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Review article

Coexistence of genetically modified (GM) and non-GM crops in the European Union. A review

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Abstract – The adoption of genetically modified (GM) crops in the European Union (EU) raises questions on the feasibility of coexistence between GM and non-GM crops. Regulations to ensure that different cropping systems can develop side-by-side without excluding any agricultural option are currently implemented or developed by member states. The aim of this review is to explore whether nationally or regionally proposed coexistence strategies comply with the general principles established by the European Commission that ask for science-based and proportionate coexistence measures. In the first part, existing legal requirements and potential sources of adventitious mixing are reviewed. It is discussed what type of coexistence measures might be necessary to keep GM inputs below the legal tolerance threshold of 0.9%. Concentrating on cross-fertilisation as the major biological source of adventitious mixing in maize, it is then assessed to which extent available scientific data on cross-fertilisation can explain the diversity of currently proposed isolation distances by several member states. In the second part, it is analysed whether currently proposed isolation distances reflect contending policy objectives towards GM crops that largely exceed the economic scope of coexistence. It is investigated how coexistence is intersecting with a wider debate about the role of GM crops in agriculture. Based on the analysis of existing cross-fertilisation data, it is concluded that some of the currently proposed isolation distances are not in line with the coexistence principles laid down by the European Commission: they are (i) excessive from a scientific point of view; (ii) difficult to implement in practice; (iii) rarely proportional to the regional heterogeneity in the agricultural landscape; and (iv) not proportional to the farmers' basic economic incentives for coexistence. Hence, the range of proposed isolation distances cannot simply be explained by different interpretations of available scientific data, possible error intervals and remaining uncertainties inherent in the scientific process. It is argued that other than scientific issues must be at play. One might thus claim that coexistence has become an arena of contending values and visions on the future of agriculture and on the role GM crops might play therein.

adventitious mixing / Bt-maize / coexistence / cross-fertilisation / flexible measures / genetically modified (GM) crops / isolation distances / liability / fixed measures / sustainable development

1. INTRODUCTION

The adoption rate of genetically modified (GM) crops shows considerable disparities between different agricultural production regions worldwide. While the global cultivation area of GM soybean, maize, cotton and canola (oilseed rape) reached 114 million hectares in 2007, the total area cropped with GM crops in the European Union (EU) was approximately 110 thousand hectares (James, 2007). Most approved GM crops worldwide are thus currently cultivated outside the EU, but might subsequently be imported and eventually further processed in the EU mostly for feeding purposes. Today, Bt-maize expressing the insecticidal protein Cry1Ab from *Bacillus thuringiensis* is the only GM crop to be cultivated in the EU. Bt-maize confers resistance against larvae of certain lepidopteran pests such as the European and Mediterranean corn borer. Following the registration of various Bt-maize varieties derived from the transgenic maize event MON810 in national catalogues and the common catalogue of varieties of agricultural plant species in 2004, the cultivation area of Bt-maize started to gradually increase in the EU, especially in areas where the two lepidopteran pests cause serious infestations. In 2007, the area cropped with Bt-maize for the first time

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Table I. Number of genetically modified (GM) maize varieties registered in national catalogues and/or the common catalogue of varieties of agricultural plant species and the area cropped with GM maize in the European Union (up to December 2007).

EU country	GM maize event	Number of registered (+) or excluded (–) varieties // Area (ha) cropped to GM maize									
		2003		2004		2005		2006		2007	
		Variety	Area	Variety	Area	Variety	Area	Variety	Area	Variety	Area
Czech Republic	MON810	0	0	0	0	0	270	0	1 290	+11	5 000
	Total	0	0	0	0	0	270	0	1 290	11	5 000
France	MON810	0	17	0	15	0	493	0	5 028	0	21 200
	Total	15	17	15	15	15	493	15	5 028	15	21 200
Germany	MON810	0	< 100	0	< 100	+3	340	+2	954	0	2 685
	Total	0	< 100	0	< 100	3	340	5	954	5	2 685
Poland	MON810	0	0	0	0	0	0	0	< 30	0	< 30
Portugal	MON810	0	0	0	0	0	760	0	1 254	+1	4 500
	Total	0	0	0	0	0	760	0	1 254	1	4 500
Slovakia	MON810	0	0	0	0	0	0	0	< 30	0	900
Spain	Bt176	+1	26 090	+2, –1	21 810	–4	0	0	0	w	w
	MON810	+4	6 070	+7	36 410	+14	53 225	+16	53 667	+12	75 148
	Total	7	32 160	15	58 220	25	53 225	41	53 667	53	75 148
The Netherlands	MON810	0	0	0	0	0	0	0	< 10	0	< 10
EU	Bt176	0	26 090	0	21 810	0	0	0	0	w	w
	MON810	0	6 187	+17	36 425	+14	55 088	+5	62 263	+39	109 473
	Total	0	32 277	17	58 335	31	55 088	36	62 263	75	109 473

Abbreviations: w = withdrawal from the European market of the transgenic maize event Bt176 and its derived products according to the Commission Decision of 25 April 2007 (2007/304/EC).

exceeded 100 thousand hectares with the highest share being grown in Spain (69%), followed by France (19%), the Czech Republic (5%), Portugal (4%) and Germany (3%) (Tab. I). Bt-maize plantings in the EU, however, accounted for less than 2% of the total EU maize cultivation area in 2007, compared with 75% in the US (Abbott and Schiermeier, 2007).

The disparity in adoption rate of GM crops between the EU and the rest of the world is generally attributed both to societal and political opposition towards agro-food biotechnology and to complex regulatory approval procedures in the EU (Chapotin and Wolt, 2007; Herring, 2008). In the mid-1990s, the advent of GM crops and their corresponding agro-food products aroused strong societal concerns (Levidow et al., 2005; Devos et al., 2006, 2008d; Levidow and Carr, 2007). Fostered by several highly publicised and successive food safety crises, public suspicion towards regulatory authorities, scientists and technocratic decision-making grew (Lofstedt, 2006). The media, which were explicitly involved in framing the public perception and societal image-building of agro-food biotechnology (Marks et al., 2007; Maeseele and Schuurman, 2008), exacerbated the social amplification of risk (Kasperson and Kasperson, 1996). In the late 1990s, the growing societal and political opposition contributed to a de facto moratorium on new market approvals of GM crops. It was adopted at a meeting of the EU Council of environmental ministers in June 1999, where five member states decided not to accept new GM crop market approvals until the existing regulatory frame was revised (Winickoff et al., 2005). Several agro-food biotechnology market applications remained subsequently blocked in the approval pipeline in the EU.

From 1999 onwards, policy-makers started to continuously revise the legal conditions under which GM crops and agro-food products were allowed to be used in the EU to slow down further erosion of public and market confidence (reviewed by Devos et al., 2006). The precautionary principle, post-market environmental monitoring and traceability were legally adopted as ways to cope with scientific uncertainties. New institutions such as the European Food Safety Authority (EFSA) were created to provide independent, objective and transparent science-based advice on the safety of agro-food biotechnology applications. Labelling and traceability of GM products became mandatory to ensure consumers' freedom of choice. Because the maintenance of different agricultural production systems is a prerequisite for providing a high degree of consumers' choice, a coexistence policy was adopted in the EU. It specifically aimed at enabling the side-by-side development of different cropping systems without excluding any agricultural option. As such, farmers would maintain their ability to make a practical choice between conventional, organic and GM crops. Since coexistence only applies to approved GM crops that were judged to be safe prior to their commercial release (Sanvido et al., 2007), safety issues fall outside the remit of coexistence (Schiemann, 2003; De Schrijver et al., 2007a).

To date there is little experience on how the new legal coexistence requirements could be implemented in the EU. Due to the heterogeneity in farm structures, crop patterns and legal environments between member states, the European Commission follows the subsidiarity principle for the implementation of legal coexistence frames. According to this principle, coexistence should be handled by the lowest authority possible. The European Commission thus limits its influence to gathering and coordinating relevant information based on on-going scientific studies at EU and national level, and to providing guidance to assist member states in establishing best practices for coexistence. These best practices then have to be developed and implemented at national or regional levels.

In the present review, it is explored – after a brief general introduction on coexistence – whether preventive (so-called ex ante) coexistence regulations currently imposed or proposed by member states comply with the general coexistence principles established by the European Commission (European Commission, 2003). First, potential sources of adventitious admixtures are considered. Secondly, concentrating on cross-fertilisation as the major biological source of adventitious mixing in maize, preventive coexistence measures are discussed that might be necessary to keep adventitious GM inputs below the legal tolerance threshold of 0.9% in the harvest of neighbouring non-GM maize fields. Given that proposed isolation distances differ considerably among member states, existing scientific cross-fertilisation studies are assessed to define a scientifically appropriate range of isolation distances. Third, it is explored what challenges the implementation of large and fixed isolation distances might entail in practice, and if such isolation distances comply with general coexistence principles laid down by the European Commission. An alternative way of managing coexistence between maize cropping systems through ex ante regulations is discussed. Finally, it is analysed whether the diversity of fixed isolation distances, as imposed or proposed by several member states, reflects contending policy objectives towards GM crops that largely exceed the economic scope of coexistence. Within this context, it is investigated how coexistence is intersecting with a wider debate about sustainable development of agriculture and the role GM crops might play therein.

2. COEXISTENCE OF GM AND NON-GM CROPS

Society typically needs regulation whenever the introduction of a new product or technology leads to an externality or a market failure (Beckmann and Wesseler, 2007). A good example is the spray drift of pesticides. Pesticide traces and residues from conventional farming can become a negative production externality if they contaminate neighbouring organic systems, and thereby lower market returns associated with 'organic' status. Because organic farming is a production system that avoids or largely excludes synthetic pesticides, plants containing pesticide traces and residues originating in conventional cropping systems are 'declassified'. If the market does not widely provide formal protection afforded to organic farms from pesticide spray drift, the market fails to serve organic producers. This market failure may justify government intervention, which has to establish clear rules on pesticide use. The cultivation of GM crops is similar, as completely avoiding the unintentional presence of GM material from approved GM crops in non-GM products – the externality – might be impossible in the agricultural context (see Sect. 2.1). Because traces of GM material can occur in non-GM products, a first role for policy-makers is to provide legal standards that ensure the coexistence of GM and non-GM crops (see Sect. 2.3).

However, defining legal standards coping with the potential occurrence of externalities might not be sufficient; once they have been defined, policies need to be designed to avoid market failures. If there is a substantial demand for non-GM crops, this will be reflected by a price difference between GM and non-GM crops. Non-GM crops will yield a price premium on the market, relative to GM crops (see Sect. 4.4). Without government intervention, farmers growing non-GM crops can suffer crop value losses due to externalities caused by adjacent farmers who grow GM crops. If the market itself provides very few incentives for correcting this problem, government intervention may be justified, just like the pesticide use rules introduced by several EU governments. Hence, to correct this market failure and to protect farmers from negative externalities of GM crop cultivation, policy-makers need to define legal coexistence rules which ensure that crop value losses are prevented or minimised (ex ante), or reimbursed (ex post) (see Sect. 2.3).

2.1. Sources of adventitious mixing

According to Article 43 of Regulation 1829/2003 on GM food and feed that entered into force in April 2004, member states are empowered to take appropriate measures to avoid the unintentional presence of GM material in other products. However, it is recognised that completely avoiding the unintentional presence of GM material in non-GM products is difficult in the agricultural context (Eastham and Sweet, 2002; Schiemann, 2003; van de Wiel and Lotz, 2006; Damgaard et al., 2007). Because agriculture is an open system, a certain extent of adventitious mixing is unavoidable. Various sources have been identified that could contribute to on-farm adventitious mixing between GM and non-GM crops (Fig. 1a): (i) the use of impure seed (Friesen et al., 2003; Jørgensen et al., 2007); (ii) cross-fertilisation due to pollen flow between neighbouring fields (Devos et al., 2005; Weekes et al., 2005; Hüsken and Dietz-Pfeilstetter, 2007; Sanvido et al., 2008); (iii) the occurrence of volunteer plants originating from seeds and/or vegetative plant parts from previous GM crops (Devos et al., 2004; Lutman et al., 2005; Messéan et al., 2007; Gruber et al., 2008); (iv) mixing of plant material in machinery during sowing, harvest and/or post-harvest operations (Bullock and Desquilbet, 2002; Demeke et al., 2006); and (v) – to a lesser extent – cross-fertilisation from certain sexually compatible wild/weedy relatives and feral plants (Devaux et al., 2007; Jørgensen, 2007; Devos et al., 2008c; Knispel et al., 2008; Pivard et al., 2008).

2.2. Labelling thresholds

In response to the difficulty of keeping genes 'on a leash', tolerance thresholds were established for the unintentional or technically unavoidable presence of approved GM material in non-GM products. If the content of GM material in a non-GM product exceeds the established tolerance threshold, the product has to be labelled as containing GM material, which may affect its market acceptability (see Sect. 2.3). According to the GM food and feed Regulation, the legal tolerance threshold for conventional food and feed products has been set at 0.9%.

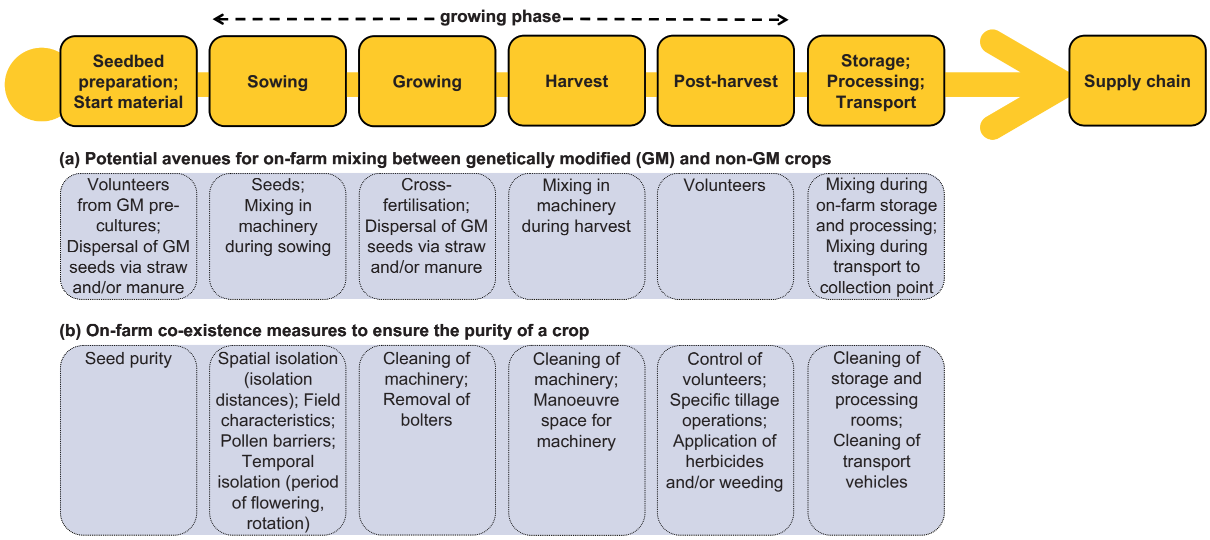

Figure 1. (a) Potential avenues for on-farm adventitious mixing between genetically modified (GM) and non-GM crops, and (b) on-farm coexistence measures to ensure the purity of a crop during the production process.

Since the scope of coexistence extends from agricultural crop production on the farm up to the first point of sale (e.g., from the seed to the silo), agricultural commodities produced on-farm will have to comply with the labelling requirements at the first point of sale (European Commission, 2003).

Organic growers principally aim at keeping their products free from any GM material. Regulation 1804/1999 on organic production of agricultural products states that the use of transgenic organisms and their derivatives is not compatible with the organic production method. The Regulation, however, foresees a de minimis tolerance threshold for the unavoidable presence of GM material in organic products. It was thus anticipated that organic producers would opt for a tolerance threshold ranging between the limit of quantification of a DNA analysis (0.1%) and the tolerance threshold for food and feed products (0.9%). In a press release published on 21 December 2005 (IP/05/1679), the European Commission emphasised that an organic product with an adventitious content of GM material below 0.9% could still be labelled as organic. On 12 June 2007, this point of view was confirmed at a meeting of the EU agriculture ministers where political agreement was reached on a new Regulation on organic production and labelling (IP/07/807). Since the organic sector advocates that GM crops are not compatible with organic farming (Verhoog et al., 2003; Altieri, 2005), they are seeking to establish the limit of quantification of a DNA analysis as the basis to determine the tolerance threshold in organic products.

For seeds no tolerance threshold has been defined yet. Considering that seeds are the first step in the production chain and that additional mixing might adventitiously occur at subsequent steps in the production chain, tolerance thresholds for seeds will be lower than 0.9% (Kalaitzandonakes and Magnier, 2004). In 2001, the Scientific Committee on Plants proposed tolerance thresholds of 0.3% for cross-pollinating crops, and 0.5% for self-pollinating and vegetatively propagated crops (SCP, 2001). As no tolerance thresholds have been established for seeds to date, any seed lot containing approved GM seeds destined for cultivation in the EU has to be labelled as containing GM material.

2.3. Legal frames on coexistence

There are principally two strategies member states have established or are developing to warrant coexistence of different cropping systems: ex ante regulations and Ex post liability schemes (Beckmann et al., 2006; European Commission, 2006; Koch, 2007). Regulations are considered ex ante if they have to be followed by GM crop adopters while growing GM crops. Ex ante regulations prescribe preventive on-farm measures that should ensure that tolerance thresholds are not exceeded in neighbouring non-GM agricultural production systems. Contrary to ex ante coexistence regulations, ex post liability schemes are backward-looking: they cover questions of liability and the duty to redress the incurred economic harm once adventitious mixing in a non-GM product has occurred after the cultivation of GM crops.

Preventive coexistence measures: For decades, seed production regulations have specified statutory segregation measures (so-called identity preservation measures) between seed crops and conventional crop production of the same species to maximise varietal seed purity. Apart from seed production, experience with identity preservation systems is also available from the cultivation of different crop types grown for different uses (Sundstrom et al., 2002). Several of the proposed measures to ensure varietal seed and crop purity can be applied within the context of coexistence to limit the adventitious content of GM material in seeds and plant products (Sundstrom et al., 2002; Devos et al., 2004; Kalaitzandonakes and Magnier, 2004; Damgaard et al., 2007; Jørgensen et al., 2007; Gruber et al., 2008). These measures include (i) the use of certified seed; (ii) spatially isolating fields of the same crop; (iii) implementing pollen barriers around fields; (iv) scheduling different sowing and flowering periods; (v) limiting carry-over of GM volunteers into the following crop through the extension of cropping intervals; (vi) cleaning agricultural machinery and transport vehicles for seed remnants; (vii) controlling volunteers and wild/weedy relatives; (viii) applying effective post-harvest tillage operations; (ix) retaining records of field history; and (x) the voluntary clustering of fields (Fig. 1b). The most drastic preventive coexistence measure is probably banning the cultivation of GM crops in a certain region. The level of containment needed to ensure coexistence is defined by tolerance thresholds: the lower the tolerance threshold, the stricter are the on-farm measures needed to meet labelling requirements.

Liability schemes: Apart from defining the level of containment needed, tolerance thresholds also determine the level of GM material that initiates the need to redress economic harm due to adventitious mixing. Only in the case when the established threshold is exceeded, the product has to be labelled as containing GM material. A lower market price or difficulties in selling products that contain traces of GM material could induce a loss of income. Economic losses are expected to be greater in organic farming than in conventional farming due to the generally higher market value of organic products. Furthermore, organic growers could lose their organic certification, precluding access to markets for organic products for several years. Market attitudes may also impose products to be free of GM material without evidence for actual adventitious mixing, in turn affecting potential markets. Since the late 1990s, major retailers have excluded GM ingredients from their own-brand food products, as a measure to respect consumers' preferences in the EU (Levidow and Bijman, 2002; Kalaitzandonakes and Bijman, 2003; Knight et al., 2008). A recent qualitative survey of GM food labels in supermarkets in France confirmed that there are almost no 'GM' labelled products on supermarkets' shelves, suggesting that food processors still favour non-GM alternatives (Gruère, 2006). Moreover, GM foodstuffs reaching retail shelves are targeted by pressure groups opposed to genetic engineering (Carter and Gruère, 2003). Due to the possibility of GM admixtures, some food manufacturers are also reluctant to purchase agricultural commodities from regions where GM crops are intensively grown (Smyth et al., 2002). Labelling products as containing GM material does, however, not necessarily lower their market value. In Spain, for instance, GM and non-GM maize are stored and processed together by grain feed manufacturers for sale as animal feed (Messeguer et al., 2006). According to the labelling requirements of the Regulation 1830/2003 on GM food and feed, products such as meat, milk and eggs obtained from animals fed GM feed do not require labelling. Since food companies and retailers only refuse GM maize that enters the food chain, coexistence measures are principally only needed near organic fields and for crops grown for human consumption. However, where the use of non-GM feed is imposed for the production of meat, milk and eggs under specific quality schemes, coexistence measures can be required near non-GM maize fields in which maize is grown for animal feed production. In Germany, for instance, the federal states have recently adopted a new set of rules for the voluntary labelling of 'GM crop-free' animal products.

Because GM crop production is the 'newcomer' in European agriculture, GM crop adopters are requested by law to take preventive coexistence measures and to bear responsibility for redressing the incurred harm caused by adventitious mixing (European Commission, 2003). Provided that the admixture occurred purely accidentally and not due to some misconduct by GM crop adopters, economic losses would in many member states be reimbursed by a compensation fund (Koch, 2007). However, if the GM crop adopter causes unlawful damage to a neighbour, he will be required to pay suitable restitution for the full economic loss of the victim. If the farmer suffering the loss deliberately or inadvertently contributed to the damage, his compensation may be reduced or, depending on the circumstances, be forfeited. Considering that various sources can contribute to the adventitious presence of GM material in non-GM products, it can become challenging to establish and prove the causal link between the incurred damage and the farmer or operator responsible for it. In Austria and Germany, for example, all neighbouring GM crop farmers that might have contributed to the admixing are jointly liable for the incurred losses, unless their individual contributions can be clearly determined. In Denmark, causation does not need to be proven strictly: closeness in space and time between a GM crop field and an adjacent non-GM maize field is sufficient to be held liable (Koch, 2007). An additional difficulty in defining causation of adventitious mixing is that traces of GM material might only become detected in subsequent steps of production and/or supply chains.

Depending on the member state, the compensation fund will either be provisioned by financial contributions from all growers, only from GM crop adopters, or from GM seed producers, retailers and other actors dealing in the transport and storage of GM crops, and/or from the government (Koch, 2007). In Portugal, for example, a flat fee per notification and a tax on GM seeds are demanded as a financial contribution to the compensation fund. Other member states impose or propose fees that vary with the planting area of the GM crop, the dissemination potential of the plant species grown, and/or with the number of neighbouring farmers having at least one non-GM maize field occurring within a specific isolation distance (Beckmann et al., 2006; Koch, 2007).

Socio-economic consequences: Coexistence measures imposed by law prior to, during and after cultivation, and laboratory analyses for testing, identifying and quantifying the content of GM material in non-GM products will inevitably entail additional costs to ensure compliance with labelling and traceability requirements (Menrad and Reitmeier, 2008). Moreover, farmers may suffer income losses due to restrictions in crop choice and management. Neighbouring farmers could restrict the cultivation possibilities of a farmer who decides to grow a GM crop, if they do not concur with his cropping intention. In the case when a GM crop adopter cannot avoid interference and cannot find mutual agreement with neighbouring farmers, he would have to renounce growing GM crops on his land. Besides spatial restrictions, temporal cultivation limitations may occur due to irreversibility. In a field where a GM crop was grown, it could temporarily be difficult to meet the 0.9% tolerance threshold if a farmer wishes to go back to a non-GM farming system. A conversion time might be required to deplete dormant GM seeds from the seed bank and/or control volunteers and weedy relatives that may contain the transgene (Devos et al., 2004; Lutman et al., 2005; Jørgensen et al., 2007; Messéan et al., 2007; D'Hertefeldt et al., 2008; Gruber et al., 2008).

The cultivation of different crops with GM and non-GM characteristics in the same region can have sociological consequences. GM crop adopters might have to negotiate with neighbouring farmers and landowners, and seek mutual agreement on their respective cropping intentions. Within this context, GM crop growers could be legally obliged to notify in advance their intentions to grow GM crops to neighbours and/or competent authorities. Similarly, contractors intervening in the cultivation or harvest of GM crops might have to be informed about the GM characteristics of the crop. In Belgium, for instance, GM crop adopters are required to dispose of written agreements from neighbours, which subsequently build the basis for an official coexistence approval for the cultivation of GM crops. In other member states, official approval of the government is granted to GM crop adopters before sowing: in Austria, farmers need approval for each single field and crop from local authorities, whilst Hungary, Ireland and the Slovak Republic consider a generic procedure (Beckmann et al., 2006; Koch, 2007).

3. COEXISTENCE OF MAIZE CROPPING SYSTEMS

Since both the cultivation area of Bt-maize and the number of Bt-maize varieties commercially available to European farmers have increased (Tab. I), regulating coexistence between maize cropping systems is currently becoming a burning issue in some EU regions. Therefore, sources of adventitious mixing and preventive coexistence measures that might be necessary to keep GM inputs below the legal tolerance threshold of 0.9% are discussed in the following sections.

3.1. Sources of adventitious mixing

Various sources can contribute to the adventitious mixing of GM material in non-GM products in maize. Maize is a cross-pollinated crop, relying on wind for the dispersal of its pollen. Most pollen is shed before silks are receptive, although up to 5% self-pollination can occur (Eastham and Sweet, 2002). In most EU countries, cross-fertilisation due to pollen flow between neighbouring maize fields represents the major potential biological source of on-farm mixing: there are no cross-compatible wild relatives of maize in the EU, and many shed maize kernels and seedlings do not survive winter cold (Gruber et al., 2008). In Mediterranean regions, however, maize volunteers frequently occur. In Spain, volunteer densities up to 7000 plants/ha have been observed, which corresponds to approximately 10% of maize planting densities (Melé et al., 2007). If left uncontrolled by weed management practices, shed kernels and – to a lesser extent – kernels on ears remaining on the soil after harvest can germinate and flower under dry and warm conditions. Although these maize volunteers can contribute to the adventitious presence of GM material in the harvest of non-GM maize in the subsequent year, recent field observations demonstrated that their contribution is limited (Melé et al., 2007). Volunteers reaching the flowering stage cross-fertilise neighbouring maize plants only locally. Furthermore, maize is not able to survive as feral populations outside cropped areas in the EU due to its high degree of domestication. Other sources, including the use of impure seed and admixing during sowing, harvest and post-harvest operations, can also contribute to the adventitious GM inputs into non-GM maize. These sources fall outside the scope of this review and will therefore not be addressed.

3.2. Preventive coexistence measures

The analysis performed here identified cross-fertilisation as the major potential biological source of on-farm mixing in maize. In the following, preventive coexistence measures are discussed that might be necessary to keep adventitious GM inputs from cross-fertilisation in the harvest of neighbouring maize fields below the legal threshold.

Isolation distances: Given that pollen concentrations and thus cross-fertilisation levels rapidly decrease with increasing distance from the pollen source, spatially isolating GM maize fields from non-GM maize fields is recognised as being an effective on-farm strategy to reduce the extent of cross-fertilisation (Eastham and Sweet, 2002; Schiemann, 2003). To keep GM inputs from cross-fertilisation in neighbouring non-GM agricultural systems below the legal threshold of 0.9%, member states are currently imposing or proposing largely differing isolation distances, ranging from 15 to 800 m (Tab. II).

Various biological, physical, experimental and analytical factors influence cross-fertilisation levels in maize and hence the definition of appropriate isolation distances (reviewed by Devos et al., 2005 and Sanvido et al., 2008). The major influencing factors are the relative sizes of and the distance between donor and receptor fields, and the flowering synchrony between donor and recipient plants, as well as local wind conditions (Debeljak et al., 2007; Hüsken et al., 2007; Messéan and Angevin, 2007; Viaud et al., 2007). The available scientific data allows the identification of a number of consistent facts and patterns, which enable making science-based recommendations, for the definition of appropriate and effective isolation distances. Compared with other wind-pollinated species, pollen grains of maize are relatively large and heavy. Due to these characteristics, maize pollen settles to the ground rapidly (Aylor et al., 2003) and has a short flight range (Jarosz et al., 2005). Most cross-fertilisation events occur within 50 m of the

Table II. Isolation distances proposed or imposed by different European member states for maize (adapted from European Commission, 2006).

Member state	Isolation distance (m) for conventional maize	Isolation distance (m) for organically grown maize	Isolation distance (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†	15* / 25°	15* / 25°	–
United Kingdom	80* / 110°	–	–

Symbols: – no details; * fodder maize; ° grain maize; † isolation distance doubles if the genetically modified maize variety contains more than one transgene.

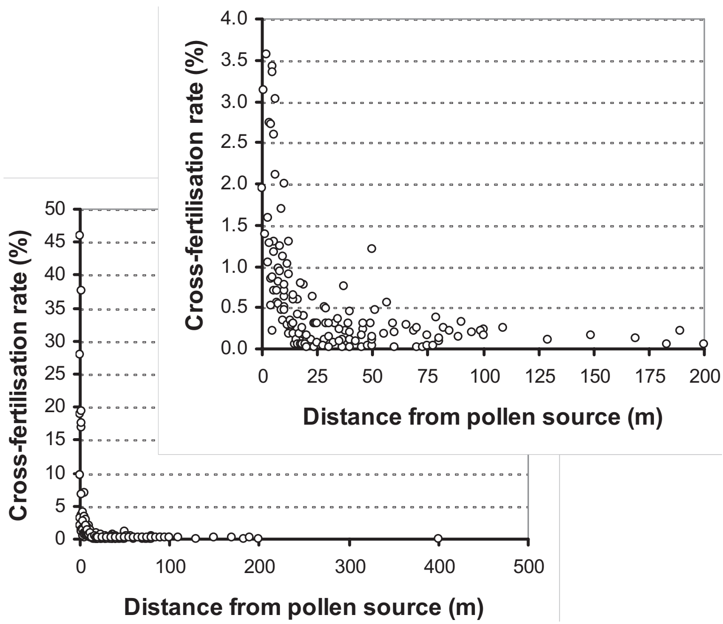

Figure 2. A meta-analysis of various data of cross-fertilisation between maize fields. Cross-fertilisation levels are represented in relation to the distance from the pollen source. The upper graph represents a magnification of the original graph (adapted from Sanvido et al., 2008).

pollen source (Fig. 2), while vertical wind movements or gusts during pollen shedding only lead to very low levels of cross-fertilisation over longer distances under suitable meteorological conditions (Bannert and Stamp, 2007; Delage et al., 2007; Haegele and Peterson, 2007; Viner and Arritt, 2007; Lavigne et al., 2008).

Existing scientific literature on pollen dispersal and cross-fertilisation (Devos et al., 2005; van de Wiel and Lotz, 2006; Hüsken et al., 2007; Sanvido et al., 2008), and on predictive vertical gene flow modelling at the landscape level (Messéan et al., 2006; Lécroart et al., 2007; Mazzoncini et al., 2007; Beckie and Hall, 2008), suggests that isolation distances ranging from 10 to 50 m would be in most cases sufficient to keep GM inputs from cross-fertilisations below the tolerance threshold of 0.9% in the harvest of neighbouring non-GM maize fields. The necessary isolation distance within the range of 10 to 50 m is influenced by (i) the seed purity of non-GM maize; (ii) field characteristics and distribution; (iii) (GM) maize share; (iv) crop type; (v) differences in sowing and flowering times; and (vi) meteorological conditions (Devos et al., 2005; Messéan et al., 2006; Hoyle and Cresswell, 2007; Beckie and Hall, 2008; Lavigne et al., 2008). An isolation distance of 50 m might in some cases not be sufficient to comply with the current tolerance threshold. This is particularly true for small, long and thin recipient maize fields that are located downwind from a larger GM maize field, where the elongated side is exposed to the GM maize field, and where plants flower synchronously with those of the donor field (Devos et al., 2005; Messéan et al., 2006; Hüsken et al., 2007). Moreover, if local pollen densities of non-GM maize fields are low, as in seed production fields, cross-fertilisation levels increase significantly (Goggi et al., 2007).

Larger isolation distances might also be needed for stacked GM maize varieties to comply with the tolerance threshold. Because a stacked GM maize variety contains more than one transgene (De Schrijver et al., 2007b), a similar cross-fertilisation rate results in a higher content of GM material expressed in percentages of haploid genomes in recipient plants, compared with a single GM maize variety. Moreover, other sources than cross-fertilisation (e.g., seed impurities) could contribute to GM inputs in non-GM products. In this case, GM inputs from cross-fertilisations may thus have to remain substantially below 0.9% in order to allow for a safety margin up to the labelling threshold in agricultural commodities. Because the final GM content in the harvest depends on various factors such as field size and harvesting procedure and because the modelling of this reduction is currently very difficult, the tolerance threshold of 0.9% is taken as an endpoint in the present review. In addition, it is important to bear in mind that no tolerance threshold for the adventitious presence of approved GM material in non-GM seeds has been defined to date. However, based on a meta-analysis of existing cross-fertilisation studies, Sanvido et al. (2008) concluded that an isolation distance of 50 m would be sufficient to keep cross-fertilisation levels below 0.5% at the border of the recipient maize field. Due to mixing of the outer and the inner parts of an entire field at harvest (where the inner parts usually contain lower GM contents than at the field border), the authors assumed the average cross-fertilisation rate would be less than 0.5% in the harvested product.

Pollen barriers: Like isolation distances, pollen barriers consisting of the same crop effectively reduce the extent of cross-fertilisation between neighbouring maize fields. If the outer parts of the maize field function as a pollen barrier, the distance towards the inner field parts increases, in turn increasing the distance GM pollen has to travel for cross-fertilisation (Devos et al., 2005). Moreover, a pollen barrier of maize produces competing pollen and/or may serve as a physical barrier to air, and consequently pollen flow. The extent of cross-fertilisation is reduced much more effectively by a pollen barrier than by an isolation distance of bare ground of the same width (Della Porta et al., 2008). Many research results confirmed that the outer plant rows in a recipient maize field function as a zone that safeguards the centre of recipient fields (Gustafson et al., 2006; Messeguer et al., 2006; Ganz et al., 2007; Sabellek et al., 2007; van de Wiel et al., 2007; Weber et al., 2007; Weekes et al., 2007; Langhof et al., 2008). With a maize barrier of 10–20 m, almost none of the remaining maize harvest in the field contains more than 0.9% GM material. Where isolation distances cannot be implemented, the removal of the first 10–20 m of non-GM maize facing the GM maize field is worth considering.

From an administrative point of view, bordering Bt-maize fields with a pollen barrier of non-GM maize might be favoured since coexistence measures have to be undertaken by the farmer growing GM crops. Not only are Bt-maize growers currently required to undertake coexistence measures, they are also contractually enforced to adopt insect resistance management (IRM) measures. For Bt-maize planting areas larger than 5 ha, a refuge zone of 20% of the transgenic area has to be planted with non-transgenic maize in order to delay the potential resistance development in lepidopteran target pests. The theory underlying the refuge strategy is that most of the resistant pests surviving on Bt-crops will mate with abundant susceptible pests from refuges, and that the hybrid progeny originating from such matings will be killed by Bt-crops, if the inheritance of resistance is recessive (Bates et al., 2005). Both coexistence and IRM measures could thus be combined since the refuge zone could also serve as a pollen barrier. Moreover, by sowing the pollen barrier/refuge zone of non-transgenic maize around GM maize, sowing machinery can be ‘cleaned’ from GM seed remnants. However, from a scientific point of view, it is unclear whether a maize pollen barrier surrounding the donor field reduces the extent of cross-fertilisation as effectively as a pollen barrier of the same depth around the recipient field. Recently, Della Porta et al. (2008) demonstrated that surrounding the recipient field with just two maize rows resulted in the same reduction in cross-fertilisation levels as surrounding the pollen donor with twelve maize rows. Because a maize pollen barrier around the donor is only trapping pollen that flies low and that is not likely to disperse far, the effect of a pollen barrier surrounding the donor field is thought to remain very local and limited (Gustafson et al., 2006; Kuparinen et al., 2007; Langhof et al., 2008). Moreover, in the case of GM herbicide-resistant maize, the cultivation of GM and non-GM maize in the same field might create practical challenges since two different weed management regimes would have to be applied on a single field.

Flowering coincidence: The temporal isolation of GM maize from non-GM maize is another valuable strategy to limit cross-fertilisation between maize cropping systems. This can be achieved by sowing maize at different dates, resulting in a difference in flowering periods (Messeguer et al., 2006; Della Porta et al., 2008). In Spain, for example, non-GM maize sown early in March/April will flower during a short period in June; it will thus mostly fertilise its own silks before GM maize sown in early May starts to flower in July/August. A time lag in flowering synchrony of at least eight days has been proven to reduce the extent of cross-fertilisation between neighbouring maize fields significantly (Messeguer et al., 2006; Palaudelmàs et al., 2007; Della Porta et al., 2008). Sowing non-GM maize early and GM maize late in the season could easily be put into practice in Mediterranean regions. Due to the high infestation of the European and Mediterranean corn borer late in the growing season, there is already a tendency to postpone the sowing of GM maize in irrigated regions in Spain (Messeguer et al., 2007). However, this approach is not feasible in non-Mediterranean regions where the window of suitable weather conditions is too short to postpone sowing, and where this postponement induces yield penalties (Messeguer et al., 2006; Weber et al., 2007; Della Porta et al., 2008).

Crop rotation: Theoretically, farmers might mutually adjust their crop rotations in order to schedule maize crops over different years and to avoid growing GM maize in the proximity of non-GM maize. Such a strategy would demand a very tight discipline and good agreements between neighbouring farmers. In practice, it could be hampered by market-driven production strategies, the share of maize in a specific area, and by growing maize in monoculture, as practised frequently in a number of member states.

GM crop-free regions or GM crop production regions: Although priority is to be given to farm-specific coexistence measures, the European Commission proposes region-wide measures (such as the clustering of GM or non-GM crops) in cases where sufficient levels of purity cannot be achieved by other means (European Commission, 2003). An important precondition to installing GM crop-free regions is that farmers jointly decide on a voluntary basis not to grow GM crops in a specific region. If these conditions are met, the competent authority can declare a ban on the cultivation of GM crops for a limited period of time in a specific region. Usually, purely economic considerations (e.g., protection of local traditional agriculture) trigger the decision for the creation of GM crop-free regions. With the installation of a 'network of GM crop-free regions', a significant number of such regions has been created all over the EU (Levidow and Boschert, 2008). On the other hand, farmers wishing to grow GM crops can demand the creation of GM crop production regions.

Biological confinement: Although most biological confinement tactics are still in their infancy, they could hold great promise to limit the extent of cross-fertilisation between GM and non-GM crops (Chapman and Burke, 2006). Instead of inserting transgenes into the nuclear genome, these could be targeted at the organelle genome of plastids and/or mitochondria, generating transplastomic plants (Daniell et al., 2005). Because plastids are absent in pollen of most angiosperm plant species, they are transmitted maternally. Although very low levels of paternal leakage and gene transfer from the chloroplast to the nucleus have been reported in some cases (Ruf et al., 2007; Svab and Maliga, 2007), the transmission of cytoplasmic organelles through pollen would greatly reduce the probability of pollen-mediated gene flow. In many plant species such as tobacco, tomato, soybean, cotton and poplar, the usefulness of chloroplast genetic engineering has been confirmed, but it still remains to be achieved in maize (Daniell, 2007; Verma and Daniell, 2007).

Cytoplasmic male sterility (CMS) is another valuable option to reduce gene flow in maize (Munsch et al., 2007; Weider et al., 2007). CMS plants are characterised by their inability to produce viable pollen. Specific mutations in mitochondrial DNA induce dysfunctions in the respiratory metabolism occurring in anther-tapetum cells during sporogenesis (Budar et al., 2003). Due to this male sterility, CMS plants have been used since the 1950s in maize seed production, as they enable ensuring cross-fertilisations without the need for mechanical or manual emasculation. Within the context of coexistence, the cultivation of CMS GM maize plants might reduce the release of transgenic pollen by up to 80%. To ensure seed set, CMS GM maize plants would have to be interplanted with male fertile maize plants – with either GM or non-GM characteristics – acting as pollen donors. Experimental data show that the use of CMS GM maize hybrid in combination with a second unrelated maize hybrid in the Plus-Hybrid System enables increasing the grain yield in some genetic backgrounds without affecting grain quality, compared with that produced by pure male fertile maize (Stamp et al., 2000; Weingartner et al., 2002, 2004; Feil et al., 2003; Munsch et al., 2007; Weider et al., 2007). However, to make this approach successful, it is important that nuclear fertility restorer genes are absent from the maize breeding pool; otherwise, the mitochondrial CMS trait might be revoked, leading to the restoration of pollen fertility (Pelletier and Budar, 2007).

Another currently explored biological confinement system relies on a series of alleles that induces cross-incompatibility between certain maize genotypes. Recipient plants with the homozygous dominant cross-incompatibility allele (GaS) only accept pollen from maize plants with the GaS genotype: non-GaS pollen (ga) from neighbouring hybrids that may or may not contain transgenes will not effect cross-fertilisation. On silks of a heterozygous GaS genotype, pollen with the recessive ga allele competes poorly against GaS pollen. Therefore, ga pollen will only yield partial seed set on styles heterozygous for GaS. However, due to breeding difficulties and genetic side-effects on yield and agronomic performance, the use of the GaS allele as a potential biological confinement system is still in the development pipeline (Hoegemeyer, 2005).

4. CHALLENGES ENTAILED BY LARGE AND FIXED ISOLATION DISTANCES

According to the European Commission guidelines for the development of national strategies and best practices to ensure coexistence, preventive coexistence measures should reflect the best available scientific evidence on the probability and sources of admixture between GM and non-GM crops (European Commission, 2003). The selection of appropriate coexistence measures should not only be based on scientific evidence, but measures should also be economically proportionate (= cost-effective) and consider regional and local constraints. Any measures exceeding what is necessary to ensure compliance with the legal tolerance threshold would therefore put an extra burden on farmers wishing to adopt GM crops. This would be in opposition to the EU coexistence objectives aiming at allowing farmers to make a practical choice between conventional, organic and GM crops (European Commission, 2003). Several member states are currently imposing or proposing large and fixed isolation distances as the sole means to keep GM inputs from cross-fertilisation below the legal tolerance threshold of 0.9%. In the following sections, it is assessed whether this complies with the science-based, appropriateness, and regional and economic proportionality principles established by the European Commission.

4.1. Science-based principle

An analysis of the currently available scientific data on cross-fertilisation shows that in many cases large and fixed isolation distances are excessive from a scientific point of view (reviewed by, e.g., Devos et al., 2005; van de Wiel and Lotz, 2006; Hüsken et al., 2007; Beckie and Hall, 2008; Sanvido et al., 2008). In practice, shorter isolation distances than those currently proposed by several member states would often be sufficient to ensure compliance with labelling requirements. Cross-fertilisation studies mimicking worst-case commercial on-farm situations demonstrated that isolation distances exceeding 50 m are not always necessary to comply with the labelling threshold of 0.9% in grain maize (Goggi et al., 2006; Gustafson et al., 2006; Pla et al., 2006; Bannert and Stamp, 2007; Kraic et al., 2007; van de Wiel et al., 2007; Weber et al., 2007; Weekes et al., 2007; Della Porta et al., 2008). Similar conclusions have been drawn from out-crossing studies performed under real agricultural situations in Spain (Messeguer et al., 2006, 2007) and from predictive vertical gene flow modelling at the landscape level in France (Messéan et al., 2006; Lécroart et al., 2007) and Italy (Mazzoncini et al., 2007). In addition, isolation distances imposed for grain maize might not be appropriate for fodder maize, considering that transgenes present in grains are diluted by vegetative plant parts in fodder maize once harvested (Weber et al., 2007; Hüsken and Schiemann, 2007). In many cases, less or no spatial isolation may be required to comply with the tolerance threshold (Devos et al., 2005; Messeguer et al., 2006, 2007; Messéan and Angevin, 2007; Sanvido et al., 2008). This may especially be the case with (i) larger and more spatially isolated recipient fields; (ii) recipient fields located in an upwind position from the closest pollen source; (iii) recipient fields isolated by physical and/or natural barriers (e.g., trees, hedgerows); or (iv) non-GM maize plants showing a time lag in flowering period compared with GM maize (Messeguer et al., 2006, 2007; Palaudelmàs et al., 2007; Della Porta et al., 2008).

4.2. Appropriateness principle

A number of prospective case studies and model simulations have shown that large and fixed isolation distances can be inappropriate in some cases. 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, the implementation of large isolation distances might not be feasible in practice (Perry, 2002; Dolezel et al., 2005; Messéan et al., 2007; Devos et al., 2007, 2008a, e; Sanvido et al., 2008). Where maize fields are located in close proximity to each other, it is highly probable that isolation perimeters surrounding GM maize fields would interfere with adjacent non-GM maize fields, in turn affecting the farmers' freedom of choice to grow GM maize. Using geographic information system datasets and Monte Carlo simulations, Devos et al. (2007, 2008a, e) investigated how isolation perimeters around GM maize fields might affect the possibility of farmers to grow GM maize on their fields in Flanders (Belgium) (Fig. 3). With isolation distances larger than 50 m, non-GM maize fields would often be situated within the isolation perimeter imposed for GM maize, especially in areas where (i) a lot of maize is grown; (ii) the share of GM maize is high; (iii) GM maize is grown on a high number of small maize fields; and/or where (iv) GM maize is randomly allocated to maize fields.

Although an isolation distance is generally implemented concentrically around GM maize fields, a GM crop adopter might theoretically also try to achieve the isolation inside his own field if mutual agreement with neighbouring non-GM farmers cannot be found. However, due to the small size of maize fields in certain European regions, this approach may not often be practicable. The area covered by a buffer zone of 25 m is equivalent to approximately 75% of a squared field of 1 ha, 51% of a 3-ha field, 40% of a 5-ha field, and to 24% of a 15-ha field. To cultivate 1 ha of GM maize with a buffer zone of 25, 100 and 200 m imposed by law, fields should have a size of 2, 9 and 25 ha, respectively. Using average Italian farm and field characteristics, Lauria et al. (2005) calculated that less than 4.6% of all Italian farms would have the minimum area necessary to cultivate almost 1 ha of GM maize if buffer zones of 200 m would have to be implemented inside the field of GM maize. However, while the static relationship between the proportion of land available for GM crops and the isolation distance has been recognised in scholarly research on coexistence (e.g., Perry, 2002; Beckmann and Wesseler, 2007), the dynamic effects have been largely ignored by the scientific community and policy-makers (see Sect. 4.4).

4.3. Regional proportionality principle

Considering the existing scientific data, it can be argued that policy-makers enforcing fixed isolation distances do not always take into account a number of factors that largely affect cross-fertilisation 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 (Messéan et al., 2006; Lipsius et al., 2006; Devos et al., 2007, 2008e; Ganz et al., 2007; Hoyle and Cresswell, 2007; Lécroart et al., 2007; Viaud et al., 2007; Lavigne et al., 2008). Currently imposed or proposed fixed isolation distances mostly ensue from cross-fertilisation studies that were performed under worst-case commercial on-farm situations: the pollen source is grown next to or completely surrounded by a recipient field, and parental plants flower synchronously. As experimental worst-case conditions might not often arise in practice, fixed isolation distances might be too conservative under real agricultural conditions. Under real agricultural conditions, fields may be planted with GM and non-GM maize varieties with different sowing or flowering dates, and maize fields may be

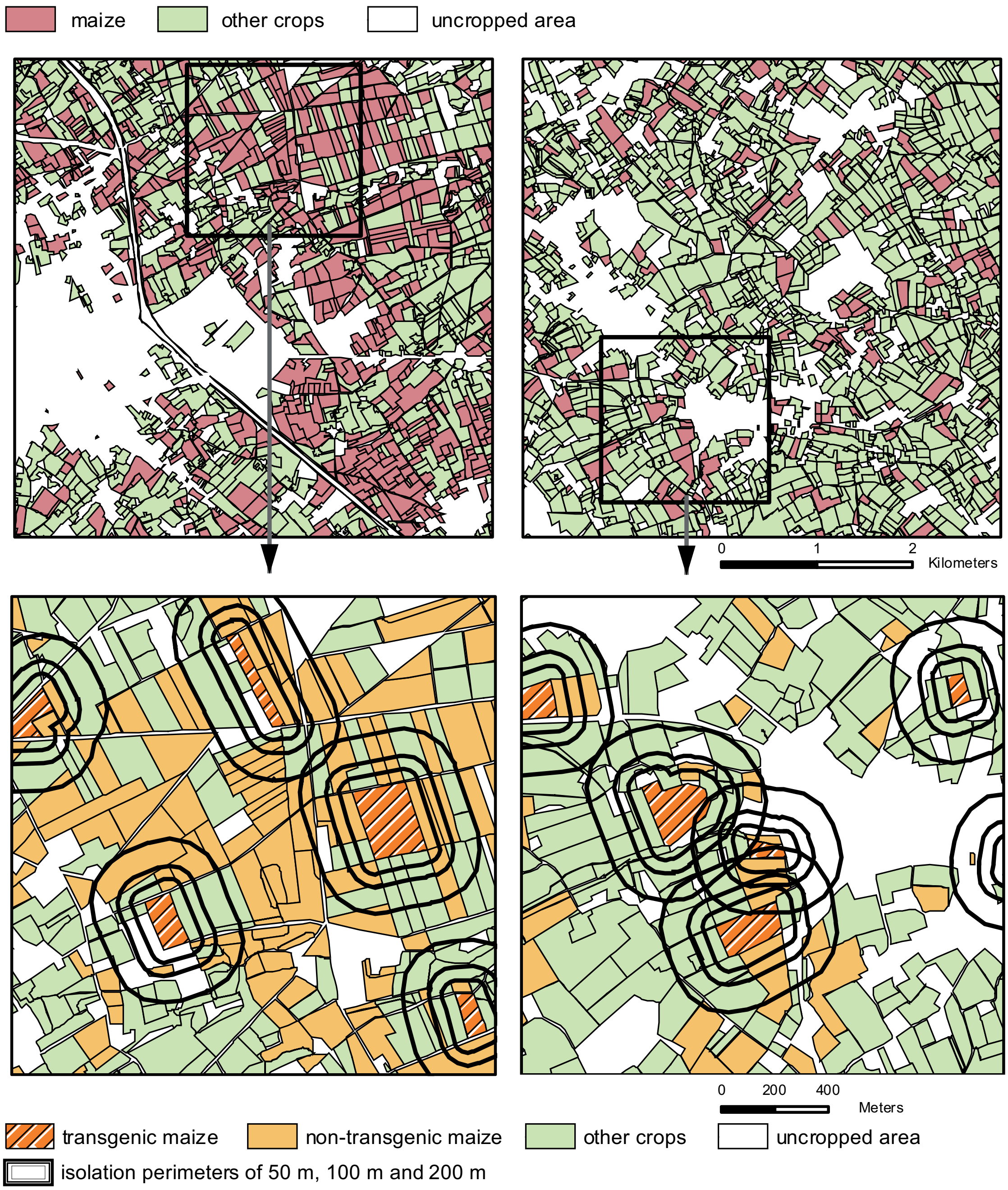

Figure 3. Maps of selected squares of 25 km^2 in an area with a high share of maize (Bocholt) [left] and in an area with a low maize share (Anzegem) [right] in Flanders (Belgium). On top: share of maize fields. Below: concentrically implemented isolation perimeters of 50, 100 and 200 m around some fields planted with genetically modified (GM) maize (Devos et al., 2007, 2008a, e).

mixed with other crops and with physical and/or natural barriers (Devos et al., 2005; Messeguer et al., 2006, 2007; Messéan and Angevin, 2007; Sanvido et al., 2008).

4.4. Economic proportionality principle

As yet, very few studies have acknowledged that coexistence is only relevant if there are economic incentives for farmers to supply both GM and non-GM maize (Demont and Devos, 2008). Economic incentives for coexistence consist either of (i) the adoption of GM maize as a way to capture 'GM gains' or (ii) the identity preservation (IP) of non-GM crops as a way to capture 'IP gains'. GM gains represent economic benefits related to the adoption of GM crops and include productivity and efficacy increases, and production cost reductions, as well as non-pecuniary benefits such as increases in management flexibility (Alston et al., 2002; Demont and Tollens, 2004; Demont et al., 2004, 2007, 2008a; Marra and Piggott, 2006). IP gains stand for the total additional income generated by price premiums captured for non-GM crops compared with GM crops. If there is a substantial demand for non-GM crops, this will be reflected by a market price premium for IP crops (Bullock and Desquilbet, 2002). However, if the content of GM material in IP crops exceeds the tolerance threshold of 0.9%, non-GM crops have to be labelled as 'containing GM material' and commercialised at the same price level as GM crops, without yielding any price premium. Even though IP crops do not have to be labelled, it is still the case that costly IP activities are necessary to guarantee the truthfulness of the (implicit) 'non-GM' claim. Further down the market chain, incentives to incur the cost of segregating GM and non-GM products naturally reside with suppliers of the 'superior' (non-GM) product (Lapan and Moschini, 2004).

The balance between GM gains following the adoption of GM maize and price premiums paid for IP maize largely dictates the share of GM and non-GM maize and therefore coexistence (Demont and Devos, 2008). Hence, both economic incentives for GM and non-GM maize are vital: if one of them is lacking, coexistence is not a problem of concern because either GM or non-GM maize will not be cultivated. Farmers will only adopt GM maize – and thus invest in imposed coexistence measures – if the benefits of using GM maize exceed the costs of the technology plus the costs of implemented coexistence measures. Other farmer segments might gain more from preserving the 'non-GM' status of their production: where price premiums for IP products can be captured due to higher market prices, farmers opting for non-GM maize will have economic incentives to apply coexistence measures. By applying coexistence measures, they avoid adventitious mixing, in turn ensuring a non-GM maize production. As long as benefits exceed costs of growing non-GM maize, these non-GM maize farmers will continue to invest in coexistence measures. Since potential GM gains are lost if a farmer opts for non-GM maize (= opportunity cost) instead of GM maize, IP gains must compensate for lost GM gains (Demont et al., 2008b).

Due to the limited adoption of GM maize in the EU (Tab. I), so far no economically important coexistence issues have been reported, even in Spain, the largest GM maize adopter. However, a recent case study focusing on the interplay between incentives and costs of coexistence suggested that imposing large and fixed isolation distances by law is not proportional to the economic incentives of coexistence (Demont et al., 2008b). Under low IP gains (when consumers are not willing to pay significant price premiums for non-GM crops), large and fixed isolation distances generate substantial opportunity costs for GM crop producers as the latter forego GM gains, whilst they are hardly capturing any compensatory IP gains. Under these conditions, if farmers still incur costs due to mere compliance with EU coexistence laws, coexistence costs would not reflect (and hence, would not be proportional to) the economic incentives for coexistence, simply because the incentive – capturing IP gains – is lacking.

On the other hand, under high IP gains (when consumers are willing to pay substantial price premiums for non-GM crops), rational farmers who forego GM gains will attempt to compensate for these opportunity costs by planting non-GM crops and trying to capture IP gains by avoiding any adventitious mixing from GM crops. However, in doing so, they risk triggering a domino-effect at the landscape level that will affect the farmers' freedom of choice to grow GM maize. The domino-effect is a dynamic spill-over effect of farmer decisions induced by enforcing large isolation distances on potential GM crop adopters. It consists of the iterative process of farmers switching their planting intentions from 'GM' to 'IP' crops to comply with isolation distances and hereby restricting planting options of neighbouring farmers. The domino-effect exacerbates the non-proportionality of large isolation distances by reducing GM crop planting options in the landscape and raising opportunity costs for GM crop adopters (Demont and Devos, 2008; Demont et al., 2008b, under review).

Farmers will only have an incentive to supply IP crops if consumers have (i) strong and sustainable preferences for non-GM crops and (ii) are willing to pay significant price premiums for them. If the opposite holds, there is no coexistence issue stricto sensu and coexistence costs will purely reflect the costs of compliance with EU coexistence laws instead of the economic incentives for coexistence. Non-GM crops will not necessarily become more expensive in absolute terms. It may well be that, in equilibrium, average crop prices have decreased as a result of the cost-reducing effect of the GM technology and negative consumer preferences for GM crops, while IP crops are sold at the pre-existing non-GM crop prices. Hence, the IP price premium does not refer to the absolute but to the relative price difference between IP and GM crops.

5. FLEXIBLE COEXISTENCE MEASURES

Based on the presented facts, it can be concluded that large and fixed isolation distances, as currently legally imposed or proposed by several member states, do not comply with the general coexistence principles established by the European Commission: they are (i) excessive from a scientific point of view; (ii) difficult to implement in practice; (iii) rarely proportional to the regional heterogeneity in the agricultural landscape; and (iv) not proportional to the farmers' basic economic incentives for coexistence. To enable appropriate (i.e., a regionally and economically proportionate) coexistence in the long run, it would be necessary to build in a certain degree of flexibility into ex ante coexistence regulations. It may be justified to apply the 'newcomer principle' in coexistence regulations with regard to the *financial responsibility* of undertaking coexistence measures and enforce GM crop adopters to reimburse non-GM farmers, provided that the latter agrees to undertaking the measures to ensure coexistence. However, enforcing the *civilian responsibility* of undertaking coexistence measures on GM crop farmers introduces rigidity in regulations, whereas leaving measures open for negotiation between farmers introduces flexibility. Hence, policy-makers could support flexibility by allowing plural coexistence measures that are negotiable between farmers on a case-by-case basis, and that are adaptable to different regional and local situations (Furtan et al., 2007; Messéan and Angevin, 2007; Demont and Devos, 2008; Demont et al., 2008b; Devos et al., 2008e).

In line with the European Commission's guidelines on coexistence, flexibility would enable the development of coexistence arrangements that are adapted to local farming and cropping systems, landscape patterns, farmer strategies and preferences, and to meteorological conditions. Because farmers are heterogeneous with respect to field conditions, managerial expertise, education, market access, pest infestation, and hence the gains they capture from adopting GM crops, flexible measures would be better adapted to the heterogeneity of GM gains (Demont et al., 2008a).

Flexible measures could be designed to be negotiable among GM and non-GM farmers, because both farmer segments have economic incentives to ensure coexistence in the long term. Theoretically, a pollen barrier of non-GM maize – which is a better-suited measure for building flexibility into coexistence regulations than isolation distances – can be planted and cultivated by the GM maize grower, at the expense of an opportunity cost that is equal to the lost GM gain for the area planted with non-GM maize. If the 'newcomer principle' is adopted with regard to the financial responsibility of undertaking coexistence measures, a pollen barrier can also be grown by the neighbour, in return for a compensation payment. In the latter case, the area planted with the pollen barrier of non-GM maize is harvested separately, sold as 'GM' and, hence, the non-GM farmer does not benefit from any IP gains. The cost of the pollen barrier would, however, be equal (and, hence, proportional) to the lost IP gains. This cost borne by the non-GM farmer could be reimbursed by the GM farmer through a compensatory payment. Demont et al. (under review) illustrated that flexible regulations could be designed in such a way that they encourage farmers to minimise total (opportunity, transaction and operational) coexistence costs, while at the same time satisfying the proportionality condition. If IP gains are negligible compared with GM gains, farmers who grow GM maize will have incentives to persuade neighbouring non-GM farmers to plant a pollen barrier on their field in return for a compensatory payment proportional to their foregone IP gains. They might even persuade the latter to grow GM maize on their fields in order to further minimise costs. If IP gains rise, the opportunity cost of pollen barriers will rise proportionally until it is cheaper for GM farmers to move the pollen barrier to their own field. Further rising IP gains will not affect coexistence costs as all pollen barriers will be planted on GM farmers' fields at an opportunity cost proportional to the GM gain. However, some GM farmers may be attracted by the high IP gains and abandon GM crop production, depending on the magnitude of their GM gains.

It can be observed that national and regional authorities are generally reluctant to adopt flexible coexistence measures due to difficulties in making them operational both from a legal and from an administrative point of view. Some member states have nevertheless already attempted to introduce some flexibility into ex ante coexistence regulations. In the Czech Republic, for example, farmers can shorten the isolation distance of 70 m towards fields planted with maize provided that every two metres of isolation distance is replaced by one buffer row of non-GM maize around the GM maize field. In Sweden, farmers are able to choose isolation distances from 15 to 50 m depending on the type of maize and on the number of transgenes contained in GM maize hybrids (European Commission, 2006).

Computer-based decision support tools may play a crucial role in a future case-by-case-based coexistence approach. They enable the prediction of potential levels of adventitious presence of GM material in the harvest of neighbouring maize fields under various agricultural conditions, and hence the achievable level of coexistence. At the local and regional level, farmers can assess in which maize fields it would not be possible to comply with the established tolerance threshold, and under which conditions both GM and non-GM maize can be grown simultaneously or in close proximity. Outcomes generated by computer-based decision support tools are expected to provide advice to farmers, administrators and policy-makers about the most optimal preventive coexistence measures to be put in place (Beckie and Hall, 2008). Examples of such tools, which are currently under validation, include (i) the global index by Messeguer et al. (2006, 2007); (ii) the matrix-based approach to a pollen dispersal model by Angevin et al. (2008); and (iii) the SIGMEA maize coexistence Advisor by Bohanec et al. (2007). Although such a case-by-case-based approach will demand much administrative effort, it may be an important step forward in making coexistence workable in practice, and in reaching appropriate and regionally and economically proportionate coexistence at the regional and landscape levels.

6. THE COEXISTENCE PARADOX

Focusing on the broad range of isolation distances proposed by several member states to ensure the spatial coexistence between maize cropping systems, one might presume that the coexistence policy objectives of some member states do not solely aim at keeping the adventitious presence of GM material in non-GM maize products below the tolerance threshold of 0.9%, but at totally avoiding any adventitious presence of GM material. The broad range of isolation distances proposed by member states cannot simply be explained by different interpretations of available cross-fertilisation data, possible error intervals and uncertainties inherent in the scientific process. Moreover, some member states (e.g., Austria) prescribe isolation distances towards ecologically sensitive areas such as nature conservation areas (Dolezel et al., 2007; Levidow and Boschert, 2008). This illustrates that more than economic issues, as defined in the European Commission's coexistence guidelines, are at play in the coexistence debate since isolation towards nature conservation areas represents a safeguard measure related to the environmental safety of an approved product. Although it is often mixed into the coexistence debate, safety issues fall outside the remit of coexistence since these crops were judged to be safe prior to their commercial release (Schiemann, 2003; De Schrijver et al., 2007a; Sanvido et al., 2007).

Viewed in a broader societal context, the diversity of proposed isolation distances reveals conflicting rationales on coexistence. One group of actors attaches itself to the European Commission's definition, which states that coexistence purely refers to the potential economic loss and impact of the admixture of GM and non-GM crops. Another group, in contrast, extends the economic issue, mentioning different additional concerns related to genetic engineering. By broadening the debate, they consequently fuel the confusion about the wider discussion on the acceptability of genetic engineering and that on coexistence of different cropping systems. The techno-scientific discussion about isolation distances is in fact hiding an underlying discussion about the type of agriculture wanted in the EU. Thereby, it is debated whether GM crops might play a role in the type of agriculture wanted and whether they might contribute to the construction of a sustainable system of crop production. On an even more fundamental level, one can detect a conflict of values pertaining to the importance of individual freedom of choice and to the trust in markets as regulators of consumer preferences. It may be argued that the broad range of isolation distances, which is supposed to satisfy standards of EU legislation, is in fact reflecting a coexistence paradox that effectively accommodates an irreconcilable divergence of positions towards GM crops.

6.1. Opponents' rationale on coexistence

Several lines of argumentation can be identified when looking at the reasoning put forward by opponents to explain their aversion towards agro-food biotechnology applications. Opponents perceive GM crops as being a further step in the industrialisation of agriculture. With the adoption of GM crops and their associated management practices, agricultural developments follow an agro-industrial path, which is associated with high productivity and efficiency (e.g., monocultures, genetic uniformity) in order to compete with standardised agricultural commodities on a global market (Hubbell and Welsh, 1998; Marsden, 2008; Russell, 2008). Opponents expect that GM crops will undermine agricultural developments focusing on added value of agricultural commodities (e.g., local speciality 'niche' products) and environmentally friendly production systems such as organic agriculture (Verhoog et al., 2003; Altieri, 2005; Levidow and Carr, 2007; Binimelis, 2008). Moreover, opponents claim that the dependence of farmers on the biotechnology industry would increase due to the need to rely upon specific chemicals for pest control, and that technology fees related to the adopted GM crops would increase input costs and create a culture of surveillance (Beckie et al., 2006).

GM crops and their associated management practices are further thought to reinforce adverse environmental effects and the negative impact of farming on biodiversity due to intensive agriculture. The vicious 'agro-chemical treadmill' would be perpetuated and even aggravated without marking a substantial break with the environmentally harmful past of intensive agriculture. Through the reliance on a component-based chemically intensive production system, symptoms of agricultural problems would be treated rather than causes. Opponents claim that the reliance on good agricultural practices (e.g., sound crop rotation) would take away many causes of agricultural problems, in turn making some current chemical-based therapies redundant (Hubbell and Welsh, 1998; Graef et al., 2007; Malézieux et al., 2008; Powles, 2008). Instead of being a remedy to current agricultural problems, as claimed by proponents, GM crops are therefore perceived by opponents as a new source of problems that are even worse than those GM crops were meant to solve. Opponents point to a number of different environmental and agricultural drawbacks associated with the cultivation of GM crops such as (i) the development of noxious, invasive weeds and the loss of the genetic identity of native species due to vertical gene flow to cross-compatible wild/weedy relatives; (ii) the invasion of GM crops into natural habitats; (iii) adverse impacts on non-targeted species; (iv) the disruption of biotic communities, including agro-ecosystems; (v) the development of resistance in the targeted pest/pathogen population; (vi) the reduction or loss of farmland biodiversity; and (vii) negative changes in physical, chemical and biological soil characteristics, resulting in decreased soil quality. Finally, appealing to the unnaturalness and irreversibility of genetic modification, various actors describe the technology as involving a high level of scientific uncertainty, thus necessitating strong precautionary measures in order to avoid a technology out of control (Brom, 2000; Verhoog et al., 2003; Streiffer and Rubel, 2004; Madsen and Sandøe, 2005; Lassen and Jamison, 2006).

Various actors oppose to the possible integration of GM crops into existing agricultural systems and regions through the installation of GM crop-free regions and through the promotion of large and fixed isolation distances in ex ante coexistence regulations. Opponents thereby often refer to a number of consumer surveys (such as the Eurobarometer) indicating that large parts of the European public seem to share scepticism towards GM crops (Gaskell et al., 2006). The argument is therefore that GM crop-free regions, ensuring more 'natural' food and feed production, are in line with consumer preferences. According to Jank et al. (2006), GM crop-free regions create a specific image for marketing regional products and services such as tourism. By preventively banning GM crops in certain areas, opponents are not only defending alternative 'less industrialised' cropping systems (Marsden, 2008), but they are also protecting the 'perceived' value of potentially affected agricultural regions (Kaiser, 2007). Within this context, pressure groups, regional/local governments, municipalities and farmers forged coalitions and succeeded in putting their prerogatives (including their sovereignty) on the agenda. Through the creation of an impressive number of GM crop-free regions across the EU, these coalitions imposed their democratic right to decide whether GM crops can be cultivated in their region. As such, coexistence is no longer a matter of private choice of farmers, who should have the freedom to choose between conventional, organic and GM crops. In effect, they claim the right to locally decide and interpret questions of safety and ensuing precaution relating to GM crops independent from the European level. From an ethical point of view, it is interesting to note that the stress on regional/local sovereignty is bought at the price of individual freedom of choice. It may thus not be too far fetched to maintain that an underlying conflict of values is one of the driving forces behind this opposition.

Finally, because the interests and preferences of non-GM crop adopters are perceived to be not fairly balanced against those of GM crop adopters and due to the individualisation of liability and redress schemes, opponents claim that coexistence will promote conflicts and ruin personal relationships between neighbouring farmers. Interests and preferences of a small group of early GM crop adopters are anticipated to outbalance those of an agricultural minority system (e.g., organic farming) (Bello et al., 2007).

6.2. Proponents' rationale on coexistence

In contrast to the opponents' view, proponents attach themselves to the European Commission's definition on coexistence, exposing a different view on the role of agricultural biotechnology. In their opinion, coexistence is feasible, provided that (i) techno-scientifically-based coexistence measures are implemented proportional to economic incentives; (ii) good agricultural practices are followed; and (iii) good agreements are made between farmers. Because agro-food biotechnology applications undergo a thorough risk assessment prior to commercialisation, proponents argue that GM crops have been proven to be safe and even safer than their conventional counterparts. Moreover, they see GM crops as a more sustainable alternative to current crop production systems that would help to minimise or even remedy adverse effects of intensive agriculture. This includes the substitution of environmentally harmful input factors by less harmful ones and improved eco-efficiency through the reduction of external chemical inputs (such as pesticides and fertilisers).

In areas with high infestation of the European and Mediterranean corn borer, claimed benefits of Bt-maize are (i) higher yield levels compared with non-GM maize varieties; (ii) less pesticide treatments; (iii) lower pest damage, resulting in decreased levels of mycotoxins (e.g., fumonisin); and therefore (iv) enhanced safety and quality for animal and human consumption (Demont and Tollens, 2004; Wu, 2006, 2007; Gómez-Barbero et al., 2008). Proponents even argue that greater efficiency, productivity and management flexibility would enhance economic competitiveness. In the case of GM herbicide-resistant crops, the biotechnology-based weed management strategy is thought to replace a set of currently used herbicides by broad-spectrum, non-selective herbicides with better environmental profiles, and to reduce the amount of active ingredients applied and herbicide doses used (Nelson and Bullock, 2003; Brimner et al., 2005; Cerdeira and Duke, 2006; Graef et al., 2007; Kleter et al., 2007, 2008; Bonny, 2008; Devos et al., 2008b; Duke and Powles, 2008; Gardner and Nelson, 2008; Shipitalo et al., 2008). The adoption of GM herbicide-resistant crops and their associated management practices might (i) increase the flexibility in timing of weed management; (ii) simplify weed management; (iii) reduce management time; (iv) lower the risk for crop injury; (v) facilitate the adoption of no-till or reduced-till planting procedures; and (vi) generate less concern with carry-over damage to rotational crops (Marra and Piggott, 2006; Sanvido et al., 2007; Devos et al., 2008b; Duke and Powles, 2008; Gianessi, 2008). Where higher-than-average herbicide rates and numbers of active substances are needed for weed control, improved control of troublesome weeds combined with a reduction in overall herbicide-use rates and number of used active ingredients might translate into economic benefits for farmers.

Furthermore, proponents would insist that only the market can in the long run provide reliable indications of true consumer preferences, and should thus be allowed to regulate balanced proportions of available GM and non-GM products. However, this statement only holds if actors in the market have access to perfect information. Since the presence of traces of GM material in food is a credence attribute, the problem of asymmetric information arises. The seller of GM products has access to information that cannot be verified by the buyer through searching or experience. If consumers perceive GM products to be different from their traditional counterparts, then demands for the banning of GM products and labelling requirements are rational (Giannakas and Fulton, 2002). The mandatory labelling system was set in place in the EU to reduce resulting welfare losses (Philips, 1988). If this labelling system reflects the necessary information for the consumer to satisfy his perception regarding safety and environmental concerns, the welfare losses will be reduced. However, if labelling is not considered reliable or the threshold does not fulfil consumers' needs, welfare losses are created and long-term market indications do not reflect true preferences of consumers. Furthermore, forcing suppliers of GM products to incur labelling costs (such as in the EU) may be counterproductive from a welfare perspective (Lapan and Moschini, 2004). Therefore, to achieve a socially desirable outcome, the cost of a trustworthy mandatory labelling regime has to be proportional to the consumers' willingness to pay for IP crops.

In the opinion of proponents, GM crops and their associated management practices enable sustaining intensive agriculture more safely through reduced environmental damage. Therefore, they argue that GM opponents currently misuse coexistence as a pretext to place a new barrier in the path of GM crops. They invert the aforesaid reasoning put forward by GM opponents and question whether an existing agricultural cropping system has the right to take hostage of a new cropping system. The complaint appeals to considerations of fairness towards innovators to prove the viability of their product on the market as long as these are found to be safe (Kaiser, 2007).

7. CONCLUSION

The controversy about and stigma of transgenic agro-food products still hold in the EU (Herring, 2008). Although regulations should ensure that different cropping systems can develop side-by-side, coexistence has become another arena of contending values and visions on future agriculture and on the role agro-food biotechnology might play therein (Devos et al., 2008d; Levidow and Boschert, 2008). The economic scope of coexistence, as defined in the European Commission's guidelines on coexistence, has been widened with issues of environmental safety, sustainable development of agriculture, globalisation, dependence and protection of local producers. Unsolved debates about the safety of GM crops held at EU or national levels have moved to regional/local levels, where the debate continues in the context of coexistence, displaying at least some features of so-called 'not-in-my-backyard' (NIMBY) arguments (Kaiser, 2007). Thereby, any distinction between environmental, agricultural, economic and socio-ethical issues proved to be blurred, fuelling the confusion about the wider debate about the acceptability of genetic engineering and the coexistence of GM and non-GM crops in the EU (Devos et al., 2008d; Levidow and Boschert, 2008). The main conflict line is between those that promote agro-food biotechnology applications as a safe and sustainable alternative to current crops and agricultural management practices, and those that defend less-industrialised cropping systems – as a future 'alternative' agricultural path – by preventively banning this novel agricultural technology.

In principle, the maintenance of different cropping systems should be ensured in European agriculture by tolerating a certain level of adventitious mixing between cropping systems. In practice, however, there seems to be low or no political willingness to tolerate any adventitious mixing from GM crops in some EU regions. To comply with the zero tolerance policy in these regions, large and fixed isolation distances are imposed by law in ex ante coexistence regulations. However, legally imposing large and fixed isolation distances entails various challenges. Based on the performed review, it is concluded that large and fixed isolation distances do not comply with the general coexistence principles set by the European Commission: they are (i) excessive from a scientific point of view; (ii) difficult to implement in practice; (iii) rarely proportional to the regional heterogeneity in the agricultural landscape; and (iv) not proportional to the farmers' basic economic incentives for coexistence. Therefore, one could interpret the deliberate use of large and fixed isolation distances as the sole preventive coexistence measure in ex ante coexistence regulations as a new local substitute for the lifted de facto moratorium. One could even go a step further by arguing that the use of large and fixed isolation distances is complementing similar political attempts intending to place a barrier in the path of GM crops. These include invoked safeguard clauses, which provisionally restrict or prohibit the use and/or sale of approved GM agro-food products on national territories or the proclamation of GM crop-free areas, which are currently emerging all over the EU. The irony is that it was the adoption of the EU coexistence policy – as the final building stone of the restyled regulatory frame on GM agro-food products – that contributed to the lifting of the de facto moratorium on new GM crop market approvals in 2004.

To move towards appropriate (i.e., regionally and economically proportionate) coexistence, there is an urgent need to build in a certain degree of flexibility into ex ante coexistence regulations. As such, it remains to be seen whether the coexistence policy will ever succeed in appeasing the contending normative positions raised on agricultural futures and the role agro-food biotechnology might play therein, not to mention letting different cropping systems exist 'peacefully' side-by-side in practice.

8. DISCLAIMER

Opinions and views expressed in the present article are strictly those of the authors, and do not represent those of the organisations where the authors are currently employed.

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