ASSESSING THE ECONOMICAL AND ENVIRONMENTAL IMPACT OF CULTIVATING GENETICALLY MODIFIED (GM) CROPS IN IRELAND

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Summary

At present, there is no GM crop cultivation in Ireland. This could change in the near future however, following the inclusion of several GM maize varieties on the EU Common Seed Catalogue in 2004. Before an Irish GM tillage sector develops, information must be provided to farmers/regulators in regard to the potential economic impact of the technology and the environmental issues associated with GM crops. This project (RMIS 5211) has examined:

1. The economic cost-benefit of cultivating several GM crops (*Phytophthora* resistant potato, *Septoria* resistant wheat, *Rhynchosporium* resistant barley, *Fusarium* resistant wheat and herbicide tolerant sugar beet)
2. The environmental issue of gene flow by modelling the propensity of seven crop species (wheat, barley, sugar beet, oilseed rape, maize, potato and ryegrass) to spread their genetic material (be it GM/non-GM) through pollen/seed-mediated gene flow.

The cost-benefit analysis specifically examined the impact of reduced chemical input and indicated that each GM crop tested would be more cost efficient than their conventional equivalent. Inputting the regimes and subsequent costs for the 2002 and 2003 growing season into the analysis, farmers would have returned a greater cost savings in 2002 for each of the GM crops, with the exception of potato. While a significant increase in gross margin was recorded for all GM crops, the greatest savings (€ha^{-1}) occurred in the case of herbicide tolerant sugar beet in the absence (9.8% saving) or presence (23.2% saving) of a yield effect. Modelling a crop's propensity to spread its genetic material ('gene flow') was achieved through the creation of a composite gene flow index (GFI) model. Taking into account both pollen and seed mediated data, presence/absence of interfertile wild relatives and current farming practises, a GFI value was returned for each crop. Unless the GM event altered the seed/pollen production of the crop, it can be anticipated that the same GFI value will apply to a GM/non-GM variety of the particular crop. Crops that returned the highest GFI values were ryegrass, oilseed rape and sugar beet. Importantly, a high GFI score does not imply the prohibition of GM varieties of that crop. Rather, it highlights those crops that possess a higher propensity for gene flow and thus require greater management precautions in light of coexistence regulations. To facilitate the provision of this and other relevant research information, a website (www.gmoinfo.ie) has been provided to further public understanding of the issues. Structured in a non-scientific format, this resource will be updated on a regular basis in response to public requests for further information and with research findings from the risk assessment programme at Oak park.

2. Introduction

In 2004, over 81 million hectares (ha) were cultivated with genetically modified (GM) crops across 17 countries worldwide (James, 2004). With the exception of Spain (approximately 100,000ha of GM maize were sown in 2004), no GM crops are currently cultivated for commercial purposes within the European Union (EU). The difference in GM crop cultivation between European and other OECD countries, has arisen as a direct result of the EU *de facto* moratorium on the cultivation of GM crops, which was established in 1998 in response to public perceptions and concerns regarding the biosafety of GM technology when applied to food production. Between 1998-2003, the response of the EU to public concerns was to introduce a series of legislative measures (Directive 2001/18; EU Regulation 1829/2003; EU Regulation 1830/2003; EU Regulation 1946/2003) to ensure informed consent, adequate labelling and traceability and to safeguard against the introduction of a GM crop, which presents a hazard to human/animal health and/or the environment.

It is anticipated that the uptake of GM seed for cultivation could commence by 2007 for maize, oilseed rape and sugar beet (PG Economics, 2003). From an Irish perspective this provides us with an opportunity to establish the implications, both environmental and economical, of GM technology prior to any GM crop cultivation. Taking advantage of this timeframe, this study was established to investigate from an Irish context, two principal issues central to GM crop cultivation:

- Will their cultivation provide an economic benefit to the farmer?
- Is it possible to quantify a crop’s potential for gene flow? This is of relevance to GM crops as concern exists in regard to the propensity of a GM crop to spread its genetic material (e.g. transgene) through pollen/seed-mediated gene flow.

2.1 Economic assessment

Information pertaining to the economics of GM crop cultivation is readily available for those countries where there has been significant cultivation of GM crops (US, China, Canada etc.). As to be expected, such information is limited for European countries where uptake has been impeded by the *de facto* moratorium. Of the research that has been completed (Gianessi et al., 2003; May, 2003; Demont and Tollens, 2004), it is clear that the application of certain GM crops (e.g. herbicide tolerant sugar beet and blight resistant potato) to particular environments have the potential to provide an economic benefit to the farmer.

Table 1: GM crops considered for economic analysis

Crop	**GM trait**
Sugar beet	Herbicide tolerance (GMHT)
Winter wheat	*Septoria tritici* resistant (GMSR)
Spring barley	*Rhynchosporium secalis* resistant (GMRR)
Winter wheat	*Fusarium* resistant (GMFR)
Potato	*Phytophthora infestans* resistant (GMLBR)

Taking account of these studies, this research aims to investigate the potential economic cost/benefit of cultivating five hypothetical GM crops in Ireland. The crops (Table 1) were selected based on their economic importance to Irish agriculture and the specific GM traits (disease and herbicide tolerance) were selected because of the difficulties arising from disease and weed control in present crop management regimes. Note, for GM sugar beet, the availability of specific crop output data permitted a more detailed analysis, which was in contrast to winter wheat, spring barley and potato where the analysis was restricted to the benefit associated with reduced chemical input. Importantly, this research has already been peer-reviewed and published (Flannery et al., 2005) and is available for review at http://www.gmoinfo.ie/research.php.

2.2 Environmental assessment

A recurring issue in regard to GM cropping centres on the potential transfer ('gene flow') of the GM trait into related weed/cultivated populations. Gene flow describes the transfer/movement of genetic material between two related plant species and can be achieved through the dispersal of viable pollen and/or the dissemination of seed. For successful pollen-mediated gene flow, the pollen has to find and fertilise a compatible wild relative or crop, which in turn must result in the formation of a fertile hybrid. Although hybrids may develop spontaneously, it is not automatically implied that they will be able to establish, survive and reproduce in the wild (Hauser et al., 2003a; Hauser et al., 2003). Similarly, seed-mediated gene flow can only be guaranteed if the germinating seed gives rise to a viable plant with the ability to reproduce.

In Europe, the issue of gene flow is of particular significance in light of present coexistence regulations, which direct that gene flow from a GM crop must be sufficiently restrictive to minimize the potential admixture of GM material with non-GM crops (European Commission, 2003). For seed-mediated gene flow, this can be achieved through the implementation of a stringent management system (Tolstrup et al., 2003). For pollen-mediated gene flow the issue is more complex as the frequency of transgene flow is influenced by pollen viability, size of pollen sources, the availability of a flowering recipient population, local topography, etc…. To offset this, isolation distances between the GM and non-GM crop have been recommended as one of several measures to ensure the effective coexistence of GM and conventional/organic crops (Tolstrup et al., 2003; Advisory Committee on Releases to the Environment, 2004). Indeed, isolation distances are appropriate for minimising crop-to-crop gene flow but this mechanism will not restrict pollen-mediated gene flow from a crop to a related wild species. Of most relevance to this is clearly the presence/absence of interfertile wild relatives within/adjacent to the crop in question.

Irish farmers cultivate several indigenous and non-indigenous crops which may or may not co-exist with an interfertile wild relative (Webb et al., 1996; Preston et al., 2002; Meade and Mullins, 2005). So, whereas wheat, barley, potatoes, and maize are alien species without interfertile wild relatives; ryegrass, oilseed rape and sugar beet are native, raising the possibility that commercial GM crops will interbreed with other varieties already growing in Ireland (Meade and Mullins, 2005).

A traditional commentary associated with such a gene flow event would gauge the risk of transgene transfer into the wild population as being high, medium or low (Eastham and Sweet, 2002). This invites the question of whether it is possible to numerically quantify the level of gene flow from a GM crop? The substitution of a 'high, medium, low' classification with a numerical index could have benefits for both the consumer and the research scientist. For the former, the provision of a distinguishable scale would assist them in understanding the risk/benefit of a particular GM crop. For the scientist, it could introduce a level of diagnostic uniformity across independent research studies. Data normalized in this way could permit (i) a more reliable comparison to be made between studies from disparate regions and (ii) provide a reliable criterion for pre-selecting GM crops based on their suitability to local agro-ecological conditions.

Gene flow indices or botanical files have been proposed as a tool to assist risk assessment strategies and could be employed to secure significant background information. In 2001, Ammann et al. (Ammann et al., 2001) discussed the potential of a gene flow index to monitor pollen-mediated gene flow in Switzerland. More recently, as part of the Bulgarian biosafety framework, an UNEP-GEF funded project (Programme, 2003) has set about preparing botanical files for over 61 plant species based on an earlier model of de Vries (de Vries et al., 1992).

In this study we describe a gene flow index (GFI) model that addresses both pollen and seed-mediated gene flow from a cultivated crop into related crop/wild relatives. To achieve this we present a numerical scale that combines four strands of analysis, which when pooled, generate a composite risk assessment describing the propensity for gene flow from each crop. This in turn will assist us in determining the potential risk of a GM trait to escape/flow from a GM crop into a related weed/crop population. Importantly, this research has already been peer-reviewed and published (Flannery et al., 2005) and is available through http://www.gmoinfo.ie/research.php.

3. Methods

3.1 Economic analysis

To examine the economic cost-benefit analysis of GM crop cultivation in Ireland, the cropping regimes of the four listed crops were compared with equivalent, hypothetical GM scenarios. All figures used were based on crop production data for Ireland and include variable and some element of fixed costs: materials (seed, fertilizers, herbicides, fungicides, insecticides, growth regulators), machinery hire (plowing, tilling, sowing, spraying, fertilizer spreading, harvesting), and miscellaneous costs (interest [7%] and transport; (O' Mahony, 2002; O' Mahony, 2003); (Teagasc, 2002; Teagasc, 2003). For the purpose of assumptions used in the economic tradeoff analysis, care was exercised in referring to non-peer-reviewed literature, which was only employed when peer-reviewed literature was not relevant to Ireland’s agronomic system.

The sugar beet analysis included data for seed cost, herbicide spray, and application costs in conjunction with data from England (May, 2003). As yield data has been reported with regard to GMHT sugar beet, the impact of the technology on yield was predicted by adopting an average reported yield effect (6%) calculated from an Irish (Mitchell, 2003) and several European trials (Moll, 1997; Brants and Harms, 1998; Tenning, 1998; Wevers, 1998; Wevers, 1998; May, 2000). The overall economic implications of the introduction of the new technology were outlined both including and excluding the yield effect, an approach adopted due to the problems associated with predicting accurate yield effects, as previously highlighted (Mitchell, 2000; Kniss et al., 2004). In contrast, yield estimates for GM wheat, barley, and potato were not available; hence, the likely cost benefits gained from increased yields associated with these GM crops could not be represented.

For winter wheat and spring barley, the cost of cultivating GMSR and GMFR winter wheat and GMRR spring barley was compared with conventional cropping regimes in terms of the impact the technology would have on fungicide sprays and their application. In the main-crop potato sector, the cost effect of decreasing the number of spray applications through the use of a GMLBR potato variety was examined. Note that to safeguard the durability of host resistance, a two-spray regime was included in the model.

Taking into account existing coexistence strategies (Tolstrup et al., 2003), it was assumed that Irish GM producers could incur additional coexistence-related costs of up to €25. Although GM seed will be more expensive than its conventional equivalent, predicting the cost is difficult, as there is no precedent in Ireland, and the cost of GM seed varies greatly between country, crop, and variety. For the purposes of this study, crop-specific seed premium prices have been used [as proposed by Alston et al. (Alston et al., 2002)] when suitable data was available from the literature. However, based on the crops examined in this analysis, a relevant crop-specific seed premium for Ireland was only available for sugar beet [average of €30/ha; (May, 2000)]. For the remaining crops, a tentative premium of 15% was assumed. Alternative seed premium assumptions were considered for the remaining crops, such as that proposed by Alston et al. (2002), where "the variable costs per acre would be the same as for a representative conventional... control technology" (p. 71). However, due to data limitations, in particular on yield estimates for the remaining crops, it was not possible to follow this approach of static average variable costs. As GM cultivation has yet to commence in Ireland, it was also assumed that GM crops would be treated as conventional crops with regard to cultivation and that GM products would be sold at the same price as conventional products. Hence, our analysis does not address the issues surrounding the 'saleability' of the products and assumes that a market for GM-derived products will develop over time.

The cropping regimes, including the spray program assumed for this analysis, were based on Farm Management Protocol (FMP) data (Teagasc, 2002; Teagasc, 2003). Compiled from annual *Crop Costs and Returns* (O'Mahony, 2002, 2003), this data set provided variable costs (i.e., plowing, tilling, sowing, spraying, fertilizer spreading, harvesting, interest, and transport) and was chosen ahead of the National Farm Survey (NFS; http://www.teagasc.ie/publications/2004/20040809.htm) data. This approach was adopted due to (a) the lack of itemized data from NFS sources and (b) the need to acknowledge the typical early adopters in a technology cycle (Fernandez-Cornejo et al., 2001), for whom the farm management protocol data was deemed more representative. To account for annual differences with respect to yield and disease pressure, both 2003 (high yield, low disease) and 2002 (low yield, high disease) were examined. The low yields obtained in 2002 were attributed to mild humid conditions, which led to elevated levels of disease pressure.

3.2 Gene Flow Index (GFI) methodology

Data presented in this research was collected from a broad literature base (scientific journals and reports) and considered in conjunction with field data from Teagasc Oak Park and information from the Teagasc Farm Advisory Service. Notably, only information that pertains to systems comparable to the Irish agricultural system was employed.

The GFI model evaluates baseline data for the main crops grown in Ireland and includes such minority crops as oilseed rape and maize. In clarifying the parameters of the model, the calculated GFI value pertains to the propensity of each crop to form viable hybrid/volunteer/feral individuals. For the purposes of this study we have made a clear distinction between the volunteer and feral niches based on the ability of a plant to grow within/outside a managed crop system respectively (Devos et al., 2004).

The model retains a simple format and is composed of four strands representing the four possible modes of pollen/seed-mediated gene flow:

- crop pollen-to-wild relative (CPW)
- crop pollen-to-crop (CPC)
- crop seed-to-volunteer (CSV)
- crop seed-to-feral (CSF)

Each strand contains several sequential questions with each question designed to provide a ‘yes/no’ (1/0) answer (Table 2), which in turn equates to a relevant score. By following this linked progression, when a question incurs an answer with a zero value that strand automatically records a total value of zero, as no gene flow can take place for the specified crop under the selected criterion.

Table 2. Components of proposed Gene Flow Index (GFI) describing the propensity for successful pollen and/or seed-mediated gene flow through four possible strands: strand CPW for crop pollen-to-wild gene flow, strand CPC for crop pollen-to-crop, strand CSV for crop seed-to-volunteer and strand CSF for crop seed-to-feral.

Strand	**Question**	**Score**
CPW	**Propensity for successful pollen-mediated gene flow between the crop and wild relatives**	
CPW1	Do interfertile wild relatives of this crop exist in Ireland?	0/1
CPW2	Is there a probability that the crop will flower and produce viable pollen during its cultivation?	0/1
CPW3	Upon flowering, is 95% of the crop pollen deposited within 1m (1), 10m (2), 50m (3), 100m (4), 250m (5) or 500m (6)?	1/2/3/4/5/6
CPW4	If flowering does occur is the wild relative in question rated as an obligate inbreeder (0), a partial inbreeder/outbreeder (1) or an obligate outbreeder (2)?	0/1/2
CPW5	If fertilization is achieved by the deposited pollen, will a viable F_1 hybrid individual establish itself?	0/1

Strand	**Question**	**Score**
CPC	**Propensity for successful pollen-mediated gene flow between the crop and related commercial varieties**	
CPC1	Is there a probability that the crop will flower and produce viable pollen during its cultivation?	0/1
CPC2	Upon flowering, is 95% of the crop pollen deposited within 1m (1), 10m (2), 50m (3), 100m (4), 250m (5) or 500m (6)?	1/2/3/4/5/6
CPC3	If flowering does occur is the receptive crop rated as an obligate inbreeder (0), a partial inbreeder/outbreeder (1) or an obligate outbreeder (2)?	0/1/2
CPC4	If fertilization is achieved by the deposited pollen, will a viable F_1 individual establish itself from the hybrid seed in the absence of mechanical/chemical control?	0/1

Strand	Question	Score
CSV	**Propensity for successful seed-mediated* gene flow from commercial crop to volunteer**	
CSV1	Does the crop produce seed during its cultivation?	0/1
CSV2	Post-harvest, will the seed survive and germinate within the confines of a managed field?	0/1
CSV3	Will the volunteer develop into a viable individual?	0/1

Strand	Question	Score
CSF	**Propensity for successful seed-mediated* gene flow from commercial crop to feral**	
CSF1	Does the crop produce seed during its cultivation?	0/1
CSF2	Following transfer from the site of cultivation will wayward seed survive and germinate?	0/1
CSF3	Will the resulting individuals establish into a viable feral population?	0/1

* 'Seed-mediated' encompasses both flower originating seed and root derived tubers

The adoption of this worst-case scenario approach was intentional and complements a previous discussion (Wilkinson et al., 2003), which advocated the use of a more structured system to assess any potential risk. As such, it maintains the practicality of the model by encompassing real-life factors that while not desired, will occur all the same; for example the occurrence of bolters in a sugar beet crop. Note, for the purposes of this research the characterization of 'seed-dispersal' relates to the dispersal of both/either the produced seed and/or the tuber of the described crop.

For all four GFI strands the decisive factor for successful gene flow is deemed to be the establishment of a viable hybrid/volunteer/feral individual, without which the exposure element (introgression of the GM trait) of any GM crop risk assessment could not occur. By restricting the analysis to just the dispersal and preliminary stage of establishing a fit individual/population, it is accepted that the model excludes the issue of hybrid/feral competitive ability. It does however; provide an initial data set that will:

(i) quantify the propensity of a crop to spread its genetic material and
(ii) provide a basis for comparatively assessing the gene-flow potential of conventional and GM varieties of a specific crop.

4. Results

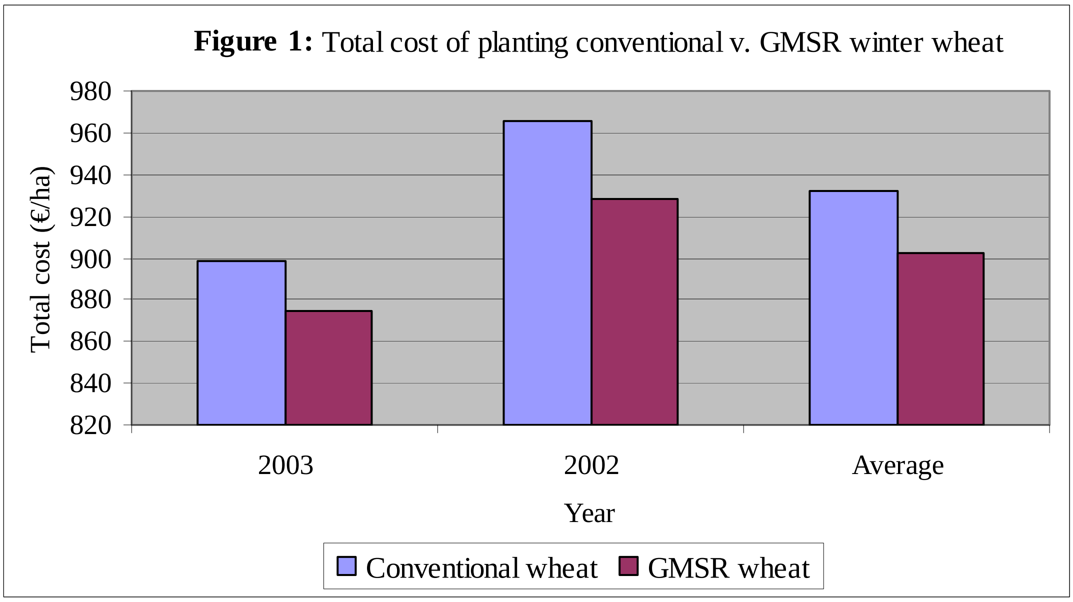
4.1 Economic assessment

4.1.1 GM Septoria resistant winter wheat

Septoria can inflict annual yield losses of 10-20% on winter wheat and requires a strict fungicidal management regime to ensure appropriate control. The more effective control regimes have been complicated with the recent emergence of fungicide resistant strains of *S. tritici* (O'Sullivan, 2004) and there is concern in regard to the continued efficacy of the remaining triazole-based strategies (McCabe, 2004). GM winter wheat varieties expressing resistance to Septoria could therefore increase the choice to the farmer who could benefit through reduced chemical input.

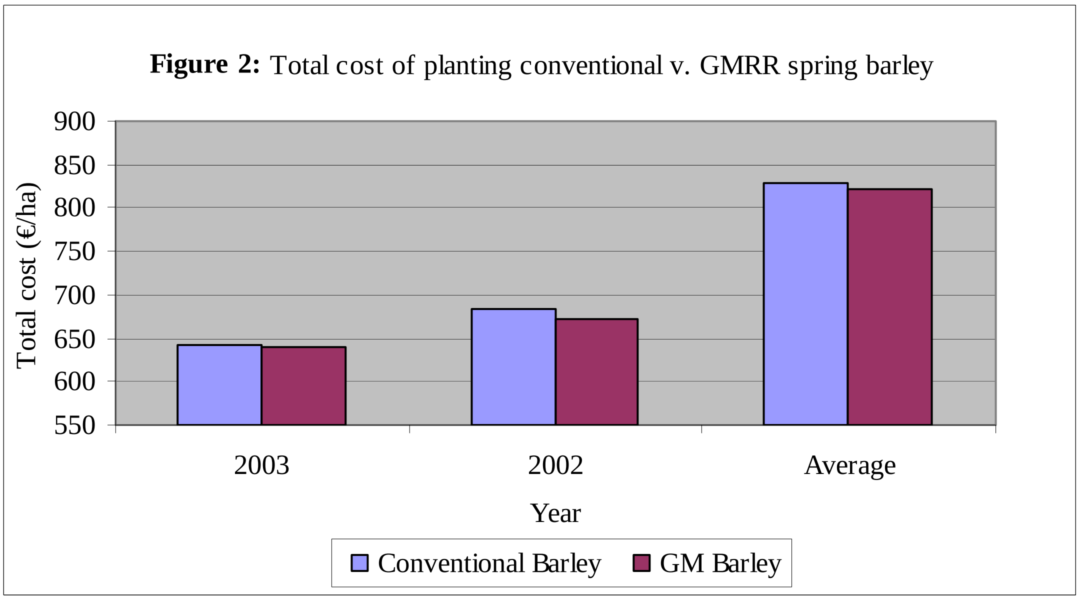
In 2003 and 2002, growers of winter wheat incurred a cost of 150 €ha^{-1} and 179 €ha^{-1} respectively for conventional fungicide applications. If commercialised, a

GMSR variety could decrease this expenditure to an average of 100 €ha^{-1} (40% savings). When these costs were incorporated into the cropping regime along with the accepted GM costs (seed cost (9 €ha^{-1} extra) and technology cost), the comparative difference between the conventional and GM regimes equated to an average cost savings of 30.5 €ha^{-1} (3.3%) for GMSR winter wheat (Figure 1): a potential 9.6% increase in profit (Figure 6).



4.1.2 GM Rhynchosporium resistant spring barley

163,270 ha of spring barley were sown in 2003 and as with wheat, disease control is crucial to achieving high yields. The primary fungal disease of spring barley is *Rhynchosporium secalis* ('leaf scald'), which is currently controlled with a fungicide mix. The development of GM *Rhynchosporium* resistant (GMRR) barley could present the farmer with an opportunity to reduce current levels of fungicide input and associated costs.



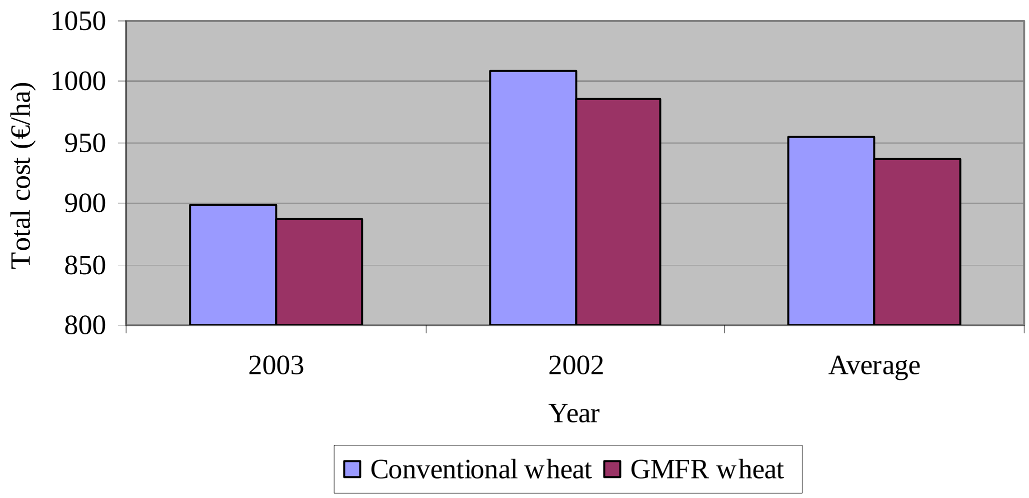
Cost evaluations showed that the adoption of GMRR spring barley could reduce the expense of fungicide applications from 75 €ha^{-1} to 37.5 €ha^{-1}. When combined with additional GM costs (seed cost (9.6 €ha^{-1} extra) and technology cost), an average cost saving of 6.9 €ha^{-1} (0.8%) could be returned to the producer (Figure 2): corresponding to a 10.5% profit increase (Figure 6).

4.1.3 GM Fusarium resistant winter wheat

Though not as prevalent as Septoria, Fusarium head blight (caused by *Fusarium avenaceum*, *Fusarium graminearum*, *Microdochium nivale*; collectively termed *Fusarium* spp.) can, under favourable conditions, produce mycotoxins, which pose a serious risk to animal and human health. As with other diseases of wheat, control is achieved through a fungicide regime. A GM winter wheat variety expressing resistance to *Fusarium* spp. (GMFR) could benefit the farmer through reduced chemical input and subsequently reduce the potential threat posed by mycotoxin accumulation.

If commercialised, GMFR varieties could decrease the fungicide requirement to an annual average of 113 €ha^{-1} (31% savings). When incorporated into the cropping regime along with the accepted GM costs (seed cost (9 €ha^{-1} extra) and technology cost), the comparative difference between the conventional and GM regimes equated to an average cost savings of 17.5 €ha^{-1} (1.8%) for GMFR winter wheat (Figure 3): a potential 5.9% increase in profit (Figure 6).

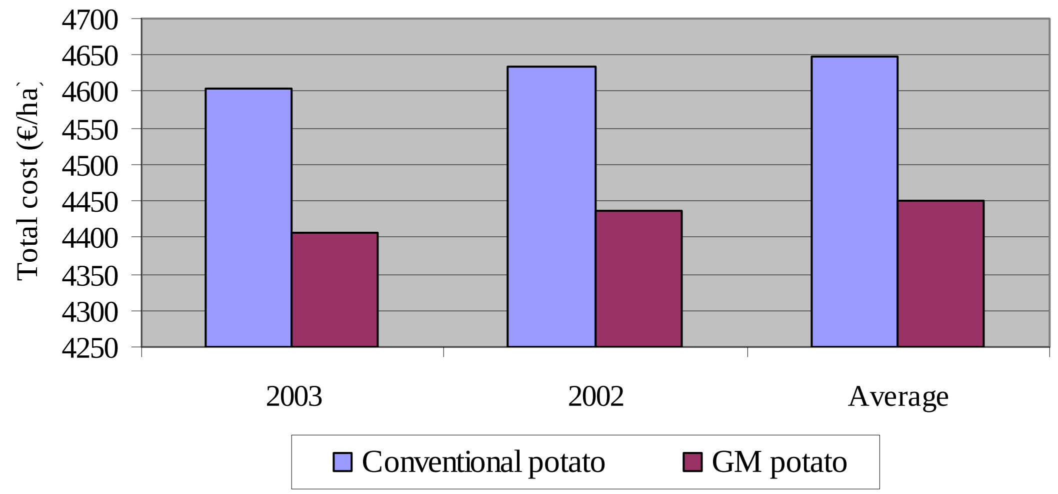
Figure 3: Total cost of planting conventional v. GMFR winter wheat



4.1.4 GM Phytophthora resistant potato

Phytophthora infestans (‘late blight’), continues to be a major problem in Ireland, causing annual losses in yield and quality estimated at €15 million per annum (Copeland et al., 1993). Present crop regimes require a regular, high-rate fungicide application at short intervals throughout the growing season. In 2003, 3.6% of Ireland’s total crop production area (14,150 ha representing 488,210 tonnes) was planted with potato with producers having to spray 12-14 times to ensure adequate blight protection (Dowley et al., 2001). The commercialisation of GM late blight resistant (GMLBR) potato variety has the potential to offer a significant cost savings to the producer (Gianessi et al., 2003).

Figure 4: Total cost of planting conventional v. GMLBR potato

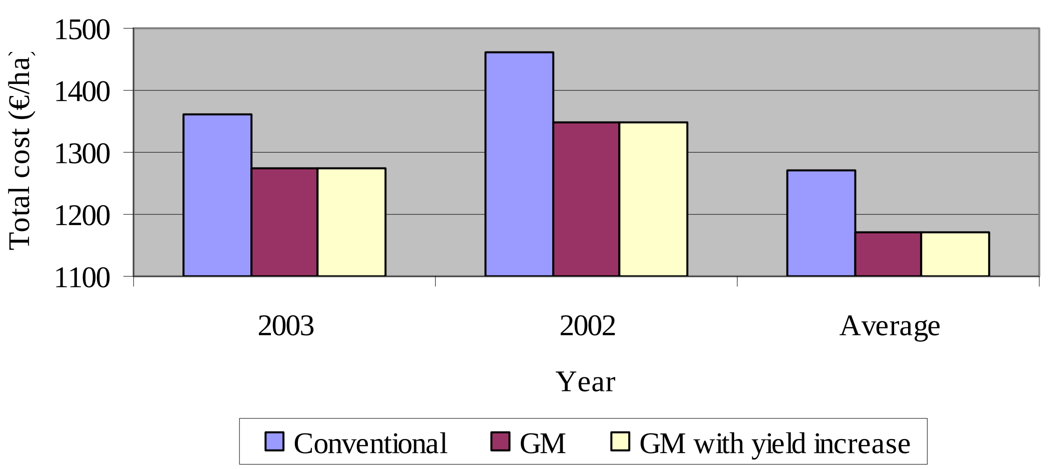


Reducing blight control applications from an average of 13/growing season to 2 in main-crop potato production could decrease associated expenditure from 286 €ha^{-1} to 60 €ha^{-1} respectively. When combined with expected GM costs (15% seed cost (122 €ha^{-1} extra) and technology cost), this would provide a cost saving of 199 €ha^{-1} (4.3%): representing a 14.5% increase in profits (Figure 4 and 6).

4.1.5 GM herbicide tolerant sugar beet

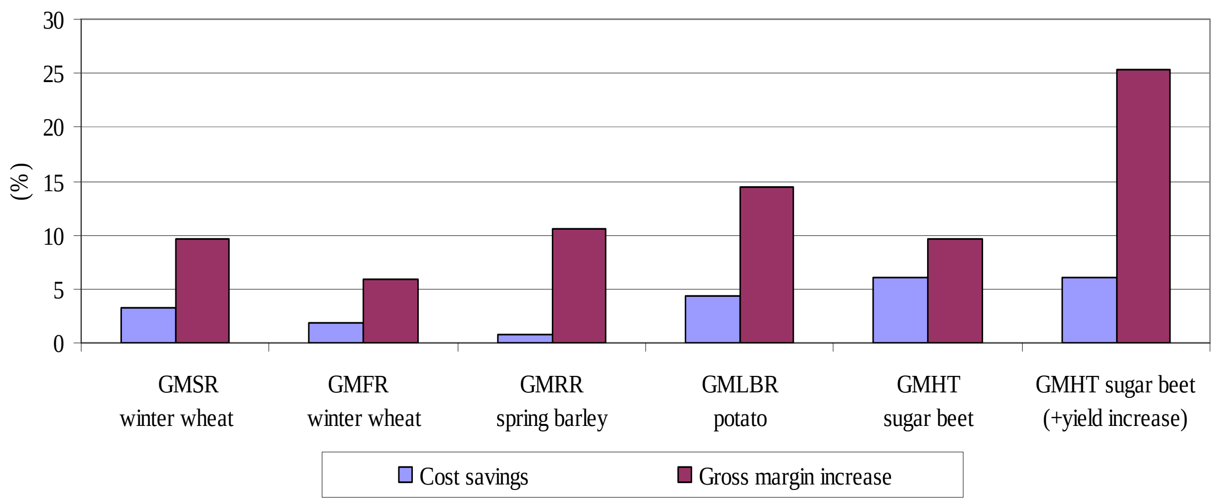
Sugar beet is a broadleaved crop that has a poor tolerance of weed competition due to its slow rate of establishment. As it is sensitive to many of the available herbicides, repeated rates of low dose herbicide are often applied to give effective weed control. Therefore, weed control is relatively expensive and poor weather conditions often further reduce the effectiveness of the herbicide treatment. Annual beet (bolters) cannot be controlled by selective herbicides and are removed by hand-rogueing or with the application of herbicide on individual plants. As the provision of herbicide tolerant GM sugar beet would provide growers with the option to use a total herbicide regime to control weeds, it is therefore considered an attractive prospect.

Figure 5: Total cost of planting conventional v. GMHT sugar beet



For GMHT sugar beet, the reduction in spray volume and number of applications combined with the additional GM costs (seed cost (30 €ha^{-1} extra) and a technology cost), resulted in an average cost saving of 85.63 €ha^{-1} (6.06%); representing a 9.69% increase in gross margin (Figure 5 and 6). When the predicted 6% yield increase (Moll, 1997; Brants and Harms, 1998; Tenning, 1998; Wevers, 1998; Wevers, 1998; May, 2000; Richard-Molard, 2001) was incorporated into the analysis, crop profitability increased from 9.69% to 25.29% (Figure 6).

Figure 6: Average impact of GM crop cultivation on cost savings and gross margins for GMSR and GMFR wheat, GMRR barley, GMLBR potato and GMHT sugar beet over 2002 and 2003.



4.2 Environmental assessment

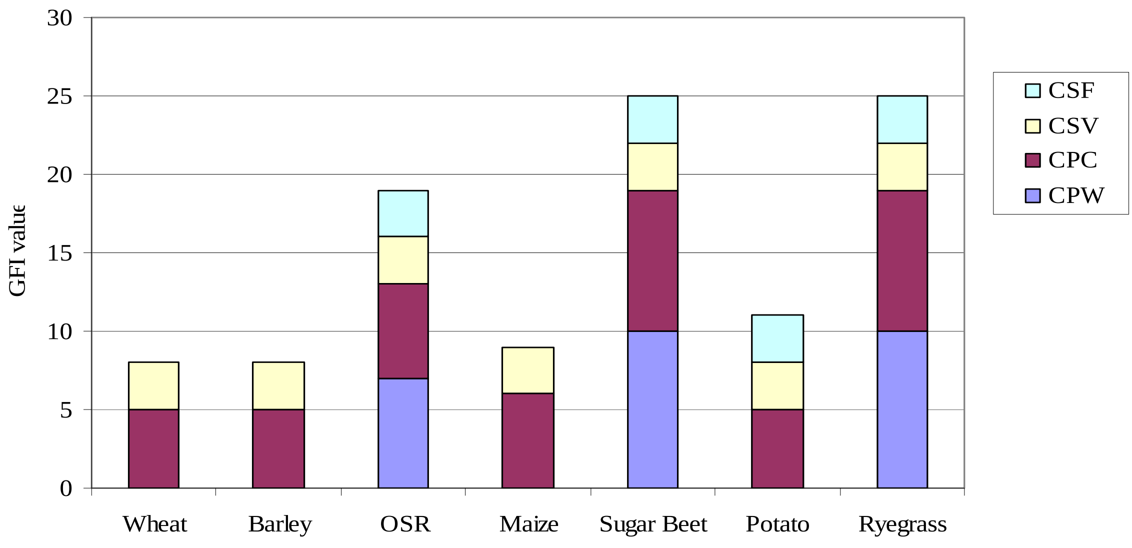
4.2.1 Crop propensity for gene flow

A composite GFI value was calculated by combining the attained values from each of the four strands (CSF, CSV, CPC, CPW) for each crop (Table 3). Represented schematically, the high propensity of both conventional ryegrass and sugar beet to disperse their genetic material is clear, with each attaining a GFI value of 25 out of a maximum 27 (Figure 7). The justification for such a value is supported by the fact that both species co-exist in Ireland with inter-fertile wild relatives, both can disperse their pollen over large distances and the initiation of feral populations from each species is a reality.

Importantly, the high GFI value for conventional sugar beet does not necessarily advocate the non-cultivation of GM sugar beet in Ireland. Rather it underlines the central importance of bolter control to ensure the effective coexistence of GM and non-GM sugar beet. This point is emphasised by re-submitting the data into a coexistence based model for sugar beet that requires stringent bolter control. In this scenario the model produces a GFI score of 6, where the likelihood of gene-flow is reduced to the establishment of volunteer and feral populations from harvested tuber fragments. The analysis could also be applied to estimate the potential for gene flow at a local level as opposed to a national scale. For example, as *B. vulgaris* ssp. *maritima* is only found along the coastal counties of Ireland, sugar beet cultivation in the midlands would negate an element of the risk associated with the CPW strand of the crop.

A GFI value of 19 for oilseed rape (Table 3 and Figure 7) confirms the ability of this species to disperse its genetic material. In contrast to sugar beet (GFI = 25), flowering is required in oilseed rape. Hence, potential mechanisms to reduce the GFI value for oilseed rape from the perspective of coexistence are limited to the implementation of large isolation distances (Tolstrup et al., 2003) and measures to reduce post-harvest seed loss.

Figure 7: Graphical representation of combined pollen and seed-mediated gene flow for wheat, barley, oilseed rape (OSR), maize, sugar beet, potato and ryegrass. GFI values attained from strands CSF, CSV, CPC and CPW (see Table 3).



The potential for pollen and seed-mediated gene flow in potato (GFI = 11) relates to combined tuber and true potato seed (TPS) production. If the model is applied to those counties in Ireland where cultivation relates solely to tuber production, the present GFI value is reduced from 11 to 6. The combined value (GFI = 11) is weighted due to the potential for crop pollen-to-crop gene flow arising from TPS production and demonstrates the "worst-case scenario" approach that has been adopted for the model. Consequently, this GFI value could be considered high for a crop that is largely grown for tuber production, from which potential modes of gene flow would only arise through volunteer (CSV) and feral (CSF) establishment; hence the alternative value, GFI = 6.

Both wheat and barley recorded a low potential for gene flow (Table 3 and Figure 7) because of the zero scores returned through strands CPW and CSF. Such a natural restriction highlights the reduced potential of gene flow that would be associated with the commercialization of GM wheat/GM barley in Ireland. In light of recent research (Van Acker et al., 2003), volunteer management would still be an essential requirement for efficient coexistence and though cereal seed multiplication is low-scale in Ireland, in those areas where it is carried out, additional precautions may be required.

The absence of inter-fertile relatives, coupled with the domestication of maize, limits potential pollen-mediated crop-to-wild gene flow and the establishment of viable ferals from the forage maize crop presently cultivated in Ireland. The propensity for gene flow arising from maize is limited to pollen-mediated crop-to-crop and seed-mediated crop-to-volunteer. Though the likelihood of both/either event occurring is minimal, the manner in which the model has been designed accentuates the fact that either event can occur; hence CSV = 3 and CPC = 6 (Table 3).

4.3 Establishment of www.gmoinfo.ie

A specific objective of this project was the collation of all research findings and relevant literature into an internet resource, that would be freely accessible to the public. This has been achieved through the design and construction of www.gmoinfo.ie. Structured in a non-scientific format to facilitate the visitors understanding of the issues, gmoinfo.ie is composed of 6 primary sections:

- EU legislation explains what organisations are responsible for the regulation of GM crops in Ireland and what legislation is in place to ensure GM crops do not pose a risk.
- Crops section presents 6 crops (barley, wheat, oilseed rape, potato, sugar beet, maize), whose history, distribution, cultivation practices and GM potential are explained.
- GM issues provides three case studies (*Bt* cotton, GM papaya, Monarch Butterfly and *Bt* maize) relevant to the GM debate and contains a section of frequently asked questions.
- Risk assessment is split equally into a description of the economic and environmental research that was conducted during this project.
- Site map provides additional information for the reader. Including research updates and a range of web-based resources for additional information.

5. Conclusions

5.1 Economic assessment

Cultivation of the described GM crops in both 2002 and 2003 would have provided savings for the producer, with a greater benefit recorded in 2002 for sugar beet, wheat, and barley due to the higher chemical inputs (Figures 1, 2, 3, 5 and 6). Based solely on fungicide/herbicide chemical cost and their cost of application, this demonstrates that under typical Irish climactic conditions, specific GM crops have the potential to economically outperform their conventional equivalents where high disease pressure and/or weed proliferation is recurrent.

Our analysis shows that GMHT sugar beet cultivation could be economically beneficial to the Irish farmer in the absence (9.69% saving) or presence (25.29% saving) of increased yield (Figure 6). This concurs with recent reports (May, 2003; PG Economics, 2003) and underlines the potential economic benefit of commercial-scale GMHT sugar beet adoption to the industry (Demont et al., 2004). It is important to note, however, that improved yields associated with current GMHT sugar beet are variable and notably dependent on local agronomic practice, as described in previous research (Mitchell, 2000). Our results indicate that although the economic benefit varies between the crops, certain GM disease-resistant cereals could prove economically valuable to the Irish farmer (Figure 6). Similarly, the cultivation of GMLBR main-crop potato could generate substantial cost savings (4.3%) when present potato production costs are considered (Figures 4 and 6). Note that cost savings for potato remained static over 2002–2003 as a direct result of current management practice where spraying is a preventative rather than a curative measure.

In addition to the provision of a potential economic benefit, it is important to note that the convenience factor associated with GM crop cultivation is significant, affording the producer the opportunity to reduce labor time, which in turn provides greater flexibility in their management practice. Such a system could appeal to Ireland's part-time farmers (34%;(Connolly et al., 2004), who may not benefit directly in terms of profitability but rather in terms of improved labor productivity.

Because no GM crops are currently cultivated in Ireland, the data described here is suggestive rather than conclusive evidence that certain GM crops will provide significant economic benefit to the Irish farmer. As with previous analyses (May, 2003), this report is based on a limited number of published studies and is therefore likely to advance and develop as European data for GM crop cultivation emerges in the near future. Consequently, the assumptions made for this paper may be altered, specifically in regard to the yield and market price of GM products or seed. As increased information becomes available from research trials in the European context, and if and when ex post data become available, the input coefficients used for the economic analysis can be updated.

Overall, the adoption of GM crops at farm level is dependent on the technology providing overall cost savings through a reduced need for pest and disease control (or different methods to do so) and/or the achievement of higher yields (CEC, 2000; Kalaitzandonakes, 2003; Magen & Imas, 2004). This report describes the first analysis of GM cultivation in Ireland. In conclusion, our analysis shows that the potential exists for GM crops to be more profitable for Irish farmers than conventional crops, if seed and coexistence costs are offset by savings in pest or disease control costs and/or by higher yields.

5.2 Environmental assessment

The principal objective of this research was to establish a baseline gene flow data set (that includes four primary modes of gene flow) for Ireland's primary crops through the provision of a simple numerical index. Following on from this, it is intended that the model will complement the assessment of future GM crops due to the availability of a set of reference GFI values against which the potential for gene flow of a particular GM variety/trait could be compared. This is a novel approach that has not been described to date and though the coexistence of GM, conventional and organic crops on Irish farms in the future cannot be ruled out. By investigating the propensity of a crop for gene flow, we foresee that this model could serve as a predictive tool to assist in pre-release risk assessment and post-release monitoring strategies.

Clearly, it is imperative that a distinction be made between the potential for gene flow and the consequence. Ecologically, the consequence of gene flow is wholly dependent upon the physiological impact of the transgene and must be addressed on a case-by-case basis. In contrast, the potential for gene flow is primarily reliant upon the reproductive biology of the crop and this can be addressed by calculating a crop's GFI value. In this research, several crops (oilseed rape, ryegrass and sugar beet) attained a high GFI value. It must not be implied from this result that these crops are not suitable for GM development. Similarly, for the crops that scored low GFI values, this does not imply gene flow will not occur. Rather a high GFI score implies that a specific crop/variety possesses a higher propensity for gene flow and thus requires greater management precautions if successful coexistence is to be attained. Conversely, a low GFI value indicates a crop which should not pose a significant challenge to the implementation of a coexistence strategy. This is evident in the case of sugar beet where a crop system which controls bolters has the capacity to reduce the GFI value from 25 to 6. What is clear from this work and reported previously (Sweet et al., 2004), is that if GM crops are to be cultivated in Ireland, crop management systems must be variety specific and take into account the cultivation of related, adjacent non-GM crops. This latter point specifically relates to the practice of seed multiplication, which from an Irish context is relevant to potato, ryegrass and to a lesser extent wheat and barley.

Logistically, the effectiveness of any coexistence strategy for Ireland will be dependent upon

- the implementation of appropriate isolation distances to minimize the impact of pollen transfer
- sound land management to ensure adequate volunteer and feral control
- the efficient hygiene of farm machinery
- the effective segregation of seed at all stages pre- and post-cultivation.

The described model engages two issues that are central to successful coexistence: pollen transfer and seed dispersal. A crop’s propensity to secure successful field-to-field gene flow through either pollen transfer or seed dispersal is addressed through strand CPC and CSV respectively (Table 2 and 3). Though ancillary, the management of ferals and wild relatives adjacent to the site of cultivation will prove an important coexistence associated task. Hence, a crop’s potential for pollen-mediated gene flow to wild relatives (CPW) and/or the establishment of ferals (CSF) is also examined.

Though coexistence is not a novel concept in the Irish tillage industry (*e.g. s*uccessful segregation of crops for seed certification purposes by the Department of Agriculture and Food), its achievement in regard to GM crops is critical. Post-implementation, the efficacy of any coexistence regime must be monitored through an interdisciplinary program of research that runs in parallel with any GM crop cultivation in Ireland.

Table 3. GFI assessment for wheat, barley, oilseed rape (OSR), maize, sugar beet (S. Beet), potato and ryegrass (grass), using the individual gene flow strands [crop pollen-to-wild (CPW), crop pollen-to-crop (CPC), crop seed-to-volunteer (CSV) and crop seed-to-feral (CSF)] as described in text and Table 2.

CPW	**Propensity for successful pollen-mediated gene flow between the crop and wild relative**							
Code	**Question**	**Wheat**	**Barley**	**OSR**	**Maize**	**S. Beet**	**Potato**	**Grass**
CPW1	Do interfertile wild relatives of this crop exist in Ireland?	0	0	1	0	1	0	1
CPW2	Is there a probability that the crop will flower and produce viable pollen during its cultivation?	---	---	1	---	1	---	1
CPW3	Upon flowering, is 95% of the crop pollen deposited within 1m (1), 10m (2), 50m (3), 100m (4), 250m (5) or 500m (6)?	---	---	3	---	6	---	5
CPW4	If flowering does occur is the wild relative in question rated as an obligate inbreeder (0), a partial inbreeder/outbreeder (1) or an obligate outbreeder (2)?	---	---	1	---	1	---	2
CPW5	If fertilization is achieved by the deposited pollen, will a viable F_1 hybrid individual establish itself?	---	---	1	---	1	---	1
	Total	0	0	7	0	10	0	10

CPC	**Propensity for successful pollen-mediated gene flow between the crop and related commercial varieties**							
Code	**Question**	**Wheat**	**Barley**	**OSR**	**Maize**	**S. Beet**	**Potato**	**Grass**
CPC1	Is there a probability that the crop will flower and produce viable pollen during its cultivation?	1	1	1	1	1	1	1
CPC2	Upon flowering, is 95% of the crop pollen deposited within 1m (1), 10m (2), 50m (3), 100m (4), 250m (5) or 500m (6)?	2	2	3	3	6	2	5
CPC3	If flowering does occur is the receptive crop rated as an obligate inbreeder (0), a partial inbreeder/outbreeder (1) or an obligate outbreeder (2)?	1	1	1	1	1	1	2
CPC4	If fertilization is achieved by the deposited pollen, will a viable F_1 individual establish itself from the hybrid seed in the absence of mechanical/chemical control?	1	1	1	1	1	1	1
	Total	5	5	6	6	9	5	9

CSV	**Propensity for successful seed-mediated gene flow from crop to volunteer**							
Code	**Question**	**Wheat**	**Barley**	**OSR**	**Maize**	**S. Beet**	**Potato**	**Grass**
CSV1	Does the crop produce seed during its cultivation?	1	1	1	1	1	1	1
CSV2	Post-harvest, will the seed survive and germinate within the confines of a managed field?	1	1	1	1	1	1	1
CSV3	Will the volunteer develop into a viable individual?	1	1	1	1	1	1	1
	Total	3	3	3	3	3	3	3

CSF	**Propensity for successful seed-mediated gene flow from commercial crop to feral**							
Code	**Question**	**Wheat**	**Barley**	**OSR**	**Maize**	**S. Beet**	**Potato**	**Grass**
CSF 3	Does the crop produce seed during its cultivation?	1	1	1	1	1	1	1
CSF	Following transfer from the site of cultivation will wayward seed survive and germinate?	1	1	1	1	1	1	1
CSF 3	Will the resulting individuals establish into a viable feral population?	0	0	1	0	1	1	1
	Total	0	0	3	0	3	3	3

6. References

Advisory Committee on Releases to the Environment (2004) Advice on scientific issues concerning the proposed regime for the co-existence of GM and non-GM crops. pp 6. http://www.defra.gov.uk/environment/acre/advice/pdf/acre_advice56.pdf

Alston JM, Hyde J, Marra MC, Mitchell PD (2002) An ex ante analysis of the benefits from the adoption of corn rootworm resistant transgenic corn technology. *AgBioForum* **5**(3): 71-84.

Ammann K, Jacot Y, Al Mazyad RP (2001) Safety of genetically engineered plants: an ecological risk assessment of vertical gene flow. Safety of Genetically Engineered Crops. Ed. R. Custers. Zwijnaarde, Belgium, Flanders Interuniversity, Institute for Biotechnology**:** pp 60-87.

Brants I, Harms H (1998) Herbicide tolerant sugar beet. Proceedings of 61st Congress of the Institut International de Recherches Betteravières, Brussels, Belgium, IIRB, pp 195-204.

Connolly L, Kinsella A, Quinlan G (2004) National Farm Survey 2003. Teagasc, Carlow.

Copeland RB, Dowley LJ, Moore JF (1993) Vulnerability of the Irish potato industry to harmful organisms. Proceedings of the Royal Irish Academy Seminar, Eds. J. A. Kavanagh and P. Brennan.

de Vries AP, Meijden VD, Brandenburg WA (1992) Botanical files - a study of the real chances for spontaneous gene flow from cultivated plants to the wild flora of the Netherlands. *Gorteria* Supplement 1.

Demont M, Tollens E (2004) First impact of biotechnology in the EU: *Bt* maize adoption in Spain. *Annals of Applied Biology* **145**(2): 197-207.

Demont M, Wesseler J, Tollens E (2004) Biodiversity versus transgenic sugar beet: the one euro question. *European Review of Agricultural Economics* **31**(1): 1-18.

Devos Y, Reheul D, de Schrijver A, Cors F, Moens W (2004) Management of herbicide-tolerant oilseed rape in Europe: a case study on minimizing vertical gene flow. *Environmental Biosafety Research* **3**: 135-148.

Dowley LJ, Leonard R, Rice B, Ward S (2001) Low input fungicide programmes for the control of late blight in potatoes. pp 15. http://www.teagasc.ie/research/reports/crops/4312/eopr-4312.htm

Eastham K, Sweet J (2002) Genetically modified organisms (GMOs): The significance of gene flow through pollen transfer. European Environment Agency, *Environmental issue report No. 28.* pp 75.

European Commission (2003) Guidelines for the development of national strategies and best practices to ensure the co-existence of genetically modified crops with conventional and organic farming. http://europa.eu.int/comm/agriculture/publi/reports/coexistence2/index_en.htm

Fernandez-Cornejo J, Daberkow S, McBride WD (2001) Decomposing the size effect on the adoption of innovations: Agrobiotechnology and precision agriculture. *AgBioForum* **4**(2): 124-136. http://www.agbioforum.org.

Flannery M-L, Meade C, Mullins E (2005) Employing a composite gene-flow index to numerically quantify a crop's potential for gene flow: an Irish perspective. *Environmental Biosafety Research* **4**(1): 29-43.

Flannery M-L, Thorne F, Kelly P, Mullins E (2005) An economic cost-benefit analysis of GM crop cultivation: an Irish case study. *AgBioforum - The Journal of Agrobiotechnology Management and Economics* **7**(4): 1.
Gianessi LP, Sankula S, Reigner N (2003) Plant Biotechnology: Potential Impact for Improving Pest Management in European Agriculture. A summary of three case studies. pp 1-9
Gianessi LP, Sankula S, Reigner N (2003) Plant Biotechnology: Potential Impact for Improving Pest Management in European Agriculture. Potato case study. pp 22. http://www.ncfap.org/
Hauser TP, Bjorn GK, Magnussen L, Shim SI (2003a) Hybrids between cultivated and wild carrots: a life history. ESF AIGM: Introgression from genetically modified plants into wild relatives and its consequences, Eds. H. C. M. den Nijs, D. Bartsch and J. Sweet. Amsterdam, Holland, January, 2003.
Hauser TP, Damgaard C, Jorgensen RB (2003) Frequency-dependent fitness of hybrids between oilseed rape (*Brassica napus*) and weedy *B. rapa* (Brassicaceae). *American Journal of Botany* **90**(4): 571-578.
James C (2004) Global status of commercial biotech/GM crops. pp 12. http://www.isaaa.org/kc/CBTNews/press_release/briefs32/ESummary/Executive%20Summary%20(English).pdf
Kniss AR, Wilson RG, Martin AR, Burgener PA, Feuz DM (2004) Economic evaluation of glyphosate-resistant and conventional sugar beet. *Weed Technology* **18**: 388-396.
May M (2000) Efficiency and selectivity of RR and LL weed control techniques compared to classical weed control systems. Proceedings of 63rd Congress of the Institut International de Recherches Betteravières. IIRB, Interlaken, Switzerland, pp 163-170.
May MJ (2003) Economic consequences for UK farmers of growing GM herbicide tolerant sugar beet. *Annals of Applied Biology* **142**: 41-48.
McCabe T (2004) New challenges for triazoles. *Irish Farmers Journal - Crop Protection*: 27-28.
Meade C, Mullins E (2005) GM crop cultivation in Ireland: Ecological and Economic considerations. *Proceedings of the Royal Irish Academy: Biology and Environment* **105B**(1): 33-52.
Mitchell B (2000) Weed control in glyphosate tolerant sugar beet. End of Project Report (EOPR) 4483. http://www.teagasc.ie/research/reports/index.htm
Mitchell BJ (2003) Control of weeds in glyphosate-tolerant sugar beet crops (*Beta vulgaris*). *Irish Journal of Agricultural & Food Research* **42**(2): 265-274.
Moll S (1997) Commercial experience and benefits from glyphosate tolerant crops. Proceedings of the BCPC Conference Weeds: 3, pp 931-940.
O' Mahony J (2002) Teagasc Crop Costs and Returns. pp 8
O' Mahony J (2003) Teagasc Crop Costs and Returns. pp 8
O'Sullivan E (2004) Cereal diseases and fungicide resistance. National Tillage Conference, Carlow, 28th January 2004.
PG Economics (2003) Consultancy support for the analysis of the impact of GM crops on UK farm profitability. pp 181 http://www.pgeconomics.co.uk/consultancy_support_gm_crops.htm
Preston CD, Pearman DA, Dines TD (2002) New Atlas of the British and Irish Flora. Oxford, Oxford University Press.
Programme (2003) The UNEP-GEF project on the implementation of the national biosafety framework of Bulgaria. Division of Global Environment Facility

Coordination, United Nations Environment Programme http://www.unep.ch/biosafety/Implementation/countries/Bulgariaoperationalreport%202003_12final.pdf

Richard-Molard M (2001) A first approach to an analysis of the benefits of using glyphosate-tolerant sugar beet. *Cited in: Gianessi, L., Silvers, C. S., Sankula, S. and Carpenter, J. E. (2002) Plant biotechnology current and potential impact for improving pest management in US Agriculture: An analysis of 40 case studies. National Centre for Food and Agricultural Policy, Washington, US pp75*

Sweet J, Simpson E, Law JR, Lutman P, Berry K, Payne R, Champion G, May M, Walker K, Wightman P, Lainsbury M (2004) Botanical and rotational implications of genetically modified herbicide tolerance in winter oilseed rape and sugar beet (BRIGHT Project). *HGCA Project Report*: pp 265. http://www.hgca.com/cms_publications.output/2/2/Publications/Publication/Botanical%20and%20rotational%20implications%20of%20genetically%20modified%20herbicide%20tolerance%20in%20winter%20oilseed%20rape%20and%20sugar%20beet%20(BRIGHT%20Project).mspx?fn=show&pubcon=1805

Teagasc (2002) Farm Management Data Handbook. pp 245

Teagasc (2003) Farm Management Data Handbook. pp 247

Tenning P (1998) Transgenic herbicide tolerant sugar beet – Present status and future developments. *Aspects of Applied Biology* **52**: 273–278

Tolstrup K, Andersen SB, Boelt B, Buus M, Gylling M, Holm PB, Kjellsson G, Pedersen S, Ostergard H, Mikkelsen SA (2003) Report from the Danish Working Group on the Co-existence of genetically modified crops with conventional and organic crops. *DIAS Report Plant Production No. 94*: pp 275

Van Acker RC, Brûlé-Babel AL, Friesen LF, Entz MH (2003) GM/non-GM wheat co-existence in Canada: Roundup Ready® wheat as a case study. Proceedings of the First European Conference on Co-existence of Genetically Modified Crops with Conventional and Organic Crops, Ed. B. Boelt. Helsingør, Denmark, 13th-14th November.

Webb DA, Parnell JAN, Doogue D (1996) An Irish Flora. Dundalk, Dún Dealgan Press.

Wevers JDA (1998) The environmental contamination of weed control in transgenic herbicide resistant sugar beet. Proceedings of 61st Congress of the Institut International de Recherches Betteravières, IIRB, Brussels, Belgium, pp 365-368.

Wevers JDA (1998) Agronomic and environmental aspects of herbicide resistant sugar beet in the Netherlands. *Aspects of Applied Biology* **52**: 393-399.

Wilkinson MJ, Sweet J, Poppy GM (2003) Risk assessment of GM plants: avoiding gridlock? *Trends in Plant Science* **8**(5): 208-212.