevent cross contamination at the specified threshold. Moreover, the more stringent the threshold, the larger the buffer needed as well. To have coexistence on the landscape analyzed when GM producers hold the property rights, a buffer area from 7.3% to 15.4% of the total landscape is needed at the less stringent threshold based on the magnitude of pollen dispersal. These numbers increase to respectively 27.1% to 33.9% in the case of the most stringent threshold. At the 0.1% threshold the amount of land that can be considered non-GM is lower than the amount of buffer to prevent excessive contamination in the non-GM area. At the 0.9% threshold a pollen dispersal described by *K*=455 results in almost equal amounts of non-GM and buffer land.

In the case where non-GM producers have the property rights, again the amount of buffers needed to prevent cross contamination increases the more stringent the thresholds become and the farther pollen moves. In particular, buffers range from 5.9% to 13.1% of the landscape surface at the 5% threshold, and from 22.8% to 27.9% of the landscape surface in case of a 0.1% threshold of cross contamination. The differences in percentages of buffers for the two alternative property right assignments arise from the particular landscape configuration, the relative size between GM and non-GM fields and the overall GM area vs. non-GM area on the landscape.

Figure 37. GM, no-GM and buffer areas for different property right assignments, pollen dispersal functions and thresholds of contamination.

	Threshold [%]	Dispersal parameter *K*	Area [%][1] GM	no-GM	Buffer
GM property rights no-GM +10%	5.0%	150	55.1%	37.6%	7.3%
		455	55.1%	31.9%	13.0%
		750	55.1%	29.4%	15.4%
	0.9%	150	55.1%	29.0%	15.9%
		455	55.1%	22.6%	22.3%
		750	55.1%	20.0%	24.9%
	0.1%	150	55.1%	17.8%	27.1%
		455	55.1%	13.7%	31.2%
		750	55.1%	11.0%	33.9%
no-GM property rights - GM +10%	5.0%	150	49.2%	44.9%	5.9%
		455	43.3%	44.9%	11.8%
		750	42.0%	44.9%	13.1%
	0.9%	150	41.6%	44.9%	13.6%
		455	37.1%	44.9%	18.0%
		750	34.8%	44.9%	20.3%
	0.1%	150	32.3%	44.9%	22.8%
		455	28.8%	44.9%	26.3%
		750	27.2%	44.9%	27.9%

[1] The constant value of 55.1% for the GM crop and the constant value of 44.9% non-GM crop indicate the amount of respectively GM and non-GM crop from the initial random land allocation shown in Figure 10.

Figure 38 combines the sensitivities performed and shows the overall value of the landscapes and its changes in percentage terms, as well as the minimum and maximum profitability in percentage terms of the maximum values of minimum and maximum profitability observed at the field level on the landscape. It can be observed that both field profitability and the overall landscape values decline for both lowering the contamination thresholds and increasing the magnitude of the dispersal of pollen. The minimum field profitability when property rights are assigned to GM producers declines by a maximum of 9%, whereas the maximum value of profitability declines by a little over 16%, and the overall landscape value declines by a maximum of just under 10%. In case of property rights to the non-GM producers, the minimum field profitability can drop by a maximum of a little over 19%, and the maximum field profitability by a maximum of a little over 12%. The situation characterized by the lowest threshold of contamination and the highest magnitude of pollen dispersal, the overall economic loss at the landscape level is a little less than 10%.

Figure 38. GM, no-GM and buffer profitability in percentage of the minimum and maximum crop profitability, and overall landscape value as a percentage of the maximum landscape value for different property right assignments, pollen dispersal functions and thresholds of contamination.

	Threshold [%]	Dispersal parameter *K*	Field profitability		Landscape overall value [%]
			% of min.	% of max.	
GM property rights no-GM +10%	5.0%	150	100.0%	100.0%	100.0%
		455	100.0%	96.3%	98.0%
		750	100.0%	95.5%	97.1%
	0.9%	150	100.0%	95.5%	97.0%
		455	97.2%	91.7%	94.7%
		750	95.2%	89.9%	93.8%
	0.1%	150	91.0%	88.7%	93.0%
		455	91.0%	86.2%	91.6%
		750	91.0%	83.6%	90.6%
no-GM property rights - GM +10%	5.0%	150	100.0%	100.0%	100.0%
		455	96.0%	96.3%	97.4%
		750	89.8%	96.3%	96.9%
	0.9%	150	89.8%	96.3%	96.7%
		455	80.6%	93.3%	94.8%
		750	80.6%	92.6%	93.7%
	0.1%	150	80.6%	92.0%	92.7%
		455	80.6%	90.1%	91.1%
		750	80.6%	87.7%	90.4%

Cross-comparison between values for the alternative property rights cannot be performed due to the way buffers are constructed (see. Chapters 4.3.2. to 4.3.5.)

The study shows that pollen dispersal affects the profitability of the crop whose producers do not have the property right. Those farmers without the property rights face buffer creation costs, whereas those with property rights (who do not have the obligation to create buffers) have profitability unaffected as a consequence of pollen dispersal. Figure 15 and Figure 17 indicate that while the profitability of one crop remains constant (right below $1500 per hectare), the other one varies by about $360 per hectare when non-GM producers must prevent the contamination of their crops through the creation of buffers, and by about $92 per hectare when property rights are assigned to non-GM producers. At the field level, the profitability of the crop whose producers do not have property rights varies according to the particular field in which the crop is grown, and one of the reasons for this is the heterogeneity of field sizes. Figure 19 shows that at the 0.9% threshold of contamination the farmer cultivates field 14 with the non-GM crop and obtains a net return per hectare that is 3.6% higher than the net return per hectare of the GM crop when non-GM profitability is 15% higher than non-GM profitability. However, the farmer that cultivates field 3 will never obtain net returns per hectare higher than the GM crop, at least up until the non-GM crop becomes 30% more profitable than the non-GM crop. This means that the farmer that cultivates field 14 has an economic incentive to grow the non-GM crop when the non-GM profitability in average terms is 15% higher than the GM profitability, whereas the farmer that grows field 3 will have an economic incentive to switch production into the GM crop unless non-GM average profitability is 30% higher than GM. Field 14 and field 3 are both irregular pentagons and have three surrounding GM fields, but the area of field 3 is less than half the area of field 14.

Another reason for the variation in net returns at the field level is the position of fields in relation to those in which the alternative crop is grown. As indicated above, the bigger the fields, the better the possibility to prevent contamination. However, the data show that small fields (for instance field 10) can sustain profitable coexistence when there are few surrounding adjacent fields that are grown with the alternative crop. Consequently, a way to reduce the economic harms of cross-contamination would be the spatial aggregation of all fields of the same type, if viable.

Size and position of fields are characteristics that influence the allocation of buffers. Even though there might be better spatial configurations that reduce cross-contamination, the field boundaries are fixed and maximum spatial efficiency cannot be achieved because fields cannot be modified in their sizes and shapes. This study shows that a constrained landscape results in lower profitability values for the crop whose farmers are not entitled with property rights compared to the situation in which the position of GM and non-GM crops is fully adjustable. As an example, when fields are not constrained in space and shape, a 10% higher non-GM profitability results in the non-GM crop more profitable, including the costs to bear the contamination, up until the GM area equals around 75% as shown in Figure 15 for property rights to GM producers at the 0.9% threshold. In presence of spatial constraints these results change. With the particular Voronoi configuration analyzed, the same property right assignments and the same 10% higher non-GM profitability ($1633/ha vs. $1485/ha) means non-GM field profitability varies from $1222/ha to $1465/ha, whereas in the absence of spatial constraints this varies from $1274/ha to the maximum of $1633/ha.

In economic terms, coexistence can only be in place when there are no incentives to switch from a production system to the other, so the spatial configuration represents an equilibrium situation in terms of net returns for both crops. However, the heterogeneity in profitability means that, when only comparing average profitability and taking into account spatially determined costs for creating buffers, there is always an incentive[15] for some farmers to switch production system to the most profitable one. When coexistence is observed, the reasons why this does not happen can be either high costs for switching production systems, or spatially specific reasons that give farmers differential competitive advantages in the production of the GM or the non-GM crop not expressed by market prices and average yields/production costs. While difficult to measure directly, the necessary competitive advantage can be elicited indirectly knowing the spatial configuration of fields, the types of crops grown in each field, and average market prices, production costs and yields for the region examined.

Reasoning in terms of equilibria, the value of the competitive advantage to prevent switching from one production system to the most profitable on average terms should equal the incentive to switch production system. In Figure 18, all positive numbers imply that GM farmers must have some degree of competitive advantage that varies from a 0.2% to an 8.4% of the overall value of the landscape. All negative numbers imply that the value of competitive advantage for non-GM farmers varies from 1.3% to 14.7 of the overall value of the landscape. At the field level, smaller fields must have a higher competitive advantage in comparison to bigger fields. For instance (Figure 19), if coexistence is observed in field 14 when non-GM is 10% more profitable than GM, the competitive advantage of that specific portion of the landscape must be lower than 3.2% GM profitability. With that same level of competitive advantage for field 3, coexistence cannot be observed even when the non-GM crop is on average 30% more profitable than the GM crop.

Due to the heterogeneity of spatially determined prevention costs, as well as the way in which buffers are constructed, it is extremely complex to identify which property right assignment is the most efficient in allowing for coexistence to be in place on a specific landscape. Figure 35

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[15] We assume a 0 costs to switch production from one type of crop to the alternative one.

and Figure 36 show that the variation in market prices (for either the GM or the non-GM crop) appears to be the only driver that determines the magnitude of economic losses or gains for non-GM producers when the GM producers have the property rights. Alternatively, when non-GM producers hold the property rights, the magnitude of the economic losses or gains for the GM producers depend uniquely on yields and production costs, whereas market prices do not have an impact. Losses for the non-GM producers are the result increasing buffer costs (buffer market prices do not increase when non-GM market prices rise). For GM producers, losses arise when GM crops increase their yields or decrease their production costs since the same does not happen for buffers. On the other hand, economic gains for non-GM producers that are not entitled with property rights arise from an increase in the market price for the alternative crop, whereas economic gains for GM producers that are not granted with property rights are the result of either increasing non-GM yields or decreasing non-GM production costs.

For the particular landscape analyzed it appears that the property right assignment that reduces both losses and gains is the one for which GM producers are obliged to create buffers (economic gains or losses equal to $53 compared to $81 per hectare). It is worth noting that all scenarios indicate above do not have the same probability of happening. The likelihood for instance for an increase in the GM market price is probably low and might for example arise from potential higher willingness to pay for 2nd generation GM products. Also, a relative increase of non-GM yields or decrease of non-GM production costs is very unlikely to happen. A reduction in non-GM production costs is very likely to also impact GM production costs (the majority of agrochemicals is used for both GM and non-GM production systems), whereas a genetic selection specifically targeted to non-GM crops might have the effect to increase non-GM yields.

8 Conclusions, limitations and future developments.

The findings of this study should be considered in light of the following assumptions: land is allocated into buffers in an optimal way, different from what is usually prescribed (homogeneous buffers in width). Perfect information for farmers is presumed, not only relating to what the neighboring farmers do, but also in terms of exact dynamics of contamination. These assumptions are needed to make possible the elicitation of the spatial components that determines the magnitude of the economic losses from buffer creation on the basis of the property right assignments.

The initial investigation of the role of heterogeneity of landscapes in terms of the possibility for GM and non-GM crops to coexists shows that the deviation from homogeneous spatial configurations determines an increasing economic harm to whom is obliged to take action to prevent cross contamination at the set threshold levels. Also, the results show the effects of spatial heterogeneity in terms of relative profitability between crops. The importance of this measure arises from the fact that it gives indication of the unobserved economic factors that determine the presence or not of coexistence between crops on the landscape. Being a preliminary study, further analyses need to be performed. In particular, the main urge is to identify adequate sets of indicators capable to reduce heterogeneity into quantifiable variables, such as for instance the perimeter/area ratio. Also, to elicit the effect of any of the indicators of spatial heterogeneity, it is important to analyze other spatial configurations, so to elicit general effects in terms of distributions of data. There are factors that are not included in the spatial analysis, such as other land types that could form natural barriers to pollen drift like hedgerows, infrastructure systems, woodland, surface waters, other crops, and urban areas. The effects that these other land types have on the possibility of coexistence vary in magnitude and require analysis to be fully understood. Rotation of crops, maturity groups of crop varieties used, sowing time and all the agricultural practices that have potential effects on flowering dates also have an impact on cross-contamination rates and therefore on the possibility of coexistence between GM and non-GM crops, but have not been taken into account in the simulation model which assumes these parameters are fixed to sharpen the focus on spatial variability. Interactions among farmers and collective action can increase the rate of coexistence due to agreements that allow farmers to better coordinate with each other. The model proposed does not simulate interactions between farmers. The time frame is one season, and this does not allow us to consider irreversibility, nor the market fluctuations and technological improvements that occur over time. Future developments can relax any of the limitations above: a possible development would be the creation of an agent based model that simulates at a micro level the interactions between farmers to elicit patterns of behavior at the macro-level that influence coexistence on a heterogeneous landscape. Such a model could tackle the issue of coordination/conflict among farmers, and create scenarios that evolve over time from initial situations to elicit alternate patterns of coexistence.

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