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Agriculture, Ecosystems and Environment 108 (2005) 291–301
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

Gene flow of oilseed rape (*Brassica napus*) according to isolation distance and buffer zone

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Received 30 April 2004; received in revised form 6 January 2005; accepted 17 January 2005

Abstract

The introduction of genetically modified (GM) crops in the EU has raised questions concerning gene dispersal and co-existence with non-GM-farming. Quantitative estimates of the gene dispersal from fields with GM-crops to fields with conspecific non-GM-crops (conventional or organic) are therefore needed in order to suggest isolation distances and other management strategies to keep GM-pollination below acceptable threshold values. A meta-analysis of available gene-flow data for oilseed rape (*Brassica napus*) was performed. The probability distribution that seeds of non-GM-oilseed rape are fertilised by foreign pollen grains from a neighbouring field of GM-oilseed rape is modelled as functions of the width of the recipient (i.e. pollen receiving) field and the distance to the pollen donor fields. Furthermore, the significance of using a buffer zone (removal of a 1–5 m border of a recipient field parallel to the pollen donor field) to reduce GM-pollination of the crop, is quantified and discussed. The predicted median and 95% credibility level of the probability of foreign pollination is calculated as a function of the width of the recipient field and the buffer zone, as well as the distance between fields. Analysis of different management strategies shows that an increasing isolation distance is more effective to reduce GM-pollen dispersal than the use of a buffer zone, especially for small recipient fields. The analysis shows that increasing the width of a recipient oilseed rape field, relative to the pollen donor field, will have a large effect on reducing the average level of fertilisation by foreign pollen within the recipient field. The results indicate that a GM-pollination percentage <0.1% will be possible if the isolation distance exceeds 100 m and the width of the non-GM-field is larger than 200 m. If a threshold value of 0.3% is acceptable, an isolation distance of 50 m should be sufficient even for smaller fields. The use of a 5 m discarded buffer zone surrounding the non-GM-field is expected to reduce GM-pollination by about a third. The implications of the results for field management in conventional and organic farming are discussed.

Keywords: *Brassica napus*; Co-existence; Gene flow; Genetically modified organism (GMO); Farm management; Pollen dispersal

1. Introduction

A much-debated issue regarding the commercial growing of genetically modified (GM) plants is the possible transfer of transgene pollen into neighbouring

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0167-8809/$ – see front matter
doi:10.1016/j.agee.2005.01.007

fields with similar crops. If a non-GM-crop is fertilised by GM-pollen, a certain percentage of the harvested seed product will contain GM. This may be objectionable to consumers, and current regulation in the EU (EU, 2003) and elsewhere limits the allowed content. In organic farming, the regulations do not allow the use of genetic engineering in the grain production system partly in order to guarantee GM-free products to the consumers (Nijhoff and Andersson, 2001). Hence, the proportion of seeds containing GMO may not exceed a critical detection level, e.g. 0.1%, if the crop is to be classified and sold as an organic crop. This includes all sources of transgene contamination during production and distribution, which is generally low in organic crops because of the separate distribution lines. The main sources for GM contamination of non-GM-crops at the farm level are: seed impurities, pollen dispersal between fields, seed dispersal with machinery, dispersal of pollen and seeds from volunteer plants, and mixing of crops after harvest (Bock et al., 2002; Kjellsson and Boelt, 2002). For conventional crops, e.g. oilseed rape, the critical level of GM contamination by pollen is therefore in practice somewhat below 0.9%, which is the threshold value for labelling of GM in food and feed by the EU (EU, 2003). It has been realised for some time (e.g. Timmons et al., 1995) that commercial release of GM-oilseed rape is likely to result in movement of GM genes to non-GM-fields.

The current study is focused on providing management measures, i.e. isolation distances and buffer zones, to reduce the level of gene flow by pollen from GM-oilseed rape to conventional and organic rape to acceptable levels. This is done by a meta-analysis of existing data from field trials in EU, North America and Australia. Oilseed rape (*Brassica napus* L.) is a partially self-fertilising summer or winter annual crop where a number of GM varieties have been developed. These include herbicide tolerant varieties that are already in commercial production outside the EU and insect resistant varieties, which are being tested (JRC, 2003). While oilseed rape is a major crop in conventional farming in EU, it has a minor but increasing importance to organic farming (Tolstrup et al., 2003). The level of outcrossing from neighbouring plants in the field or from pollen dispersed by wind and insects varies between 12 and 47% (Becker et al., 1992). The relative importance of insects and wind for pollination seems to vary and no general conclusions can be made except that bees and wind can result in cross-pollination at distances of more than 5 km from the source (Eastham and Sweet, 2002; Ramsay et al., 2003). The concentration of oilseed rape pollen in the air normally decreases rapidly (exponentially) with the distance from the source (Metz et al., 1997). Cross-pollination may also show irregular patterns depending on prevailing wind directions (Eastham and Sweet, 2002), the topography and distribution of insect pollinator populations, including beehives (Ramsay et al., 2003).

2. Analysis of gene flow

Oilseed rape pollen are normally produced in an abundant amount (e.g. 9.3 ± 0.5 kg pollen per ha per day, Westcott and Nelson, 2001) over a period of approximately 4–5 weeks. The dispersal of the pollen is a stochastic process where the majority of the pollen grain are dispersed over a short distance (Lavigne et al., 1998). Due to the dispersal pattern of oilseed rape pollen and the large pollen production within an oilseed rape field, it is expected that the proportion of foreign pollen, i.e., pollen that are produced in a neighbouring field of oilseed rape, is reduced along a transect running from the border towards the centre of the field. This is caused by dilution of the foreign pollen from the massive pollen production in the receiving field. The dilution effect of foreign pollen from the same species may be used in the management for co-existence of organic and conventional crops with GM-crops. Hence, the proportion of successful GM-pollen in a non-GM-field with the same crop may be reduced by:

1. exclusion of a narrow, 2–5 m wide, strip of the non-GM-field, i.e., the buffer zone, opposite the GM-crop at the time of harvest,
2. increasing the width of the non-GM-field,
3. increasing the distance between the GM- and the non-GM-field, i.e., the isolation distance, or by using a combination of different methods.

The probability that a foreign oilseed rape pollen grain will result in a successful fertilisation in a neighbouring oilseed rape field will, in the following, be denoted as the probability of foreign pollination. (Note that the use of the concept ''foreign pollination'' in this paper differs from the normal use of the concept in plant reproductive biology.) A number of empirical studies have quantified the probability of foreign pollination between oilseed rape experimental plots or fields (hereafter all denoted ''fields''), and it seemed appropriate to make a quantitative synthesis of the gathered data in the form of a meta-analysis of the probability of foreign pollination. Most of the conducted gene-flow experiments fall into two design classes:

I. The fields are situated next to each other (adjacent fields) and the probability of foreign pollination is measured as a function of the distance from the common edge.

II. The fields are separated by some distance (non-adjacent fields) and the probability of foreign pollination is measured at a single or few locations within the field so that only a mean probability of foreign pollination can be determined for the field.

A literature search for studies of gene flow in oilseed rape was performed and studies that belonged to either one of the two specified design classes were selected for the current meta-analysis (Table 1).

The selected empirical studies in Table 1 have used variable sized fields with different varieties of oilseed rape, geographic locations, detection methodologies, inter-field distances, intra field sampling designs, etc. Any study using male-sterile plants as the pollen receiver was excluded, because such studies, although

Table 1
Published sets of oilseed rape (*Brassica napus*) gene flow data selected for meta-analysis

Country, number of recipient fields	Donor field size	Recipient field size/ width	Distance between fields/distance to sample sites	Detection method (marker)/data for parameter estimates	Design class[a]/number of samples	References
Australia, 63 fields (190 locations)	25–100 ha	25–100 ha/–	0–3000 m/3 samples per field (no distances given)	Herbicide tolerance/ graphs	II/60	Rieger et al. (2002)
Canada, 2 fields	16–64 ha	16–64 ha/ 400–800 m[b]	1 m/20–100 m	Herbicide tolerance/ outcrossing frequency	II/2	Downey (1999), Eastham and Sweet (2002)
Canada (11 locations)	–	–/–	0/0–800 m	Gene stacking/ outcrossing frequency	II/7	Beckie et al. (2001)
France (3 locations)	1 ha	–, trap plants in surrounding area	0/0–130 m	Herbicide tolerance/ percentage double resistance	I/76, 79, 24	Champolivier et al. (1999)
Sweden, Denmark, Germany (5 locations)	–	20–40 m^2/5 m	0/5 m	Isozymes/outcrossing frequency	I/20	Becker et al. (1992)
UK, –	ca. 9 ha	–, trap plants in the area	100–600 m/–	Herbicide tolerance/ outcrossing frequency	II/7	Simpson cit. in Eastham and Sweet (2002)
UK, 4 plots	400 m^2	400 m^2/20 m	200, 400 m/–	Herbicide tolerance/ outcrossing frequency	II/4	Scheffler et al. (1995)
UK, 2 fields	10 ha	10 ha/316 m[b]	0 m/5–250 m	Herbicide tolerance/ outcrossing frequency	I/15, 17	Norris cit. in Eastham and Sweet (2002)
UK, 2 fields	10 ha	0.8 ha/89 m[b]	0 m/0–92 m	Herbicide tolerance/ outcrossing frequency	I/13	Simpson cit. in Eastham and Sweet (2002)
UK, 1 field	8 ha	7 ha/265 m[b]	0 m/0–200 m	Herbicide tolerance/ outcrossing frequency	I/42	Norris and Sweet (2001)
USA, 2 sites	–	–, trap beds and barriers	4 m, 8 m/–	Kanamycin marker/ outcrossing frequency	II/4	Morris et al. (1994)

[a] Design classes: (I) adjacent fields, (II) non-adjacent fields.
[b] Estimated value.

they give a good estimate of the process of pollen dispersal (e.g. Lavigne et al., 1998), do not include the important effect of dilution of the foreign pollen due to massive pollen production of a normal pollen producing oilseed rape crop.

It is known that the spatial distribution and sizes of the pollen donating and recipient fields, has an important influence on the probability of outcrossing (Ingram, 2000; Eastham and Sweet, 2002), and pollen dispersal may be simulated deterministically in a specific and complex cultivation system (Colbach et al., 2001a, 2001b), where the effect of two or more donor fields in a specific spatial setting may be considered. However, the approach used in this paper is to take advantage of the relatively large number of data that are available from field trials world-wide, and treat the variable field sizes, oilseed rape varieties, and geographic locations as random variables and fit simple empirical statistical models to the experimental measurements of the probability of foreign pollination. In the present study the probability of foreign pollination is expressed as a function of the width of the recipient field, the distance between fields, and the width of a border or buffer zone in the recipient field.

3. Modelling pollination

Simple empirical models were used to characterise the probability of foreign pollination from a donor field to a recipient field. Due to the two different types of available data, the modelling of adjacent and non-adjacent fields was treated separately.

3.1. Adjacent fields

Imagine a single partially self-fertilising rapeseed plant standing on the border between two adjacent fields. A proportion of the plant seeds are expected to be the result of self-fertilisation with a probability of θ_1, and the remaining $(1-\theta_1)$ seeds are expected to result from an equal amount of pollination from each field. Thus the expected proportion of foreign pollination at the border of two adjacent fields is $(1-\theta_1)/2$. Now imagine a perpendicular transect from the border into the recipient field, characterised by the distance, x, from the common border. Due to the dilution of foreign pollen with distance, the proportion of fertilisation from foreign pollen would be expected to decrease along the transect. Furthermore, it seems that most successful rape pollen reach the recipient plant within a relatively short distance from the pollen donating plant (Lavigne et al., 1998). Consequently, it may be necessary to model the dilution of pollen close to the pollen donating plants differently from the dilution of pollen more distant from the pollen donors.

A compound exponentially decreasing function is used to model the decrease in the probability of foreign pollination at the distance x from the common border:

$$g_a(x) = \begin{cases} \dfrac{1-\theta_1}{2}\exp(-\theta_{2n}x) & x \le d \\ \dfrac{1-\theta_1}{2}\exp(-\theta_{2n}d)\exp(-\theta_{2f}(x-d)) & x > d \end{cases} \tag{1}$$

where θ_{2n} measures the relatively fast decrease in the probability of foreign pollination near the common border and θ_{2f} measures the relatively slow decrease in the probability of foreign pollination further from the common border. Based on the results by Lavigne et al. (1998) the transition point, d, where the relatively fast decrease in the probability of foreign pollination is reduced, is set to 3 m.

If a strip of the field (i.e. the buffer zone) of width Z closest to the pollen donating field is not harvested, then the average probability of foreign pollination in the recipient field (an organic or a conventional field) of width X is:

$$G_a = \frac{1}{X-Z}\int_Z^X g_a(x)\,dx \tag{2}$$

3.2. Non-adjacent fields

The above model assumes that the two fields are adjacent. However, in actual farming practice, some distance will typically separate the fields. It is therefore necessary to modify the model in this case, but the nature of the available data put a constraint on the way the model could be modified. Due to the nature of the available data the correction has to be made by adjusting for the expected reduction in the *average* probability of foreign pollination in the recipient field as a function of the distance between the fields.

The effect of the distance between fields, Y, on the average probability of foreign pollination from a pollen donating field into a recipient field is modelled by another exponentially decreasing function:

$$G_n = \theta_3 \exp(-\theta_4 Y) \quad (3)$$

where θ_3 measures the average probability of foreign pollination if the two fields were adjacent, and θ_4 measures the decrease in the average probability of foreign pollination with increasing distance between fields.

Two alternative models to the exponentially decreasing function (3) were tried:

(i) a two-parameter inverse power model was fitted to the non-adjacent field data, but the fit of this model was consistently upward biased at intermediary and high distances,
(ii) a two-parameter modified Weibull function that includes the exponential decreasing function as a special case (Neubert et al., 1995) was also fitted to the data, but this model had a lower maximum likelihood value for the same number of free parameters and was unstable for some of the relevant parameter space. Furthermore, the hypothesis of an exponentially decreasing function was accepted ($P = 0.18$) in this model.

None of the used alternative fat-tailed models showed a significant qualitative change, and it was concluded that the reported results are not highly sensitive to the selected model when the fields are close or at medium distances.

Finally, it may be of interest to estimate the average probability of foreign pollination in the strip that is not harvested (the buffer zone), which may be calculated by:

$$\frac{X}{Z}\left(G_{(z=0)} - G\left(1 - \frac{Z}{X}\right)\right) \quad (4)$$

4. Results

All data points for each design class (Table 1) that could be obtained either directly from published tables or indirectly from published figures were given equal importance (not weighted) and combined in order to determine the Bayesian posterior distribution of the parameters.

The five parameters in the two models may be regarded as two independent sets of parameters:

i. θ_1, θ_{2n} and θ_{2f}, which are fitted using data of the probability of self-fertilising and the combined data of the probability of foreign pollination of design class 1 (adjacent fields).
ii. θ_3 and θ_4, which are fitted using the combined data of the probability of foreign pollination of design class 2 (non-adjacent fields).

The joint Bayesian posterior distribution of θ_1, θ_{2n} and θ_{2f} was obtained by fitting model (1) to the combined data of the probability of foreign pollination of design class 1 (Table 1). To include available information from two sets of data on the probability of self-fertilisation (Becker et al., 1992; Olsson, 1960) a prior distribution of θ_1 in the form of the two-parameter beta-distribution was fitted to the data ($\alpha = 13.14$ and $\beta = 6.88$, moment estimation approach (Johnson et al., 1995)).

The prior distributions of θ_{2n} and θ_{2f} were assumed to be uninformative. The joint likelihood function of the parameters θ_1, θ_{2n} and θ_{2f} was calculated assuming homogenous and normally distributed residuals after both the combined data and model (1) was Box–Cox transformed ($\lambda_1 = -40$, $\lambda_2 = 2$) (Seber and Wild, 1989). The maximum likelihood estimates of the parameters fitted the combined data quite well (Fig. 1).

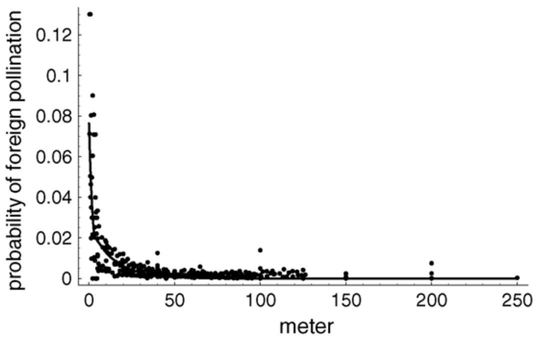

Fig. 1. Probability of foreign pollination in adjacent fields as a function of the distance from the common border. Points are the combined data of design class 1 ($n = 286$). Line is the fitted model (1) with the maximum likelihood estimates of the parameters ($\hat{\theta}_1 = 0.84$, $\hat{\theta}_{2n} = 0.43$, $\hat{\theta}_{2f} = 0.07$).

All the three parameters were significantly different from zero (likelihood ratio tests: $P < 0.0001$ for all tests), θ_{2n} was significantly higher than θ_{2f} (likelihood ratio test: $P < 0.0001$), thus the assumption of a relatively fast decrease in the probability of foreign pollination near the common field border was confirmed (see also Lavigne et al., 1998). The joint Bayesian posterior probability of θ_1, θ_{2n} and θ_{2f} was obtained by combining the specified prior distributions and the joint likelihood function of the parameters according to Bayes formula. A contour plot of the density of the joint Bayesian posterior probability of θ_{2n} and θ_{2f} shown at the mean of the marginal posterior distribution of θ_1 is shown in Fig. 2. The contour plot indicates which combinations of θ_{2n} and θ_{2f}, which are most probable (most white), according to the model and the fitted data.

Likewise, the joint Bayesian posterior distribution of θ_3 and θ_4 was obtained by fitting model (3) to the combined data of the probability of foreign pollination of design class 2 (Table 1). The prior distributions of both θ_3 and θ_4 were assumed to be uninformative. The joint likelihood function of the parameters θ_3 and θ_4 was calculated assuming homogenous and normally distributed residuals after both the combined data and model (3) was Box–Cox transformed ($\lambda_1 = -35$, $\lambda_2 = 2$). There was a relatively large unexplained variation in the combined data set, possible due to variation in field sizes, consequently the fit of the model (3) was not optimal (Fig. 3).

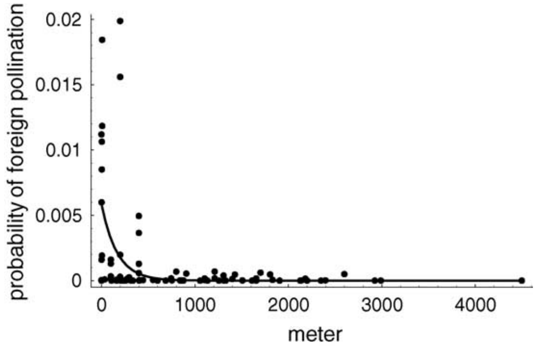

Fig. 3. Average probability of foreign pollination in non-adjacent fields as a function of the distance between the fields. Points are the combined data of design class 2 ($n = 84$). Line is the fitted model (3) with the maximum likelihood estimates of the parameters ($\hat{\theta}_3 = 5.87 \times 10^{-3}$, $\hat{\theta}_4 = 6.01 \times 10^{-3}$).

Both parameters were significantly different from zero (likelihood ratio tests: $P < 0.0001$ for both tests). The joint Bayesian posterior probability of θ_3 and θ_4 was obtained by combining the uninformative prior distributions and the joint likelihood function of the parameters according to Bayes formula. Since a significant fraction of the data from non-adjacent fields (design class II, Table 1) came from a single Australian study (Rieger et al., 2002), the densities were calculated both with and without the Australian data, in order to assess how sensitive the results are to this particular study (Fig. 4). There is a large unexplained variation in the combined data set, which partly may be explained by an unknown variation in field sizes.

The expected probability of foreign pollination in a field will be reported by the median and the 95% percentile (the 95% credibility level, i.e. in 5% of the fields, the average GM-content is expected to be higher than the shown value). The 95% credibility level is chosen because this value is relevant to the organic or conventional farmer who may need a 95% assurance level that the proportion of seeds pollinated with GM-pollen (i.e., GM-containing) is below a required threshold level.

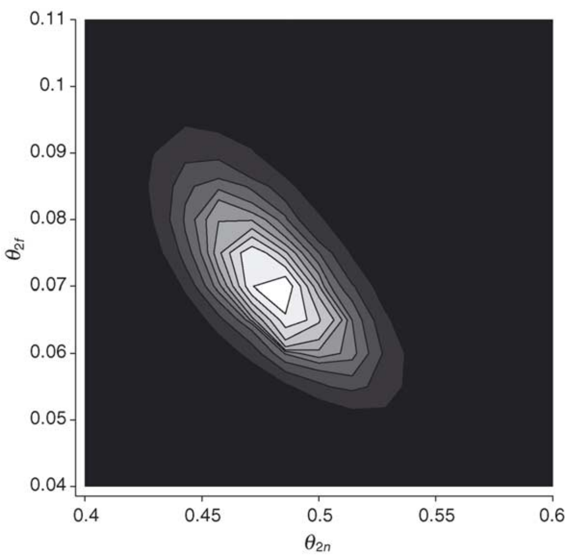

Fig. 2. Contour plot of the density of the joint Bayesian posterior probability of θ_{2n} and θ_{2f} shown at the mean of the marginal posterior distribution of θ_1. Increasing whiteness indicate an increasing density.

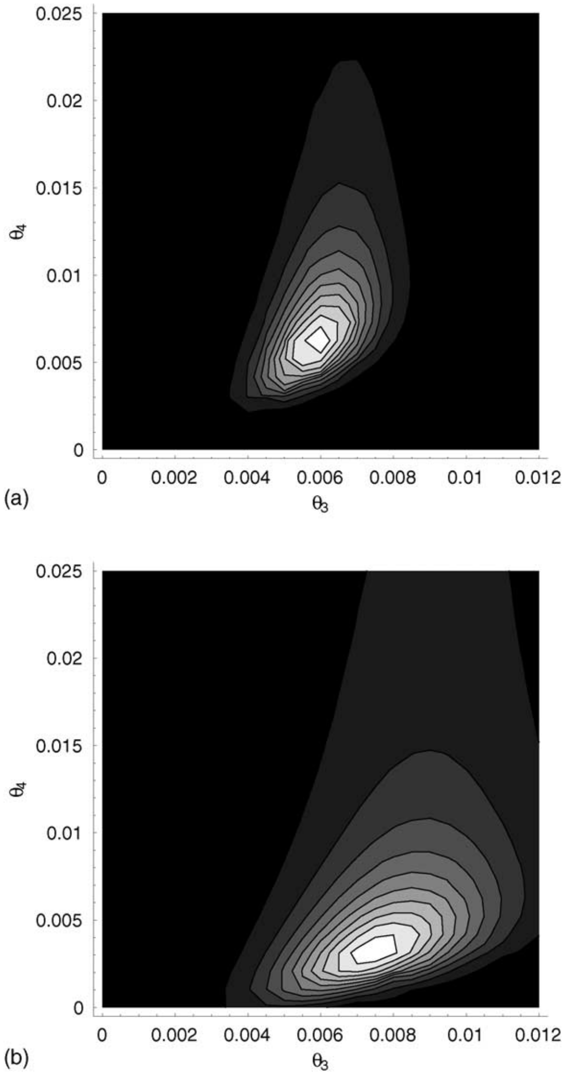

Fig. 4. Contour plot of the density of the joint Bayesian posterior probability of θ_3 and θ_4. Densities are fitted with (a) and without the Australian data (b). Increasing whiteness indicate an increasing density.

The distribution of the average probability of foreign pollination, G_a, in adjacent fields given the width of the field, X, and the width of the buffer zone, Z, may be obtained by random sampling (the rejection method, e.g. Rose and Smith, 2001) from the joint posterior distribution of the three model parameters and calculate G_a using model (2) (Table 2).

From the numerical examples in Table 2, it is clear that both the width of the recipient field and the width of the discarded buffer zone have large effects on the probability of foreign pollination due to the effect of dilution of foreign pollen. Generally, the effect of a 5 m discarded border zone was to reduce the probability of foreign pollination in the rest of the field by 1/3 (Table 2).

Similarly to the case of adjacent fields, the distribution of the average probability of foreign pollination, G_n, in non-adjacent fields given the distance between fields, Y, may be obtained by random sampling from the joint posterior distribution of θ_3 and θ_4. Since a significant fraction of the data from non-adjacent fields (design class II, Table 1) came from a single Australian study (Rieger et al., 2002), the probability of foreign pollination was calculated both with and without the Australian data, in order to assess how sensitive the results are to this particular study (Fig. 5).

It is possible to combine the information of the decline in the probability of foreign pollination along a transect in the organic field primarily due to dilution of foreign pollen (Fig. 1), and the decline primarily due to separation between fields (Fig. 3). The expected combined width of the observed non-adjacent fields may be calculated by taking the limit of Eq. (4) when the between-field distance approaches zero (θ_3) and setting it equal to Eq. (2) and solving for an unknown X, the width of the recipient field. Using this method on all the data of design class II, the expected combined width of the observed non-adjacent fields was found to be about 57 m, which is not contradicted by the limited number of reported field widths (Table 1). Now, assuming that the decline in the probability of foreign pollination along a transect in the organic field may be predicted by θ_{2f}, as suggested in Eq. (3), the information on the effect of the width of the recipient field and the information on the effect due to separation between fields may be combined to express the probability of foreign pollination at variable distances between fields and widths of the recipient field (Fig. 6).

5. Discussion

The present study is based on the assumption that the included data set are representative of contemporary oilseed rape farming practices. It was chosen to

Table 2
Probability of fertilisation from foreign pollen in adjacent fields of oilseed rape

Buffer zone (m)	Width of the field (m)						
	50	100	150	200	300	400	500
0	0.91 (0.83)	0.47 (0.42)	0.32 (0.28)	0.24 (0.21)	0.16 (0.14)	0.12 (0.11)	0.09 (0.08)
1	0.78 (0.70)	0.41 (0.36)	0.27 (0.24)	0.20 (0.18)	0.14 (0.12)	0.10 (0.09)	0.08 (0.07)
2	0.71 (0.63)	0.37 (0.32)	0.24 (0.21)	0.18 (0.16)	0.12 (0.10)	0.09 (0.08)	0.07 (0.06)
3	0.67 (0.59)	0.35 (0.30)	0.23 (0.19)	0.17 (0.15)	0.11 (0.10)	0.08 (0.07)	0.07 (0.06)
4	0.64 (0.56)	0.33 (0.28)	0.22 (0.18)	0.16 (0.14)	0.11 (0.09)	0.08 (0.07)	0.06 (0.05)
5	0.62 (0.53)	0.31 (0.26)	0.21 (0.17)	0.15 (0.13)	0.10 (0.08)	0.08 (0.06)	0.06 (0.05)

Ninety five percentage of credibility level and the median of the average foreign pollination (in %) between adjacent fields at various levels of the width of the field (X) and the width of the omitted border (Z).

model the variable field sizes, oilseed rape varieties, and geographic locations in the experiments as random variables as if the experiments were made with a randomly picked field size, oilseed rape varieties, and geographic location. However, this is not an adequate description of how experiments are made. The fields in an agricultural system are expected on average to be larger than the fields used in the analysed experiments. This would result in lower rates of foreign pollination than predicted by the model.

In the Australian study the field sizes were relatively large, from 25 to 100 ha (Rieger et al., 2002). The field sizes used in other field experiments (excluding Australia) were lower, ranging from 0.8 to 16 ha (Table 1). In Denmark, the size of the majority of fields (approx. 93%) is less than 10 ha, while approx. 75% of the fields are less than 5 ha (Tolstrup et al., 2003). The probability of foreign pollination in the analysed fields from Australia tends to be lower than the probability observed in the other studies, which could consequently be caused by the effect of larger field sizes. Other possible explanations are that the bee populations are smaller in Australia and that the conditions during flowering may be dryer, resulting in reduced pollen viability (Salisbury, 2002). Furthermore, contamination of the commercial seed with herbicide resistant (imidazolinone) varieties has been suggested as explanation for some unexpected

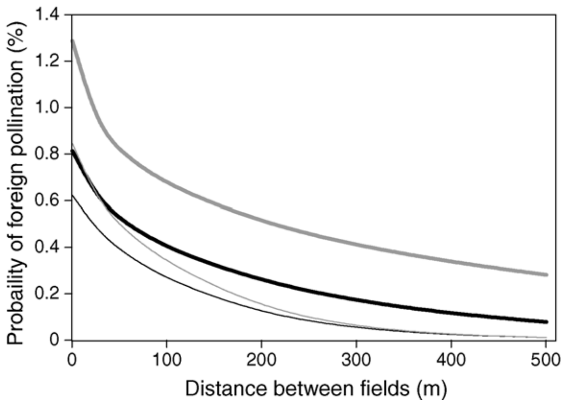

Fig. 5. Probability of fertilisation from foreign pollen in non-adjacent fields of oilseed rape. Ninety five percentage of credibility level (fat line) and the median (thin line) of the average foreign pollination (in %) between non-adjacent fields as a function of the between-field distance. Results are shown both with (black) and without the Australian data (grey).

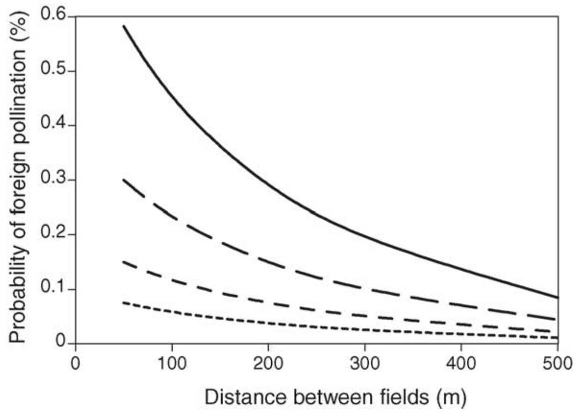

Fig. 6. Probability of fertilisation from foreign pollen in relation to distance between fields and field width. Data from both adjacent and non-adjacent fields has been used and no buffer zone was assumed. The 95% credibility level of the average foreign pollination is shown in percentage. The width of the fields are 50 m (full line), 100 m (large dashed line), 200 m (medium dashed line), and 400 m (small dashed line).

high levels of foreign pollination at long distances (anon. reviewer).

The size of the donor and the recipient fields are similar in most of the cases where specific data is available (Table 1). Since the average probability of foreign pollination is expected to decrease with the size of the recipient field and increase with the size of the pollen donor field, both the actual field sizes and the relative proportion of donor to recipient fields influence the probability of foreign pollination. If more information of the size of fields were available, it would be possible to make a correction for field size by making the parameters θ_3 and θ_4 functions of field size. Likewise, given enough data it would be possible to correct for geographic location and direction of the prevailing wind. By modelling long-distance wind dispersal of pollen in the landscape and including the distribution of GM- and non-GM-fields, the relative probability of GM-pollination may be predicted at the field level (Løfstrøm et al., 2003).

In general, the predicted probability of foreign pollination between fields is relatively low if an adequate distance separates them or if the recipient field is wide. Therefore, it is possible to suggest management strategies, which will enable the co-existence of non-GM- and GM-crops in the same region.

Based on the results of the modelling, different situations/scenarios appear for management strategies to reduce foreign GM-pollination. An isolation distance of 200 m between GM-oilseed rape and organic oilseed rape fields should be sufficient even for very small fields (field width of 50 m) to keep the GM-pollination of the organic crops below 0.3%. This is comparable with existent requirements for production of certified seeds of oilseed rape for farmer use (Tolstrup et al., 2003) where the minimum distances to areas with other varieties are 100 m (self-fertile) or 300 m (hybrids). If the field are larger (field width of 100 m) 50 m isolation should be sufficient (Fig. 6). The results also indicate that GM-pollination percentages below 0.1% will only be possible for isolation distances above 100 m and then only if the width of the organic field is above 200 m. However, in cases where hybrid varieties with male-sterile plants are used in the recipient crop, the probability of foreign pollination will be higher than with conventional cultivars (Sweet et al., 1999; Ingram, 2000) and larger than those predicted by the models. Isolation distance used for regulation of gene flow is found to be most effective for self-fertile target crops, but ineffective for male-sterile target crops (Walklate et al., 2004).

Increasing the size (width) of the field to 200–400 m (≈4–12 ha), and thereby diluting the foreign pollen to a lower proportion, is an effective way of reducing the average pollen flow from GM-fields to an organic field. For small fields, e.g. less than 4 ha, the results indicate that increasing the isolation distance will be the most effective management tool for reducing the average gene flow between crops. The use of a discarded border crop will also reduce GM-pollination, and if it is impossible to increase the width of the organic field or the isolation distances between organic fields and GM-fields, excluding the border area (e.g. a 5 m buffer zone) of the organic field closest to the GM-field may be a relatively cost-effective management strategy. Border zones of 10 m or more have been used in Canada to reduce outcrossing in oilseed rape, and preliminary results indicates that they can be effective in reducing pollen-mediated gene flow in small fields (Staniland et al., 2000). In most cases, several GM-farms are present in the surroundings of the organic field, and the entire buffer zone around the field should be excluded. The discarded border crop may still be harvested, but because of the higher GM-content it should not be used and distributed as an organic or a non-GM-crop.

6. Conclusions

Even if the level of GM contamination from pollen have been controlled to an acceptable level by adequate isolation distances and buffer zones, additional sources of dispersal will require control and management. Hence contamination of certified seed from accidental mixing with GM-seeds can occur and GM-seed may be dispersed with farming equipment when machinery is shared with non-GM-farmers (see Tolstrup et al., 2003). Populations of volunteer GM-oilseed rape from the seed bank can also become a troublesome source for GM contamination in the field if cropping intervals are too short (e.g. less than 8–12 years, Tolstrup et al., 2003). Gene transfer from GM to feral populations of oilseed rape is also likely to occur (Wilkinson et al., 1995) especially if field management is neglected and could act as secondary sources for GM dispersal. If herbicide-tolerant GM-oilseed rape is cultivated, gene stacking of different types of tolerances may occur (Beckie et al., 2003) and need special considerations in management. There is still uncertainty about the relative importance of the different routes for adventitious presence, although volunteers, seed dispersal and pollen dispersal are generally considered most important (Norris and Sweet, 2001). The co-existence of GM-farming with conventional non-GM- and organic farming will require both effective control measures, evaluation by monitoring and further research on dispersal routes and management methods.

Acknowledgements

Thanks to Anne Marie Plejdrup for extracting the data from figures and other sources in the literature, and to Jesper Bak and Birgit Nielsen for commenting on a previous version of the manuscript. We also wish to express many thanks to The Danish Research Centre for Organic Farming (DARCOF) for support and suggestions. The research was financed by a grant from the Danish Ministry of Food, Agriculture and Fisheries.

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