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Case Study

A method to search for optimal field allocations of transgenic maize in the context of co-existence

Yann DEVOS[1]*, Mathias COUGNON[1], Olivier THAS[2] and Dirk REHEUL[1]*

[1] Department of Plant Production, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, 9000 Ghent, Belgium
[2] Department of Applied Mathematics, Biometrics and Process Control, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, 9000 Ghent, Belgium

Spatially isolating genetically modified (GM) maize fields from non-GM maize fields is a robust on-farm measure to keep the adventitious presence of GM material in the harvest of neighboring fields due to cross-fertilizations below the European labeling threshold of 0.9%. However, the implementation of mandatory and rigid isolation perimeters can affect the farmers' freedom of choice to grow GM maize on their fields if neighboring farmers do not concur with their respective cropping intentions and crop plans. To minimize the presence of non-GM maize within isolation perimeters implemented around GM maize fields, a method was developed for optimally allocating GM maize to a particular set of fields. Using a Geographic Information System dataset and Monte Carlo analyses, three scenarios were tested in a maize cultivation area with a low maize share in Flanders (Belgium). It was assumed that some farmers would act in collaboration by sharing the allocation of all their arable land for the cultivation of GM maize. From the large number of possible allocations of GM maize to any field of the shared pool of arable land, the best field combinations were selected. Compared to a random allocation of GM maize, the best field combinations made it possible to reduce spatial co-existence problems, since at least two times less non-GM maize fields and their corresponding farmers occurred within the implemented isolation perimeters. In the selected field sets, the mean field size was always larger than the mean field size of the common pool of arable land. These preliminary data confirm that the optimal allocation of GM maize over the landscape might theoretically be a valuable option to facilitate the implementation of rigid isolation perimeters imposed by law.

Keywords: adventitious mixing / co-existence / cross-fertilization / field allocation / genetically modified crops / isolation perimeters / simulations

INTRODUCTION

Since the adoption of a co-existence policy at the European level in April 2004 (EC, 2003b), Member States (MS) have established or are developing a diversity of *ex ante* co-existence regulations and *ex post* liability schemes (Beckmann et al., 2006; EC, 2006). In *ex ante* co-existence regulations, preventive on-farm measures are prescribed to comply with the established labeling threshold for the adventitious presence of authorized genetically modified (GM) material in non-GM products, whilst *ex post* liability schemes cover questions of liability and the duty to redress the incurred harm caused by adventitious mixing. Because cross-fertilization has been defined as the major potential biological source of on-farm mixing in maize, and because cross-fertilization levels rapidly decrease with increasing distance from the pollen source (Schiemann, 2003), a diversity of isolation perimeters ranging between 15 and 800 m are proposed or imposed legally to spatially isolate GM maize fields from non-GM maize fields (Tab. 1). These isolation perimeters should ensure that the adventitious presence of GM material in non-GM products due to cross-fertilizations does not exceed the tolerance threshold of 0.9%. Exceeding the tolerance threshold will trigger the labeling of the product as containing GM material.

However, imposing wide and rigid isolation perimeters by law entails three main challenges. First, cross-fertilization studies mimicking worst-case commercial on-farm situations demonstrated that in many

* Corresponding authors: Dirk.Reheul@UGent.be;
Yann.Devos@efsa.europa.eu

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Table 1. Isolation perimeters proposed or imposed legally by some European Member States to ensure the co-existence between maize cropping systems (adapted from EC, 2006).

Member State	Isolation perimeter (m) for conventional maize	Isolation perimeter (m) for organically grown maize	Isolation perimeter (m) for maize seed production
Czech Republic	70	200	–
Denmark	200	200	200
France	50	–	–
Germany	150	300	–
Hungary	400	800	800
Ireland	50	75	–
Luxembourg	800	800	800
The Netherlands	25	250	250
Poland	200	300	–
Portugal	200	300	–
Slovakia	200	300	–
Spain	50	50	300
Sweden[c]	15[a] / 50[b]	15[a] / 50[b]	–
United Kingdom	80[a] / 110[b]	–	–

[a] Forage maize; [b] grain maize; [c] isolation perimeter doubles when GM maize varieties contain more than one transgene.

cases isolation perimeters over 50 m are not necessary to comply with the labeling threshold of 0.9% in grain maize (Bannert and Stamp, 2007; Della Porta et al., 2008; Goggi et al., 2006; Gustafson et al., 2006; Kraic et al., 2007; Pla et al., 2006; van de Wiel et al., 2007; Weber et al., 2007; Weekes et al., 2007). Similar conclusions have been drawn from out-crossing studies performed in real agricultural situations of co-existence in Spain (Messeguer et al., 2006, 2007) and from predictive vertical gene flow modeling at the landscape level in France (Lécroart et al., 2007; Messéan et al., 2006) and Italy (Mazzoncini et al., 2007). Considering that in fodder maize, transgenes are diluted over both grains and vegetative plant parts, isolation perimeters imposed for grain maize might be excessive for fodder maize (Hüsken and Schiemann, 2007). Moreover, larger and more spatially isolated recipient fields, recipient fields located in upwind position from the pollen source, recipient fields isolated by physical and/or natural barriers (*e.g.* trees, hedgerows), or non-GM maize plants showing a time lag in sowing and flowering dates compared with GM maize are less prone to cross-fertilization (Della Porta et al., 2008; Messeguer et al., 2006, 2007; Palaudelmàs et al., 2007). In such cases, less or no spatial isolation could be sufficient to comply with the labeling threshold (Devos et al., 2005; Messéan and Angevin, 2007; Messeguer et al., 2006, 2007; Sanvido et al., 2008).

Second, a number of case studies and simulations have shown that the implementation of wide isolation perimeters might not always be feasible in practice, especially in areas where maize is grown on a substantial part of the agricultural area and/or where maize fields are small and scattered throughout the cropped area (Devos et al., 2007b, 2008; Dolezel et al., 2005; Messéan et al., 2006; Perry, 2002; Sanvido et al., 2008). Where maize fields are close to each other, it is probable that each GM maize field would interfere with many non-GM maize fields. If farmers do not concur with the respective cropping intentions and crop plans of their neighbors and if no alternative co-existence measures are proposed by law, mandatory and rigid isolation perimeters might affect the farmers' freedom of choice to grow GM maize, which is at odds with European co-existence objectives (EC, 2003a).

Third, rigid isolation perimeters do not take into account a number of factors that largely affect cross-fertilization in maize. These include regional heterogeneity in GM maize share, cropping patterns, field characteristics and distribution, as well as meteorological conditions such as wind direction and speed (Devos et al., 2008; Ganz et al., 2007; Lécroart et al., 2007; Lipsius et al., 2006; Messéan et al., 2006; Viaud et al., 2007). Moreover, rigid isolation perimeters are not proportional to the farmers' basic economic incentives for co-existence (see Demont et al., 2008 for more details).

To ensure proportionate, fair and consistent co-existence of maize cropping systems at the regional and landscape level, it has been argued that a certain degree of flexibility should be built into *ex ante* co-existence regulations (Demont et al., 2008; Devos et al., 2008; Messéan and Angevin, 2007). This might be achieved by proposing plural co-existence measures that are adaptable to different regional situations and that are negotiable between farmers, rather than simply relying on mandatory and rigid isolation perimeters. Addressing co-existence on-farm enables the development of locally

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adapted co-existence arrangements, which are adapted to local farming and cropping variables, farm and field characteristics, landscape patterns, and to meteorological conditions (EC, 2003a). However, in practice, regional heterogeneity is still poorly accommodated in *ex ante* co-existence regulations (EC, 2006). Due to difficulties in making flexible co-existence measures operational from a legal point of view, national/regional authorities are reluctant to adopt such measures.

Provided that rigid isolation perimeters continue to be prescribed in *ex ante* co-existence regulations without creating any legal room for alternatives, in theory, the implementation of rigid isolation perimeters could be facilitated by restricting the cultivation of GM maize to areas with a low share of maize, and/or by growing GM maize in large clusters or in a low number of large fields (Devos et al., 2007a). Numbers of non-GM maize fields and farmers having non-GM maize fields occurring within isolation perimeters also are reduced when short isolation perimeters (< 50 m) are implemented. If supplemented with a shift in sowing and flowering dates and/or with the installation of a pollen barrier, short isolation perimeters may offer similar guarantees to comply with the labeling threshold than wide isolation perimeters (Devos et al., 2005, 2008; Sanvido et al., 2008).

In the present theoretical case study, a new strategy focusing on the spatial distribution of GM maize is developed to improve the farmers' freedom of choice to grow GM or non-GM maize when rigid isolation perimeters are imposed by law. A method is developed to search for optimal field allocations of GM maize, in order to minimize the proportions of non-GM maize fields and farmers that have at least one non-GM maize field occurring within isolation perimeters implemented around GM maize fields.

METHODOLOGICAL APPROACH

Spatial analyses

Using a digital map of agricultural fields of the region Anzegem (Flanders, Belgium) for 2004 (Devos et al., 2008), the shortest distance between arable fields – suitable for the cultivation of maize – was calculated from edge to edge with a spatial accuracy of approximately 0.25 m in a square of 25 km^2. Calculated distances were arranged in a distance matrix. The digital map, provided by the Flemish Land Agency, contained information about the cultivated crop, the size of the field, the field identification number, and the field relation number that corresponds to the farmer who uses the field. These field attributes were extracted from the geographic information system (GIS) datasets. Spatial analyses were performed in the software ArcView 3.1.

Scenarios

Maize was taken as study object, because it is a major crop in Flanders that occupies approximately 26% of the agricultural area and 36% of the arable land (NIS, 2008). However, it should be noted that the study area was one with a low maize share. As GM maize is not cultivated in Belgium yet, three scenarios (S) were simulated, in which some farmers act in collaboration by sharing/pooling the allocation of all their arable land for the cultivation of GM maize:

- S1-10%: 10% of the farmers with the largest maize area are selected to pool the allocation of their arable land;
- S2-10%: 10% of the farmers, who are selected randomly, pool the allocation of their arable land;
- S2-30%: 30% of the farmers, who are selected randomly, pool the allocation of their arable land.

It was assumed that the first GM maize growers probably would be the farmers with the largest maize areas, since they would be able to allocate their co-existence costs over a larger maize area. This scenario is expected to correspond to potential developments in a take-off situation of GM maize plantings. Sharing allocation of all the suitable arable land for the cultivation of GM maize increases the opportunities to allocate GM maize.

Considering that GM crop production is currently the "newcomer" in the EU, farmers who grow GM maize are responsible for taking appropriate on-farm measures to limit the adventitious mixing due to cross-fertilization. If spatial interference with neighboring non-GM maize farmers cannot be excluded, and if mutual agreement cannot be reached, GM maize growers will not be able to cultivate GM maize. Therefore, GM maize growers will have to adapt their cropping intentions and crop plans to those of non-GM maize growers. To limit spatial interference with neighboring non-GM maize farmers, it was assumed that GM maize growers would optimally allocate GM maize on their land. Moreover, previous investigations showed that maize shares are relatively stable over successive years in the studied region, indicating that non-GM maize fields can be considered as stable/fixed at the regional scale (Devos et al., 2007b, 2008).

For each scenario, the implementation of a mandatory and rigid isolation perimeter of 10, 25, 50 and 100 m around GM maize fields was tested. Based on recent reviews of the scientific literature on pollen dispersal and cross-fertilization in maize (Devos et al., 2005; Hüsken et al., 2007; Sanvido et al., 2008; van de Wiel and Lotz, 2006), and on predictive vertical gene flow modeling at the landscape level (Lécroart et al., 2007; Messéan et al., 2006), it was concluded that isolation perimeters ranging between 10 and 50 m – depending on the seed purity, field characteristics and distribution, crop types, differences in sowing and flowering times and on meteorological conditions – would be sufficient to comply with the labeling threshold of 0.9%. The isolation perimeter of 100 m represented a more conservative measure that could apply to stacked GM maize events. Because a stacked GM maize event contains more than one transgene (De Schrijver et al., 2007), a similar cross-fertilization rate will result in a higher content of GM material expressed in percentages of haploid genomes in recipient plants, compared with a single GM maize event. Therefore, stacked GM maize events might need wider isolation perimeters to comply with the labeling threshold. Moreover, sources other than cross-fertilization, such as seed impurities and the mixing in machinery and/or post-harvest procedures, could contribute to the adventitious presence of GM material in non-GM products under Belgian conditions. As a result, the GM-input from cross-fertilization may have to remain substantially below 0.9%.

Calculations and statistical analyses

Based on the distance matrix and field attributes ensuing from the spatial analyses, the proportions of non-GM maize fields and farmers having at least one non-GM maize field occurring within the isolation perimeters implemented around GM maize fields were calculated. Fields and their corresponding farmers falling within perimeters of several GM maize fields were only counted once. Calculations were performed using the statistical software R 2.3.1.

Within the common allocation pool of arable land of the selected farmers, GM maize was allocated randomly until a predefined maize area (called field set), needed to fulfill the farmers' maize demand, was reached. This random selection was repeated many times (see Tab. 2 for number of runs). Per random field set, the proportions of non-GM maize fields (and their corresponding farmers) occurring within the implemented isolation perimeters were calculated. The lower were the proportions of non-GM maize fields and farmers, the better. From the fourth run onwards, the best three field sets were stored by the computer. Results of any subsequent run were compared with this basket of best three field sets. If the computer found a better field set, this new set was exchanged for the worst set in the basket. Runs were stopped by the operator when the composition of the basket did not change anymore; that is, when the proportions of non-GM maize fields falling within the isolation perimeters did not further decrease.

To estimate the efficiency of optimally allocating GM maize in minimizing the proportions of non-GM maize fields and farmers that have at least one non-GM maize field occurring within the implemented isolation perimeters, three control scenarios (SC) were tested within the same allocation pool of arable land as in scenarios S1-10%, S2-10% and S2-30%. Instead of searching for optimal GM maize field allocations, GM maize was randomly allocated to the selected pool of arable land in the control scenarios. Through a Monte Carlo analysis, fields to be planted with GM maize were selected randomly until the maize area needed was reached during 10 000 independent runs. For each run, the proportions of non-GM maize fields and farmers having at least one non-GM maize field occurring within isolation perimeters were calculated. Average values of these runs were compared with the values calculated in the previous scenarios.

RESULTS

The common pool of arable land of the 10% largest maize farmers (10) consisted of 123 fields covering an area of 174.1 ha with 82.3 ha of maize. The average field size was 1.4 ha, meaning that approximately 58 fields would be needed to fulfill the farmers' maize demand.

For an isolation perimeter of 10 m, a set of 44 fields was found for the cultivation of GM maize for which the proportions of non-GM maize fields falling within the isolation perimeter was 2.9% (corresponding to five fields), involving 5.8% of all non-GM maize farmers (or five farmers). These proportions increased to 13.2% (23 fields) and 20.7% (18 farmers), respectively, when the isolation perimeter was increased from 10 m to 100 m (Tab. 2).

Proportions of non-GM maize fields and farmers falling within the isolation perimeter of 10 m of randomly allocated GM maize fields were 10.3 ± 1.6% and 17.6 ± 2.6%, respectively. These proportions increased to 23.8 ± 2.4% of all non-GM maize fields and 32.7 ± 2.9% of all non-GM maize farmers when an isolation perimeter of 100 m was implemented.

The mean size of the best three selected field sets for the cultivation of GM maize (1.6 ha) in scenario S1-10% was larger than the mean size of the pooled fields (1.4 ha) when an isolation perimeter of 10 m is implemented. For the implementation of an isolation perimeter of 100 m, the selected field sets had a mean size of 1.7 ha (Tab. 3). Results for the other two scenarios are given in Tables 2 and 3.

CONCLUSION

The optimal allocation of GM maize to any field of the shared pool of arable land of farmers who act in collaboration enabled the reduction of the proportions of

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Table 2. Proportions of non-GM maize fields and farmers having at least one non-GM maize field falling within isolation perimeters of 10, 25, 50 and 100 m for the best field set (S1-2) and for 10 000 random GM maize field allocations (SC1-2) when some farmers act in collaboration by pooling the allocation of their arable land for the cultivation of GM maize in the square of 25 km^2 in Anzegem (Flanders, Belgium).

Rigid isolation perimeter (m)	Number of runs	Number of GM maize fields	GM maize area (ha)	Proportion of non-GM maize fields (%)	Proportion of non-GM maize farmers (%)	Proportion of non-GM maize fields (%)	Proportion of non-GM maize farmers (%)	Quotient of proportions of non-GM maize fields	Quotient of proportions of non-GM maize farmers
			S1-10%			SC1-10%		SC1-10% / S1-10%	
10	520 000	44	82.3	2.87	5.75	10.34 ± 1.61	17.60 ± 2.64	3.60	3.06
25	240 000	54	82.5	4.60	8.05	11.72 ± 1.75	19.18 ± 2.70	2.55	2.38
50	230 000	58	83.1	5.75	10.35	14.14 ± 1.89	22.75 ± 2.91	2.46	2.20
100	250 000	50	84.8	13.22	20.69	23.77 ± 2.40	32.72 ± 2.92	1.80	1.58
			S2-10%			SC2-10%		SC2-10% / S2-10%	
10	100 000	18	35.9	0.48	1.14	4.78 ± 0.95	10.68 ± 2.08	9.96	9.37
25	120 000	18	36.2	1.90	4.55	6.07 ± 1.07	13.37 ± 2.35	3.20	2.94
50	120 000	18	36.1	1.90	4.55	6.83 ± 1.13	14.44 ± 2.35	3.60	3.17
100	140 000	14	35.8	4.29	10.23	9.15 ± 1.20	18.18 ± 2.40	2.13	1.78
			S2-30%			SC2-30%		SC2-30% / S2-30%	
10	200 000	51	92.9	3.11	7.35	13.10 ± 2.43	24.60 ± 4.34	4.21	3.35
25	600 000	52	93.1	4.35	10.29	15.58 ± 2.61	28.73 ± 4.50	3.58	2.79
50	350 000	49	94.4	6.83	16.18	19.84 ± 3.06	34.10 ± 4.66	2.91	2.10
100	690 000	47	93.3	11.80	23.53	29.55 ± 3.72	45.35 ± 4.66	2.50	1.92

Abbreviations: S1-10% = 10% of the farmers with the largest maize area optimally allocate GM maize on the common pool of arable land.
SC1-10% = 10% of the farmers with the largest maize area randomly allocate GM maize on the common pool of arable land.
S2-10% or S2-30% = 10 or 30% of the farmers, who are selected randomly, optimally allocate GM maize on the common pool of arable land.
SC2-10% or SC2-30% = 10 or 30% of the farmers, who are selected randomly, randomly allocate GM maize on the common pool of arable land.

Table 3. Average field sizes of the best three field sets to be planted with GM maize and of the common allocation pool of arable land per tested scenario in Anzegem (Flanders, Belgium).

Scenario	Average field size (ha) of best field sets Fixed isolation perimeters				Average field size (ha) of common pool
	10	25	50	100	
S1-10%	1.6	1.6	1.7	1.7	1.4
S2-10%	2.1	1.9	2.1	2.5	1.4
S2-30%	1.8	1.7	1.8	1.9	1.5

non-GM maize fields and farmers that have at least one non-GM maize field occurring within the implemented isolation perimeters. Compared with the random allocation of GM maize, at least two times less non-GM maize fields and their corresponding farmers occurred within the isolation perimeters implemented around optimally allocated GM maize fields. However, due to the small set of selected farmers, and because only one site*year was considered, caution is required when interpreting, extrapolating and scaling up these observations. Further investigations are needed to test whether other sets of farmers and sites change the outcome or give robustness to the preliminary results.

Not surprisingly, the mean field size of the selected field sets for the cultivation of GM maize proved to be systematically larger than the mean size of fields from the common pool of arable land. This indirectly confirms that growing GM maize in a small number of large fields facilitates the implementation of mandatory and rigid isolation perimeters (Devos et al., 2007b, 2008).

It remains to be seen whether the proposed method would be a valuable instrument for the agriculture community. In Southwest France and some other EU regions, for example, grain maize for animal feed is cultivated in proximity to maize production for starch, polenta and sweet maize, as well as with maize seed production. To maintain crop and varietal seed purity between the different maize cultivation systems and to maximally separate their crops, neighboring farmers seek mutual agreement about their respective cropping intentions and crop plans prior to sowing. As a consequence, at the regional scale, cropping patterns are fragmented or patchy with patches of similar crops at the regional scale (Bock et al., 2002; Schiemann, 2003; Sicard, 2003). Similar approaches could be envisaged for organizing the optimal allocation of GM maize in the context of co-existence and/or for the confinement of pharmaceutical crops (Marvier, 2008). To make the proposed method workable, farmers will have to talk to each other in due time. Not only should farmers make good agreements prior to sowing, farmers acting in collaboration should also be willing to grow GM maize on the selected fields of the common allocation pool of arable land. In practice, there might be logistic, economic and agronomic reasons to withdraw some fields from the shared pool of arable land. Various constraints such as water supply, soil properties, market-driven production strategies, field size and access, or location of food processing factories, machinery and of labor resources might affect field choices (Castellazzi et al., 2007). Moreover, if the same farmers act in collaboration for the cultivation of GM maize over successive years, it might lead to a tight monoculture of maize. Larger and more spatially isolated fields will be selected more frequently for the cultivation of GM maize than other fields in the studied case. Therefore, the method should be fine-tuned by taking into account several drivers of crop rotation and the allocation of crops to certain fields (*e.g.* Castellazzi et al., 2007).

If rigid isolation perimeters are nationally/regionally imposed by law and if neighboring farmers do not concur with their respective cropping intentions and crop plans, previous studies have demonstrated that grouping all GM maize fields in a large cluster is theoretically the most efficient way to minimize spatial co-existence interference between neighboring farmers (Devos et al., 2007b, 2008). However, this tactic collides with the freedom of land use and with good agricultural practices, since clustering is expected to favor and strengthen monoculture. Although the random allocation of GM maize fields offers the highest freedom of land use, it leads to the largest spatial co-existence problems. Optimally allocating GM maize theoretically offers an intermediate solution, as it minimizes spatial co-existence problems without jeopardizing the freedom of land use totally. Therefore, this tactic is worth considering as one of the possible means to ensure spatial co-existence between maize cropping systems in *ex ante* co-existence regulations.

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