Policies for the regulation of coexistence between GM and conventional crops

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Abstract – **Pollen-mediated gene flow is one of the main concerns associated with the introduction of genetically modified (GM) crops, since growers of GM varieties normally do not take into account its possible impact on conventional and organic growers therefore generating negative externalities. Should a premium for non-GM varieties emerge on the market, 'contamination' with GM pollen would generate a revenue loss for growers of non-GM varieties. The existence of such externalities has led the European Union (EU) to put forward the concept of coexistence in order to guarantee farmers' freedom to plant both conventional and GM varieties without generating economic losses to conventional farmers. The first part of this paper develops a simple economic model analysing the problem of pollen-mediated gene flow as a particular kind of production externality. The model, although simple, provides useful insights into the policy needed to regulate coexistence.**

Since pollen-mediated gene flow is distance-dependent, the externalities will depend on the spatial structure of GM adoption in the landscape. The second part of the paper, taking GM herbicide tolerant oilseed rape (Brassica napus) as a model crop, uses a Monte Carlo experiment to generate data and then estimate the effect of some important policy variables (i.e. number of GM and conventional fields in the landscape, width of buffer zones and spatial aggregation) on the magnitude of the externality associated with pollen-mediated gene flow. Our results show that buffer areas on conventional fields are more effective than those on GM fields and that the degree of spatial aggregation exerts the largest marginal effect on the externality to conventional growers. The implications of the results for the coexistence policies in the EU are then discussed.

Keywords – **coexistence, pollen-mediated gene flow, Monte Carlo simulation.**

I. INTRODUCTION

The coexistence of genetically modified (GM) and conventional crops in the EU is admitted under the principle that farmers should be able to cultivate freely the crops they choose, be it GM crops, conventional or organic crops. However, this is qualified by the need to account for any economic consequences of adventitious presence of material from one crop to another [1]. In principle, the environmental aspects of the introduction of GM crops are addressed before authorisation for their release is granted (EC Directive 18/2001). The economic consequences of GM crop introductions are not. So the problem is to identify ex ante measures that will deal with the efficiency issues raised by GM crops. There are two issues involved. One relates to the ability of GM material to mix with conventional material through pollen and seed dispersal, and so physically to contaminate conventional crops [2]. The other relates to the attitudes of consumers to GM crops (i.e. their willingness to pay a premium for conventional products), and so to the cost of GM contamination of conventional crops. Since the negative consequences of the introduction of GM crops on conventional crops are not taken into account in market transactions between GM and conventional producers, they indicate the existence of a production externality. Since the level of contamination is distance-dependent (i.e. conventional plots closer to GM plots will show higher levels of contamination) spatial considerations are important.

There already exist mechanisms to detect the existence of contamination – i.e. the physical evidence for this externality. In 2003 the EU adopted two Regulations (EC Regulation 1829/2003 and 1830/2003) establishing a 0.9% threshold for the maximum adventitious presence (AP) of GM material in conventional food and feed, and setting up the principles of traceability of GM material along the production chain. However, there do not yet exist mechanisms to internalise the damages associated with contamination.

In this paper we consider this problem in relation to one of the GM crops that is currently under consideration in the EU: herbicide tolerant oilseed rape (simply GM OSR from now on). GM OSR is already extensively grown in Canada (as canola) and elsewhere because of its greater flexibility in weed management [3]. There is evidence of GM OSR contamination of neighbouring and successive conventional crops in those countries [2] and that this contamination has economic consequences (e.g. the virtual cessation of organic canola farming in Saskatchewan, Canada, as reported in [4]). In other words, there is evidence that the introduction of GM OSR outside of the EU has involved spatial production externalities. We consider how such externalities might be addressed if GM OSR is admitted in the EU. Economic analysis of coexistence is limited. So for example [5] illustrates how under mandatory labelling the introduction of GM crops in the EU might be welfare reducing. [6] illustrate how the evolving coexistence regulations in the EU might reduce the appeal of growing GM varieties. Our objective is first, to develop an analytical model capable of framing the efficiency issues raised by the coexistence of GM and conventional crops in the landscape. Second, we wish to use the available information about pollen-mediated gene flow and carry out a Monte Carlo experiment to characterise the relationship between the magnitude of the externality at the landscape level and a number of important 'policy variables' (namely 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 can be very useful in order to discuss the different policy options for coexistence.

The structure of the paper is as follows. Section two presents the analytical model to describe the coexistence problem on the basis of a production externality framework. Section three illustrates the Monte Carlo simulation used to generate data on pollen-mediated gene flow, starting from an individual OSR plant dispersal function (IDF). Section four uses the generated data to fit a functional form for the pollen-mediated gene flow externality. The last session discusses the main results and draws some conclusions.

II. THE ECONOMIC MODEL

The problem we wish to address is the internalisation of spatial externalities whose characteristics depend on the pattern of adoption of GM technology. All fields are of identical size, but the effect of the GM trait and hence the incentive to adopt GM technology differs between farms and is affected by the regulatory system. In particular, the stricter the regulatory system, the lower will be the number of farmers adopting GM varieties. Hence a number of farmers (i.e. the GM adopters) will allocate their land between the GM variety and an alternative crop (e.g. winter wheat), while other farmers (i.e. the non-adopters) will allocate their land between conventional OSR varieties and the alternative crop. Denote with L_g the arable land available to those farmers who adopt GM and with $L_c = \overline{L} - L_g$ the area available to the 'non-adopters' (where $\overline{L}$ denotes the total arable land). We suppose that regulation of coexistence takes place before the new technology is introduced and in order to capture the effect of the regulatory system on the appeal of the GM technology we hypothesize two different scenarios:

- The 'unregulated' scenario: coexistence is not explicitly regulated. This is the system currently in practice in North America. In this case the number of adopters will be relatively large and the land available to adopters and non-adopters will be respectively L_g^U and $L_c^U = \overline{L} - L_g^U$.

- The 'regulated' scenario: the regulator announces that coexistence will be regulated through the introduction of a moderate levy/tax on GM OSR land allocation, a moderate (mandatory) buffer on the edge of those GM fields adjacent to conventional fields and some incentives to pursue the clustering of GM and conventional OSR fields away from each other in order to maximise joint GM and conventional growers profits. In this case the number of adopters will be lower, and the arable land available to adopters and non-adopters will be respectively $L_g^R < L_g^U$ and $L_c^R = \overline{L} - L_g^R > L_c^U$.

We assume that adoption of GM varieties is irreversible and we exclude the possibility that

farmers grow both GM and conventional varieties of the same crop. In the case of GM OSR these are plausible assumptions since OSR seeds persist in the seedbank for many years making cultivation of conventional OSR in those fields difficult [7]. The analysis is static and confined to the farm level and only addresses the problem of coexistence between GM and conventional OSR varieties, therefore excluding organic OSR (organic OSR production is extremely limited in the EU). We do not include the costs of herbicide resistance development, through gene flow or volunteers' dispersal, in the analysis since they have been shown to be quite low elsewhere (around C\$ 2 per acre in Canada, [8].

Consumer preferences for conventional produce imply that the price of conventional crops (p_c) is higher than the price of the GM crop (p_g) (e.g. [9]). The price of the other crop is (p_a). Farmers cannot influence these prices by their actions. Technology is represented through standard (i.e. concave) production functions denoted as $f_g(\bullet)$, $f_c(\bullet)$ and $f_a(\bullet)$ for GM OSR, conventional OSR and the alternative crop respectively. Please note that the purpose of the analytical model is to frame the problem of coexistence in terms of production externalities. As such sufficient conditions for optimality are not discussed here, although it can be shown that with appropriate restrictions on the functional forms they will be satisfied.

The physical basis of the externality is assumed to be cross pollination. Pollen from GM varieties contaminates conventional varieties within some distance. Other sources of contamination (e.g. adventitious presence in seeds) are excluded for simplicity. When contamination at field level exceeds a certain threshold (0.9% in our case) the product must be labelled as containing GM and will be sold at the lower price p_g. Let E denote the contamination cost to the conventional farmers. Since pollen-mediated gene flow is distance-dependent contamination can be reduced through the adoption of buffer areas on adjacent conventional and/or GM fields and/or by increasing clustering [10].

A. The 'unregulated' approach

The first case we wish to address refers to a situation in which coexistence is not formally regulated. This is essentially what happens in North America. In this case GM farmers have no incentive to set up any buffer 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. In this case it is obvious that GM farmers will set $d_g=0$ and $e_g=0$ and their problem can be represented as follows

$$\underset{l_g, l_{ag}}{Max} \; p_g f_g\left(l_g\right) - c_g l_g + p_a f_a\left(l_{ag}\right) - c_a l_{ag} \quad (1.a)$$

Subject to $l_g + l_{ag} = L_g^U$ (1.b)

GM farmers maximize profits through the choice of land allocation to the GM OSR l_g and to the alternative crop l_{ag}, given a 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 (i.e. all other inputs are applied in fixed proportions).

The first order necessary conditions (FONC) for problem (1.a, 1.b) require

$$p_g \frac{df_g}{dl_g} - c_g = p_c \frac{df_a}{dl_{ag}} - c_a \quad (1.c)$$

From (1.c), 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 equalized. GM farmers will in general ignore any impact on conventional farmers. If the external effect of cross-pollination is negative, the area allocated to GM OSR will be too large from the social point of view.

The problem for the conventional farmers can be represented as follows

$$\underset{l_c, l_{ac}, d_c, e_c}{Max} \; p_c f_c\left(\hat{l}_c\right) - c_c \hat{l}_c - ha_c(\bullet)$$
$$+ p_a f_a\left(l_{ac}\right) - c_a l_{ac} - we_c - E(\bullet) \quad (2.a)$$

Subject to $l_c + l_{ac} = L_c^U = \overline{L} - L_g^U$ (2.b)

With $\hat{l}_c = l_c - a_c$. Conventional farmers maximize profits through the choice of land allocation to conventional OSR l_c, the alternative (to conventional OSR) crop l_{ac} and buffer width d_c on conventional OSR fields adjacent to GM OSR fields so as to create a buffer area a_c, the coordination effort e_c to

cluster conventional fields away from GM fields, given 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). Define a generic index of spatial aggregation (A) such that $0 \leq A \leq 1$ (where the value 0 reflects a completely disaggregated configuration and the value 1 a completely aggregated one). From percolation theory [11] we know that for $l_c=l_g=0$ A will be identically equal to 1, since if no OSR (conventional and GM) is grown the whole landscape will be planted with the alternative crop and the configuration of the landscape will be totally aggregated. If we exclude such a trivial case, then A will be 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 $a_c = a_c\left(l_c, l_g, d_c, A\left(e_g, e_c\right)\right)$. The magnitude of the buffer area will be zero if no GM OSR or no conventional OSR are grown and if the buffer width is zero.

The term E in (2.a) represents the externality due to pollen-mediated gene flow and reflects the premium $\Delta p = p_c - p_g$ lost on the contaminated conventional OSR production C. The literature on pollen-mediated gene flow suggests that for given premium, the externality will be increasing in the magnitude of the GM and conventional OSR area, decreasing in buffer width and decreasing in the level of spatial aggregation [12]. Then we can write

$$E = E\left(l_g, l_c, A\left(e_g, e_c\right), d_g, d_c\right)$$
$$= \Delta p \times C\left(l_g, l_c, A(\bullet), d_g, d_c\right) \quad (2.c)$$

$$C(\bullet) = f_c\left(CL\left(l_g, l_c, A(\bullet), d_g, d_c\right)\right) \quad (2.d)$$

$$\frac{\partial E}{\partial l_g} = \Delta p \times \frac{\partial C}{\partial l_g} > 0 \qquad \frac{\partial E}{\partial A} = \Delta p \times \frac{\partial C}{\partial A} < 0$$
$$\frac{\partial E}{\partial d_g} = \Delta p \times \frac{\partial C}{\partial d_g} < 0 \qquad \frac{\partial E}{\partial d_c} = \Delta p \times \frac{\partial C}{\partial d_c} < 0 \quad (2.e)$$

Where CL in (2.d) reflects the conventional OSR area (net of the buffer) with AP levels above the 0.9% threshold.

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. [13] and [14]). 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 C will increase when the GM area in the landscape increases (first inequality in 2.e). 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. [15], [12] and [16]). It is then reasonable to expect that increasing spatial aggregation of GM and/or conventional fields in the landscape (i.e. clustering) will reduce the magnitude of C (second inequality in 2.e). Finally, since pollen-mediated gene flow is distance-dependent (e.g. [17] and [18]), 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 2.e). The inequalities in (2.e) can be interpreted as hypotheses and will be tested empirically in section 4. Note that in (2.e) we do not specify the partial derivative $\partial E / \partial l_c$ 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 [14], the AP level in each conventional field will be 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. 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.

The FONC for problem (2.a, 2.b) include

$$\left(p_c \frac{df_c}{d\hat{l}_c} - c_c \right) \frac{\partial \hat{l}_c}{\partial l_c} - h \frac{\partial a_c}{\partial l_c} - \frac{\partial E}{\partial l_c}$$

$$= p_a \frac{df_a}{dl_{ac}} - c_a \qquad (2.f)$$

$$\left(c_c - h - p_c \frac{df_c}{d\hat{l}_c} \right) \frac{\partial a_c}{\partial d_c} - \frac{\partial E}{\partial d_c} = 0 \qquad (2.g)$$

$$\left(c_c - h - p_c \frac{df_c}{d\hat{l}_c} \right) \frac{\partial a_c}{\partial A} \frac{\partial A}{\partial e_c} - \frac{\partial E}{\partial A} \frac{\partial A}{\partial e_g} - w = 0 \quad (2.h)$$

From (2.f) conventional farmers will increase the land area committed to conventional OSR so as to equate marginal returns on alternative crops, taking into account the cost of buffers (i.e. the second term on the l.h.s. of 2.f) and the contamination cost (the third term on the l.h.s. of 2.f). From (2.g) conventional farmers will increase defensive buffer widths up to the point where the marginal external damage saved (i.e. the last term on the l.h.s. of 2.g) is equal to the marginal net benefit of crop production forgone (i.e. the first term on the l.h.s. of 2.g). From (2.h), 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 magnitude of the buffer required (i.e. the first element on the l.h.s. of 2.h) and the reduction in the contamination cost (i.e. the second element on the l.h.s. of 2.h) will equate 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 [19].

B. The 'regulated' approach

The inefficiency associated with the externality E originates from GM growers' decisions about planting 'excessive' GM OSR, by their reluctance to adopt 'appropriate' separation distances to create buffer areas and to invest in 'appropriate' levels of coordination to increase clustering. The adjectives 'excessive' and 'appropriate' refer to the existence of a 'social optimum' in which the joint profits of GM adopters and non-adopters are maximised. The social optimum presupposes some form of regulation but it does not require the total elimination of the externality. In these circumstances it is reasonable to assume that the number of GM adopters will be lower than in the unregulated case. For the purpose of the analysis define GM farmers' buffers as $a_g = a_g \left(l_g, l_c, d_g, A(e_g, e_c) \right)$, with similar properties as the already defined conventional farmers' buffers a_c. Then the social optimum can be obtained as follows

$$\underset{l_g, l_{ag}, l_c, l_{ac}, d_g, d_c, e_g, e_c}{Max} \; p_g f_g \left(\hat{l}_g \right) - c_g \hat{l}_g - h a_g +$$

$$p_a f_a \left(l_{ag} \right) - c_a l_{ag} - w e_g + p_c f_c \left(\hat{l}_c \right) - c_c \hat{l}_c \qquad (3.a)$$

$$- h a_c + p_a f_a \left(l_{ac} \right) - c_a l_{ac} - w e_c - E$$

Subject to $l_g + l_{ag} = L_g^R, \; l_c + l_{ac} = L_c^R = \overline{L} - L_g^R$ (3.b)

The FONC for problem (3.a, 3.b) include

$$\left(p_g \frac{df_g}{d\hat{l}_g} - c_g \right) \frac{\partial \hat{l}_g}{\partial l_g} - h \frac{\partial a_g}{\partial l_g}$$

$$- \left(p_c \frac{df_c}{d\hat{l}_c} - c_c + h \right) \frac{\partial a_c}{\partial l_g} - \frac{\partial E}{\partial l_g} = p_a \frac{df_a}{dl_{ag}} - c_a \qquad (3.c)$$

$$\left(c_g - h - p_g \frac{df_g}{d\hat{l}_g} \right) \frac{\partial a_g}{\partial d_g} - \frac{\partial E}{\partial d_g} = 0 \qquad (3.d)$$

$$\left(c_g - h - p_g \frac{df_g}{d\hat{l}_g} \right) \frac{\partial a_g}{\partial A} \frac{\partial A}{\partial e_g}$$

$$+ \left(c_c - h - p_c \frac{df_c}{d\hat{l}_c} \right) \frac{\partial a_c}{\partial A} \frac{\partial A}{\partial e_g} - \frac{\partial E}{\partial A} \frac{\partial A}{\partial e_g} - w = 0 \qquad (3.e)$$

$$\left(p_c \frac{df_c}{d\hat{l}_{ac}} - c_c \right) \frac{\partial \hat{l}_{ac}}{\partial l_{ac}} - h \frac{\partial a_c}{\partial l_c} - \frac{\partial E}{\partial l_c}$$

$$- \left(p_g \frac{df_g}{d\hat{l}_g} - c_g + h \right) \frac{\partial a_g}{\partial l_c} = p_a \frac{df_a}{dl_{ac}} - c_a \qquad (3.f)$$

$$\left(c_c - h - p_c \frac{df_c}{d\hat{l}_c}\right)\frac{\partial a_c}{\partial d_c} - \frac{\partial E}{\partial d_c} = 0 \qquad (3.g)$$

$$\left(c_c - h - p_c \frac{df_c}{d\hat{l}_c}\right)\frac{\partial a_c}{\partial A}\frac{\partial A}{\partial e_c}$$

$$+\left(c_g - h - p_g \frac{df_g}{d\hat{l}_g}\right)\frac{\partial a_g}{\partial A}\frac{\partial A}{\partial e_c} - \frac{\partial E}{\partial A}\frac{\partial A}{\partial e_c} - w = 0 \qquad (3.h)$$

It is interesting to compare (3.c, 3.d, 3.e, 3.f, 3.g and 3.h) with (1.c) and (2.f, 2.g and 2.h). From (3.d) GM farmers will invest in buffers up to the point where its marginal costs (i.e. the first term on the l.h.s. of 3.d) equals the social marginal benefits associated with the reduction in the contamination cost E (i.e. the second term on the l.h.s. of 3.d). This is in sharp contrast with the situation encountered in the 'unregulated' approach, where GM farmers set d_g=0. Since in the regulated case GM farmers might be required to adopt a buffer (i.e. d_g>0), expression (3.e) implies that their socially optimal investment in coordination effort should be determined so as to balance its marginal cost w with its marginal benefits in terms of a) reduction of GM farmers buffer through increased aggregation (i.e. the first term on the l.h.s. of 3.e), b) reduction of conventional farmers buffers through increased aggregation (i.e. the second term on the l.h.s. of 3.e) and c) reduction in the contamination cost (i.e. the third term on the l.h.s. of 3.e). When GM buffers are adopted, GM farmers land allocation decisions will also be different from the 'unregulated' case (as in 1.c). From (3.c) 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 (i.e. the second term on the l.h.s. of 3.c), the marginal effects on conventional farmers through the cost of contamination (i.e. the fourth term on the l.h.s. of 3.c) and the cost of the conventional buffer area (i.e. the third term on the l.h.s. of 3.c), are equalized. This suggests that the presence of GM OSR affects conventional farmers in two ways: a) by imposing some degree of contamination and b) by affecting the magnitude of the conventional buffers (since the buffer must be applied on all the edges of conventional fields adjacent to GM fields). From (3.f) 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 farmers buffer area (i.e. the last term on the l.h.s. of 3.f) are equalized. By comparing expression (3.f) with (2.f) it is evident how when GM buffers are applied, *conventional farmers land allocation decisions have also an effect on GM farmers*. As such at the social optimum this external effect must be accounted for. Expression (3.g) is identical to (2.g). Finally, expression (3.h) suggests that for conventional farmers the socially optimal level of coordination effort should be determined by balancing its marginal cost w with its marginal benefits in terms of a) reduction in conventional farmers buffers (i.e. the first term on the l.h.s. of 3.h), b) reduction in GM farmers buffers (i.e. the second term on the l.h.s. of 3.h) and reduction of the contamination cost (i.e. the third term on the l.h.s. of 3.h). By comparing (3.h) with (2.h) it appears that *in the unregulated regime also conventional farmers will not invest enough in coordination effort*, since they will ignore the benefits occurring to GM farmers from increased aggregation.

Denote the solution to (3.a, 3.b) as $SO \equiv \left(l_g^*, l_{ag}^*, l_c^*, l_{ac}^*, d_g^*, d_c^*, e_g^*, e_c^*\right)$. The corrective mechanism to achieve the social optimum could include a mandatory buffer on GM fields adjacent to conventional fields consistent with joint profit maximization d_g^*, a tax τ_g^* on the GM OSR land allocation (accounting for the crop contamination externality and for the effect on conventional growers buffer area) and a tax τ_c^* on conventional OSR land allocation (accounting for the effect on GM growers buffer area) and some mechanism (e.g. a penalty) to incentivate both GM and conventional farmers to invest the appropriate resources in coordination effort. It is very likely that $\tau_g^* > \tau_c^*$ and if the effect of land al location decisions of one category of farmers on the magnitude of the buffer areas of the other category is relatively small (i.e. $\partial a_c/\partial l_g \cong 0$ and $\partial a_g/\partial l_c \cong 0$), then $\tau_g^* \cong \partial E/\partial l_g$ and $\tau_c^* \cong 0$.

It is perhaps worth mentioning how another solution could be to require GM farmers to adopt buffers wide enough to ensure that *no contamination at all* occurs on any conventional fields (i.e. total elimination of the externality). Without going into the details, it can be shown that this approach is likely to be inefficient for different reasons. First, it

might require GM farmers to adopt buffer areas larger than socially optimal. This in turn will discourage the planting of GM varieties, beyond what it would be socially desirable. Also, conventional farmers have no incentives to self protect so they will plant an excessive area of conventional OSR, they will introduce no buffers and they will not invest in coordination effort to increase aggregation.

III. THE MONTE CARLO SIMULATION

The analytical model presented in section 2 provides a schematic way to illustrate how the problem of coexistence clearly falls within the remit of production externalities. However, it is very difficult to make any detailed prescription on coexistence policies (apart from the general ones derived above) when little information about the nature of the GM externality exists. Our 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 (i.e. land allocation decisions, buffer width and degree of spatial aggregation). We will refer to such decision variables as 'policy variables', since any policy to regulate coexistence (e.g. tax on GM land allocation, mandatory buffers, incentives to increase aggregation) will ultimately act on them.

The large body of research on pollination biology has established that pollen concentration decreases rapidly within a few metres from the source but low levels can be detected at longer distances. This can be represented by a leptokurtic curve (e.g. [18]). Starting from an IDF, it is possible to use Monte Carlo simulations in order to characterise the functional form of the externality (expressions 2.c) and derive some insights into possible regulatory policies.

The model employed here is relatively simple, since it does not take into account important factors like flower synchrony, seed survival, emergence patterns etc., but it rather focuses on some of the variables that are expressly being targeted by the evolving coexistence regulations in the EU (i.e. the 'policy variables'). [20], for example, rely on the GENESYS model ([21] and [22]) 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. Also, the approach developed here could be integrated into more complex models.

In this paper we start from the model developed in [24] 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 more complete exposition presented in [23] and [24]. A 100 ha landscape, consisting of a 1000×1000 two-dimensional grid of cells, each measuring $1m^2$, 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[1]. In order to calculate the level of GM cross-pollination in each conventional field an average IDF, as estimated by [18], is used. Different IDF for OSR have been estimated (e.g. [25] and [17]). Each one would generate slightly different results, but given the preliminary nature of our analysis we believe that starting from [18] 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

$$g(\delta) = K \frac{(0.125)^2}{2\pi} e^{-0.125\delta}$$ (where δ is the radial distance from the source and K is a constant to ensure the integral of the function is unity). From

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

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 [18], the selfing rate was found to be 0.589 ± 0.065. As no information was reported as to 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[2] 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 the production function $f_c(\bullet)$ is needed (as in 2.d). 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 $C = f_c(CL) = 3(CL)^{0.9}$.

The main purpose of the simulation is to generate data in order to estimate expressions (2.c) and to test (2.e). Notice that for given premium Δp, the externality E is entirely defined by the 'contaminated output' C (see expression 2.c). Therefore our effort will be concentrated on estimating C. To ensure enough variability in the data generation process and better estimate their effect on C, 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 metres, 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 C. 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 [26]. 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) [19]. 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. 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. The level of spatial aggregation is quantified by using the index developed by [27]

$$A = \sum_{i=1}^{n} A_i \times \alpha_i \qquad (4.a)$$

$$A_i = \varepsilon_{i,i} / \max\_\varepsilon_{i,i} \qquad (4.b)$$

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. Remember that 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).

IV. RESULTS

Through repeated simulations (3000 runs) we generate data in order to estimate (2.c) and test (2.e). Table 1 provides descriptive statistics for the main data recorded during the simulation, while Figure 1 illustrates the simulation environment.

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

Table 1 Descriptive statistics for the variables in the simulation

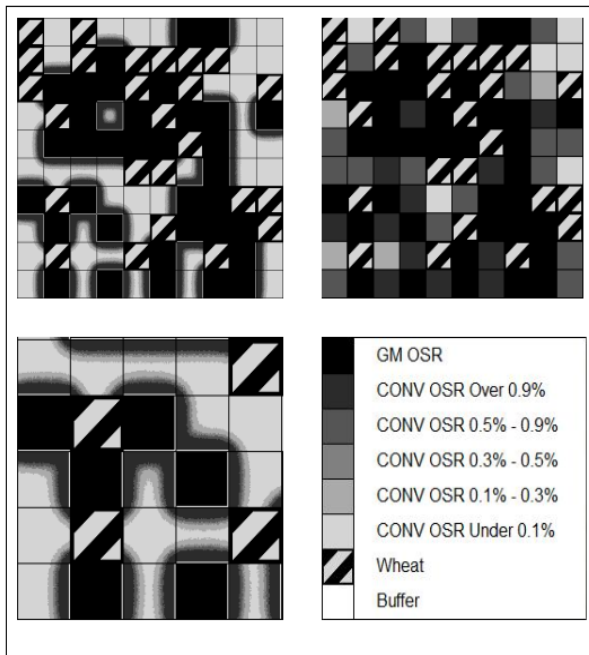| Variables	Description (Unit)	Mean	S.D.	Min.	Max.	# Cases
l_g	# of 1ha GM fields (# and/or ha)	32.5	11.5	13	52	3000
l_c	# of 1ha conv. fields (# and/or ha)	29.9	10.7	12	48	3000
d_g	Buffer width on GM fields (m.)	4.9	3.1	0	10	3000
d_c	Buffer width on conv. fields (m.)	5.1	3.2	0	10	3000
A	Aggregation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

Figure 1 Pollen-mediated AP levels in conventional fields at $1m^2$ 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.

A. The contaminated output C

The data generated through the simulation are used to fit the following functional form for C in (2.c)

$$\log(C) = \beta_0 + \beta_1 \log(l_g) + \beta_2 \log(l_c) + \beta_3 d_g + \beta_4 d_c + \beta_5 A + u \quad \text{(5.a)}$$

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

Expression (5.a) is estimated through Generalised Least Squares (GLS), in order to correct for the detected heteroskedasticity in the error terms u [28]. The correct specification hypothesis is tested through the RESET test [28] and cannot be rejected at the 0.1% significance level. The estimation results are reported in Table 2.

Table 2 Regression coefficients (and standard errors) reflecting the effect of the listed variables on the logarithm of the contaminated output log(C).

Variables	Coefficients (β) of expression 5.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

Estimation of (5.a) yields the predicted value $\overline{\log(C)}$ and the regression standard error $\overline{\sigma}$. Then the predicted value of C can be retrieved as follows [29]

$$\overline{C} = \exp(\overline{\sigma}^2/2)\exp(\overline{\log(C)}) \quad \text{(5.b)}$$

If information about the premium Δp exists, the externality E can be computed as in (2.c).

B. 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 we look at the marginal effect (ME). Given a function $\varphi(x_1...x_n)$, the ME with respect to the k-th variable is defined as $ME_k = \partial\varphi(\bullet)/\partial x_k$. The ME indicates the change in the dependent variable (C in our case) associated with small changes in the independent variable under consideration (assuming that all other dependent variables are constant). Estimating the ME for of the different 'policy variables' on C is important in order to make some inferences about the policies to regulate coexistence, on the basis of the arguments developed in section 2. The second column in Table 3 illustrates the MEs for C, when all the dependent variables are evaluated at their sample mean[3].

Table 3 Estimated marginal effects of the listed variables on the contaminated output C (from expression 5.b) when A is set to the sample mean (second column) and to the sample maximum (last column). The standard errors reported in the table have been computed using the delta method, as illustrated in [28].

Variables	C (Expression 5.b)	
	A=0.4	A=0.66
l_g	0.51***	0.42***
	(0.009)	(0.019)
l_c	0.26***	0.21***
	(0.008)	(0.012)
d_g	-0.9***	-0.74***
	(0.031)	(0.039)
d_c	-1.96***	-1.62***
	(0.028)	(0.067)
A	-8.89***	-7.32***
	(1.71)	(1.13)

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 (2.e). Also $\partial C/\partial l_c > 0$, implying that the 'dilution effect' is dominated by the 'production effect'. The MEs analysis suggests that the degree of spatial aggregation is the 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 of contamination is reduced. Also notice that in our experiment both conventional and GM buffers are left bare. It is plausible that if conventional buffers were planted with conventional OSR (subsequently sold as GM), the effectiveness of conventional buffers could be even higher (since the OSR on the buffers would produce pollen that would compete with the GM pollen).

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, to understand how the MEs 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. These results are illustrated in lat column on the right in Table 3.

By comparing the last two columns in Table 3, it is immediately evident that the relative importance of the different variables does not change even though all the marginal effects are smaller (i.e. when A is higher a change in any dependent variable has a smaller impact on C). This suggests that the results are quite robust to changes in the level of aggregation designed to better represent real situations.

V. DISCUSSION

This paper first develops an analytical model to analyse the problem of coexistence and then uses 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 production externalities and provides a number of stylised results. First, in the 'laissez-faire' regime GM farmers will adopt no measures to reduce

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[3] The MEs vary along the function φ(x₁…xₙ). As such they must be estimated at a certain 'point'. In table 3 we calculate the MEs at the sample mean.

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 [19]. The maximization of joint profits (i.e. the social optimum) requires GM farmers to reduce their GM plantings, adopt some buffers and invest some resources in clustering. Also notice that *when GM buffers are in place, conventional farmers planting decisions and clustering efforts have an effect on GM farmers*. This aspect should be considered when designing coexistence policies. In general the prescription of mandatory buffers on GM fields so as to eliminate the externality is economically inefficient since it might excessively reduce the GM adoption and might eliminate any incentive of the conventional farmers to self-protect. In general, policy interventions to achieve the social optimum should include:

1. A levy on GM land allocation to account for the effects of GM farmers planting decisions on the contamination cost and on the cost of conventional buffers. If the marginal effect of GM farmers planting decisions on the magnitude of conventional farmers' buffers is small, the value of the levy will be close to the value of the marginal contamination cost.
2. A moderate mandatory buffer on GM fields to account for the benefits to conventional farmers in terms of reduction of the contamination cost.
3. A smaller levy on conventional OSR land allocation to account for the effect of conventional farmers planting decisions on the cost of GM buffers. If the effect of conventional farmers planting decisions on the magnitude of the GM buffer is small, the value of the levy will be close to zero.
4. Incentives for both conventional and GM farmers to increase clustering, to account for the 'public' benefits of spatial aggregation.

The last point is particularly interesting. Since the extent of contamination is decreasing in the degree of spatial aggregation, the regulator could propose lower levies rates and lower mandatory GM buffers width when higher degrees of clustering are achieved. Experimental results suggest that economic incentives can be quite effective at increasing spatial aggregation of different land uses [30].

Over the past years, considerable effort has been devoted to the study of the implications of pollen-mediated gene flow for coexistence for a number of crops, including OSR (e.g. [31], [20] and [23] and [24]). The Monte Carlo experiment in this paper is innovative in different respects. First, it looks at the implications of pollen-mediate gene flow on the externality to conventional growers at the landscape level with particular attention to the role of the relative area of GM and conventional crops, buffers width and spatial aggregation. Second, by analysing the effect of buffer areas on both GM and conventional fields the paper provides useful information on the relative effectiveness of these measures. 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 [17]), could make spatial aggregation less important. Increasing field size would probably reduce the extent of contamination. [32] record AP levels at field scale below 0.03% in Australia, where field size varies between 25 and 100 ha. Despite these limits, our results are still relevant for coexistence policies. As already mentioned the current focus of coexistence policies is on the establishment of mandatory buffers on GM fields so as to drive contamination to zero. Our experiment's results suggest that conventional buffers are always more effective than GM buffers. We have already pointed out how establishment of mandatory buffers on GM fields so as to achieve zero contamination is economically inefficient. This argument is made stronger by the fact that buffers on GM fields are also 'technically' less efficient than buffers on conventional fields. If the difference in the buffer cost for GM and conventional farmers is not too big (i.e. if the premium Δp is not too high), than even at the social optimum it might be preferable to have conventional farmers to adopt larger buffers than GM farmers. The Monte Carlo experiment also suggests that the degree of spatial aggregation is the element with the largest ME on the contamination externality. However, the extent to which increases in coordination effort (necessaries to increase spatial aggregation) should be pursued will clearly depend on the costs of coordination. It is then obvious that

any step that could lower the costs of coordination is likely to be very important for coexistence. Given the large number of farmers that could be involved in coordination of planting decisions, the best way to reduce coordination costs could be to work at a more centralised level (e.g. through regional farmers associations). This is quite a common practice in certified seed production (e.g. maize seed production in France), where the need to avoid cross-pollination is of paramount importance. The identification of the specific policies for coexistence is beyond the remit of this paper and would have to be addressed on a case-by-case basis. The practical management issue for coexistence in the EU is to determine the relative pay-off to the different strategies to abate the externality (e.g. reducing the GM area through a levy, mandatory buffers, increasing spatial aggregation) for farming systems in which there is considerable variation in field size.

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