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Quantifying the effect of buffer zones, crop areas and spatial aggregation on the externalities of genetically modified crops at landscape level

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ABSTRACT

The development of genetically modified (GM) crops has led the European Union (EU) to put forward the concept of 'coexistence' to give farmers the freedom to plant both conventional and GM varieties. Should a premium for non-GM varieties emerge in the market, 'contamination' by GM pollen would generate a negative externality to conventional growers. It is therefore important to assess the effect of different 'policy variables' on the magnitude of the externality to identify suitable policies to manage coexistence. In this paper, taking GM herbicide tolerant oilseed rape as a model crop, we start from the model developed in Ceddia et al. [Ceddia, M.G., Bartlett, M., Perrings, C., 2007. Landscape gene flow, coexistence and threshold effect: the case of genetically modified herbicide tolerant oilseed rape (*Brassica napus*). Ecol. Modell. 205, pp. 169–180] use a Monte Carlo experiment to generate data and then estimate the effect of the number of GM and conventional fields, width of buffer areas and the degree of spatial aggregation (i.e. the 'policy variables') on the magnitude of the externality at the landscape level. To represent realistic conditions in agricultural production, we assume that detection of GM material in conventional produce might occur at the field level (no grain mixing occurs) or at the silos level (where grain mixing from different fields in the landscape occurs). In the former case, the magnitude of the externality will depend on the number of conventional fields with average transgenic presence above a certain threshold. In the latter case, the magnitude of the externality will depend on whether the average transgenic presence across all conventional fields exceeds the threshold. In order to quantify the effect of the relevant 'policy variables', we compute the marginal effects and the elasticities. Our results show that when relying on marginal effects to assess the impact of the different 'policy variables', spatial aggregation is far more important when transgenic material is detected at field level, corroborating previous research. However, when elasticity is used, the effectiveness of spatial aggregation in reducing the externality is almost identical whether detection occurs at field level or at silos level. Our results show also that the area planted with GM is the most important 'policy variable' in affecting the externality to conventional growers and that buffer areas on conventional fields are more effective than those on GM fields. The implications of the results for the coexistence policies in the EU are discussed.

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1. Introduction

In Europe the main production-related issues associated with the introduction of GM crops are being addressed in the coexistence debate (e.g. Bock et al., 2002; Boelt, 2003). Coexistence is entirely an economic problem and therefore it does not refer to the environmental impact of GM crops, which is dealt with separately before authorization for release into the environment of these crops is granted (according to EU Directive 18/2001) and will not be addressed here[1]. The ability of transgenic crops to produce pollen and 'contaminate' conventional (and organic) produce has led the European Council to adopt two important regulations on GM food and feed. The Council has established the maximum level of tolerance for adventitious presence (AP) of GM material in conventional product at 0.9%. Beyond this threshold, products have

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[1] This does not apply to confined commercial releases of traits that might pose human or environmental risk, but might be allowed to be cultivated in very regulated conditions which provide sufficient trait confinement.

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to be labelled as containing or originating from GM material. Should a premium for non-GM products appear in the market (e.g. Chern et al., 2002), the AP of GM material in conventional crops would generate a negative externality on conventional growers. This externality will exhibit a *threshold effect*: it will be zero for levels of AP below 0.9% but will jump to the full value of the externality for levels of AP above 0.9%. It is therefore important to understand how the extent and spatial distribution of GM crops in the landscape and the adoption of specific farm management practices (e.g. buffer areas on GM and conventional fields) affect conventional growers through the negative externality.

In this paper, we focus on oilseed rape (OSR) (*Brassica napus* L.) because it is an important crop in the EU and for which GM herbicide tolerant (HT) varieties are already extensively grown in other countries (e.g. Canada). OSR has been modified to be tolerant to broad-spectrum herbicides. The main reason for the large-scale adoption of GM HT OSR appears to be the greater flexibility in weed management allowed by such varieties (e.g. Canola Council of Canada, 2001). Surveys reveal that even European farmers consider the greater flexibility in weed control practices to be the main reason for adopting GM HT OSR (Graef et al., 2007). We look at the implications of pollen-mediated gene flow for the coexistence of GM and conventional crops and therefore exclude the impact on organic growers. We also ignore other sources of gene flow, such as seed lot contamination (e.g. Friesen et al., 2003) and ferals and volunteers[2].

Gene flow through pollen is controlled by a number of factors including level of outcrossing and mode of pollen dispersal. A large body of research has established that pollen concentration decreases rapidly within a few metres from the source (e.g. see Salisbury (2002) for a review). This can be represented graphically by a leptokurtic curve (e.g. Klein et al., 2006; Lavigne et al., 1998). Because pollen mediated gene flow is distance-dependent, the level of transgenic presence in conventional fields will depend (among other things) on the number of GM and conventional fields in the landscape, the width of buffer areas and the level of spatial aggregation. In its guidelines for coexistence the European Commission (EC) explicitly refers to the necessity of adopting buffer areas on adjacent GM and conventional fields (European Commission, 2003). In the same document the EC suggests that voluntary collaboration among farmers to achieve a more spatially aggregated configuration of GM and conventional fields would be desirable.

Our objective is to assess the impact of different ‘policy variables’ on the magnitude of the externality associated with the AP of GM material in conventional produce at the landscape level. Ceddia et al. (2007) assessed the effect of spatial aggregation and extent of GM and conventional OSR area in the landscape on the magnitude of the externality to conventional growers. In this paper we expand the analysis in order to also account for the effect of specific farm management practices aimed at reducing the level of AP. On the basis of the policy indications on coexistence developed in recent years (e.g. Bock et al., 2002; Tolstrup et al., 2003) we include in our analysis the adoption of buffer areas on adjacent GM and conventional fields. This is important to understand the nature of the GM externality, and hence to develop strategies for minimizing the external costs of GM technology. The effect of separation distances between GM and conventional fields has not been included in the analysis. The omission is due to the fact that the concept of separation distance is meaningful only when referred to the distance between two individual fields. When looking at a landscape containing many fields (GM and conventional) it can be substituted by some measure of average distance. We feel that the use of an index of spatial aggregation, reflecting the degree of clustering of GM and conventional fields, will, to some extent, also reflect the average distance between GM and conventional fields in the landscape (i.e. higher aggregation implies higher average distance between GM and conventional fields). Finally, our analysis is essentially a static one (i.e. based on a single year), since it does not account for the impact of volunteers and feral populations. The structure of the paper is as follows. In Section 2, on the basis of the coexistence approach, we develop an analytical model for the externality associated with pollen-mediated gene flow under the alternative hypothesis that AP is detected at the field level or at the landscape level. We then illustrate the Monte Carlo experiment used to generate data on pollen mediated gene flow starting from an OSR individual plant pollen dispersal function (IDF). In Section 3 we use the generated data to estimate the analytical expressions developed in section 2. In the final section we discuss the most important findings and draw the major conclusions.

[2] In the EU the area of organic OSR is extremely limited (Brookes and Barfoot, 2004). Begg et al. (2006) note how GM volunteers might also represent a source of AP, but only in those fields where GM varieties were previously sown. This problem entirely pertains to the private decisions of each individual grower and therefore does not need regulatory intervention. The effects of seed lot contamination would be equivalent to operating with lower thresholds for maximum AP, and therefore would not affect the structure of our analysis.

2. Materials and methods

In the EU the coexistence of GM, conventional and organic agriculture is admitted as long as the economic consequences AP of GM material in conventional (and organic) crops are accounted for. When looking at the aggregate value of the externality across all conventional growers, the stage at which the AP of GM material is detected (at the farm gate or at the silo level) is important for the magnitude of the externality and for the policy options available to the regulator. At the moment it is safe to assume that detection of adventitious GM presence in conventional produce will occur at the field level (as in speciality grains). However, it is also interesting to look at the case where detection occurs at the silo level (e.g. because of accidental mixing). In this case it is possible that farmers will still receive the higher price (e.g. if the accidental mixing is not attributable to their fault or negligence), and the economic loss will fall on grain buyers instead. We model the two cases separately.

2.1. No grain mixing

In this case the test to ascertain whether the AP of GM material in conventional produce exceeds the 0.9% threshold is performed at the individual field level (i.e. at the farm gate). This is standard practice in the production of speciality grains, where the existence of significant premiums favours the use of contract farming and allows the contractor to check the quality of the individual crop harvests (e.g. Fulton et al., 2003). The farmer will lose the premium if the average AP level in his/her field exceeds the threshold. At the landscape level, the loss to conventional farmers will depend on the number of conventional fields generating produce with average AP levels above the threshold. The magnitude of the externality (E) across all conventional growers can then be expressed as

$$E = \Delta p \times C \tag{1}$$

where Δp indicates the premium for conventional produce and C indicates the conventional output originating from those fields with AP of GM material above the 0.9% threshold. From expression (1) it is clear that if $\Delta p = 0$ (i.e. if consumers show no preference for conventional produce) the externality will disappear. It is also clear that for a given premium the magnitude of E depends on C. The literature on pollen-mediated gene flow helps to shed some light on the factors that are likely to affect C. There are many factors controlling pollen-mediated gene flow, including level of outcrossing (i.e. fertilisation by foreign pollen), mode of pollen dispersal, area density of donors and recipients plants and level of spatial aggregation. In this paper we are interested in exploring the effect of the size of donor and recipient populations in the landscape (i.e. the GM and conventional OSR areas), level of spatial aggregation of the fields in the landscape and width of the buffer areas on the edges of adjacent GM and conventional fields. These variables are among those most likely to be considered in the regulation of coexistence. Thus, it follows that

$$C = F[\mathrm{CL}(l_G, l_C, A, d_G, d_C)] = C(l_G, l_C, A, d_G, d_C) \tag{2.a}$$

$$\frac{dF}{d\mathrm{CL}} > 0, \quad \frac{d^2F}{d\mathrm{CL}^2} \leq 0 \tag{2.b}$$

$$\frac{\partial C}{\partial l_G} > 0, \quad \frac{\partial C}{\partial A} < 0, \quad \frac{\partial C}{\partial d_G} < 0, \quad \frac{\partial C}{\partial d_C} < 0 \tag{2.c}$$

where CL indicates the area (net of the buffer) corresponding to those conventional fields with AP levels above the 0.9% threshold, F represents the production function necessary to convert an area measure (i.e. ha) into production volume (i.e. tons), l_G indicates the area corresponding to the fields planted with GM varieties, l_C the area corresponding to the fields planted with conventional varieties, A is an index of spatial aggregation, d_G indicates the width of the buffer area on the edge of GM fields adjacent to conventional fields and d_C indicates the width of the buffer area on conventional fields adjacent to GM fields.

Expression (2.b) implies that C only depends on the area CL (i.e. all other production factors are assumed to be applied in fixed proportion to land) on the basis of a production function F with decreasing marginal productivity. This is a common and reasonable assumption in agricultural production models, and reflects the fact that when crop areas are expanded poorer quality land and/or other inputs available only in fixed quantities might be used.

In general the greater the magnitude of the source population in a landscape (compared to the sink population), the higher will be the degree of outcrossing observed in the sink population (e.g. Bateman, 1947; Crane and Mather, 1943). In our case this implies that the higher the GM area in the landscape, the higher will be the level of AP in conventional fields. It is then reasonable to expect that both CL and C will increase when the GM area in the landscape increases (first inequality in expression (2.c)). On the other hand the level of outcrossing is higher when source and sink populations are scattered in the landscape (i.e. disaggregated) compared to situations in which source and sink populations are 'aggregated' in different parts of the landscape (e.g. Ennos and Clegg, 1982; Handel, 1983; Nieuwhof, 1963). It is then reasonable to expect that increasing spatial aggregation (i.e. clustering) of GM and/or conventional fields in the landscape will reduce the magnitude of C (second inequality in expression (2.c)). Finally, since pollen mediated gene flow is distance-dependent (e.g. Klein et al., 2006; Lavigne et al., 1998), it is reasonable to expect that C will decrease if the width of buffer areas on both GM and conventional fields increases (third and fourth inequality in expression (2.c)). The inequalities in expression (2.c) can be interpreted as hypotheses and will be tested empirically in Section 4. Note that in expression (2.c) we do not specify the partial derivative $\partial C/\partial l_C$ since a-priori its sign is ambiguous. On one hand an increase in the conventional crop area is likely to 'dilute' the AP level (i.e. 'dilution effect'), since an increase in the size of the receiving population (relative to the magnitude of the donor population) will lead to an increase in the targets for the pollen and to a reduction in the average rate of fertilisation from foreign pollen sources (e.g. Crane and Mather, 1943), the AP level in each conventional field will be the lower the larger the area planted with conventional crops. This would suggest a negative sign for the partial derivative. On the other hand, an increase in the conventional OSR area will increase the conventional output susceptible of having AP levels above 0.9% (i.e. 'production effect'). Even if AP level in each field is likely to be lower, the number of fields with AP above 0.9% might increase when the number of conventional fields increases[3]. This would suggest a positive sign for the partial derivative. Therefore, we delay the discussion of the sign of this partial derivative to the empirical analysis in Section 4.

2.2. Grain mixing

In this case grains from different conventional fields in the landscape are mixed together before the level of AP is ascertained. Although this is not standard practice when dealing with speciality grains, the mixing could still happen accidentally. To address this hypothesis, we assume that all the grains from the conventional fields in the landscape are mixed together. The value of the 'mixed grains' will depend on whether the average AP level in the mixed conventional grains AC is above or below the 0.9% threshold. Notice that in the case of accidental mixing it is possible that farmers will still receive the higher price (e.g. if the mixing is not attributable to their fault or negligence), and the economic loss will fall on the grain buyer. Such a loss still represents an externality and can be expressed as

$$\begin{aligned} &E = \Delta p \times F(l_C - \mathrm{buffer}_C) \quad \text{if} \quad \mathrm{AC} > 0.9\% \\ &\quad \text{otherwise} \quad E = 0 \end{aligned} \tag{3}$$

where $F(l_C\text{–buffer}_C)$ indicates the conventional output as a function of the land allocation to conventional OSR l_C net of the buffer and AC is the level of AP averaged across the whole conventional produce. Expression (3) implies that if AC exceeds the threshold then all the conventional produce will be contaminated and the grain buyer will face a loss. If AC is below the threshold, then no loss occurs.

When looking at the factors determining AC, once again we focus our attention on the 'policy variables', namely the area planted with GM and conventional varieties in the landscape, the level of spatial aggregation A and the width of the buffer areas on GM and conventional fields, so that

$$\mathrm{AC} = \mathrm{AC}(l_G, l_C, A, d_G, d_C) \tag{4.a}$$

$$\frac{\partial \mathrm{AC}}{\partial l_G} > 0, \quad \frac{\partial \mathrm{AC}}{\partial l_C} < 0, \quad \frac{\partial \mathrm{AC}}{\partial A} < 0, \quad \frac{\partial \mathrm{AC}}{\partial d_G} < 0, \quad \frac{\partial \mathrm{AC}}{\partial d_C} < 0 \tag{4.b}$$

Notice how in expression (4.b) we assume that increasing the conventional OSR area will reduce the average AP level. When AP is averaged across the whole conventional crop area, it is reasonable to expect that the larger the area the lower will be AC. Once again the inequalities in expression (4.b) are hypotheses and will be tested in the empirical analysis in Section 4.

2.3. The Monte Carlo experiment

The model employed here is relatively simple, since it does not take into account important factors like flower synchrony, seed

[3] However, the proportion of conventional fields with AP levels above 0.9% is likely to decrease when the number of conventional fields is increased.

survival, emergence patterns etc., but it focuses instead on some of the variables that are expressly being targeted by the evolving coexistence regulations in the EU. Colbach et al. (2005), for example, relies on the GENESYS model (Colbach et al., 2001a,b) to make accurate assessments of gene flow in OSR under 'real' agricultural conditions. By focusing on a more limited number of variables we are able to provide stylised results on the effectiveness of different instruments to minimise the externality at the landscape level, while accounting for situations where AP detection occurs at the individual field or silo levels. Also, the approach developed here could be integrated into more complex models.

In this paper we start from the model developed in Ceddia et al. (2007) and extend it to account for the effect of buffer areas on conventional and GM fields. Given the similarities between the two approaches, we only provide a brief description here and refer the reader to the cited paper. A 100 ha landscape, consisting of a 1000×1000 two-dimensional grid of cells, each measuring 1 m^2, is defined. The crop landscape can then be modelled as consisting of plants placed at the centre of each of these cells. This grid of cells is divided conceptually into 100 identical 1 ha fields. This field size was chosen because of computational constraints and given the variability in field sizes across the EU it is difficult to identify typical field sizes. Since the purpose of the analysis is not to make exact predictions but rather to provide stylized results, the limitations to the analysis imposed by small field size is not necessarily a problem.

Assume that a proportion l_G of the 100 fields consists of GM OSR, a proportion l_C consists of conventional OSR while the remaining $100 - l_G - l_C$ fields consist of another crop (e.g. winter wheat, barley etc.). Also assume that when a GM OSR and a conventional field are adjacent to each other buffer areas of width d_G and d_C are applied on the bordering sides of the fields. In this experiment both the GM and conventional buffers are assumed to be left bare[4]. In order to calculate the level of GM cross-pollination in each conventional field an average IDF, as estimated by Lavigne et al. (1998), is used. Different IDFs for OSR have been estimated (e.g. Devaux et al., 2007; Klein et al., 2006). Each one would generate slightly different results, but given the preliminary nature of our analysis we believe that starting from Lavigne et al. (1998) is appropriate. Using this pollen dispersal function for OSR 54.65% of the pollen produced in a cell falls on the square itself, while the remaining 45.35% disperses according to the negative exponential function $f(d) = K((0.125)^2/2\pi)e^{-0.125d}$ (where d is the radial distance from the source and K is a constant to ensure the integral of the function is unity). From this function, for each non-GM cell, we calculate the proportion of pollen received that is GM.

In addition to pollen flow, the ovules targeted are important. OSR is partially self-fertilised: only a proportion of the ovules of each plant will be fertilised by foreign pollen. In the experiments carried out by Lavigne et al. (1998), the selfing rate was found to be 0.589 ± 0.065. As no information was reported on the shape of this distribution, the model assumes a uniform distribution for simplicity. GM AP levels at the scale of fields, as the average of the AP level of each cell in that field[5] can then be obtained.

During the simulation the area of conventional crop (net of the buffer) corresponding to those fields with AP levels above the 0.9% threshold, CL, was recorded. In order to compute C a production function F is needed (as in expression (2.a)). To specify this function we draw on UK data on OSR production and area over the period 1984–2003 and fit a Cobb–Douglas form. The value of the scale parameter is adjusted in order to account for the difference between the magnitude of our simulation environment (100 ha) and UK acreage of winter OSR (200,000–500,000 ha). On the basis of the estimated relationship we set $C = F(\mathrm{CL}) = 3(\mathrm{CL})^{0.9}$. Finally we calculate AC as the average GM content across all conventional fields.

The main purpose of the simulation is to generate data in order to estimate expressions (2.a) and (4.a) and to test expressions (2.c) and (4.b). To ensure enough variability in the data generation process and better estimate their effect on C and AC, in each run of the simulation we assume that the 'policy variables' are drawn from independent uniform distribution as follows: $l_G \sim U(13,52)$, $l_C \sim U(12,48)$, $d_G \sim U(0,10)$ and $d_C \sim U(0,10)$. The maximum width of the buffer areas was set at 10 m, given the relatively small size of the fields (1 ha).

Starting from an IDF function allows us to account not only for the effect of GM OSR area, conventional OSR area and buffers, but also to assess the effect of spatial aggregation of GM and conventional fields in the landscape on both C and AC. In each simulation run the position of the GM and conventional fields in the landscape was randomly assigned. In reality it is reasonable to believe that fields with similar crops are not located randomly in the landscape (e.g. Castellazzi et al., 2007). In particular, the presence of the externality might induce the recipient of the externality (the conventional farmers in our case) to cluster away from the generators (the GM fields in our case) (e.g. Parker and Munroe, 2007). However, assuming random field locations is necessary in the Monte Carlo experiment in order to obtain sufficient variability in the aggregation variable A to better estimate its effects on C and AC, respectively. Once C and AC have been estimated, it is still possible to infer the implications of changes of the relevant variables (e.g. crop areas, buffer areas) for different levels of spatial aggregation. The level of spatial aggregation is quantified by using the aggregation index developed by He et al. (2000).

$$A = \sum_{i=1}^{n} A_i \times a_i \tag{5.a}$$

$$A_i = \frac{e_{i,i}}{\max\_e_{i,i}} \tag{5.b}$$

where A: aggregation index for the landscape, A_i: aggregation index for the ith class, $e_{i,i}$: total number of edges shared by the ith class, max_$e_{i,i}$: maximum (possible) number of edges shared by the ith class, a_i: % of the landscape occupied by the ith class, n: total number of classes.

The aggregation index is a number between 0 and 1 and is equal to 0 (is equal to 1) when the configuration is completely disaggregated (aggregated).

3. Results

Through repeated simulations (3000 runs), we generate data in order to estimate expressions (2.a) and (4.a) and tests (2.c) and (4.b). Table 1 provides descriptive statistics for the main data recorded during the simulation while Fig. 1 illustrates the simulation environment.

3.1. The output with AP levels above 0.9%

The data generated through the simulation are used to fit the following functional form for expression (2.a)

$$\log(C) = \beta_0 + \beta_1 \log(l_G) + \beta_2 \log(l_C) + \beta_3 d_G + \beta_4 d_C + \beta_5 A + u \tag{6.a}$$

[4] An extension of the model could consider the effect of having conventional buffers planted with OSR which could be subsequently sold as GM.

[5] In doing so, the cells that belong to the buffer areas are not considered.

Table 1
Descriptive statistics for the variables in the simulation

Variables	Description (unit)	Mean	S.D.	Minimum	Maximum	# Cases
l_G	# of 1 ha GM fields (# and/or ha)	32.523	11.503	13	52	3000
l_C	# of 1 ha conventional fields (# and/or ha)	29.891	10.753	12	48	3000
d_G	Buffer width on GM fields (m)	4.969	3.15	0	10	3000
d_C	Buffer width on conventional fields (m)	5.149	3.163	0	10	3000
A	Aggregation index	0.411	0.058	0.246	0.663	3000
CL	Conventional fields with AP $\geq$ 0.9% (ha)	6.23	6.21	0	35	3000
C	Output produced on CL (tons)	18.71	18.58	0	104.1	3000
AC	Average AP level in all conventional fields (%)	0.59	0.30	0.075	1.82	3000

Given the use of logarithm transformation, observations in which $C = 0$ have been dropped from the sample.

Expression (6.a) is estimated through generalised least squares (GLS), in order to correct for the detected heteroskedasticity in the error terms u (Wooldridge, 2002). The correct specification hypothesis is tested through the RESET test (Wooldridge, 2002) and cannot be rejected at the 0.1% significance level. The estimation results are reported in Table 2.

Estimation of expression (6.a) will yield the predicted value $\overline{\log(C)}$ and the regression standard error $\bar{\sigma}$. Then the predicted value of C can be retrieved as follows (Wooldridge, 2000)

$$\bar{C} = \exp\left(\frac{\bar{\sigma}^2}{2}\right)\exp(\overline{\log(C)}) \tag{6.b}$$

If information about the premium Δp exists, the externality E can be computed through expression (1).

A preliminary analysis of the results in Table 2 suggests that C increases with the area planted with GM and conventional OSR (l_G and l_C, respectively) and decreases as the width of buffer areas (d_G and d_C) and the degree of spatial aggregation (A) increase.

3.2. The average level of AP across all conventional produce

The following expression is fitted to expression (4.a)

$$\log(\text{AC}) = \gamma_0 + \gamma_1\log(l_G) + \gamma_2\log(l_C) + \gamma_3\log(d_G) + \gamma_4\log(d_C) + \gamma_5\log(A) + u \tag{7.a}$$

Again, given the use of logarithm transformation observations with $d_G = 0$ and $d_C = 0$ have been dropped from the sample (all the other variables are always different from zero).

Expression (7.a) is estimated through ordinary least squares (OLS), since the null hypothesis of homoskedastic error terms, u,

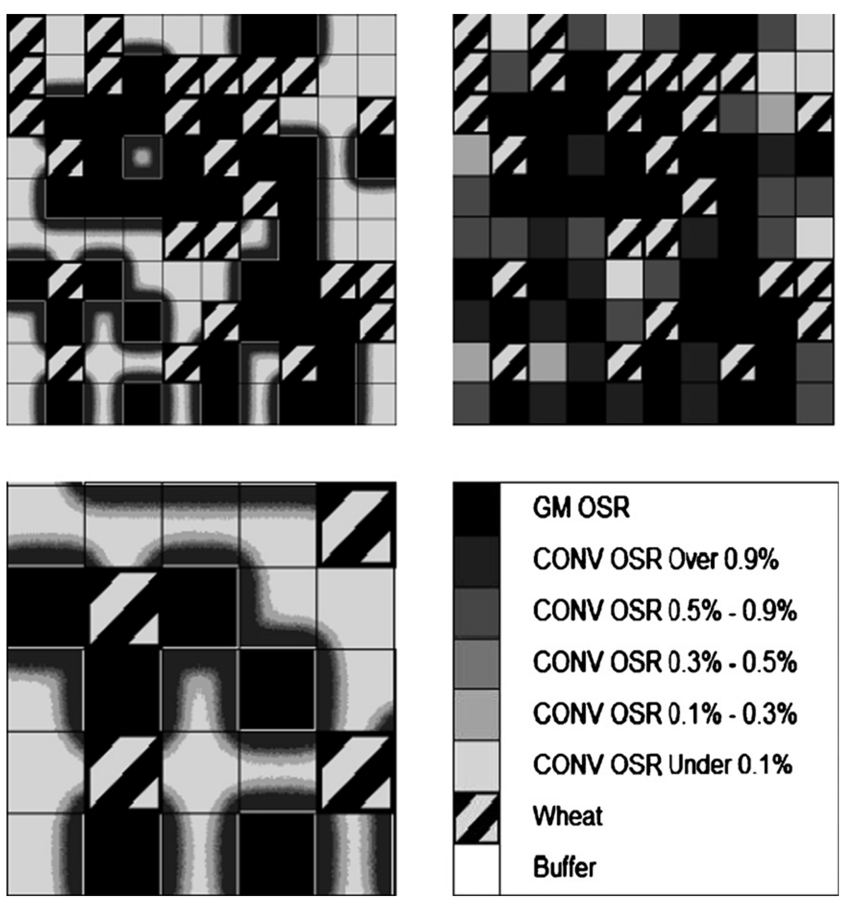

Fig. 1. Pollen mediated AP levels in conventional fields at 1 m^2 level (top left panel) and averaged within a field (top right panel). The bottom left panel illustrates an enlargement of the top left panel, while the colour scale used is represented in the bottom right panel.

Table 2
Regression coefficients (and standard errors) reflecting the effect of the listed variables on the conventional output with adventitious presence above 0.9% (C)

Variables	Coefficients (β) of expression (6.a) (and standard errors)
Constant	-3.34^{***} (0.12)
$\log(l_G)$	1.47^{***} (0.021)
$\log(l_C)$	0.67^{***} (0.019)
d_G	-0.078^{***} (0.0023)
d_C	-0.17^{***} (0.0024)
A	-0.77^{***} (0.13)
Adjusted R^2	0.81
N	2,628
$\Pr > F$	0.0000

The significance level ***corresponds to 0.1%.

Table 3
Regression coefficients (and standard errors) reflecting the effect of the listed variables on the average level of adventitious presence across all conventional fields (AC)

Variables	Coefficients (γ) of expression (7.a) (and standard errors)
Constant	-3.21^{***} (0.043)
$\log(l_G)$	1^{***} (0.009)
$\log(l_C)$	-0.11^{***} (0.009)
$\log(d_G)$	-0.22^{***} (0.005)
$\log(d_C)$	-0.32^{***} (0.005)
$\log(A)$	-0.29^{***} (0.027)
Adjusted R^2	0.89
N	2,491
Pr > F	0.0000

The significance level ***corresponds to 0.1%.

could not be rejected at the 0.1% significance level. The RESET test does not allow us to reject the null hypothesis of correct specification at the 0.1% significance level. The estimation results are reported in Table 3.

Estimation of expression (7.a) will yield the predicted value $\overline{\log(\mathrm{AC})}$ and the regression standard error $\bar{\sigma}$. Then the predicted value of AC can be retrieved as follows (Wooldridge, 2000):

$$\overline{\mathrm{AC}} = \exp\left(\frac{\bar{\sigma}^2}{2}\right)\exp(\overline{\log(\mathrm{AC})}) \tag{7.b}$$

If Δp is known E can now be calculated according to expression (3) and using the usual production function.

A preliminary analysis of the results in Table 3 suggests that AC is increasing in the area planted with GM OSR and decreasing in the area planted with conventional OSR, in the width of buffer areas (d_G and d_C) and in the degree of spatial aggregation (A).

3.3. Comparative analysis

In order to assess the effect of changes in the variables l_G, l_C, d_G, d_C and A on C and AC, respectively, we look at the marginal effect (ME) and elasticity. Given a function $f(x_1, \ldots, x_n)$, the ME with respect to the kth variable is defined as $\mathrm{ME}_k = \partial f(\cdot)/\partial x_k$, while the elasticity with respect to the same variable is defined as $\varepsilon_k = \partial f(\cdot)/f(\cdot)/\partial x_k/x_k$. The ME indicates the change in the dependent variable (C and AC in our case) associated with small changes in the independent variable under consideration (assuming that all other dependent variables are constant). However, Cariboni et al. (2007) noted that when independent variables are expressed in different units (as in our case) the use of the elasticity is more appropriate. The elasticity indicates the % change in the dependent variable for a 1% change in the independent variable under consideration (assuming that all other dependent variables are held constant). Table 4 illustrates the ME and elasticity for C and AC, when all the dependent variables are evaluated at their sample mean[6].

Under the hypothesis of no grain mixing, the analysis of the ME tells us that C is increasing in the GM area and is decreasing in the width of the buffers (on GM and conventional fields) and in the degree of spatial aggregation. This confirms the hypothesis in expression (2.c). Also $\partial C/\partial l_C > 0$, implying that if no grain mixing occurs the 'dilution effect' is dominated by the 'production effect'. The ME analysis suggests that when no grain mixing occurs, the degree of spatial aggregation is the most important factor in determining C. Moreover, it appears that buffer areas on conventional fields are more effective than buffer areas on GM fields. This could be due to the fact that the largest AP concentration occurs always on the edges of conventional fields (i.e. when such edges are left bare because of the buffers, the AP levels within the field are significantly lowered and therefore a larger proportion of fields will register AP levels below 0.9% which in turn will greatly reduce the magnitude of C). Also when the buffer is applied on the conventional fields the conventional output susceptible to contamination is reduced. However, an analysis of the elasticities indicates that spatial aggregation is the least important factor in affecting C. A 1% increase in spatial aggregation will reduce C by only 0.32%, while a 1% reduction in the GM area will reduce C by 1.47%. The analysis of elasticity confirms that buffer areas on conventional fields are more effective in reducing C than analogous buffers on GM fields.

Under the hypothesis of grain mixing, the analysis of the ME tells us that AC is increasing in the GM area and is decreasing in the conventional crop area (because of dilution), in the width of the buffers (on GM and conventional fields) and in the level of spatial aggregation, confirming the hypothesis in expression (4.b). Spatial aggregation turns out to be the most important factor in affecting AC. When we look at elasticities, the effect of spatial aggregation is dominated by the effect of the GM area and buffer areas on conventional fields. Even in this case conventional buffers are always more effective than GM buffers.

Until now we assumed that all variables, including A are evaluated at the sample mean. We already pointed out how in reality the distribution of GM and conventional fields in the landscape might be more clustered than what our simulation assumes. Then, it is possible to use the estimated relationships for C and AC, respectively, to understand how the ME and the elasticities described above change when A is increased. To see this we set A at its sample maximum value ($A = 0.663$), while keeping all the other dependent variables at the sample mean. The new results are illustrated in Table 5.

By comparing the results in Table 5 with those reported in Table 4, it is immediately evident that the relative importance of the different variables, whether assessed on the basis of ME or elasticities, does not change. It is also evident that all the marginal effects are smaller (i.e. when A is higher a change in any dependent variable has a smaller impact on C and AC). However, when looking at elasticities the only difference is in the effect of A on C. This suggests that the results are quite robust to changes in the level of aggregation designed to better represent real situations. In particular, when A is increased to its maximum value, the elasticity of C with respect to A changes from -0.32 to -0.51 (i.e. the response becomes more elastic).

[6] Both ME and elasticity vary along the function $f(x_1, \ldots, x_n)$. As such they must be estimated at a certain 'point'. In Table 4, we calculate ME and elasticity at the sample mean. Given the 'log–log' specification in (7.a), the estimated coefficients already represent elasticities.

Table 4
Estimated marginal effects and elasticities of the listed variables on the conventional output with adventitious presence above 0.9% (as from expressions (6.a) and (6.b)) and on the average level of adventitious presence across all conventional fields (as from expressions (7.a) and (7.b))[a,b]

Variables	C (expression (6.a) and (6.b))		AC (expression (7.a) and (7.b))	
	Marginal effect	Elasticity	Marginal effect	Elasticity
l_G	0.51^{***} (0.009)	1.47^{***} (0.021)	0.014^{***} (0.00016)	1^{***} (0.009)
l_C	0.26^{***} (0.008)	0.67^{***} (0.019)	-0.0017^{***} (0.00015)	-0.11^{***} (0.009)
d_G	-0.9^{***} (0.031)	-0.43^{***} (0.00002)	-0.019^{***} (0.00049)	-0.22^{***} (0.005)
d_C	-1.96^{***} (0.028)	-0.95^{***} (0.00003)	-0.027^{***} (0.00046)	-0.32^{***} (0.005)
A	-8.89^{***} (1.71)	-0.32^{***} (0.008)	-0.34^{***} (0.032)	-0.29^{***} (0.027)

The significance level ***corresponds to 0.1%.
[a] All dependent variables are evaluated at the sample mean.
[b] The standard errors for the marginal effects and elasticities reported in the table have been computed using the delta method, as illustrated in Wooldridge (2002).

Table 5
Estimated marginal effects and elasticities of the listed variables on the conventional output with adventitious presence above 0.9% (as from expressions (6.a) and (6.b)) and on the average level of adventitious presence across all conventional fields (as from expressions (7.a) and (7.b))[a,b]

Variables	C (expression (6.a) and (6.b))		AC (expression (7.a) and (7.b))	
	Marginal effect	Elasticity	Marginal effect	Elasticity
l_G	0.42^{***} (0.019)	1.47^{***} (0.021)	0.013^{***} (0.00025)	1^{***} (0.009)
l_C	0.21^{***} (0.012)	0.67^{***} (0.019)	-0.0015^{***} (0.00012)	-0.11^{***} (0.009)
d_G	-0.74^{***} (0.039)	-0.43^{***} (0.00002)	-0.017^{***} (0.0005)	-0.22^{***} (0.005)
d_C	-1.62^{***} (0.067)	-0.95^{***} (0.00003)	-0.024^{***} (0.00054)	-0.32^{***} (0.005)
A	-7.32^{***} (1.13)	-0.51^{***} (0.012)	-0.18^{***} (0.015)	-0.29^{***} (0.027)

The significance level ***corresponds to 0.1%.
[a] A is set to the sample maximum ($A = 0.663$) while all other dependent variables are evaluated at the sample mean.
[b] The standard errors for the marginal effects and elasticities reported in the table have been computed using the delta method, as illustrated in Wooldridge (2002).

4. Discussion

Coexistence in the EU aims to guarantee both farmers and consumers freedom of choice between GM, conventional and organic production. Over the past years, considerable effort has been devoted to studying the implications of pollen-mediated gene flow for coexistence for a number of crops, including OSR. Damgaard and Kjellson (2005), on the basis of existing data on pollen-mediated gene flow in OSR, analysed the effect of separation distances, conventional field width and buffer width on the average AP level within the receiving field. Their results show how AP declines with increasing separation distances, increasing conventional field width and increasing buffer width. Colbach et al. (2005), relying on the GENESYS model (Colbach et al., 2001a,b) used a Monte Carlo experiment to assess the effect of field characteristics and crop patterns on the AP level in a given field. Their results show that cropping systems are more important than field characteristics. Ceddia et al. (2007), starting from an OSR IDF, developed a Monte Carlo simulation and analysed the effect of the extent of GM adoption and spatial aggregation on the externality to conventional growers at the landscape level, with and without grain mixing. On the basis of the analysis of ME the authors concluded that the degree of spatial aggregation is much more important when no grain mixing occurs. Analysis of pollen-mediated gene flow has been focused mainly on the effect of distance on cross-pollination rates at a certain point in the field and to a lesser extent on the effect of agricultural practices on levels of AP averaged within a field (e.g. Colbach et al., 2005; Damgaard and Kjellson, 2005). Our analysis is innovative in different respects. First, it extends the analysis by looking at the implications of AP on the externality to conventional growers at the landscape level. While the effects of crop areas and spatial aggregation on the landscape externality to conventional producers have been analysed before, the effects of buffer areas have not. Second, it looks at the effect of buffer areas on both GM and conventional fields. To the best of our knowledge, an analysis comparing the relative effectiveness of buffers on GM and conventional fields has not yet been published. Third, the paper also carries out the analysis based on elasticity, since this might be a more appropriate indicator than ME (Cariboni et al., 2007). The way in which the effects of the different 'policy variables' on the externality to conventional growers are quantified bears important consequences for policy, and therefore, particular care should be taken in choosing the appropriate indicator. When looking at ME, our results suggest that spatial aggregation is far more important when no grain mixing occurs as in Ceddia et al. (2007). However, when relying on the elasticity this is no longer true, since it turns out that a 1% increase in A will reduce C by 0.32% and AC by 0.29%. When looking at the effects of buffers, our experiment indicates that d_C is always more effective than d_G with or without grain mixing. The current model could be easily extended to account for situations in which conventional buffers are planted with conventional OSR. In this case it is likely that the effectiveness of a conventional buffer would be even higher (since the conventional buffer would produce additional pollen that would compete with the GM pollen). Finally, in our experiment the most important variable turns out to be the magnitude of the GM crop area (l_G) since a 1% reduction in l_G would reduce C by 1.47% and AC by 1%. The results are also quite robust to changes in the degree of spatial aggregation, designed to represent more realistic situations (e.g. land use clusters).

Our results cannot be immediately generalised, since they depend on the parameter values and the IDF chosen in our experiment. For example, using a different IDF with a 'fatter tail' (i.e. higher level of gene flow at longer distances as in Klein et al., 2006), could make spatial aggregation less important and/or it could make buffer areas on GM fields more important. Increasing field size would probably reduce the extent of AP level at field and landscape levels. Rieger et al. (2002) record AP level at field scale below 0.03% in Australia where field size varies between 25 and 100 ha.

Despite these limitations, our results are still relevant for coexistence policies. At present the main focus of such policies turns out to be the establishment of mandatory buffer areas on GM fields (so that no conventional fields have AP above 0.9%) and to a lesser extent to promote clustering of GM and conventional fields in different parts of the landscape. Our experiment indicates that with or without grain mixing the effect of the magnitude of the GM area and buffers on conventional fields always dominates the effect of spatial aggregation and buffers on GM fields. Therefore, specific attention should be devoted to these factors when designing coexistence policies. Since conventional growers are the recipients of the externality, it is reasonable to expect that they will spontaneously adopt buffer areas on their own fields adjacent to GM fields in order to self-protect and so no specific regulatory intervention would be needed in this respect. GM growers, on the other hand, as generators of the externality have no incentives to reduce their plantings of GM varieties to benefit conventional growers. This calls for a specific intervention of the regulator so as to induce GM growers to reduce their GM area by introducing a mechanism (e.g. tax on GM seeds, legal redress, etc.) to internalize the externality. The identification of the specific policies for coexistence is beyond the scope of this paper and would have to be addressed on a case-by-case basis taking into account not only the biological characteristics of the species under consideration but also characteristics of the landscape (e.g. field sizes and shapes) and socio-economic factors (e.g. consumers' preferences, etc.). To this end, it would be extremely interesting to integrate our approach into more complex models (e.g. Colbach et al., 2001a,b, 2005). The practical management issue in the case of coexistence in the EU is to determine the relative pay-off to the different strategies to abate the externality (i.e. reducing GM area, increasing spatial aggregation, increasing buffer areas) for farming systems in which there is considerable variation in field size.

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References

Bateman, A.J., 1947. Contamination of seed crops. I. Relation with isolation distance. Heredity 1, 303–336.

Begg, G.S., Hockada, S., McNicol, J.W., Askew, M., Squire, G.R., 2006. Modelling the persistence of volunteer oilseed rape (*Brassica napus*). Ecological Modelling 198, 195–207.

Bock, A.K., Lheureux, K., Libeau-Dulos, M., Nilsagard, H., Rodriguez-Cerezo, E., 2002. Scenarios for coexistence of genetically modified, conventional and organic crops in European agriculture. Synthesis Report. Available at http://europa.eu.int/comm/agriculture/publi/reports/coexistence/index_en.htm.

Boelt, B., 2003 (Ed.). Proceedings of the 1st European conference on the coexistence of genetically modified crops with conventional and organic crops. Published by the Danish Institute of Agricultural Sciences, Research Centre Flakkebjerg DK-4200, Slagelse, Denmark.

Brookes, G., Barfoot, P., 2004. Co-existence of GM and non GM arable crops: the non GM and organic context in the EU. PG Economics Ltd. Dorchester, UK, May 2004. Available at http://www.pgeconomics.co.uk/pdf/Co-existencestudyEU_PG_Economicsmay2004.pdf.

Canola Council of Canada, 2001. An agronomic and economic assessment of transgenic canola. Available at http://www.canola-council.org/manual/GMO/gmo_main.htm.

Cariboni, J., Gatelli, D., Liska, R., Saltelli, A., 2007. The role of sensitivity analysis in ecological modelling. Ecological Modelling 203, 167–182.

Castellazzi, M.S., Perry, J.N., Colbach, N., Monod, H., Adamczyk, K., Viaud, V., Conrad, K.F., 2007. New measures and tests of temporal and spatial pattern of crops in agricultural landscapes. Agriculture, Ecosystems and Environment 118, 339–349.

Ceddia, M.G., Bartlett, M., Perrings, C., 2007. Landscape gene flow, coexistence and threshold effect: the case of genetically modified herbicide tolerant oilseed rape (*Brassica napus*). Ecological Modelling 205, 169–180.

Chern, W.S., Rickertsen, K., Tsuboi, N., Fu, T., 2002. Consumer acceptance and willingness to pay for genetically modified vegetable oil and salmon: a multiple-country assessment. AgBioForum 5 (3), 105–112.

Colbach, N., Clermont-Dauphin, C., Meynard, J.M., 2001a. GENESYS: a model of the influence of cropping system on gene escape from herbicide tolerant rape seed crops to rape volunteers. I. Temporal evolution of a population of rape seed volunteers in a field. Agriculture, Ecosystems and Environment 83, 235–253.

Colbach, N., Clermont-Dauphin, C., Meynard, J.M., 2001b. GENESYS: a model of the influence of cropping system on gene escape from herbicide tolerant rape seed crops to rape volunteers. II. Genetic exchanges among volunteer and cropped populations in a small region. Agriculture, Ecosystems and Environment 83, 255–270.

Colbach, N., Molinari, N., Meynard, J.M., Messean, A., 2005. Spatial aspects of gene flow between rapeseed varieties and volunteers. Agronomy for Sustainable Development 25, 355–368.

Crane, M.B., Mather, K., 1943. The natural cross-pollination of crop plants with particular reference to radish. Journal of Applied Biology 30, 301–308.

Damgaard, C., Kjellson, G., 2005. Gene flow of oilseed rape (*Brassica napus*) according to isolation distance and buffer zone. Agriculture, Ecosystems and Environment 108, 291–301.

Devaux, C., Lavigne, C., Austerlitz, F., Klein, E.K., 2007. Modelling and estimating pollen movement in oilseed rape (*Brassica napus*) at the landscape scale using genetic markers. Molecular Ecology 16, 487–499.

Ennos, R.A., Clegg, M.T., 1982. Effect of population substructuring on estimates of outcrossing rate in plant populations. Heredity 48, 283–292.

European Commission, 2003. Commission Recommendation of 23 July 2003 on guidelines for the development of national strategies and best practices to ensure the coexistence of genetically modified crops with conventional and organic farming (Document number C (2003) 2624). Official Journal L 189, 29/07/2003: 0036–0047.

Friesen, L.F., Nelson, A., Van Acker, R.C., 2003. Evidence of contamination of pedigreed canola (*Brassica napus*) seedlots in western Canada with genetically engineered herbicide resistance traits. Agronomy Journal 95, 1342–1347.

Fulton, J., Pritchett, J., Pederson, R., 2003. Contract production and market coordination for speciality crops: the case of Indiana. Paper presented at the Symposium 'Product Differentiation and Market Segmentation in Grains and Oilseeds: Implications for Industry in Transition'. Washington DC, January 27–28 2003. Available online at http://www.farmfoundation.org/projects/documents/Fulton.pdf.

Graef, F., Stachow, U., Werner, A., Schütte, G., 2007. Agricultural practice changes with cultivating genetically modified herbicide-tolerant oilseed rape. Agricultural Systems 94, 111–118.

Handel, S.N., 1983. Pollination ecology, plant population structure and gene flow. In: Real, L. (Ed.), Pollination Biology. Academic Press Inc., pp. 163–211.

He, S.H., DeZonia, B.D., Mladenoff, D.J., 2000. An aggregation index (AI) to quantify spatial patterns of landscapes. Landscape Ecology 15, 591–601.

Klein, E.K., Lavigne, C., Picault, H., Renard, M., Gouyon, P.H., 2006. Pollen dispersal of oilseed rape: estimation of the dispersal function and effects of field dimension. Journal of Applied Ecology 43, 141–151.

Lavigne, C., Klein, E.K., Vallee, P., Pierre, J., Godelle, B., Renard, M., 1998. A pollen dispersal experiment with transgenic oilseed rape. Estimation of the average pollen dispersal of an individual plant within a field. Theoretical and Applied Genetics 96, 886–896.

Nieuwhof, M., 1963. Pollination and contamination of *Brassica oleracea* L. Euphytica 12, 17–26.

Parker, D.C., Munroe, D.K., 2007. The geography of market failure: edge-effect externalities and the location and production patterns of organic farming. Ecological Economics 60, 821–833.

Rieger, M.A., Lamond, M., Preston, C., Powles, S.B., Roush, R.T., 2002. Pollen-mediated movement of herbicide resistance between commercial canola fields. Science 296 (5577), 2386–2388.

Salisbury, P.A., 2002. Genetically modified canola in Australia. In: Downey, R.K. (Ed.), Agronomic and Environmental Considerations. Australian Oilseeds Federations, p. 69.

Tolstrup, K., Andersen, S.B., Boelt, B., Buus, M., Gylling, M., Holm, P.B., Kjellson, J., Pedersen, S., Ostergard, H., Mikkelsen, S.A., 2003. Report from the Danish working group on the coexistence of genetically modified crops with conventional and organic crops. Ministry of Food, Agriculture and Fishery, Danish Institute of Agricultural Sciences.

Wooldridge, J., 2000. Introductory Econometrics: A Modern Approach. South-Western College Publishing.

Wooldridge, J., 2002. Econometric analysis of cross section and panel data. The MIT Press, Cambridge, Massachussets.