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GM CROP CULTIVATION IN IRELAND: ECOLOGICAL AND ECONOMIC CONSIDERATIONS

Conor V. Meade and Ewen D. Mullins

ABSTRACT

Like many states in the European Union, Ireland has yet to fully commit itself to genetically modified (GM) crop technology. The general position of the Irish Government is 'positive but precautionary'. However, with the European-wide de-facto moratorium on commercial production of GM crops now ended, many strategically important decisions regarding the commercial deployment of such crops and their co-existence with conventional/organic crops need to be considered. To date, little research on the environmental impact of GM crops has been carried out in Ireland, and the provision of relevant local information lags far behind that available in other countries in the European Union. In this paper, we discuss much of the new ecological and economic data that have emerged since the moratorium on GM crops was introduced in 1998, assess the likely impacts of pest-oriented GM crops should they be introduced to Ireland and examine criteria for post-release monitoring. We also describe the likely commercial demand for these crops and the consequent priorities for ecological research. We argue that the impact of GM technology needs to be assessed in relation to the environmental impact of modern agriculture as a whole. Public unease in relation to this technology may be addressed if adequate resources are made available for independent Irish research on the issue.

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INTRODUCTION

In light of the resurgence in the debate surrounding genetically modified (GM) crops, it is critical that the Irish public can access unbiased information on GM crop issues that has been produced through impartial research. To date, a minimal amount of Irish research has been undertaken to evaluate the risk/benefit of GM crop cultivation, and nationally the research effort is far behind that of other European Union (EU) states. To rectify this, several joint research programmes have been established—by the National University of Ireland, Maynooth, Trinity College Dublin and the Teagasc Crop Research Centre, Oak Park, Carlow—investigating gene flow between crops and their wild relatives. These projects focus on: (i) oilseed and wild rape (*Brassica napus/B. rapa*) (Flannery *et al.* 2004; Cloney *et al.* 2003); (ii) Italian and perennial ryegrass (*Lolium multiflorum/L. perenne*) (Meade *et al.* 2004); and (iii) cultivated and wild oats (*Avena sativa/A. fatua*) (Meade *et al.* 2004). As a prelude to formal publication of these new research findings, this paper has been compiled to provide an insight into the possible outcomes society could expect if GM crops were to be incorporated into Irish cropping systems. The paper is composed of two sections: the first deals with ecological impacts of GM crops, and the second outlines the economic factors of GM crop cultivation, including an assessment of input costs within Irish crop systems. For reasons of practicality, it has been assumed in this latter discussion that in the coming years GM crops will be grown commercially in Ireland.

The worldwide acreage of GM plants has increased steadily since the first commercial plantings in 1995–96. The growth in the acreage devoted to such plants represents a 35-fold increase, and no other crop technology has achieved such a rapid rate of adoption (James 2002b). The principal GM crops, which are cultivated primarily in the US (39 million ha., 66% of the world total), Argentina (13.5 million ha., 23%), Canada (3.5 million ha., 6%) and China (2.1 million ha., 4%), include soybean, maize, cotton and oilseed rape. The dominant traits for these crops are herbicide tolerance and insect resistance (James 2002b). Worldwide investment in new transgenic crops continues to grow, and in the medium to longer term it is anticipated that a diverse range of crops targeted at pest control, salt and drought tolerance, improved nutrition and food quality, environmental amelioration and the production of biopharmaceuticals and primary industrial materials will be commercially available to Irish farmers (McGloughlin and Burke 2000).

Like much of Europe, Ireland has yet to formally commit itself to this new agricultural technology. No commercial licences for GM crops are currently on issue from the Environmental Protection Agency, which is the competent authority for the control and monitoring of genetically modified organisms (GMOs) in Ireland (T. McLaughlin, pers. comm.). Ireland is, however, engaged in a much wider review of how agriculture can and should develop from this point forward, particularly in relation to farm subsidies, food and animal health standards and the need to manage the rural environment in a sustainable manner (Department of Agriculture, Food and Rural Development 2000). In this context, although the unofficial position in relation to the use of GM technology is 'positive but precautionary', many strategically important decisions still have to be made regarding research and development and the commercial deployment of novel GM crops (Inter-Departmental Group on Modern Biotechnology 2000). We aim in this paper to (i) provide a composite picture of the probable impacts of licensed GM crops, that is, crops that have been proven to have no extraordinary negative ecological or food chain impacts, to (ii) consider how GM crops might be monitored post-release and to (iii) discuss scenarios where cultivation is either not advisable, for environmental reasons, or not likely, for environmental and/or economic reasons. We touch only briefly on the question of co-existence of GM, conventional and organic crops, as this issue is to be addressed in detail in an upcoming report from the Department of Agriculture and Food.

ARABLE AGRICULTURE IN IRELAND

The potential impact of GM crops should be evaluated in relation to the current status of Irish agriculture, and in particular the relatively small size of the arable sector. Ireland is unique in Europe in that agriculture is overwhelmingly grassland oriented, with some 91% of cultivated land given over to pasture, meadow and silage (CSO 2002). Of the remaining 9%, 6.75% is made up of cereals and maize, with less than 2% dedicated to fruit, vegetable and root crops (Table 1). Arable croplands are restricted in distribution, forming a significant minority of farmlands only in east Munster and south and east Leinster. Chemical inputs are a major feature of crop production and include herbicides; pesticides to protect against viral, fungal and insect pests; fertilisers and associated co-factors. Total pesticide inputs in Irish agriculture in the year 2000 amounted to 2325 tonnes, including 73 tonnes of insecticide, 679 tonnes of fungicide, 1261 tonnes of herbicide and 312 tonnes of other associated compounds (OECD 2002). The vast majority of these inputs were used in arable crop production. Overall, there has been a 28% increase in pesticide usage since 1980, and the intensity of the application of pesticides on Irish arable farmland is now above the average for the OECD as a whole (OECD 2002). While the increased usage of arable pesticides will have had a local impact on non-agricultural species, it has not resulted in large-scale contamination of freshwaters. Eutrophication caused by nutrient runoff continues to be the principal source of freshwater pollution in Ireland (EPA 2004).

Although arable fields are restricted in distribution, they form an important ecological element in the Irish landscape and support a wide range of animal and plant species (Webb *et al*. 1996; Taylor and O'Halloran 2002). However, changing agricultural practice, including intensification, the switch from spring to winter crops and a loss of marginal hedgerows, as well as an overall decline in the area under cultivation over the past three decades has caused a dramatic decrease in many species dependent on arable practices (Curtis and McGough 1988; Taylor and O'Halloran 2002). In discussing the possible introduction of GM crops in Ireland, it is important to recognise both the underlying trend towards intensification in arable farming and the occlusion of wild and semi-wild species that occurs as a result of this process.

THE AGROECOLOGY OF GM CROPS

Much new data about the ecological impacts of GM crops have emerged since Ireland and the EU introduced a *de facto* moratorium on GM crop cultivation at the end of the 1990s, largely in response to widespread public unease about the potential harm of the technology (Department of the Environment 1998; O'Donnell *et al*. 1999). Perhaps the most acute environmental concern is in relation to gene flow, that is, the transfer of genes from GM crops to non-GM crops and their wild relatives (WRs). Irish farmers cultivate a variety of indigenous and non-indigenous crops, which may or may not have an interfertile WR growing on the island (Table 1). Wheat, potatoes, peas, runner beans and maize are all crops without interfertile WRs in Ireland; however, ryegrass, clover, sugar beet, oats, carrots, oilseed rape and apples are all either native or interfertile with other wild natives. Clearly this raises the possibility that commercial GM crops will interbreed with close relatives already growing in Ireland. Conventional crops in non-GM farms may also exchange genes with adjacent interfertile GM crops, raising the possibility of cross-contamination. So, how might we estimate the level of gene flow that is likely to take place with these crops, and what do we know about background levels of gene flow in agroecological systems?

Crop-to-WR gene flow has always been a feature of crop agroecology, particularly in centres of origin where cultivated varieties and their interfertile WRs grow side by side (De Candolle 1886; Anderson 1949; Barrett 1983; Hancock 1992; Harlan 1992; Ellstrand *et al.* 1999). This flow of DNA from crops to WRs impacts on the genetic identity and integrity of WR populations, and it may cause both the evolution of weediness

Table 1—Irish crops: cultivation area, wild relatives and availability of GM varieties, 2002.

	Area grown 2000 [× 1000 hectares][1,2]	*Change 1985–2000 [× 1000 hectares]*[3]	*Interfertile wild relatives in Ireland*	*Commercial GM varieties available*	*% GM worldwide*[4]
Root/seed crops					
Barley *Hordeum vulgare* L.	182.31	−91.00	—	—	
Wheat *Triticum aestivum* L.	77.96	−9.60	—	—	
Sugar beet *Beta vulgaris* L.	32.20	−0.10	+	+	
Arable silage (mixed species)	24.43	n/a	—	—	
Oats *Avena sativa* L.	16.82	−4.70	+	—	
Maize *Zea mays* L.	13.98	+13.98	—	+	**18**
Potato *Solanum tuberosum* L.	13.53	−18.57	—	+	
Fodder beet *Beta vulgaris* L.	5.14	+1.30	+	+	
Oilseed rape *Brassica napus* L.	2.68	−2.10	+	+	**5**
Cabbage group *B. oleracea* L.	2.43	−1.27	+	—	
Beans *Phaseolus vulgaris* L.	1.50	n/a	—	—	
Fodder rape/kale *B. napus* L.	0.95	n/a	+	+	**5**
Carrot *Daucus carota* L.	0.64	n/a	+	—	
Turnip *Brassica rapa/napus*	0.56	n/a	+	+	**5**
Parsnip *Pastinaca sativa* L	0.27	n/a	+	—	
Lettuce *Lactuca sativa* L.	0.17	n/a	—	—	
Organic field crops	0.18	n/a	—	—	
Fruit					
Apples *Malus domestica* Borkh.	0.70	n/a	+	—	
Strawberry and other fruit	0.52	n/a	+/−	+	
Indoor crops					
Mushroom *Agaricus* spp	***	n/a	+	—	
Lettuce *Lactuca sativa* L	0.10	n/a	—	—	
Tomato *Lycopersicon*	0.03	n/a	—	+	
Mixed fruit	0.08	n/a	+/−	+	
Grassland					
Perennial ryegrass *Lolium perenne* L.			+	–	
Italian ryegrass L. *multiflorum* Lam.			+	–	
Clover *Trifolium repens* L.			+	–	
Pasture (including on rotation)	2,218.14	−30.86			
Silage (including on rotation)	1,074.69	+309.00			
Hay meadow (including on rotation)	242.60	−144.00			
Rough grazing	506.50	−134.50			

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[1] CSO Census of Agriculture 2002.

[2] Industry Profile: Horticulture. An Bord Glas 2001.

[3] Department of Agriculture and Food 2002.

[4] James 2002b.

and the erosion of local genetic diversity (Ellstrand and Elam 1993). For example, in ten of the world's thirteen most important crops, including wheat, barley and maize, there is substantial evidence for hybridisation between cultivated lines and WRs. Crop/WR hybridisation has been implicated in the evolution of weediness in seven of these cases; while in two crops such hybridisation has engendered an extinction risk for wild relatives (Ellstrand *et al*. 1999).

The evolution of weediness and the extinction of WR populations through introgressive hybridisation are strongly associated with a disproportionately high pollen and seed rain from cultivated crops (Ellstrand and Elam 1993; Rhymer and Simberloff 1996). However, even at very low levels gene flow is capable of counteracting ambient patterns of genetic change within populations (Slatkin 1987). The cultivation of GM crops in Ireland raises the possibility that transgenes will also be readily incorporated into WR populations, with consequences similar to or perhaps more unpredictable than those observed with conventional crops (Fig. 1) (Hancock *et al*. 1996; Rissler and Mellon 1996; Ellstrand *et al*. 1999; Hails 2000).

To date, GM/WR hybrids have been rarely recorded, most probably because the three most important GM crops—maize, soya and cotton—have generally not been grown either sympatrically with interfertile WRs or near their centres of origin; that is, they are grown outside Central America, East Asia and South Asia, respectively (James 2002). How long this situation will continue is unknown: transgenic DNA elements appear to have been identified in native Mexican maize crops, suggesting the illicit use of outbreeding GM lines smuggled from the US (Quist and Chapela 2001); and transgenic cotton is currently undergoing trials in India (James 2002). Significantly, investigations of oilseed rape crops that are grown sympatrically with WR populations reveal gene flow and hybridisation patterns similar to those observed for conventional crops (Norris 2003; Warwick *et al*. 2003).

Hybridisation is dependent on pollen migration from the GM crop, and several strategies are being investigated to try and suppress and/or eliminate this pollen movement. The most common approach is to use either reproductive isolation (reducing the possibility of pollen movement by transforming naturally inbreeding or male-sterile crop lines) or physical isolation (using crop barriers and/or applying crop isolation distances) (Waines and Hegde 2003). Recommended isolation distances vary according to the pollination mechanism of the crop concerned, the size of crop plots and prevailing wind/insect migration patterns.

Predominantly inbreeding Irish crops such as wheat, barley and potato require small isolation distances, usually under 20m, to ensure that less than 0.5% of pollen reaches prospective hybrid partners. Conversely, outbreeding crops such as maize, oilseed rape and sugar beet require between 100m and 300m isolation to reduce pollen flow to similarly low levels (Eastham and Sweet 2002). In this latter group, the motility of the pollen vector (wind speed or insect migration) and the size and shape of the crop area can have a major influence on the amount of pollen that moves beyond the recommended isolation distance, thereby causing significant variation in margin-of-error estimates (Eastham and Sweet 2002). Consequently, the greater the duration and/or extent of cultivation of these crops in Ireland, the greater the chance that pollen will routinely spread beyond the recommended isolation distance. Given this probability, novel isolation strategies such as induced male sterility are being investigated to prevent transgene movement altogether, by preventing pollen formation in the flower (Rosellini *et al*. 2001). An alternative isolation method using chloroplast-only transformation—chloroplasts are typically inherited maternally so are not present in pollen (Daniell *et al*. 2002)—is theoretically less reliable, as repeated backcrossing between feral progeny and adjacent wild relatives leads to incorporation of the chloroplast into this population (Fig. 1 (A)).

TRANSGENES IN THE WILD

The viability in the wild of crop/WR hybrids largely determines the extent, duration and intensity of their ecological impact (Linder and Schmitt 1994; Hauser *et al*. 1998; Ellstrand *et al*. 1999), although there are also many additional stochastic factors that may influence the ultimate survivorship of any given progeny (Carson and Templeton 1984; Arnold 1992; Rieseberg *et al*. 1995; Ellstrand *et al*. 1996). Similarly, in order for a given transgene to become properly established in wild Irish populations in the manner of normal gene alleles, second and subsequent generation GM/WR hybrid progeny would need to be fit and competitive; and if transgenes are to spread more rapidly than normal, it is understood that they must also be advantageous (Fig. 1 (B)). Initial research suggests that while one or more of these criteria may be satisfied at any one time in a crop/WR hybrid zone, the simultaneous satisfaction of them all may be quite rare (Wolfenbarger and Phifer 2000), particularly when the stability of transgenes in hybrid genomes is factored into the equation.

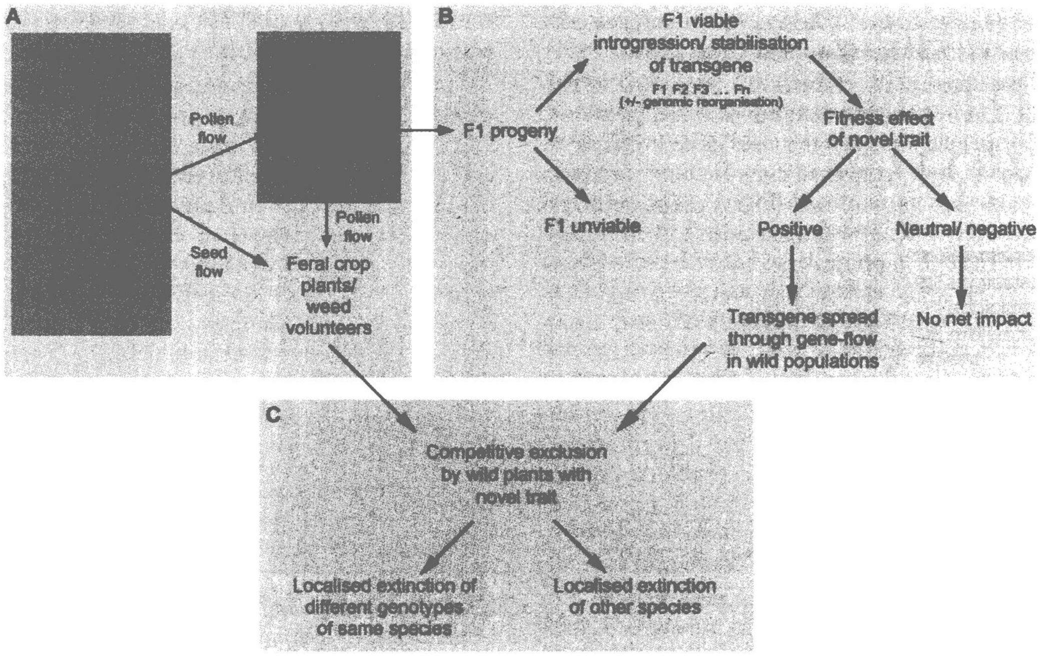

Fig. 1 — Transgene movement from GM crops: (A) Pollen and seed flow patterns between cultivated crops, feral crops and wild populations; (B) Introgression of transgenes and novel traits into wild plants; (C) Ecological effects of the spread of plants containing novel trait.

But how frequent is this 'rare' confluence of factors, and how significant might it be? Investigations by Allison Snow and colleagues at Ohio State University in the US, into the ecology of GM *Helianthus* (sunflower) containing insecticidal genes from *Bacillus thuringiensis* (Bt) revealed that flowers of transgenic lines that were resistant to lepidopteran damage produced a proportionally greater amount of seed than did non-Bt lines (Dalton 2002; Snow *et al*. 2003). As cultivated and wild sunflowers can freely interbreed, biological theory would predict that if increased fecundity is maintained in F_{2+} and back-cross generations with wild plants, a dramatic increase in the lambda value (or finite rate of increase) of the Bt crop/WR progeny would be observed, thereby allowing it to out breed and to out compete non-Bt wild relatives (Fig. 1(B), (C)).

However, more prolonged studies into oilseed rape have revealed the impact of transgenes to be less clearcut. Field hybrids between various GM *B. napus* lines and *B. rapa* have been found to be viable and show consistent but reduced levels of transgene expression compared to the GM cultivar (Snow *et al*. 1999; Halfhill *et al*. 2001; 2002). In the case of hybrids between Bt *B. napus* and *B. rapa*, transgene expression is significantly reduced in back-cross hybrids produced in the field, with second generation back-cross plants proving to be less competitive than wild *B. rapa* when grown on wheat fields (Stewart *et al*. 2003). Analysis of back-cross progeny using molecular markers identified a lower than expected incidence of *B. napus* germplasm, suggesting that the genetic load (or reduced fitness) associated with conventionally bred crop genes as a whole makes most hybrids less fit in the wild (Stewart *et al*. 2003). This lowered fitness results in a thinning of the hybrid progeny from the wild metapopulation (Fig. 1 (B)) and in the long run is predicted to reduce the probability of large-scale introgression of the Bt gene (Adam 2003).

Long-term stability of transgenes is also a significant factor in determining the impact of crop/WR hybridisation. Many studies show that transgenes have pleiotropic effects that have an impact far beyond the targeted cellular and metabolic pathways (Almon *et al*. 1997; Thiele *et al*. 1999; Saxena and Stotzky 2001(a)) and these effects may, over time, influence GM/WR hybrid fitness in unpredictable ways, including through reduced seed production (Purrington and Bergelson 1997), increased rates of outcrossing (Bergelson *et al*. 1998) or having no effect other than enhanced fitness in the presence of the target pathogen (Saeglitz *et al*. 2000).

A recent development in the area of patent control, which has potential uses in controlling transgene expression in WR hybrids, is the use of chemical-inducible promoters. Novel promoter mechanisms can be engineered so that specific chemicals must be applied to the GM plant either before transgene expression can begin or for so long as it is required — thereby preventing wild or feral

GM hybrids from utilising the transgene for ecological advantage (Zou and Chua 2000).

The emerging picture of transgene introgression into wild populations is a complex one, involving many factors that are closely linked to life-history and ecological traits in both the crop and wild plant populations (Fig. 1). The principal research question in relation to gene flow from GM to interfertile WR populations has thus shifted from whether or not gene flow will take place in pollen-producing or pollen-accepting GM crop lines (evidence suggests that it will), to whether or not transgenes will influence WR fitness and spread in wild populations.

DIRECT AND INDIRECT ECOLOGICAL EFFECTS OF TRANSGENE ACTIVITY

The most immediate ecological impacts of GM crop cultivation in Ireland are likely to be the direct effects of transgene expression on farmland ecosystems (Fig. 2). These effects impact primarily on the pest organisms targeted by individual transgenes, including weed plants targeted by genes modified for herbicide tolerance. However, there are many potential secondary or indirect effects that can arise from the deployment of GM crops. These effects could materialise either as a result of successful control of the target pest population, whereby dependent herbivores, predators, pathogens and parasitoids come under indirect pressure due to a diminished food source, or they may arise directly from the impact of the GM crops on non-target organisms (Rissler and Mellon 1996; Groot and Dicke 2002).

In herbicide-tolerant crop systems, the impacts on non-target organisms are expected to result from successful control of weed populations. This expectation is borne out in the findings from large-scale crop trials (Farm Scale Evaluations) in Britain for GM herbicide-tolerant (HT) maize, oilseed rape and sugar beet. In relation to the latter two crops, a decrease in aerial and ground-living invertebrate populations was recorded compared to conventional controls, with these changes being attributed to a reduction in weed populations in the study fields and field margins (Brooks *et al.* 2003; Hawes *et al.* 2003; Haughton *et al.* 2003; Roy *et al.* 2003). Population levels in parasitoids were positively correlated with the reductions (and increases) in host insect groups; however, detritivorous springtails (*Collembola*) increased in all the GMHT fields due to a greater availability of decaying plant matter. Overall, an altered abundance of food sources was the significant factor in these changes; there were only minor, though unmeasured, impacts associated with the type of herbicide spray used in the trials (Hawes *et al.* 2003).

In the case of transgenic crops producing specific anti-pest/pathogen compounds, the direct and indirect effects on Irish ecosystems would be complex. Indirect multitrophic effects of toxic compounds are not unique to GM crops and are widely documented in the ecological literature, suggesting a dynamic utilisation of these compounds by both competing and co-operating organisms. For example, many plant allelochemicals/secondary metabolites are toxic to invertebrate herbivores and actively deter feeding, which results in reduced vigour and a significantly reduced level of survivorship in dependent parisitoids and entomogenous nematodes (Barbercheck 1993; Brooks 1993; Epsky and Capinera 1994).

In certain plant families the production of these toxic allelochemicals is endogenous, e.g. cucurbitacin in the Cucurbitaceae (Barbercheck *et al.* 1995) and nicotine in the Solanaceae (Barbosa *et al.* 1986); however, in other groups they are produced by symbionts rather than by the principal host, e.g. the alkaloids produced by endophytic *Acremonium* spp in *Festuca* grasses (Grewal *et al.* 1995). Invertebrate herbivores can in turn utilise allelochemicals for their own defence, as is the case with the North American Monarch butterfly (*Danaus plexippis*), which feeds on milkweed (*Asclepias curassavica*) and ingests and sequesters cardiac glycosides, which subsequently provide an effective defence against preying blue jays (*Cyanocitta cristana bromia*) (Riechstein *et al.* 1968; Roeske *et al.* 1976).

In the context of GM Bt crops, infection of susceptible insect larvae by free living *Bacillus thuringiensis* has been shown in many studies to significantly reduce the survival of insect-dependent parasitoids and parasites. However, as the majority of evidence suggests that Bt toxins are highly target-specific (e.g. against the herbivorous Lepidoptera), the most likely cause of increased mortality in dependent parasites is a diminished food supply (see Brooks 1993). For example, recent investigations of anti-lepidopteran *Cry* proteins produced by GM Bt crops found no direct toxic effect on a range of other organisms, including flies, bees, beetles (for *Cry1A(c)*—Sims 1995), and earthworms, nematodes, protozoa, bacteria and fungi (for *Cry1A(b)*—Saxena and Stotzky, 2001b).

Insect-resistant GM crops are most likely to directly affect non-target organisms in Irish ecosystems where it is not possible to distinguish between pest and non-pest species, either because the transgenic trait has broad-spectrum activity or because susceptible target and non-target species frequent the same ecological spaces. Broad-

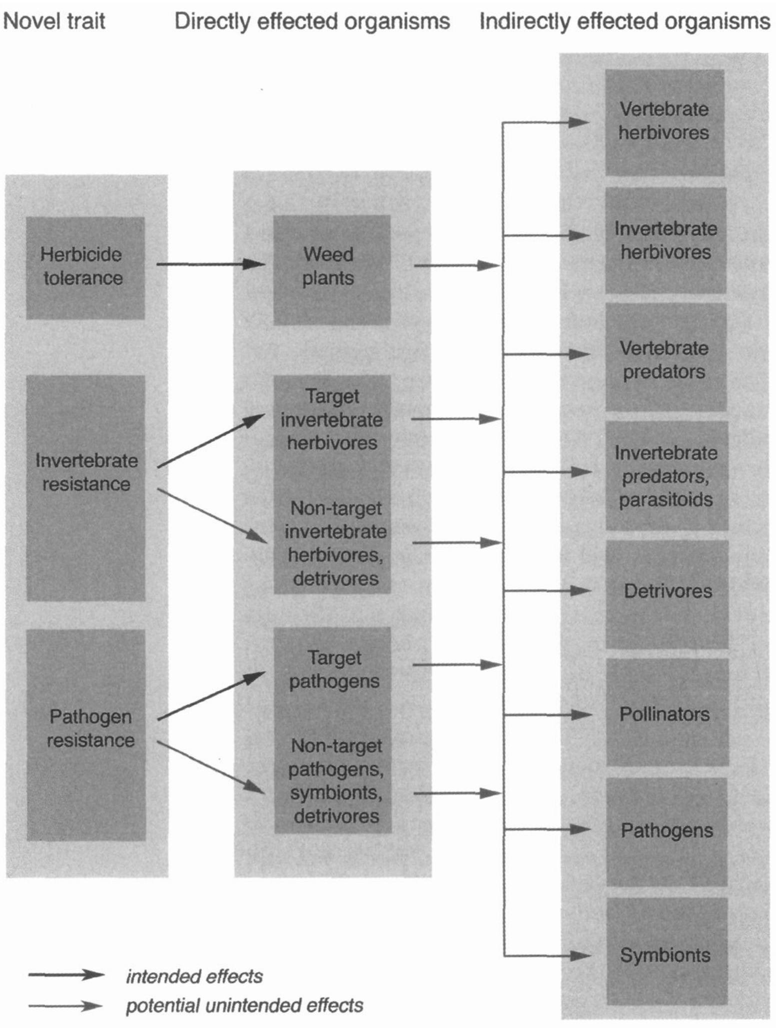

Fig. 2—Direct and potential indirect effects of transgene activity on organisms within agro-ecosystems.

spectrum activity is relatively easy to describe in this context. For example, when honeybees are fed pollen food containing the lepidopteran-specific *Cry1B(a) Bt* or a general insect trypsin inhibitor (both of which can be used to target herbivores), only the latter has any effect on the health and behaviour of the non-herbivore bees (Malone *et al*. 2001). Equally, non-target (e.g. other than caterpillar) toxicity might also be expected from GM crops producing *CryIIA Bt* protein as a defence against Lepidopteran pests for example, because this protein is also toxic to Dipteran species (Sims 1997).

The effects of ecological proximity are more difficult to establish. For example, Bt maize is highly effective against the European corn-borer; however, because the gene coding for the *Cry1A(b)* protein is universally expressed, and is found in pollen, it has been shown to be potentially toxic to Monarch butterflies that frequent the immediate habitat where the protein is present, in this case maize fields (Losey *et al*. 1999). However, Sears *et al*. (2001) demonstrated that such a high level of toxicity was highly unlikely in the field, and even when present was only linked to one GM line (*Event 176*) that was rapidly diminishing in usage.

Bt toxins can also be released into the rhizosphere, either through root exudates (Saxena *et al*. 1999) or following the death and decay of Bt GM plants (Palm *et al*. 1996). Many non-target insects such as Collembola and Carabidae can thus become exposed over long periods of time, particularly given that *Cry*-proteins have been shown to remain toxic for up to 234 days after release from living cells (Tapp and Stotzky 1998). However, despite such persistence and availability, non-target toxic effects have yet to be demonstrated for Bt proteins that diffuse into the rhizosphere (Saxena and Stotzky 2001b).

Interestingly, potatoes engineered with nematode resistance have shown slightly different effects in the rhizosphere (Cowgill *et al*. 2002). Although cultivation of the transgenic plants was found to have no effect on the numbers of micro arthropods, free-living nematodes or the rate of nutrient cycling in the soil, a suppression of bacterial and fungal activity was recorded, suggesting that longer-term impacts may need to be assessed.

Large-scale deployment of GM crops in Ireland has the potential to increase selective pressure in favour of resistance in pest populations, as has occurred in response to the wide use of chemical pesticides. This would pose a particular concern for organic and other farmers who are reliant on Bt as a conventional insecticidal spray (Scriber 2001; Shelton *et al*. 2002). However, initial data from studies in the United States on the impact of Bt cotton on Bt resistance in the pink bollworm revealed that a reduction in the pest population size as a result of Bt cotton cultivation did not result in a rapid increase in the bollworm's natural resistance to Bt (Tabashnik *et al*. 2000). These data also suggest that effective management of pest populations and their resistance can be achieved through careful spatial planning of Bt crop deployment, ultimately reducing the need for additional, less effective, insecticides (Carrière *et al*. 2001; 2003).

If GM crops are commercially grown in Ireland they will be deployed into pre-existing agroecological environments, and the direct and indirect ecological effects will be broadly similar to those resulting from conventional chemical spraying, albeit through the targeting of different metabolic pathways in individual pests. However, there are significant differences between the two regimes. The most important of these relates to the fact that GM crops are intended to facilitate a more targeted dose of pesticide than are conventional chemical treatments, with a consequent reduction in both the number and diversity of organisms affected *in-situ* and in the extent of run-off/groundwater contamination *ex-situ* (Chrispeels and Sadova 1994; Conner *et al*. 2003). For GMHT crops, however, it has been demonstrated in various farm scale evaluations in Britain that it is the spraying management regime rather than the GM crop trait *per se* that is critical in determining *in-situ* and *ex-situ* effects (Dewar *et al*. 2003; Hawes *et al*. 2003), and so generalising about these intended outcomes is fraught with difficulty.

Certainly farmers in the US have been able to significantly reduce the level of pesticide applications for GM Bt maize, soya and cotton when compared to conventional crops (James 2002b; Pray *et al*. 2002). In parallel, certain Irish and European trials of GMHT sugar beet have demonstrated that the GM crop required a lower absolute level of herbicide per hectare compared to a conventional control, and the active herbicide (glyphosate) used in these cases degraded more rapidly than did constituent chemicals in conventional sprays (Wevers 1997, 1998; Mitchell 2000; Wilson *et al*. 2002). The increased efficacy of glyphosate also facilitates delayed spraying on the gap lines between drills, resulting in higher weed and arthropod biodiversity in crop fields than is the case with conventional spraying regimes, with no apparent effect on sugar-beet yield and quality (Dewar *et al*. 2003). Conversely, Benbrook (2001) has reported a marginal increase in the quantity of herbicide applied to GMHT soybean crops in the US compared to conventional crops, albeit with a reduction in the variety of active ingredients applied.

Collectively, these data indicate that environmental benefits could be achieved in Ireland through the use of certain GM crops under certain conditions, particularly in relation to making farm management more flexible and responsive. However, not all GM crops offer these benefits—chemical inputs have increased in some cases. Certain GM crops have also shown transgene-specific negative ecological impacts, such as Bt sunflower, which has the potential to generate ecologically fit GM hybrids in the wild, and *Event 176* Bt maize, which is potentially harmful to non-target Lepidoptera in the field. Therefore, generalisations about the ecological impact of pest-oriented GM crops in Ireland being wholly positive or wholly negative are not sustainable. It is the trait rather than the breeding technology that is of importance. However, as with conventional crops, local and regional management regimes are the major influence on direct and indirect ecological impacts. It is only localised, case-by-case testing that will reveal the true environmental impact of a particular GM crop.

CRITERIA FOR ASSESSING ECOLOGICAL IMPACTS OF GM CROPS IN IRELAND

The deliberate release of GM organisms into the Irish environment is covered by European Directive 2001/18/EC (transposed into Irish law as Statutory Instrument no. 500 of 2003). Under this Standard Instrument, environmental risk assessment prior to deliberate release must consider 'the potential risks, whether direct or indirect, arising from the transfer of one or more genes from a GMO to another organism, the nature of the organism to be released and the receiving environment'. It is assumed that these considerations will be satisfactorily addressed for every commercial GM crop entering the Irish market; however, it is already clear that this may not be enough to allay public concerns over the release of GM organisms (Department of the Environment 1998; O'Donnell *et al*. 1999).

A second provision under Directive 2001/18/EC is for post-release monitoring, whereby GMO licence applicants are obliged to identify any direct or indirect, immediate and/or delayed adverse effects of GMOs, their products and their management that may arise post-release. This kind of post-release monitoring may address many of the concerns of stakeholders in Ireland, including consumers, farmers, the tourism industry, environmental groups and state bodies. However, such monitoring is likely to gain public confidence only where it is carried out by an independent body (O'Donnell *et al*. 1999).

Considering the range of ecological impacts that have been investigated for GM crops, many different criteria could be utilised for post-release monitoring (Table 2). Existing approaches to measuring the ecological impact of agriculture largely focus on the incidence of nutrient-derived pollution, either in terms of the presence of specific chemicals or their compound environmental effect. These kinds of measures are clearly relevant to GM crops with an enhanced capacity for nutrient uptake and utilisation. The toxicological impact of pest-resistant GM crops could be assessed using specific measures of pesticide contamination, although no annual monitoring policy for pesticide contamination is currently in place (EPA 2004).

While there are no ecological impacts that are unique to GM crops (Figs 1 and 2), additional post-release ecological impact criteria might be appropriate for addressing specific public concerns about the technology. We have identified three such criteria: gene flow, biodiversity trends and ecosystem functions (Table 2). Gene-flow monitoring is specifically concerned with the interfertile WRs of GM crops listed in Table 1 and would involve background monitoring for the appearance of transgenes in these WR populations (Fig. 1). Reduction and extinction of native WR genotypes through hybridisation and competition from feral GM crops would also need to be considered. Baseline data for monitoring this type of change could come from flora guides (e.g. Webb *et al*. 1996) and from census/distribution accounts (Scannell and Synott 1987; Preston *et al*. 2002).

Broader trends in biodiversity could be measured in several ways (Table 2), including monitoring for changes in: (i) rare or endangered species included in the Irish Red Data Book; (ii) indicator species that play a crucial role in the food chain; (iii) figurehead species of particular value to tourism and recreation (such as butterflies, flowering plants and predatory birds and mammals) and (iv) general trends in biodiversity as recorded in various biological records.

An assessment of the impacts on ecosystems as a whole could be achieved through the monitoring of ecosystem function, which broadly refers to the processing and provision of resources in natural ecosystems, including biomass cycling (e.g., carbon use), nutrient cycling (e.g., for use by agriculture) and the maintenance of stability in the face of physical disturbance (e.g., storms, climate change) or biological disturbance (invasive species, pathogen outbreak).

There are Irish national surveys and/or specific case studies that address the impact of conventional agriculture under each of these ecological criteria; however, the available data for the equivalent impact of GM crop cultivation is much more limited (Table 2). The provision of adequate baseline data for future monitoring clearly requires a much greater investment in research into the impact of GM crop cultivation.

ECONOMIC FACTORS INFLUENCING THE UPTAKE OF PEST-RESISTANT GM CROPS

Multiple reasons exist to support the rapid rate of acceptance of GM crops; however, the greatest motivation, directly and indirectly, is economic. In the US, for example, the adoption of insect resistant Bt cotton along the Cotton Belt has resulted in a mean profit advantage of $16 to $170 per acre, whereas the average net benefit of growing herbicide resistant ('Roundup Ready') cotton is between $17 and $108 per acre in the same states (Marra *et al*. 2002). In Hawaii, the introduction of a papaya variety engineered for resistance to the papaya ring spot virus ended an epidemic that had threatened to destroy an industry with an annual turnover of $45 million (Zakour and McCandless 1998). In a broader context, the eight GM crop cultivars adopted by US growers in 2001 reportedly saved $1.2 billion in production costs (Gianessi *et al*. 2002), generating a tangible impact across many crop sectors.

The economic benefits derived from GM crops vary considerably between continents, countries, states and even counties, being influenced by a myriad of social, agricultural and economic factors. In relation to Bt cotton, for example, economic gains approximated to US$550 per hectare in China (Pray *et al*. 2002), US$50 per hectare in South Africa and between US$25 and US$50 per hectare in Australia and Argentina (James 2002a). However, increased productivity can also have a negative impact on commodity prices. This was observed in China in 2001, where the price of GM cotton declined by 30% compared to the previous year (Pray *et al*. 2002). These cases underline the importance of researching each GM introduction on a case-by-case, location-by-location basis, as a one-fits-all economic model is inappropriate.

The principal economic advantage to Irish farmers of growing a GM variety that is resistant to a pathogen (insect, fungus or virus) or a herbicide is that the plant will produce significantly higher yield in the presence of the pathogen or weed compared to the non-GM varieties. At the same time, the GM crop may not require multiple applications of pesticide/fungicide that would be typical for a conventional crop. Such changes raise new management options for the farmer. James (2002a) has estimated that for Bt cotton production in 2001, insecticide applications were reduced by up to fourteen applications in China, seven applications in South Africa, five in India and two in the US, where several states have recorded substantial reductions in insecticide use (Benbrook 2001). In China, the country that experienced the largest cutback in applications, this reduction was equivalent to a 78,000-tonne decrease in the amount of insecticide used (Pray *et al*. 2002). When this figure is combined with data from 1999 and 2002, it emerges that the use of Bt cotton has reduced by 123,000 tonnes the amount of formulated insecticide administered to the Chinese cotton crop (Pray *et al*. 2002). Globally, it has been estimated that the cultivation of Bt cotton in 2001 reduced overall insecticide usage by 13% (James 2002a).

With regard to herbicide-tolerant (HT) crops, the economic costs and benefits have proven somewhat more ambiguous. Firstly, many of the benefits associated with herbicide tolerance are not transferable between crops. For example, the adoption of HT soybean in the US has led to a significant decrease in herbicide use; however, this reduction has not been evident for HT cotton (Fernandez-Cornejo and McBride 2000). The cultivation of HT soybean in the US has been a notable commercial success, with over 65% of soybeans cultivated in 2001 being herbicide tolerant (Benbrook 2001). The principal motivation for HT soybean uptake by farmers is the flexibility that the novel crop introduces to existing weed management programmes (Gianessi and Carpenter 2000; Benbrook 2001). Four years of data collected by the US Department of Agriculture support two conclusions: fewer active ingredients were applied to GM soybean compared to the non-GM soybean crops, but at the same time there was a slight increase in the volume of herbicide used (Benbrook 2001).

In the absence of appropriate regulation and safety, the practice of applying chemical protectants to crops is a hazardous task. The Green Revolution of the 1960s advocated the wide-scale use of chemicals to protect higher-yielding crops from a myriad of pests and diseases. This practice, which was intended to increase yield and sustainability, inadvertently encouraged the evolution of more virulent pests and pathogens, causing farmers to increase chemical applications to the point where their own health was adversely affected. Even in the US, where adherence to farm health and safety is considered high, more than 10,000 poisonings are still recorded each year (Phipps and Park 2002). The introduction of GM crops has had a significant impact on the extent of poisonings in certain agricultural systems. For example, the adoption of Bt cotton in one region of China between 1999 and 2001 saw a reduction in pesticide poisonings from 22% with conventional cotton crops to 4.7% with Bt cotton (Huang *et al.* 2002). Similarly, in South Africa there is substantial evidence to suggest that Bt cotton, compared with the conventional crop, has indirectly decreased the level of poisoning of agricultural workers (James 2002a). In combination, these data from China and South Africa point to several positive economic, management and social impacts of pest-resistant GM crops, factors that are crucial to farmer acceptance of GM technologies.

Table 2—Potential criteria for assessing the ecological impacts of GM crop cultivation in Ireland.

	Irish case studies and data sources		*Irish GM crop impact studies*	
Agrochemical pollution				
Groundwater quality	EPA 2004	[national survey]		
Eutrophication	EPA 2004	[national survey]		
Fertiliser use (NPK)	Coulter *et al.* 2002	[national survey]	Mitchell 2000	[sugar beet c.s.*]
Pesticide use	OECD 2002	[composite national data]	Mitchell 2000	
Gene-flow				
Crop/wild relative hybridisation	Stace 1975	[Irish hybrid flora]	Flannery *et al.* 2002	[*Brassica napus* c.s.]
	Webb *et al.* 1996	[Irish flora]	Cloney *et al.* 2003	[*B. rapa* c.s.]
	Preston *et al.* 2002	[flowering plants, atlas]	Meade *et al.* 2004	[*Lolium spp* c.s.]
Biodiversity trends				
Endangered species	Curtis and McGough 1988	[Irish Red Data Book]		
Wild relatives	Scannell and Synott 1987	[Census of Irish flora]		
	Webb *et al.* 1996	[Irish flora]		
Indicator species	Good 1995	[fauna c.s.*]	Mitchell 2000	
	Heritage Council 2000	[fauna, flora],		
	Cooke *et al.* 2002	[barn owl c.s.]		
	Taylor and O'Halloran 2002	[corn bunting c.s.]		
Figurehead species	Richardson 2000	[bats, atlas]		
	Gibbins *et al.* 1993	[birds, atlas]		
	Asher *et al.* 2001	[butterflies, atlas]		
	Preston *et al.* 2002	[flowering plants, atlas]		
General trends	Heritage Council 2002	[biological datasets]		
Ecosystem functions				
Biomass	Cruickshank *et al.* 1998	[Carbon mass, N. Ireland]	Mitchell 2000	
	Giller and O'Donovan 2002	[grassland c.s.]		
Nutrient cycling	Gardiner and Ryan 1964	[soil types]		
	Herlihy *et al.* 1979	[nitrogen availability]		
Ecosystem stability	Giller and O'Donovan 2002	[grassland c.s.]		

*c.s. = *case study*.

The realisation of these economic, management and social benefits is contingent upon penetration of GM-derived foods into consumer markets, and on this issue consumers in the US and EU appear diametrically opposed. While GM foods are readily consumed in the US, Europeans are reticent about and often hostile towards the use of GM ingredients. These differing consumer attitudes have ramifications across many areas of international trade, particularly in relation to market access for GM food products in the EU, thus highlighting the importance of developing international codes of practice in relation to GM crop production, segregation and labelling.

For the majority of countries that grow GM crops (and several others that do not, including Ireland), the approval process associated with the adoption of novel GM crops is strictly regulated through state-funded organisations. Prior to approval, all modified cultivars typically undergo an environmental risk assessment that considers potential harm to human health and the natural environment. Although the food safety crises that arose throughout Europe in the mid-1990s related to health scares in non-GM products, these crises amplified consumer distrust of state regulatory agencies within the EU. Consequently, over the last five to eight years, consumer confidence in the ability of these organisations to safeguard the food supply has been continuously eroded.

A casualty of this scepticism about state agencies has been the EU approval process for new GM crops, which was halted in 1998. The European Commission subsequently assembled a novel labelling and traceability proposal (EU regulation 1830/2003), which has recently been turned into legislation by the European Parliament. This regulation mandates that all products that have more than 0.9% of their ingredients derived from GM organisms must be labelled accordingly, even if the product no longer contains the modified DNA. In such a case, the product is to be termed 'GM-derived'. These labelling provisions will impart all the pertinent GM-related information required to enable European consumers to choose between GM and non-GM products. It is anticipated that the introduction of this legislation will reopen the market in the EU for GM material, though it has been forecast that GM seed will not be widely available to EU producers of maize until 2005–6, and in the case of GM oilseed rape and sugar beet seed, not until 2006–7 (Brookes and Barfoot 2003).

Quite aside from the direct impact on GM growers, the labelling law raises an important issue for non-GM farmers whose crops adjoin GM plots in neighbouring farms. Under current proposals recommended by the European Commission (2003/556/EC), the admixture of GM derived pollen and/or seed into a non-GM equivalent crop would result in the non-GM produce being labelled as GM if the content of GM material transferred exceeded the 0.9% threshold. To offset this scenario, GM crops will have to be compartmentalized from non-GM crops. This will require a novel approach to land management, with emphasis on the efficient segregation of crops (through spatial separation and crop-barriers) and of machinery and on the control of volunteers. In response to the European Commission's published guidelines for the establishment of best practices in regard to the co-cultivation of GM crops with conventional/organic crops (European Commission 2003) a technical working group has been established in Ireland by the Department of Agriculture. The remit of this group is to develop proposals for a national strategy and best practices to ensure the co-existence of GM and non-GM crops, and it is anticipated that recommendations from this working group will be finalised in Spring 2005.

A recent report prepared for the New Zealand Ministry of the Environment concludes that co-existence between GM and non-GM crops is possible (Christey and Woodfield 2001). This report specified three elements that are essential for achieving effective co-existence: a robust regulatory approach, a 'whole of production chain' perspective, and case-by-case testing. In practical terms, the effective management of co-existence is likely to be problematic, particularly in countries, regions or industries where management of traceability is limited or sparsely resourced. Difficulties of this nature were central to the Zambian government's 2002 decision to refuse GM food aid from the United States, on the basis that such food aid would jeopardise agricultural links between Zambia and the European Union (BBC 2002).

In Europe, it is anticipated that the newly proposed laws relating to GMOs will allow full market access for GM food, restart the GM crop approval process and, at the same time, appease those member states and citizens who are against GM food or who do not wish to see the GM field-crop moratorium lifted (Scott 2003).

CROP COSTS AND MARGINS AND THE GM NICHE IN IRELAND

Ultimately, GM crop cultivation in Ireland is not tenable unless there is consumer acceptance of GM food ingredients, regardless of whether the GM component is targeted at the consumer, that is, as a novel quality in the food product, or at the producer, by helping to reduce costs. However, in the event that acceptance by Irish consumers becomes a reality, what might the impacts of GM crop cultivation be? The main factor influencing utilisation of licensed GM crops will be market demand—both from consumers (in terms of food products and food production standards) and from producers (in terms of input-reducing/cost-saving crops) (McGloughlin and Burke 2000).

The current generation of GM crops is overwhelmingly targeted at pest resistance, and cost savings are realised through a reduction in the level of pest-control inputs required during the crop cycle. Input costs associated with crop production in the US have driven research and development in novel crop technology over the last decade. However, with the spread of technological capability to Europe and beyond, more locally tailored pest-resistance crops are likely to emerge throughout the world in the medium to longer term. A potential indication of future demand from Irish producers for pest-resistant GM crops might be garnered from current cost structures in arable crop production, and in particular from costs for crop protection. Teagasc figures (Fig. 3) reveal several trends in the costs and types of inputs associated with the four main arable crop groups (cereals, fruit and vegetables, processed oil and sugar crops and fodder crops), and these provide a guide as to the likely targets for novel GM traits.

As a percentage of annual inputs, cereals and fruit and vegetables generally require much higher fungal and pest protection than do the fodder and processed crops, while herbicide costs are highest in the latter two groups and for certain low-growing fruiting plants such as strawberries and peas. Insecticide consumes the highest proportion of the inputs budget for carrots and spring oilseed rape, but represents the lowest input cost for peas, beans and cabbage. Fertiliser is a requirement of all crops, but it absorbs the lowest percent of input costs in apple and strawberry production. Seed costs tend to be significantly higher for fruit and vegetables than for the other crop groups, although seed is also an important cost for certain fodder crops that otherwise require relatively low input levels.

Grassland production differs markedly from arable crop cultivation in that fertiliser accounts for almost 100% of the annual input budget for grassland. Herbicide and fungicide applications are required only periodically, at relatively low levels, and in a very small proportion of farms nationally; insecticide is not required at all (Teagasc 2002).

If we factor in the areas under cultivation for each of the crops (Table 1) and assume that the appropriate GM lines become commercially available in Ireland in the short to medium term, we can make a tentative prediction of how trends in national demand for pest-resistant GM crops might develop, and how these trends might impact on agroecological systems. It is probable that the highest overall demand will be for crops with fungal resistance, particularly in cereals and potatoes. Herbicide resistance in sugar beet will also have market demand, and the least overall demand will be for insect resistance in crops such as oilseed rape and carrots.

Transgenic pathogen-resistant crops, and in particular fungal-resistant crops, have been much slower to appear than insect-resistant and herbicide-tolerant crops, mainly because of the difficulty in isolating and characterising genetic resistance mechanisms (Jones 2001; McDowell and Woffenden 2003). However, recent genetic analysis in several model plant species has accelerated this isolation/characterisation process, and many novel pathogen-resistant plants have begun to appear as a result. These include: potato with enhanced resistance to blight (*Phytophthora infestans*) (Song *et al.* 2003); barley with complete resistance to 'stem rot' (*Puccinia graminis* f. sp. *tritici*) (Horvath *et al*. 2003); 'blackleg'- (*Leptospaeria maculans*) resistant oilseed rape (Wretbald *et al.* 2003); and sunflower with improved resistance to 'stem rot' (*Sclerotinia sclerotiorum*) (Burke and Rieseberg 2003).

Improved understanding of defence signalling also promises wider availability of durable broad-spectrum resistance (Cao *et al*. 1998; Moffat 2001). Taken together, these developments clearly suggest that fungal-resistant GM crops are likely to reach the marketplace in the near future, with profound effects on farmer demand for pest-resistant GM crops in Ireland. Ecological research on fungal resistant transgenes is still in its infancy worldwide (Brown 2001), however, existing Irish expertise in plant pathology can be readily co-opted to assist in the task of risk assessment.

The demand for pest-resistant crops will also have a significant regional bias correlated with the concentration of tilled land in the east and southeast of the country, as is the case with conventional pesticide usage. However, as technology advances in the medium to longer term, modifications that increase nitrogen, phosphate and sodium availability to all crop plants are likely to appeal to grassland farmers as well.

Inferring that existing input cost structures will translate into market demand for GM crops, as we have done, assumes that novel transgenic lines will deliver genuine cost reductions for Irish farmers. But is this likely? One useful example in this context is genetically-modified, herbicide-tolerant (GMHT) sugar beet (*Beta vulgaris* ssp. *vulgaris*), one of the better studied GM crops in Europe and to date the only one for which field evaluations have been carried out in Ireland (Mitchell 2000).

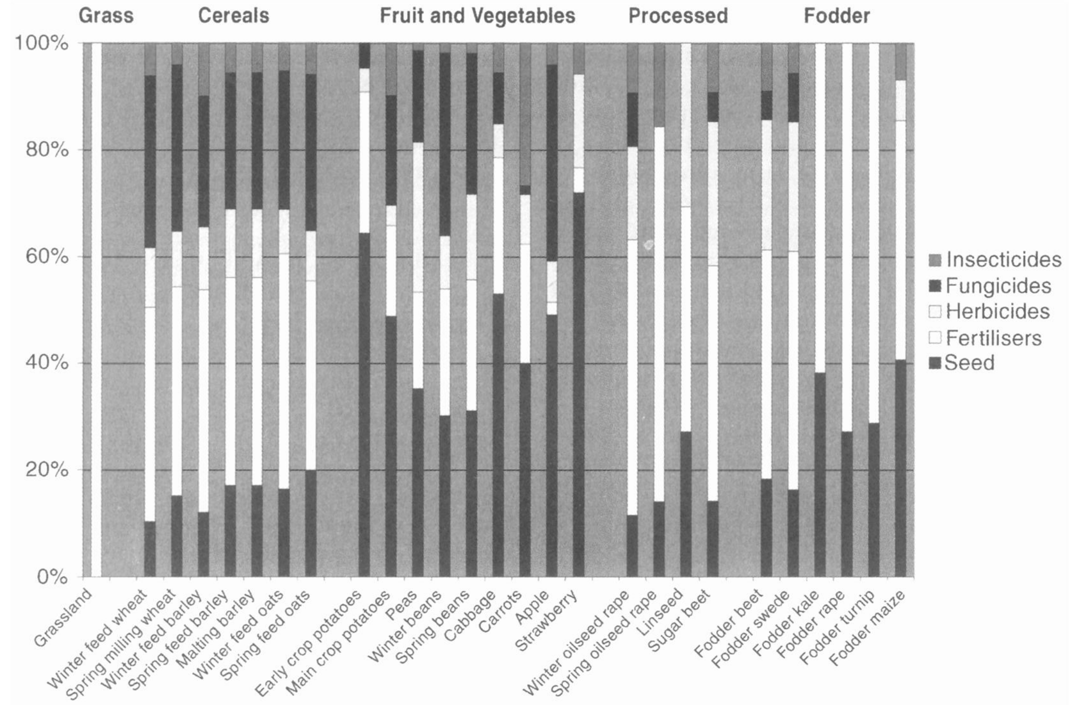

Fig. 3— Annual costs for insecticide, fungicide, herbicide, fertiliser and seed inputs for Irish crops (as a percentage of total input costs). Data from Teagasc (2002).

Herbicide spraying is a significant financial and management consideration for sugar-beet growers. The slow first season growth of the crop renders it vulnerable to a variety of colonising weeds, while volunteer crop weeds such as weed beet and potatoes (*Solanum tuberosum*) are also a significant problem (Mitchell 2000). Untreated, these weed infestations can reduce sugar-beet yields dramatically, and in some cases lead to total abandonment of the crop (Schweizer and Dexter 1987; Mitchell 2000; May 2001). Crop protection for sugar beet can absorb as much as 15% of total production costs (Mitchell 2000), and in certain cases the cost of protection can be much higher (Leeds 2002; May 2003).

Conventional control methods involve the post-emergence application of low-dose herbicide cocktails when weeds are at the few-leaf stage, with an average of four to seven sprays required for effective weed control over the growing season (Mitchell 2000; Dewar *et al*. 2003; May 2003). Spraying is curtailed during stress periods (e.g. extremes of temperature, sunshine), when the beet crop becomes susceptible to herbicide toxicity. In addition to chemical treatment, manual hoeing is also increasingly required to deal with weed-beet infestations (May 2001; B. Mitchell, Teagasc, pers. comm.).

One novel GMHT sugar beet that has received particular research attention is the glyphosate-resistant Roundup Ready sugar beet, developed by Monsanto Corporation. Glyphosate is a broad-spectrum systemic herbicide that kills target plants by disrupting the aromatic amino acid biosynthesis pathway, and as such it is not suitable for use with conventional sugar beet crops. However, the Monsanto GM variety counters the toxicity of glyphosate through the up-regulation of a specific gene involved in the targeted pathway. Field trials supported by Monsanto in Ireland and the UK suggest that this GMHT sugar beet allows effective control of weeds, including weed beet and potatoes, with one to two post-emergence applications of glyphosate, while marginally or significantly increasing the yield and vigour of the crop when measured against a conventional control crop (Mitchell 2000; Wilson *et al*. 2002; Dewar *et al*. 2003).

Even allowing for increased seed technology costs, the total financial savings for the average farmer are considerable (Mitchell 2000; May 2003). Clearly, if these cost savings are repeated for other input-oriented GM crops, market demand will be significant. Indeed, the large-scale uptake of GM crops by farmers in countries outside the EU is strongly correlated with the types of economic and management advantages evident for GMHT sugar beet (James 2002a).

While economic benefits such as these will certainly enhance the market for GM crops, demand in certain Irish sectors will probably also arise out of necessity. The gradual homogenisation of existing crop varieties under cultivation worldwide, coupled with the intensive use of crop protectants, has had the combined effect of accelerating the capacity of many plant pathogens to cause disease (Moffat 2001). From an Irish perspective, classic examples of this rapid pathogen evolution can be seen in both potato blight (*Phytophthora infestans*) and winter wheat leaf blotch (*Septoria tritici*). In the case of the latter, the cereal pathogen has developed strong resistance to the primary class of prophylactic fungicides (strobilurins). The resistant strain (G143A) was first observed in Ireland during the 2001–2 growing season, and preliminary results from a nationwide survey completed by Teagasc indicate that it has already established itself throughout the cereal-growing regions of the country (Mullins 2004). In the case of potato blight, strains have become more virulent, more resistant to fungicides and more durable in the over-winter phase than ever before (Garelik 2002). Many of these changes are believed to be associated with the spread of sexually-reproducing strains from Mexico into Europe, and more recently, into Ireland (Dowley *et al*. 2000). Consequently, as conventional fungicide sprays become progressively obsolete, sustainable integrated pest management for certain crops may become more reliant on the use of transgenic/molecular breeding, and in particular on the introduction and/or up-regulation of polygenic multi-locus resistance (Landeo 2002).

Gianessi *et al*. (2003) have estimated that under current economic and phytopathology circumstances, a blight-resistant potato variety could significantly reduce annual Irish expenditure on fungicide. Allowing for an assumed increase in seed costs of €0.7 million, the report by Gianessi *et al*. suggests that net income for the Irish potato sector could increase by up to €5 million and the annual potato yield by 1800 tonnes if a blight-resistant potato variety were introduced. Recent advances in the isolation of novel sources of blight resistance mean that engineering potatoes for this resistance is very achievable in the medium term (Song *et al*. 2003).

All of the above analyses are subject to an important consideration for biotech companies in the European market that are producing GM crops, namely the potential cost of active co-existence management and post-release monitoring. In a climate of continued consumer hostility towards genetic modification, it is also likely that additional insurance premiums will apply to biotech companies seeking commercial releases: projected insurance costs were cited by Monsanto Corporation in its recent decision to end GM crop development in Europe (Uhlig 2003). An increase in public confidence in the technology will probably lead to a reduction in insurance risk. Similarly, as post-release ecological and co-existence data accumulate, improved management and co-ordination will probably result in reduced costs for these factors also.

DISCUSSION AND CONCLUSION

The debate that surrounds the whole issue of GM crops has become highly polarised, making it increasingly difficult to decipher scientific fact from speculation and conjecture. In an attempt to overcome this predicament various initiatives have been started to produce transparent, scientific guidelines to monitor the risk/benefit of GM crops, and many of these are now freely available on the Internet (Table 3).

Perhaps the most pertinent question in relation to the ecological impact of GM crops is not whether they will be damaging to the environment (conventional agriculture in all its forms is inherently damaging to the environment), but whether or not GM technology will ameliorate the damage already taking place (Tiedje *et al*. 1989). Ireland's rural landscape is not a pristine 'green' environment that might perhaps be compromised for the very first time by the introduction of GM crops. Rather, it is amongst the most heavily fertilised land anywhere on earth, with an average application of 14.21 tonnes of fertiliser per hectare of farmed land compared to an average of 11.13 tonnes in the EU as a whole (OECD 2002). Agricultural land is also subject to considerable herbicide and pesticide inputs wherever arable farming is practiced (OECD 2002).

Therefore, in a holistic agroecological context, the question of whether GM crops are damaging to the environment might properly be phrased: Are they more or less damaging than conventional crop-production systems? Indeed, as Ireland attempts to move away from an emphasis on quantity and towards quality in agricultural production, including consideration of environmental, community and income quality (Department of Agriculture 2000), it may be that GM crops have a role to play in diminishing our overall impact on the environment, if not necessarily our impact on particular species and food webs.

Without the consent of society at large the future of GM crops remains in doubt (Nap *et al*. 2003). If consumers are against the presence of GM crops in the food chain, then there will be no economic benefit to growers in using the new technology. However, it is possible that the increasing body of data relating to the direct ecological impacts of GM crops and the provision of post-release monitoring will help address public concern over the effect this new technology will have on the natural environment. In this context, it should be acknowledged that unexpected benefits, as well as problems, will come to light.

Equally, it has been demonstrated that gene flow from outbreeding GM crops to other crops/WRs can and will take place in much the same way as for non-GM crops, and the trait coded for by the transgene will determine whether or not it perseveres outside cultivation, that is, whether or not it confers a competitive advantage to the plant concerned. However, acceptable levels of gene flow from GM crops to other crops and WRs will be determined by public opinion as much as by scientific advice, and all stakeholders are probably aware that the majority may decide that this acceptable level is zero. In such a scenario, there will be no market for outbreeding, pollen-producing GM cultivars, even if the transgenes and hybrids concerned will not survive outside cultivation.

However, while acknowledging the many objections to GM crops on a philosophical basis alone, we would appeal for a rational holistic analysis of the options facing Irish and world agriculture at this juncture. These options include organic farming, integrated pest management and 'business as usual' management strategies based on high-input agrochemicals. Completely precluding the use of pest-resistant GM crops bars us from using a dynamic and effective tool for increasing our control of agriculture, and therefore our ability to control the environmental impact of agriculture.

Thus far the only analysis of an actual GM crop in Ireland has focused on agronomic factors such as costs, logistics and crop yields. For Ireland to meaningfully participate in the assessment of GM crop technology, a more pro-active, field-based analysis programme is required, with adequate

Table 3—Internet resources representing biased/unbiased sides of the GM crop debate.

Association/Organisation	*Internet URL*
AgBio World Foundation	http://www.agbioworld.org/
AgBiotech Reporter Newsletter	http://www.bioreporter.com/
Agricultural Biotechnology in Europe	http://www.abeurope.info/
Bio-scope	http://www.bio-scope.org/index.cfm
Council for Agricultural Science and Technology	http://www.cast-science.org
Council for Biotechnology Information	http://www.whybiotech.com/
Economics and Management of Agrobiotechnology	http://www.agbioforum.missouri.edu/
Essential Biosafety	http://www.essentialbiosafety.info/main.php
European Association for Bioindustries	http://www.europabio.org
European Commission site on the deliberate release and placing on the EU market of GMO products	http://gmoinfo.jrc.it/
European Food Safety Authority	http://www.efsa.eu.int/
European Network on the safety assessment of GM food crops	http://www.entransfood.com/
Food and Agricultural Organisation of the United Nations	http://www.fao.org/
Foundation for Biotechnology and Awareness	http://www.fbae.org/toc.htm
GMO Guidelines project	http://www.gmo-guidelines.info/
Greenpeace	http://www.greenpeace.org
Information resource on the safety of Agricultural Biotechnology	http://www.foodsafetynetwork.ca/ge.htm
International Forum for Genetic Engineering	http://www.anth.org/ifgene/
International Service for the Acquisition of Agri-biotech applications	http://www.isaaa.org/kc/
John Innes Research Centre, UK	http://www.gmissues.org/
Literature resource for Agricultural Biotechnology	http://www.agbiotechnet.com
National Centre for Food and Agricultural Policy	http://www.ncfap.org/biotech.htm
Biosafety of Genetically Modified Organisms	http://www.worldbiosafety.net
OECD global database of GM field trials to 1999	http://webdomino1.oecd.org/ehs/biotrack.nsf
Economic Research Service, U.S. Dept. of Agriculture	http://www.ers.usda.gov/Publications/
Pew Initiative on Food and Biotechnology	http://pewagbiotech.org/

provision for full ecological impact assessment. It is likely that the input-oriented GM crops with the greatest market appeal for Irish farmers, and so the greatest potential acreage, are cereals with fungal resistance. Herbicide-tolerant crops are likely to be less significant, and insect-resistant crops the least significant of all. From a risk analysis perspective, the direct and indirect ecological impacts of cultivating these GM crops are measurable. The extent of gene flow from GM crops to other crops and wild relatives is also measurable, and whereas predicting the outcomes of transgene movement is more difficult, with proper research support it can also be done.

Whereas the majority of GM crop trial reports are accurate for the subject/region studied, the extrapolation of results into a broader general context is unwise. If GM crops are to be adopted in Ireland, it must be acknowledged that the geographical, environmental and socio-economic influences of a designated site do have a profound impact on the assessment process. From an Irish context, this is important. If we are to develop an accurate risk/benefit assessment process for this technology, then a more responsible and pro-active research approach must be adopted. There is no doubt that the ecological questions relating to GM crop cultivation can be answered.

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