The Australian Journal of
Agricultural and Resource Economics
Journal of the Australian Agricultural and Resource Economics Society

The Australian Journal of Agricultural and Resource Economics, 55, pp. 126–143

On the regulation of spatial externalities: coexistence between GM and conventional crops in the EU and the 'newcomer principle'*

Michele Graziano Ceddia, Mark Bartlett, Caterina De Lucia and Charles Perrings†

Pollen-mediated gene flow is one of the main concerns associated with the introduction of genetically modified (GM) crops. Should a premium for non-GM varieties emerge on the market, 'contamination' by GM pollen would generate a revenue loss for growers of non-GM varieties. This paper analyses the problem of pollen-mediated gene flow as a particular type of production externality. The model, although simple, provides useful insights into coexistence policies. Following on from this and taking GM herbicide-tolerant oilseed rape (Brassica napus) as a model crop, a Monte Carlo simulation is used to generate data and then estimate the effect of several important policy variables (including width of buffer zones and spatial aggregation) on the magnitude of the externality associated with pollen-mediated gene flow.

Key words: coexistence, Monte Carlo simulation, pollen-mediated gene flow, production externalities.

1. Introduction

The coexistence of genetically modified (GM) and conventional crops in the EU is permitted by the principle that farmers should be able to cultivate freely the crops they choose, be they GM, conventional or organic. However, this is qualified by the need to account for any economic consequences arising from the adventitious presence (AP) of material from one crop in another (European Commission 2003). In 2003, the EU adopted two Regulations (EC Regulation 1829/2003 and 1830/2003) establishing a 0.9 per cent threshold for the maximum AP of GM material in conventional food and feed. As GM material can mix with conventional material (through pollen dispersal, for example) and as consumers might have a negative attitude towards GM produce, this leads to an externality problem. Because the level of contamination is distance dependent, spatial considerations are important. The aim of

* A previous version of this paper 'Policies for the regulation of coexistence between GM and conventional crops' was presented at the 12th Congress of the European Association of Agricultural Economics, 26-29 August 2008, Ghent, Belgium.

† Michele Graziano Ceddia (email: m.ceddia@reading.ac.uk) is at Department of Food Economics and Marketing, University of Reading, Reading, UK. Mark Bartlett is at Department of Computer Science, University of York, Heslington, York, UK. Caterina De Lucia is at Environment Department, University of York, Heslington, York, UK. Charles Perrings is at ecoSERVICES Group, School of Life Sciences, Arizona State University, Tempe, AZ, USA.

doi: 10.1111/j.1467-8489.2010.00518.x

regulation must be to identify measures (ex-ante and/or ex-post, Kolstad *et al*. 1990) that deal with the efficiency issues raised by GM crops.

An externality occurs when a decision by one actor directly affects another actor's utility/production relationship and no compensation is paid (Baumol and Oates 1988). Arrow (1970) shows such interdependences between utility/production relationships reflect the lack of a sufficiently rich set of markets and conflict with allocative efficiency. Markets may be missing for various reasons, including because of ill-defined property rights or excessive transaction costs. Coase's approach requires the definition of property rights as a way to stimulate private bargaining and promote efficiency (Coase 1960).

The different assignment of property rights in North America and in the EU has led to different regulations on coexistence. In North America, property rights have been assigned to GM adopters. This means that there is the right to grow GM without any special care for the effects on conventional and organic produce. In contrast, in the EU, property rights have been assigned to conventional and organic farmers (i.e., the 'newcomer principle') through the introduction of ex-ante technical measures (aiming at the elimination of the external cost) and ex-post liability (Beckmann *et al*. 2010). In an idealised situation in which there were no transaction costs, both allocations would stimulate bargaining and promote efficiency, although with different distributional implications. However, given transaction costs, bargaining may not occur, and assigning property rights to the GM adopter will favour the spread of GM varieties. In contrast, property rights assigned to conventional and organic growers will hinder GM adoption in the presence of transaction costs (Beckmann and Wesseler 2007).

The purpose of this paper is to show that, regardless of why property rights have been assigned to conventional/organic farmers, the EU measures go well beyond the promotion of allocative efficiency, which should be the prime reason for regulating coexistence. This is attributed to three reasons. First, the technical measures proposed in various EU Member States (e.g., buffer areas on GM fields) have the objective of completely eliminating the external cost. This is not consistent with efficiency, because it removes any incentive for the 'victim' to self-protect (Baumol and Oates 1988). Second, the liability measures reinforce this problem by providing victims with compensation. Metcalfe (1995) observes that *'...innovations are invariably connected with change and uneven distribution of their consequences...inevitably there will be gainers and losers and while the former may in principle be able to compensate the latter – otherwise we would have technical regress rather than technical progress – there is no reason why this compensation should take place...here one need only consider the consequences of allowing the owners of a group of firms to sue a more competitive rival for innovation related loss of profit to see the importance of this point.'* (pp. 413–414). Finally, as the simple economic model will show, a mutual interdependence exists between 'emitters' and 'victims'. Vatn and Bromley (1997) show that in such circumstances, efficiency may require abatement to be undertaken by both the 'emitters' and the 'victims'.

Over the past few years, economic literature on coexistence has begun to emerge. Munro (2007) is concerned with characterising a partial equilibrium in the presence of GM-contamination externalities. Separation distances between fields are the central element of his analysis. Similarly, Belcher *et al.* (2005) use a 'game of life' simulation to assess the effect of growing GM crops. Demont *et al.* (2009) use spatial analysis to discuss the relative merit of separation distances against buffer zones. Despite parallel advances in the agricultural/ecological literature, which have led to estimates of pollen dispersal curves, the existing economic research has not explicitly used pollen dispersal functions to assess the extent of contamination. Instead, it is common to rely on arbitrary heuristics (e.g., fields within a specific distance will be contaminated above the threshold). Such models do not allow the study of measures designed to limit the extent of cross-pollination between GM and conventional fields, such as the use of buffer areas around field edges. To identify a suitable policy, regulators should know not only the cost associated with it, but also its effectiveness.

In this paper, the general problem is considered with specific reference to one GM crop that is currently under consideration in the EU: herbicide-tolerant (HT) oilseed rape (henceforth simply GM OSR). GM OSR is already extensively grown in Canada and elsewhere because of its greater flexibility in weed management. There is evidence both that GM OSR contamination of conventional crops has occurred in those countries and that this contamination has had economic consequences (Friesen *et al.* 2003). This paper considers how such externalities might be addressed if GM OSR is admitted to the EU. To achieve this, an analytical model is first developed, which is capable of framing the efficiency issues raised by the coexistence of GM and conventional crops in the landscape. The available information about pollen-mediated gene flow is then used to characterise the relationship between the magnitude of the externality at the landscape level and a number of important 'policy variables', specifically the area of GM and conventional OSR in the landscape, the width of buffers on GM and conventional fields and the degree of spatial aggregation. This information is then used to inform a discussion on the different policy options for coexistence.

The structure of the remainder of the paper is as follows. Section 2 presents the analytical model to describe the coexistence problem within the framework of a production externality. Section 3 illustrates the Monte Carlo simulation used to generate data on pollen-mediated gene flow. Section 4 then uses the generated data to fit a functional form for the pollen-mediated gene flow externality. In particular, a far more flexible functional form than previously used (Ceddia *et al.* 2009) is considered. The last section discusses the results and draws conclusions.

2. The economic model

The problem addressed is the internalisation of spatial externalities whose characteristics depend on the pattern of GM technology adoption. In the model all fields are of identical size, but the effect of the GM trait on farms' economic returns differs between farms. This therefore impacts on the incentive of individual farms to adopt GM technology, which is also affected by the way in which the regulatory system assigns property rights (Beckmann *et al.* 2010). As a result, a number of farmers (the GM adopters) will allocate their land between the GM variety and an alternative crop, while other farmers (the non-adopters) will allocate their land between conventional OSR varieties and the alternative crop. Denote as L_g the arable land available to those farmers who adopt GM and $L_c = \overline{L} - L_g$ as the area available to the 'non-adopters', where $\overline{L}$ denotes the total arable land. Regulation of coexistence is assumed to occur before the new technology is introduced. For simplicity, the following two cases are considered:

- Property rights are assigned to GM farmers (as in North America). In this case, cultivation of GM varieties does not require the adoption of particular measures to prevent contamination of non-GM crops. The number of adopters will be relatively large, and the land available to adopters and non-adopters will be, respectively, L_g^U and $L_c^U = \overline{L} - L_g^U$.
- Property rights are assigned to conventional/organic farmers. However, rather than requiring the complete elimination of the externality (through ex-ante technical measures and/or ex-post liability), it is assumed that coexistence is moderately regulated so as to maximise joint profits of adopters and non-adopters. In this case, the number of GM farmers will be lower and the arable land available to adopters and non-adopters will be, respectively, $L_g^R < L_g^U$ and $L_c^R = \overline{L} - L_g^R > L_c^U$.

It is assumed that adoption of GM varieties is irreversible, and the possibility that farmers grow both GM and conventional varieties of the same crop is excluded. The analysis is static,[1] confined to the farm level and only addresses the problem of coexistence between GM and conventional OSR varieties, therefore excluding organic OSR. The costs of herbicide resistance development are not included in the analysis because they have been shown to be quite low (of the order of C$2 per acre in Canada, Canola Council of Canada 2005).

A consumer preference for conventional produce implies that the price of conventional crops p_c is higher than the price of the GM crop p_g (Chern *et al.* 2002). The price of the other crop is p_a. Farmers cannot influence these prices by their actions. Technology is represented through standard (concave)

[1] For dynamic considerations in the case of irreversible adoption of GM crops, see Beckmann *et al.* (2010).

production functions denoted as $f_g(\cdot)$, $f_c(\cdot)$ and $f_a(\cdot)$ for GM OSR, conventional OSR and the alternative crop, respectively.

The physical basis of the externality is assumed to be cross-pollination. Other sources of contamination (e.g., AP in seeds) are excluded for simplicity. When contamination at field level exceeds a 0.9 per cent threshold (as per EU regulations), the product must be labelled as GM and will be sold at the lower price p_g. Let E denote the contamination cost to the conventional farmers. Pollen-mediated gene flow is distance dependent. Contamination can therefore be reduced by increased clustering of fields of similar crop types or through the adoption of buffer areas on adjacent fields of conventional and/or GM crops (Tolstrup *et al.* 2003).

2.1. GM farmers have the 'property rights'

When assigned property rights, GM farmers have no incentive to set-up buffers or to cluster GM fields away from conventional fields to mitigate contamination of neighbouring conventional farmers. Let d_g denote the width of the buffer on GM fields and e_g denote the 'coordination effort' of GM farmers necessary to increase clustering. GM farmers will set $d_g = 0$ and $e_g = 0$, and their problem can be represented as follows

$$\underset{l_g, l_{ag}}{\text{Max}}\ p_g f_g(l_g) - c_g l_g + p_a f_a(l_{ag}) - c_a l_{ag} \tag{1}$$

$$\text{Subject to}\ l_g + l_{ag} = L_g^U \tag{2}$$

GM farmers maximise profits through their choice of land allocation to GM OSR l_g and to the alternative crop l_{ag}, given the fixed amount of land available L_g^U, the technology, output prices p_g and p_a and variable costs c_g and c_a. Land is the only argument of the production functions; all other inputs are applied in fixed proportions. The first-order necessary conditions (FONC, see Appendix) for problem (1, 2) imply that GM farmers will increase the area committed to GM crops up to the point where the marginal returns on GM OSR and the alternative crop are equalised, ignoring any impact on conventional farmers. The corresponding problem for the conventional farmers can be represented as follows

$$\underset{l_c, l_{ac}, d_c, e_c}{\text{Max}}\ p_c f_c(\hat{l}_c) - c_c \hat{l}_c - h a_c(\cdot) + p_a f_a(l_{ac}) - c_a l_{ac} - w e_c - E(\cdot) \tag{3}$$

$$\text{Subject to}\ l_c + l_{ac} = L_c^U = \overline{L} - L_g^U \tag{4}$$

where $\hat{l}_c = l_c - a_c$. As with GM farmers, conventional farmers maximise profits through the choice of land allocation to conventional OSR l_c and the alternative crop l_{ac}. In addition, they also choose appropriate buffer widths d_c

on conventional OSR fields adjacent to GM OSR fields (so as to create a buffer area a_c[2]) and a coordination effort e_c to cluster conventional fields away from GM fields. This is all under the constraints of a fixed amount of land L_c^U, technology, output prices p_c and p_a, variable production costs c_c and c_a, buffer area maintenance costs h and coordination effort costs w. The magnitude of the buffer area a_c depends on the area allocated to conventional OSR (the larger l_c the larger the buffer area a_c) and GM OSR (the larger l_g the larger the likelihood of a GM and conventional OSR field being adjacent), on the buffer width d_c eventually adopted and on the level of spatial aggregation (the more clustered the configuration the smaller the buffer area). Let A be a generic index of spatial aggregation such that $0 \leq A \leq 1$, where zero reflects a completely disaggregated configuration and one a completely aggregated one. From percolation theory[3] (Gustafson and Parker 1992), it is known that for $l_c = l_g = 0$, A will be identically equal to one, as if no OSR (conventional or GM) is grown, the whole landscape will be planted with the alternative crop, and the configuration of the landscape will be totally aggregated. If this trivial case is excluded, A is an increasing function of GM and conventional farmers' coordination efforts e_g and e_c. The conventional farmers' buffer area can then be expressed as $a_c = a_c(l_c, l_g, d_c, A(e_g, e_c))$. The magnitude of the buffer area will be zero if no GM OSR or no conventional OSR is grown and if the buffer width is zero.

The externality E in Equation (3) reflects the premium $\Delta p = p_c - p_g$ lost on the contaminated conventional OSR production. For given premium, the externality will be increasing in the magnitude of the GM area and decreasing in both buffer width and the level of spatial aggregation. It can be written:

$$E = E(l_g, l_c, A(e_g, e_c), d_g, d_c) = \Delta p \times C(l_g, l_c, A(\cdot), d_g, d_c) \quad (5)$$

$$C(\cdot) = f_c(CL(l_g, l_c, A(\cdot), d_g, d_c)) \quad (6)$$

$$\begin{array}{ll} \dfrac{\partial E}{\partial l_g} = \Delta p \times \dfrac{\partial C}{\partial l_g} > 0 & \dfrac{\partial E}{\partial A} = \Delta p \times \dfrac{\partial C}{\partial A} < 0 \\ \dfrac{\partial E}{\partial d_g} = \Delta p \times \dfrac{\partial C}{\partial d_g} < 0 & \dfrac{\partial E}{\partial d_c} = \Delta p \times \dfrac{\partial C}{\partial d_c} < 0 \end{array} \quad (7)$$

where C and CL in Equations (5, 6), respectively, indicate the conventional OSR output and area (net of the buffer) with AP levels above the 0.9 per cent threshold.

In general, the larger the source population (GM OSR) in a landscape, the higher the degree of outcrossing observed in the sink population

[2] It is assumed that buffers are left bare. This assumption may be not realistic, but is maintained nevertheless to keep consistency with the cross-pollination Monte Carlo experiment illustrated in section 3. An extension of the model could consider the case with planted buffers.

[3] Percolation theory is concerned with the behaviour of connected clusters in a random network.

(conventional OSR) (Bateman 1947). It is reasonable to expect that C will increase when the GM area in the landscape increases (first inequality in Eqn 7). On the other hand, the level of outcrossing is higher when source and sink populations are scattered in the landscape (disaggregated) compared to situations in which source and sink populations are 'aggregated' in different parts of the landscape (e.g., Ennos and Clegg 1982). It is therefore also reasonable to expect that increasing spatial aggregation of GM and/or conventional fields in the landscape will reduce C (second inequality in Eqn 7). Finally, because pollen-mediated gene flow is distance dependent (e.g., Klein *et al*. 2006), 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 inequalities in Eqn 7). Each of the inequalities in Equation (7) can be interpreted as hypotheses and will be tested empirically in section 4. Note that in Equation (7), the partial derivative $\partial E/\partial l_c$ is not specified because, a priori, its sign is ambiguous. An increase in the conventional crop area is likely to 'dilute' the average AP level in each conventional field ('dilution effect'), suggesting a negative sign for the partial derivative. However, an increase in the conventional OSR area will increase the conventional outputs susceptible of having AP levels above 0.9 per cent ('production effect'), suggesting a positive sign for the partial derivative. Therefore, the discussion of the sign of this partial derivative is delayed to the empirical analysis in section 4.

The FONC for problem (3, 4), presented in the Appendix, imply that conventional farmers will increase the land area committed to conventional OSR so as to equate marginal returns on alternative crops, taking into account both the cost of buffers (the second term on the lhs of Eqn 15) and of the contamination (the third term on the lhs of Eqn 15). Conventional farmers will increase defensive buffer widths up to the point where the marginal external damage saved (the last term on the lhs of Eqn 16) is equal to the marginal net benefit of crop production forgone (the first term on the lhs of Eqn 16). Finally, conventional farmers will invest in coordination of planting decisions to cluster the conventional OSR fields, up to the point where the marginal benefits of the reduction in the buffer required (the first element on the lhs of Eqn 17) and the reduction in the contamination cost (the second element on the lhs of Eqn 17) are equal to the marginal cost w. This is in line with empirical evidence suggesting that the recipients of an externality tend to cluster away from the generators (Parker and Munroe 2007).

2.2. Conventional farmers have the 'property rights': the case of moderate regulation

Let us now consider the case in which coexistence is moderately regulated with the objective of maximising joint profits (MJP) of both GM and conventional farmers. In these circumstances, it is reasonable to assume that the number of GM adopters will be lower than in the previous case. For the purpose of the analysis, let $a_g = a_g(l_g, l_c, d_g, A(e_g, e_c))$ denote the GM farmers' buffers. Then MJP can be obtained as follows

$$\max_{l_g, l_{ag}, l_c, l_{ac}, d_g, d_c, e_g, e_c} p_g f_g(\hat{l}_g) - c_g \hat{l}_g - h a_g + p_a f_a(l_{ag}) - c_a l_{ag} - w e_g + p_c f_c(\hat{l}_c) - c_c \hat{l}_c - h a_c + p_a f_a(l_{ac}) - c_a l_{ac} - w e_c - E \quad (8)$$

$$\text{Subject to } l_g + l_{ag} = L_g^R,\ l_c + l_{ac} = L_c^R = \overline{L} - L_g^R \quad (9)$$

It is interesting to compare the FONC for problems (1, 2) and (3, 4) with those of problem (8, 9) (see Appendix). From Equation (19), GM farmers will invest in buffers up to the point where their marginal cost (the first term on the lhs of Eqn 19) equals the social marginal benefits associated with the reduction in the contamination cost E (the second term on the lhs of Eqn 19). This is in sharp contrast with the situation encountered in problem (1, 2), where GM farmers set $d_g = 0$. Because in the MJP case, GM farmers might be required to adopt a buffer ($d_g \geq 0$), expression (20) implies that their investment in coordination effort should be determined so as to balance its marginal cost with its marginal benefits in terms of three factors. First, a reduction in GM farmers' buffer through increased aggregation (the first term on the lhs of Eqn 20). Second, a reduction in conventional farmers' buffers through increased aggregation (the second term on the lhs of Eqn 20) Third, a reduction in the contamination cost (the third term on the lhs of Eqn 20). When GM buffers are adopted GM farmers' land allocation decisions will also be different from problem (1, 2) (as in Eqn 14). From Equation (18), GM farmers will increase the GM OSR area up to the point where marginal returns on alternative land uses, taking into account the cost of their own buffer (the second term on the lhs of Eqn 18), the marginal effects (MEs) on conventional farmers of contamination (the fourth term on the lhs of Eqn 18) and the cost of the conventional buffer area (the third term on the lhs of Eqn 18), are equalised. This suggests that the presence of GM OSR affects conventional farmers in two ways: by imposing some degree of contamination and also by affecting the magnitude of the conventional buffers (as the buffer must be applied on all the edges of conventional fields adjacent to GM fields). From Equation (21), conventional farmers will increase conventional OSR area up to the point where marginal returns on alternative land uses, taking into account also the effects on GM buffer area (the last term on the lhs of Eqn 21), are equalised. By comparing expression (21) with (Eqn 15), it is evident that when GM buffers are applied *conventional farmers' land allocation decisions also have an effect on GM farmers*. When pursuing MJP this external effect must be accounted for. Expression (22) is identical to (Eqn 16). Finally, expression (23) suggests that for conventional farmers the level of coordination effort consistent with MJP should be determined by balancing its marginal cost with its marginal benefits in terms of reduction in conventional buffers (the first term on the lhs of Eqn 23), reduction in GM buffers (the second term on the lhs of Eqn 23) and reduction in the contamination cost (the third term on the lhs of Eqn 23). By comparing Equation (23) with Eqn (17), it appears that when property rights are assigned solely to conventional growers *conventional farmers will not invest enough in coordination effort* because they will ignore the benefits that accrue to GM farmers from increased aggregation.

Denote the solution to Equations (8, 9) as $\text{MJP} \equiv (l_{\text{g}}^*, l_{\text{ag}}^*, l_{\text{c}}^*, l_{\text{ac}}^*, d_{\text{g}}^*, d_{\text{c}}^*, e_{\text{g}}^*, e_{\text{c}}^*)$. The corrective mechanism to achieve the MJP could include several factors. First, a mandatory buffer on GM fields adjacent to conventional fields consistent with MJP (but not with the complete elimination of the contamination cost) d_{g}^*. Second, two taxes, τ_{g}^* on the GM OSR land allocation (accounting for crop contamination and for the effect on conventional buffer area) and τ_{c}^* on conventional OSR land allocation (accounting for the effect on GM growers buffer area). Third, a mechanism to incentivise both GM and conventional farmers to invest the appropriate resources in coordination effort. It is very likely that $\tau_{\text{g}}^* > \tau_{\text{c}}^*$, and if the effect of land allocation decisions of one category of farmers on the magnitude of the buffer areas of the other category is relatively small (i.e. $\partial a_{\text{c}}/\partial l_{\text{g}} \cong 0$ and $\partial a_{\text{g}}/\partial l_{\text{c}} \cong 0$), then $\tau_{\text{g}}^* \cong \partial E/\partial l_{\text{g}}$ and $\tau_{\text{c}}^* \cong 0$.

3. The Monte Carlo simulation

The objective in the rest of the paper is to characterise the function describing the contamination externality, with particular attention to the effect of the different decision variables, and to discuss its implications for coexistence policies. Such decision variables are referred to as 'policy variables' because any policy to regulate coexistence (such as a tax on GM land allocation or mandatory buffers) will ultimately act on them.

The model employed here is relatively simple because it does not take into account important factors like flower synchrony, seed survival, etc (e.g., Colbach *et al.* 2001). But it rather focuses on some of the variables that are expressly being targeted by the evolving coexistence regulations in the EU. By focusing on a more limited number of variables the model is able to provide stylised results on the effectiveness of different instruments to minimise the externality at the landscape level.

In this paper, only a brief description of the model employed is provided. The interested reader is referred to the more complete exposition presented in Ceddia *et al.* (2007, 2009). 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 (Figure 1).

Assume that a proportion l_{g} of the 100 fields consists of GM OSR and a proportion l_{c} consists of conventional OSR while the remaining $100 - l_{\text{g}} - l_{\text{c}}$ fields consist of another crop. Also assume that when a GM OSR and a

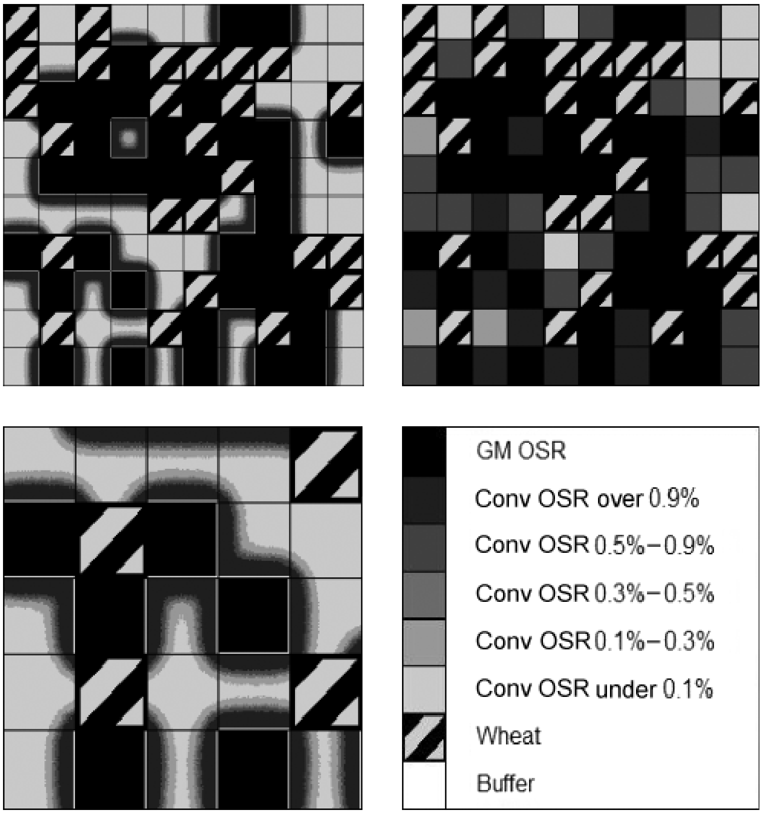

Figure 1 Pollen-mediated adventitious presence levels in conventional fields at 1 m^2 level (top left panel) and averaged within a field (top right panel). The bottom left panel illustrates an enlargement of the top left panel, while the colour scale used is represented in the bottom right panel.

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] To calculate the level of GM cross-pollination in each conventional field, an average individual dispersal function (IDF), as estimated by Lavigne *et al.* (1998), is used. Using this pollen dispersal function for OSR, 54.65 per cent of the pollen produced in a cell falls on the square itself, while the remaining 45.35 per cent disperses according to the negative exponential function $g(\delta) = K\frac{(0.125)^2}{2\pi}e^{-0.125\delta}$ (where δ is the radial distance from the source, and K is a constant to ensure the integral of the function is unity).[5] GM AP levels at the scale of fields, as the average of the AP level of each cell in that field[6], are then obtained.

[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] Notice that in Lavigne *et al.* original paper the function is specified as $g(\delta) = K\frac{(0.375)^2}{2\pi}e^{-0.375\delta}$ because their basic distance unit is 3 m.

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

During the simulation, the area of conventional crop (net of the buffer) corresponding to those fields with AP levels above the 0.9 per cent threshold, CL, was recorded. To compute C, UK OSR production data are used to fit the following functional form, $C = f_c(CL) = 3(CL)^{0.9}$.

The main purpose of the simulation is to generate data to estimate expressions (5) and to test (7). Note that for given premium Δp the externality E is entirely defined by the 'contaminated output' C. Therefore, the effort will be concentrated on estimating C (expression 6). To ensure enough variability in the data generation process and to better estimate their effect on C, in each run of the simulation, 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, reasonable given the relatively small size of the fields (1 ha). Basing dispersal on an IDF function allows us to assess the effect of spatial aggregation of GM and conventional fields in the landscape. In each simulation run the position of the GM and conventional fields in the landscape was randomly assigned. In reality it is likely that fields with similar crops are not located randomly in the landscape but that the presence of the externality might induce the recipient of the externality to cluster away from the generators (Parker and Munroe 2007). However, assuming random field locations is necessary in the Monte Carlo experiment to obtain sufficient variability in the aggregation variable A to better estimate its effects on C. Once C has 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 (see Ceddia *et al.* 2009). The level of spatial aggregation is quantified by using the index developed by He *et al.* (2000)

$$A = \sum_{i=1}^{n} A_i \times \alpha_i \quad 0 \leq A \leq 1 \tag{10}$$

$$A_i = \varepsilon_{i,i} / \max\_\varepsilon_{i,i} \tag{11}$$

where A: Aggregation index for the landscape; A_i: Aggregation index for the i-th class; $\varepsilon_{i,i}$: total number of edges shared by the i-th class; $max\_\varepsilon_{i,i}$: maximum (possible) number of edges shared by the i-th class; α_i: % of the landscape occupied by the i-th class; n: total number of classes.

4. Results

Through 3000 simulation runs data are generated to estimate Equations (6) and test (7). Table 1 provides descriptive statistics for the data recorded during the simulation.

Table 1 Descriptive statistics for the variables in the simulation

Variables	Description (unit)	Mean	SD	Min	Max	# Obs
l_g	# of 1 ha genetically modified (GM) fields (# and/or ha)	32.5	11.5	13	52	3000
l_c	# of 1 ha conv. fields (# and/or ha)	29.9	10.7	12	48	3000
d_g	Buffer width on GM fields (m)	4.9	3.1	0	10	3000
d_c	Buffer width on conv. fields (m)	5.1	3.2	0	10	3000
A	Aggregation index	0.4	0.06	0.25	0.66	3000
CL	Conv. fields with adventitious presence ≥ 0.9% (ha)	6.2	6.2	0	35	3000
C	Output produced on CL (tons)	18.7	18.6	0	104.1	3000

4.1. The contaminated output C

The data generated were used to estimate (6). As no information is available on the possible functional form, a Box–Cox transformation is used as follows

$$\tau(C,\lambda) = \beta_0 + \beta_1\tau(l_g,\lambda) + \beta_2\tau(l_c,\lambda) + \beta_3 d_g + \beta_4 d_c + \beta_5 A + u \tag{12}$$

where

$$\tau(x,\lambda) = \frac{x^{\lambda} - 1}{\lambda} \tag{13}$$

The choice of transformed variables in Equation (12) reflects the fact that this specification yields the best results[7] and that as $\lambda \to 0$ the model converges to the log-log model estimated in Ceddia *et al*. (2009). In the estimation observations with $C = 0$ are dropped, as in this case $\lambda = 0$ cannot be defined. As both the linear and log-log model are nested in Equation (12), we use a likelihood ratio test to determine whether $\lambda = 0$ and $\lambda = 1$ should be rejected. Estimation results for Equation (12) are presented in Table 2.

The results of the test are presented at the bottom of Table 2 and allow the rejection of the hypothesis that $\lambda = 1$ (linear model) and $\lambda = 0$ (log-log model). The Box–Cox transformation with $\lambda = 0.2868$ is the best model.

4.2. Comparative analysis

To assess the effect of changes in the variables l_g, l_c, d_g, d_c and A on C, the MEs are considered. The last row in Table 3 illustrates the MEs for C.

For comparison purposes, the corresponding MEs associated with the log-log specification published in Ceddia *et al*. (2009) are presented in the first row. Although the variables' ranking (in terms of magnitude of MEs) does

[7] Different specifications of the Box–Cox transformation are selected between on the basis of information criteria.

Table 2 The estimated Box–Cox model (Eqn 12)

	Coefficient	SE	$P[\|Z\| > z]$
Transformed variables			
l_g	1.13	0.021	0.000
l_c	0.55	0.016	0.000
Non-transformed variables			
Constant	−3.04	0.20	0.000
d_g	−0.18	0.008	0.000
d_c	−0.36	0.015	0.000
A	−0.95	0.29	0.001
Transformation parameter			
λ	0.2868	0.015	0.000
Model Log-L	−7683.99		
Model $P[\|Z\| > z]$	0.000		
Obs.	2628		
Test H_0	Restricted LogL	LR χ^2	$P > \chi^2$
$\lambda = 0$	−7854.97	341.97	0.00
$\lambda = 1$	−8621.84	1875.72	0.00

Table 3 Marginal effects on the contaminated output C at the model's sample mean

Model	l_g	l_c	d_g	d_c	A
Log–Log	0.51*	0.26*	−0.9*	−1.96*	−8.89*
Box–Cox	0.62*	0.32*	−1.22*	−2.45*	−6.45*

*0.1% significance level.

not change across models, it appears that the MEs are always larger in the Box–Cox model. The one exception to this is the spatial aggregation variable A. The results presented are qualitatively analogous to those in Ceddia *et al.* (2009). C is increasing in the GM area and decreasing in the width of the buffers (both on GM and conventional fields) and in the degree of spatial aggregation. This confirms the hypothesis in Equation (7). Additionally, $\partial C/\partial l_c > 0$, implying that the 'dilution effect' is dominated by the 'production effect'. The MEs analysis suggests that the degree of spatial aggregation is the single 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 may be attributed to the fact that the largest AP concentrations always occur on the edges of conventional fields; when the buffer is applied on the conventional fields the conventional output most susceptible to contamination is reduced.

5. Discussion

The possibility of contamination of conventional/organic produce with GM material and the consumers' aversion towards GM produce makes coexistence between GM and conventional crops an issue of spatial externalities. Regulation of coexistence in North America and in the EU reflects the different assignment of property rights. In the EU the 'newcomer principle' assigns property rights to conventional/organic farmers through the introduction of ex-ante technical measures necessary to keep contamination below the established threshold and ex-post liability (e.g. Beckmann *et al.* 2010).

This paper first developed a model to analyse the problem of coexistence and then used a Monte Carlo simulation to assess the nature of the externality associated with pollen-mediated gene flow.

The analytical model draws on the theory of externalities and provides a number of stylised results. When property rights are assigned to GM farmers they will adopt no measures to reduce contamination of conventional farmers. Conventional growers, as recipient of the externality, will protect themselves by adopting buffers on the edges of their conventional fields neighbouring GM fields and will tend to cluster away from GM fields. This result is consistent with the existence of spatial externalities (Parker and Munroe 2007).[8]

In contrast, when property rights are assigned to conventional farmers but the aim is the maximisation of joint profits the economic model shows that coexistence involves mutual interdependences between conventional and GM farmers for the following reasons:

1. The cost of contamination to conventional growers depends also on GM farmers' decisions about land allocation, buffers and coordination.
2. The cost of having a buffer on conventional fields (i.e., the cost of self protection) also depends on GM farmers' land allocation and coordination decisions.
3. The cost of having a buffer on GM fields (i.e., the cost of abatement) also depends on conventional farmers' land allocation and coordination decisions.
4. Coordination of planting decisions among farmers (GM and/or conventional) provides a 'public good' (i.e., the benefits of spatial aggregation) and therefore involves externalities.

The current coexistence regulatory framework in the EU is likely to be inefficient, not because it assigns property rights to conventional farmers (the 'newcomer principle'), but because it requires the complete elimination of the externality and damage compensation therefore removing any incentive for the victims to self-protect. Additionally, it only focuses on the first two points above, failing to recognise the mutual interdependence between 'emitters' and 'victims' (Vatn and Bromley 1997).

[8] Although not explicitly analysed here, it is easy to imagine what would happen if property rights were assigned to conventional growers in such a way as to require full compensation and zero contamination costs (as currently in the EU): GMO farmers would protect themselves, for example by increasing clustering, as mentioned in Consmüller *et al.* (2009).

The Monte Carlo experiment allows us to rank different ‘policy variables’ for containing the cross-pollination. The most effective is found to be spatial aggregation, followed in order by buffers, GM land allocation decisions and conventional crop land allocation decisions. This is in line with recent research arguing in favour of a more flexible regulation of coexistence, based on the use of buffers and coordination (Demont *et al.* 2009). The simulation also shows that conventional buffers are always more effective than GM buffers.

As coordination provides a public good (higher clustering) it will be undersupplied. The extent to which increases in the coordination effort necessary to increase spatial aggregation should be pursued will clearly depend on the costs of coordination (Furtan *et al.* 2007; Consmüller *et al.* 2009). Any measure that could lower the costs of coordination is likely to be very important for coexistence. Additionally, the economic model suggests that MJP does not require conventional farmers to have no buffer areas. If buffers on conventional fields are more effective at abating the externality MJP could require conventional farmers (the ‘victims’) to invest more in this measure than GM farmers. This has already been raised by Vatn and Bromley (1997), albeit in a different context. As GM land allocation decisions are also important in determining the magnitude of the cross-pollination externality coexistence policies should target this aspect through a Pigovian tax or other such instruments. Finally, as conventional crop land allocation decisions are important not only in determining the magnitude of the cross-pollination externality, but also affect GM farmers (i.e., affecting the size of the GM buffer as outlined in the economic model), coexistence regulations should also consider this aspect.

The results presented cannot be immediately generalised because they depend on the specific model assumptions (e.g., bare buffers), the IDF chosen in the simulation and on field size. The identification of specific policies for coexistence is beyond the remit of this paper and must be addressed on a case-by-case basis. Despite this, the findings expressed here should provide useful ground for future research.

Acknowledgements

The authors thank three anonymous referees and one associate editor for the useful comments that helped them to improve the manuscript. Usual disclaimers apply.

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Appendix

The first-order necessary conditions for problem (1–2) are

$$p_{\mathrm{g}}\frac{\mathrm{d}f_{\mathrm{g}}}{\mathrm{d}l_{\mathrm{g}}}-c_{\mathrm{g}}=p_{\mathrm{c}}\frac{\mathrm{d}f_{\mathrm{a}}}{\mathrm{d}l_{\mathrm{ag}}}-c_{\mathrm{a}} \tag{14}$$

The first order necessary conditions for problem (3–4) are

$$\left(p_{\mathrm{c}}\frac{df_{\mathrm{c}}}{d\hat{l}_{\mathrm{c}}}-c_{\mathrm{c}}\right)\frac{\partial\hat{l}_{\mathrm{c}}}{\partial l_{\mathrm{c}}}-h\frac{\partial a_{\mathrm{c}}}{\partial l_{\mathrm{c}}}-\frac{\partial E}{\partial l_{\mathrm{c}}}=p_{\mathrm{a}}\frac{df_{\mathrm{a}}}{dl_{\mathrm{ac}}}-c_{\mathrm{a}} \tag{15}$$

$$\left(c_c-h-p_c\frac{df_c}{d\hat{l}_c}\right)\frac{\partial a_c}{\partial d_c}-\frac{\partial E}{\partial d_c}=0 \tag{16}$$

$$\left(c_{\mathrm{c}}-h-p_{\mathrm{c}}\frac{\mathrm{d}f_{\mathrm{c}}}{\mathrm{d}\hat{l}_{\mathrm{c}}}\right)\frac{\partial a_{\mathrm{c}}}{\partial A}\frac{\partial A}{\partial e_{\mathrm{c}}}-\frac{\partial E}{\partial A}\frac{\partial A}{\partial e_{\mathrm{g}}}-w=0 \tag{17}$$

The first-order necessary conditions for problem (8–9) are

$$\left(p_{\mathrm{g}}\frac{\mathrm{d}f_{\mathrm{g}}}{\mathrm{d}\hat{l}_{\mathrm{g}}}-c_{\mathrm{g}}\right)\frac{\partial\hat{l}_{\mathrm{g}}}{\partial l_{\mathrm{g}}}-h\frac{\partial a_{\mathrm{g}}}{\partial l_{\mathrm{g}}}-\left(p_{\mathrm{c}}\frac{\mathrm{d}f_{\mathrm{c}}}{\mathrm{d}\hat{l}_{\mathrm{c}}}-c_{\mathrm{c}}+h\right)\frac{\partial a_{\mathrm{c}}}{\partial l_{\mathrm{g}}}-\frac{\partial E}{\partial l_{\mathrm{g}}}=p_{\mathrm{a}}\frac{\mathrm{d}f_{\mathrm{a}}}{\mathrm{d}l_{\mathrm{ag}}}-c_{\mathrm{a}} \tag{18}$$

$$\left(c_{\mathrm{g}}-h-p_g\frac{df_g}{d\hat{l}_g}\right)\frac{\partial a_g}{\partial d_g}-\frac{\partial E}{\partial d_g}=0 \tag{19}$$

$$\left(c_{\mathrm{g}}-h-p_{\mathrm{g}}\frac{\mathrm{d}f_{\mathrm{g}}}{\mathrm{d}\hat{l}_{\mathrm{g}}}\right)\frac{\partial a_{\mathrm{g}}}{\partial A}\frac{\partial A}{\partial e_{\mathrm{g}}}+\left(c_{\mathrm{c}}-h-p_{\mathrm{c}}\frac{\mathrm{d}f_{\mathrm{c}}}{\mathrm{d}\hat{l}_{\mathrm{c}}}\right)\frac{\partial a_{\mathrm{c}}}{\partial A}\frac{\partial A}{\partial e_{\mathrm{g}}}-\frac{\partial E}{\partial A}\frac{\partial A}{\partial e_{\mathrm{g}}}-w=0 \tag{20}$$

$$\left(p_{\mathrm{c}}\frac{\mathrm{d}f_{\mathrm{c}}}{\mathrm{d}\hat{l}_{\mathrm{ac}}}-c_{\mathrm{c}}\right)\frac{\partial\hat{l}_{\mathrm{ac}}}{\partial l_{\mathrm{ac}}}-h\frac{\partial a_{\mathrm{c}}}{\partial l_{\mathrm{c}}}-\frac{\partial E}{\partial l_{\mathrm{c}}}-\left(p_{\mathrm{g}}\frac{\mathrm{d}f_{\mathrm{g}}}{\mathrm{d}\hat{l}_{\mathrm{g}}}-c_{\mathrm{g}}+h\right)\frac{\partial a_{\mathrm{g}}}{\partial l_{\mathrm{c}}}=p_{\mathrm{a}}\frac{\mathrm{d}f_{\mathrm{a}}}{\mathrm{d}l_{\mathrm{ac}}}-c_{\mathrm{a}} \tag{21}$$

$$\left(c_{\mathrm{c}}-h-p_{\mathrm{c}}\frac{\mathrm{d}f_{\mathrm{c}}}{\mathrm{d}\hat{l}_{\mathrm{c}}}\right)\frac{\partial a_{\mathrm{c}}}{\partial d_{\mathrm{c}}}-\frac{\partial E}{\partial d_{\mathrm{c}}}=0 \tag{22}$$

$$\left(c_{\mathrm{c}}-h-p_{\mathrm{c}}\frac{\mathrm{d}f_{\mathrm{c}}}{\mathrm{d}\hat{l}_{\mathrm{c}}}\right)\frac{\partial a_{\mathrm{c}}}{\partial A}\frac{\partial A}{\partial e_{\mathrm{c}}}+\left(c_{\mathrm{g}}-h-p_{\mathrm{g}}\frac{\mathrm{d}f_{\mathrm{g}}}{\mathrm{d}\hat{l}_{\mathrm{g}}}\right)\frac{\partial a_{\mathrm{g}}}{\partial A}\frac{\partial A}{\partial e_{\mathrm{c}}}-\frac{\partial E}{\partial A}\frac{\partial A}{\partial e_{\mathrm{c}}}-w=0. \tag{23}$$